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Description of the NIF Laser

M. Spaeth, K. Manes, D. H. Kalantar, P. E. Miller, J. E. Heebner, E. S. Bliss, D. R. Speck, T. G. Parham, P. K. Whitman, P. J. Wegner, P. A. Baisden, J. A. Menapace, M. W. Bowers, S. J. Cohen, T. I. Suratwala, J. M. Di Nicola, M. A. Newton, J. J. Adams, J. B. Trenholme, R. G. Finucane, R. E. Bonanno, D. C. Rardin, P. A. Arnold, S. N. Dixit, G. V. Erbert, A. C. Erlandson, J. E. Fair, E. Feigenbaum, W. H. Gourdin, R. A. Hawley, J. Honig, R. K. House, K. S. Jancaitis, K. N. LaFortune, D. W. Larson, B. J. Le Galloudec, J. D. Lindl, B. J. Macgowan, C. D. Marshall, K. P. McCandless, R. W. Mccracken, R. C. Montesanti, E. I. Moses, M. C. Nostrand, J. A. Pryatel, V. S. Roberts, S. B. Rodriguez, A. W. Rowe, R. A. Sacks, J. T. Salmon, M. J. Shaw, S. Sommer, C. J. Stolz, G. L. Tietbohl, C. C. Widmayer, R. Zacharias

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ABSTRACT

The possibility of imploding small capsules to produce mini-fusion explosions was explored soon after the first thermonuclear explosions in the early 1950s. Various technologies have been pursued to achieve the focused power and energy required for laboratory scale fusion. Each technology has its own challenges. For example, electron and ion beams can deliver the large amounts of energy but must contend with Coulomb repulsion forces that make focusing these beams a daunting challenge. The demonstration of the first laser in 1960 provided a new option. Energy from laser beams can be focused and deposited within a small volume; the challenge became whether a practical laser system can be constructed that delivers the power and energy required while meeting all other demands for achieving a high-density, symmetric

implosion. The National Ignition Facility (NIF) is the laser designed and built to meet the challenges for study of high-energy-density (HED) physics and inertial-confinement-fusion (ICF) implosions. This paper describes the architecture, systems, and subsystems of NIF. It describes how they partner with each other to meet these new, complex demands and describes how laser science and technology were woven together to bring NIF into reality.

Keywords: ICF, Laser, Fusion Driver, NIF Laser

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I. INTRODUCTION

The NIF laser at Lawrence Livermore National Laboratory (LLNL) (see Fig. 1) is the culmination of 50 years of work directed toward providing a facility that can aggressively support high-energy-density-science activities (HEDS).¹ It provides important experimental capabilities to the Stockpile Stewardship Program and supports both fundamental science experiments and research for the ignition of thermonuclear burn in the laboratory. NIF is the world's largest optical system, simultaneously delivering the highest-energy and highest-power laser pulses of any facility operational today. It is precise, delivering shots meeting stringent

performance requests more than 95% of the time. It can routinely deliver near-ultraviolet ($0.351\ \mu\text{m}$, 3ω) energy on target of greater than 1.8 MJ within pulse shapes that meet the requests of users from the inertial confinement fusion (ICF), high-energy-density, and astrophysics communities. Although NIF was designed to serve a number of missions, the most demanding of these missions is ICF, and this description of NIF is provided in that context.^{2, 3, 4, 5, 6}

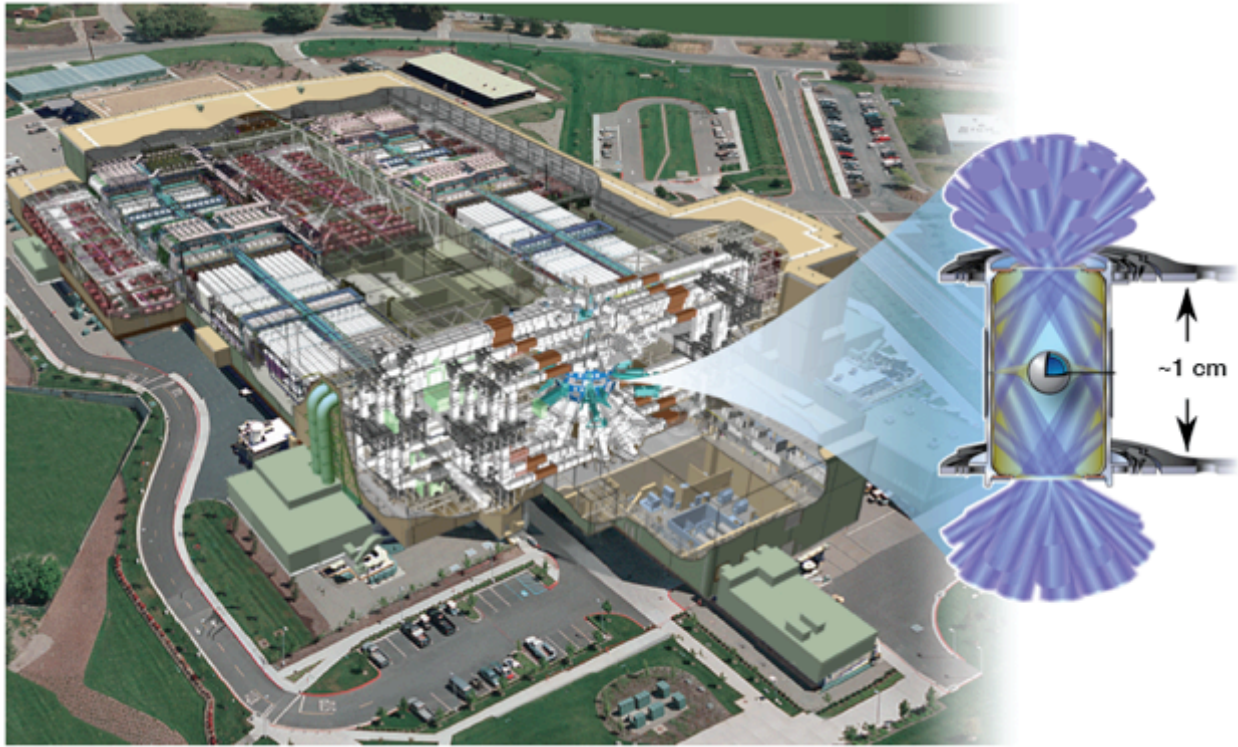


Fig. 1: A cut-away view of the NIF laser facility. The footprint of the building covers an area equivalent to just over three football fields. NIF is currently configured for the study of indirect-drive ICF targets, imploding capsules at the center of a surrounding x-ray-emitting hohlraum. In NIF, 192 converging laser beams heat a $\sim 1\ \text{cm}$ hohlraum to a radiation temperature of $\sim 300\ \text{eV}$.⁷

II. DEVELOPING THE ARCHITECTURE OF NIF

A timeline of events that led to the realization of NIF is provided in Fig. 2. Although this is not intended to be a historical document, the technical motivations for the NIF design and the

technical decisions made for its component designs were shaped by the information available at the time. This schedule will serve as a backdrop for discussions throughout this article regarding the description of the laser.

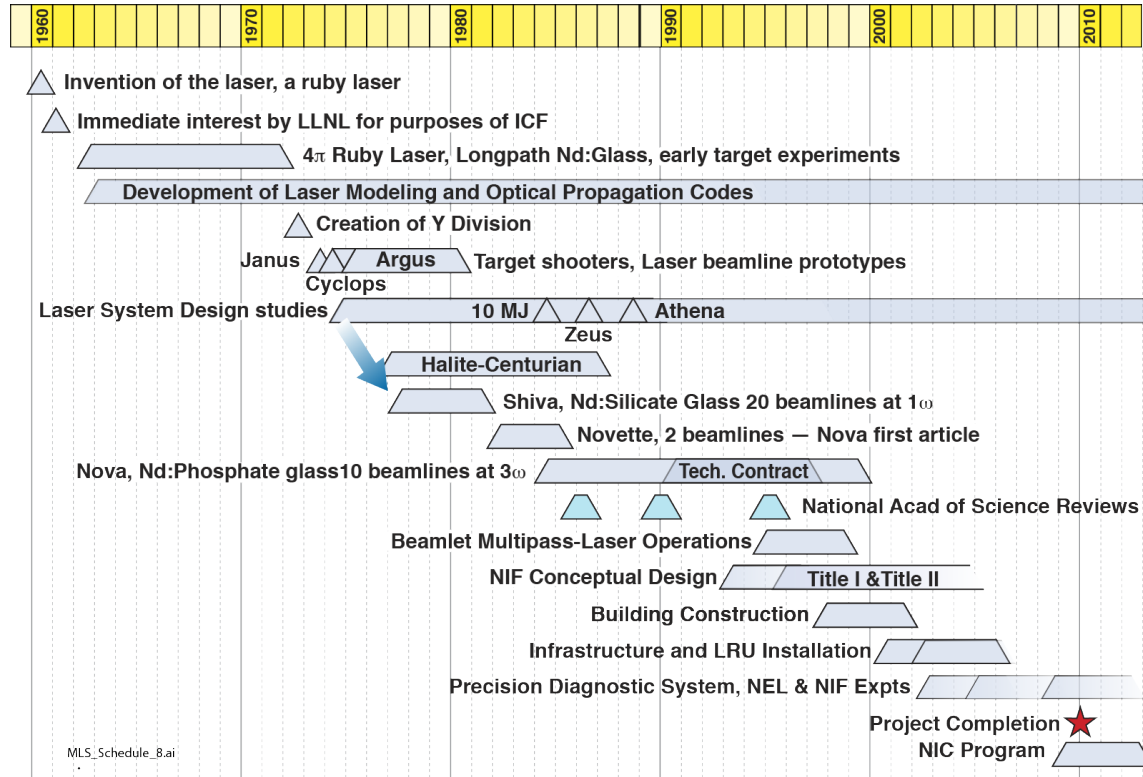


Fig. 2: Historic timeline of events at LLNL after invention of the ruby laser, in pursuit of a large laser driver for study of high-energy density physics.

Work directed toward demonstration of laser-driven inertial confinement fusion at the Lawrence Livermore National Laboratory began shortly after the invention of the laser was announced in 1960.^{8, 9} During the next ~10 years, exploratory work was conducted at LLNL on both lasers and the interaction of intense light with plasmas using a variety of laser media then available, including ruby, several excimers (the “Rapier” KrF laser with pulse compression and shaping), CO₂, and Nd:Glass.¹⁰ In 1962, the director of LLNL, Johnny Foster (John S. Foster

Jr.), formed “Q Division” under the leadership of Ray Kidder with the charter to study the interaction of electromagnetic radiation with matter and applications for thermonuclear fusion.¹¹

Fig. 3 is a photograph of the first target chamber built to study these interaction experiments at LLNL. In the summer of 1972, Carl Haussman collected the Q Division effort and other laser work being conducted around LLNL and co-located all of their activities, organizing this combined effort into the newly formed Y Division. Shortly thereafter, John Emmett from NRL joined LLNL and became the leader of Y Division.¹² Laser activities then became centered in the northeast corner of LLNL.

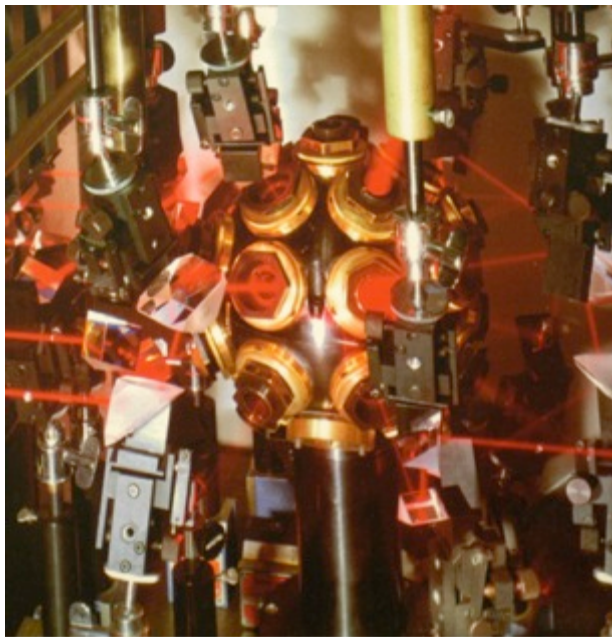


Fig. 3: The first target chamber at LLNL, referred to as “ 4π ” has a diameter of 15 cm. In this photograph it is being illuminated by 12 beams from a ruby laser.¹³

As work after 1972 continued, a number of lasers—Cyclops,¹⁴ Janus, and Argus¹⁵—were built at LLNL and used to study laser interactions with targets. In fact, after invention of the laser, interest in exploring laser-driven inertial confinement fusion developed across the U.S. and

around the world. In addition to the work at LLNL, research in the U.S. began at KMS Fusion, Los Alamos National Laboratory (LANL), Sandia, University of Rochester (in particular OMEGA 24 began operating in 1980), Naval Research Laboratory, and many universities. Operating these lasers led to better understanding of the needs of an ICF target and to the constraints and design flexibilities that had to be considered as laser development continued.¹⁶ Code predictions of target behavior and work with targets in these systems set goals for the wavelength and performance of future laser systems. Forward-looking laser work focused on identifying robust and scalable candidates in the ~MJ class with a wavelength in the near UV.

Coming up with the concepts for the architecture of both the building and the beamlines discussed in this paper took years to accomplish. By its nature, an ICF driver is large and expensive; recognition of this perspective drove effort for reducing the wide field of laser-design choices then available in search of a combined laser and target-chamber architecture that could produce the highest energy and power for the lowest capital cost while staying within optical damage and other limits. By 1972, some of the earliest computerized simulation tools were being used for estimating the cost and schedules of potential fusion drivers. Hundreds and thousands (and eventually tens and hundreds of thousands) of potential system designs were graded on a “bang-for-the-buck” scale and the several best candidates moved forward for more consideration during subsequent design cycles of each of the laser systems built at LLNL (Cyclops, Janus, Argus (Ref. 15), Shiva,¹⁷ Novette¹⁸ and Nova^{19, 20, 21}). One understanding that came out of work on these systems is that the ability of the plasma to absorb light improves as the laser wavelength is reduced. The third harmonic of Nd³⁺ .3 ω , at 0.351 nm was chosen as the goal at LLNL to avoid the very significant increase in optical damage problems that would be encountered at the fourth harmonic, 4 ω , at 0.263 nm. During the mid-to-late 1980s, using tools that had been

developed in the course of designing Nova, three formal design studies of large ICF laser systems were completed at LLNL: The MultiMegaJoule Laser Design,²² Zeus, and Athena.²³ On the basis of these studies, a number of cost-driving, laser-system features came to be understood, giving insights that persisted into concepts for NIF, including that the system cost scales sub-linearly with the surface area of the amplifier assembly and that the cost of the conventional facility typically scales with the footprint area of the floor. For NIF, these insights led to grouping beamlines together in the largest practical amplifier assemblies (2×4 square-beam bundles in six-bundle clusters that will be seen in Section VI.A) and to housing of the laser and target bays in a 3D, multi-floor structure.

Shiva and Nova were major engineering projects that required creation of a laser engineering component of the engineering capabilities at LLNL. Laser scientists and engineers worked together with hundreds of industrial collaborators to produce the drawing and procurement packages necessary for construction of these lasers. The parallel Atomic Vapor Laser Isotope Separation (AVLIS) Program at LLNL worked with the same engineering staff to develop concepts for reliability, availability and maintainability of laser systems centered around full integration of Line Replaceable Units (LRUs) as integral components of systems designed for 24/7 operation. See Section III.B for a description of how LRUs are deployed in NIF.

Results from experiments performed with Shiva and Nova are reported in Reference 7. At DOE's request, the National Academy of Sciences (NAS) reviewed the Department of Energy's Inertial Confinement Fusion Program and subsequently mandated a set of sub-scale experiments to be performed on Nova, designated as the Nova Technical Contract. These experiments were designed to narrow the uncertainties for NIF target design and to refine the Primary Criteria for the NIF laser. Emphasis was given to study of coupling of light into the hohlraum and combined

tests of symmetry and hydrodynamic instability. Results of the Nova Technical Contract are given in Reference 7 and the NAS final report.²⁴

System studies continued from the mid-1980s into the early and mid-1990s. These studies relied on a then state-of-the-art suite of performance, risk, and cost analysis codes of varying speed and accuracy, developed specifically for fusion laser design. These codes modeled pumping (lamp size, pump duration, and reflectors), extraction, linear and nonlinear propagation, damage (surface and filamentation), frequency conversion, and cost. Fast codes such as ChainOp²⁵ allowed a quick survey of many design possibilities, varying the laser aperture (for aperture scaling), pumping intensity and duration, disk counts, disk thickness, disk doping, and other parameters of the designs. The more accurate but slower physical-optics code Prop92 could then complete more detailed analyses of the most promising designs.²⁶ In the early 1990s, Prop92 and other special purpose numerical models were refined with improved physics, engineering, and cost data, and a multi-computer cluster was deployed for rapid multi-case analysis. Four different optimization techniques were deployed to automatically scan for the most cost-effective and safest designs.²⁷ With input from these tools, the design team selected the final optical design of the NIF beamlines (Ref. 1). At this point in the design sequence, the optical elements were simply levitated in 3D space, still without the mechanical support and environmental protection features that would be added later. The laser-driven elements of the Functional Requirements and Primary Criteria discussed in the next section were written with this optical design in hand. A description of subsequent refinement of this laser design will continue in Section III

II.A. The Functional Requirements and Primary Criteria of NIF

In 1993, early work on a non-site-specific conceptual design report (CDR) for NIF was authorized by then Secretary of Energy, Admiral James Watkins. The Primary Criteria for the NIF laser were developed on the basis of the expected fluid dynamic behavior of an imploding capsule and the expected response of the hohlraum plasma to the incoming light. The Functional Requirements for the major systems of NIF described the performance needed from the laser in order to meet the Primary Criteria set by an ICF target. A laser wavelength in the near UV had been the choice of the inertial confinement fusion community after experiments using Argus, Shiva, Novette and Nova at LLNL and other facilities around the world had demonstrated plasma behavior significantly more favorable for shorter wavelength light (Ref. 7). There have been no changes regarding laser performance between the original and the most recent update to the Functional Requirements and Primary Criteria (FR&PC) given in Reference 28. The FR&PC (see summary in Table I) were formally established after work on *The NIF Laser Design and Cost Basis Document*,²⁹ and the subsequent *NIF Conceptual Design Report*³⁰ were finished in 1993 and 1994, respectively.

TABLE I: Summary of the NIF Functional Requirements and Primary Criteria (FR&PC). The laser was also required to be capable of “routine operation” at 1.8 MJ at 0.351 μm . Although the FR&PC explicitly states that the requirements need not be demonstrated simultaneously, operations planning always assumed simultaneity as necessary for any individual experiment.

Level 1 Primary Criteria	Description	Level 2 Funct Req'm'ts	Description
Laser Pulse Energy	≥ 1.8 MJ	Laser Pulse Duration	Up to 20 ns
Laser Pulse Pk Power	≥ 500 TW	Pulse Dynamic Range	$\geq 50:1$
Laser Wavelength	0.35 μm	Capsule Irrad Symmetry	2 cones/hemisph, ea w ≥ 8 beams
Beamlet Power Bal	RMS quad deviation avg over 2 ns, fm Rev X point design spec	Prepulse Power	$< 10^8$ W/cm ² per hemispere
Beamlet Positioning	≤ 50 μm rms	Laser Pulse Spot Size	Design energy within ≤ 600 μm
Direct-Drive	Shall not to be precluded	Beam Smoothness	Shall have ability to do spatial & temporal beam conditioning
Laser Safety	Comply with ANSI Z136.1	Focusing & Pointing	Should have flexibility for users
Recovery Time	≤ 8 h between full system shots	Diagnostic Capability	See <i>NIF Laser System Performance</i>

The high-level architecture of the facility shown in Fig. 1 was chosen to meet irradiation symmetry requirements derived from ignition target design code predictions completed at LLNL and LANL. (For a broader discussion of “ignition”, see “Overview: Development of the National Ignition Facility and the Transition to a User Facility for the Ignition Campaign and High Energy Density Scientific Research”, also in this issue of *FS&T*.) These codes predicted that the required capsule irradiation symmetry for indirect drive targets could be achieved with architectural features of a laser that included at least two “cones of light” with at least 8-fold azimuthal symmetry entering a laser entrance hole (LEH) at each end of a hohlraum. Cost optimization and beam transport considerations by the NIF Conceptual Design Team led to the beam geometry seen in Fig. 4 and now used in NIF. Similar design calculations for uniform illumination Direct Drive targets done by LLE indicated that for optimal irradiation, it would be necessary to move some of the NIF beams to additional ports located near the equator of the NIF chamber.^{31,32} These additional ports were built into the NIF chamber. LLE later concluded that it would also be possible to pursue Polar Direct Drive (PDD) using the NIF indirect-drive irradiation geometry.³³

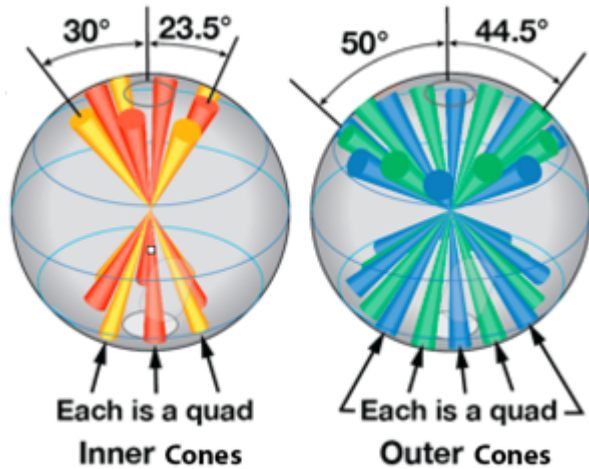


Fig. 4: Architecture for the inner and outer cones of NIF, including the configuration of beams as they converge at Target Chamber Center (TCC).

The number of beams to be delivered by NIF was established on the basis of target requirements for both symmetry and beam conditioning. “Beam Smoothness”, listed in Table I requires the laser to have the ability for spatial and temporal beam conditioning.³⁴ As described by the *NIF Laser Design Basis* (Ref. 1), flowdown of this smoothing specification added the need for each of the (at least) 48 directed inputs needed for symmetry (now called quads) to consist of 4 beams overlapping in an f/8 configuration. These 48-beam, directed inputs now appear as 48 ports around the target chamber, each supplying four laser beams per port. The combination of the symmetry and smoothness requirements led to a minimum of 192 beamlines in NIF. To meet the requirement of 1.8 MJ of total laser energy on target each laser beam is required to deliver ~ 9.4 kJ of 3ω light to the target while also meeting the other requirements defined in Table I. Selection of the beam dimension that could deliver this amount of energy had to await selection of the target chamber diameter.

Cost considerations drove the chamber diameter smaller, while consideration of damage to the final optics and the target-chamber wall pushed it larger. After settling on a final optic standoff of ~8 m and a chamber wall radius of ~5 m, attention was turned to selection of the laser beam dimension. Again this was driven smaller by consideration of cost and the availability of optical materials and driven larger by consideration of the combination of optical damage concerns, optical materials availability, target-alignment tolerances, and generation of the desired optical profiles at the target. In the end, the beamline aperture was limited by the dimensions of crystal optics that were believed could be grown during the time frame of facility construction.

Laser system designers and material suppliers settled on ~37 cm square laser beams within a clear aperture of 40 cm. For each beam to be capable of delivering ~9.4 kJ to the target, it was required to handle an average 3ω fluence (energy per unit area) of $>8.5 \text{ J/cm}^2$ on its final optics—an amount more than ten times higher than any prior laser system had ever delivered during regular operation.

Simultaneity of laser-pulse arrival time, symmetry requirements for the irradiation of the target, and the need to avoid having directly opposing beams across the target chamber drove the final angular placement of the beam ports on the target chamber wall and the path for routing the beams from the linearly aligned laser amplifiers to the radially directed final optics.

Once the overall layout and features of the large amplifiers and frequency converters were defined, these elements could be combined with designs for the low-energy, low-power front end of the laser.

II.B. Building and Beamline Architectures Respond to FR&PCs

The major construction units of the NIF building that provide the architectural features described above are shown in Fig. 5. The two laser bays each house two clusters of 1ω amplifiers (each cluster consisting of 48 individual beams in 6 bundles). The close-packed linear arrays of 1ω beams are turned toward the center of the target chamber in the switchyards, where the linear arrays are redirected into an array of radially converging beams. The infrared 1ω light is converted to the ultraviolet at 3ω just before entering the target chamber, thus minimizing the number of optics that must interact with the short-wavelength 3ω beams.



Fig. 5: Top-level optical architecture of the NIF Facility. Spatial-filter telescopes and large 1ω amplifiers (wavelength of $1.053\text{ }\mu\text{m}$) are most evident in the laser bays. Switchyards house the transport mirrors; capacitor bays store electrical energy for energizing the large amplifiers; light is converted to $0.351\text{ }\mu\text{m}$ in the target bay, just before entering the target chamber.

The specific layout of the NIF facility was defined by the science and technology of materials and support equipment expected to become available during the approximately 10

years surrounding the turn of the 21st century. Design choices were made not only out of concern for meeting the technical specifications for each and every shot, but also for achieving “routine operations” over an operational life of at least 30 years. Elements of this long-term strategy can be seen throughout the architecture and in the design of individual systems and subsystems.

The next level of detail of the architecture and the optical layout of the NIF laser is provided in Fig. 6, using a combination of CAD-like and iconic drawings to illustrate the concepts that are important for a beamline and to relate events along a beamline with the building locations where they occur. Throughout this article, the NIF beamlines will be discussed in terms of their three major systems: the Injection Laser System (ILS), the 1ω Main Laser System (MLS), and the Final Optics Assemblies (FOAs). The ILS creates and tailors the laser pulse desired for a shot. The MLS receives the output of the ILS and amplifies that 1ω light to the desired levels of energy and power, handing over this pulse to the FOAs for frequency conversion and focus of the light on the target.

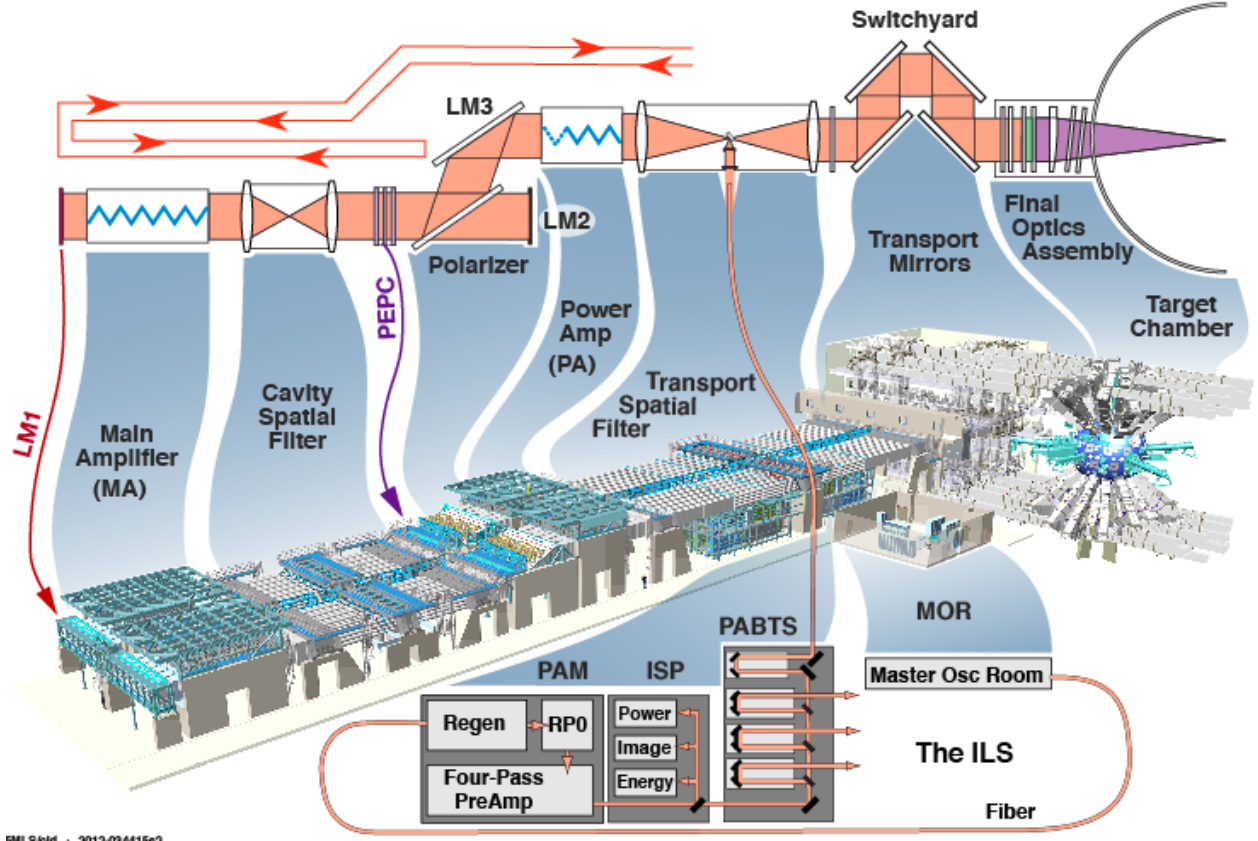


Fig. 6: Schematic view of the laser systems and components along a beamline, indicating their locations on the corresponding CAD drawing. This CAD drawing illustrates one of the two Laser Bays of NIF. There are two Clusters of lasers in each Laser Bay. Each Cluster consists of six Bundles; each Bundle includes eight laser beams. (A closer look at the number of beams in a bundle is included in Section VI.A)

As seen in Fig. 6, the ILS is comprised of the Master Oscillator Room (MOR), the preamplifier modules (PAMs) (including the regenerative preamplifier and the four-pass preamplifier), and the preamplifier beam transport system (PABTS). After being split into four parts in the PABTS, the energy from the PAMs is directed into the large amplifiers by mirrors located near the focal region of the transport spatial filters.

All of the large 1ω optics, including the large amplifiers in the Main Amplifier (MA), the telescopes of the Cavity Spatial Filters (CSF), the large aperture Plasma Electrode Pockels Cell (PEPC), the large amplifiers in the Power Amplifier (PA), the telescopes of the Transport Spatial Filters (TSF), and the large transport optics, are collectively called the 1ω Main Laser System, the MLS. The CSF and TSF play important roles in maintaining the beam quality as the beams propagate through the amplifier chains. A key feature of the MLS for reducing the unit cost of NIF compared to the unit cost for all previous large-aperture laser systems is indicated by the red line and red arrows just above the iconic beamline in Fig. 6. This red path follows four passes that are made through the MA, which are made possible by the new PEPC switching technology and multiplexing of each of these laser passes at a small angle (compared to the other three).

The Final Optics Assemblies (FOAs) hold the last and most individually expensive optics encountered by the light along its path. These optics include the frequency conversion crystals, the fused silica focusing lens, and other optics for laser beam conditioning, diagnostic sampling and protection from target debris.

One of the beamline features that cannot be seen at the scale of Fig. 6 is a technique called “relay imaging” used all along the beamlines for keeping the intensity profiles of the beams as uniform as possible as they pass optical surfaces. Relay imaging is one element of an overall beamline design strategy chosen for minimizing the possibility of hot spots and nonlinearities, giving good phase-front control of the propagating beams and significantly lowering the likelihood of optical damage along its path.³⁵ More on this is included in Section VI.A. Also not seen in this beamline characterization is that the glass laser slabs in the amplifiers are held vertically and set at Brewster’s angle with respect to the beam polarization. For future reference, we note that shots to target-chamber center are not always taken with the large amplifiers firing.

Shots used for setup or diagnostic purposes are sometimes taken with only the regenerative preamplifier or the regenerative preamplifier and the four-pass preamplifier operating. These two types of shots are known as “regen shots” and “rod shots.”

The large-scale structural features of the laser and its major subsystems seen in Fig. 6 were defined as part of Title I activities described in the Laser Program Annual Report for 1997.³⁶ By this point in time drawings of the exterior of the laser looked much like that given in Fig. 1 and the Title I work had formed the basis for design of the conventional facility. In addition to developing strategies for procurement of the glass and crystal optics, during Title I, important progress was made in understanding many areas of the laser design, including the deformable mirrors; handling of optical ghosts; location of the PAMs below the long transport-spatial-filter telescopes; laser diagnostics along the beamlines; beamline and target alignment; concepts for in-situ diagnostics of damage to optical components; and concepts for removing or displacing the unconverted 1ω light from the 3ω light headed toward the target.

II.C. Flow Down of Top-Level Requirements to Systems and Subsystems

Lessons learned from the many years of previous research led to the system design outlined above and to the flowdown of responsibilities described in Fig. 7. Each system has responsibilities for meeting its own flow-down requirements and for working with the other systems to satisfy the full-system requirements.

Most of the laser features identified in Fig. 7 are focused on meeting the requirements for each individual shot; one, however, focuses on meeting the requirement for routine operation—that is, operating day-after-day, shot-after-shot, for hundreds of shots per year, all without a

reduction in performance. A natural outcome of planning for long-term operation is that initial assembly will use the same techniques and equipment designed for continuing maintenance.

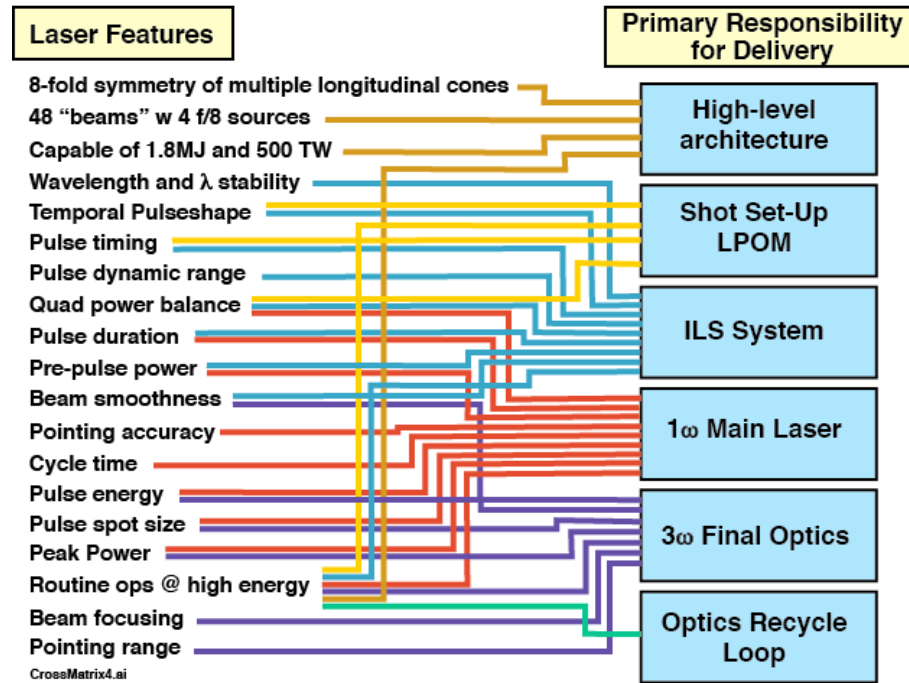


Fig. 7: Allocation of primary responsibility of each part of the laser design for meeting each of the elements of the Functional Requirements and Primary Criteria. The order of topics is arranged for insight on the distribution of flow-down requirements to the various subsystems.

II.D. From the Master Oscillator to the Target: A Trip Through a Laser Beamline

With the beamline architecture given in Fig. 6 as background, the next paragraphs will follow the path of the light from the MOR to target-chamber center. The laser pulse is initially generated in a fiber oscillator (one of three, each capable of operating at an independent wavelength) located in a rack in the master oscillator room (MOR). Each single pulse is used to generate input for one or more cones of NIF by a series of fiber-optic subsystems that provide low-energy preamplification, pulse splitting, spectral conditioning, and temporal pulse shaping,

all within the Master Oscillator Room. The light from the MOR, at a level of ~ 200 pJ, is then injected into the preamplifier module, the PAM. A simplified drawing of the MOR and PAM is given in Fig. 6; more detail is provided in Section V, The Injection Laser System. The first preamplifier section is a diode-pumped, regenerative amplifier (regen) where after 58 round trips the energy is raised to ~ 10 mJ. After leaving the regen, the beam is spatially magnified by a factor of ~ 20 and passed through a set of beam-shaping masks located at the first optical relay plane, RP-0, where it acquires its nominally square shape with an edge dimension of ~ 18 mm. Next, the pulse enters the second part of the PAM, the four-pass preamplifier, where a flashlamp pumped Nd:glass rod brings the energy up to ~ 6 J. After leaving the four-pass preamplifier, the beam enters the PABTS and passes by the input sensor package (ISP), where a diagnostic pick-off sends a small portion of its light to sensors for power, energy, and near- or far-field optical profile. Beyond the ISP, while still in the PABTS, the beam is split into four individual beams and image-relayed through the final small-optics relay plane (RP-10). One of the now-tailored outputs of the ILS becomes the input beam for one of the 1ω Main Laser System chains, as shown in Fig. 8 (Ref. 37).

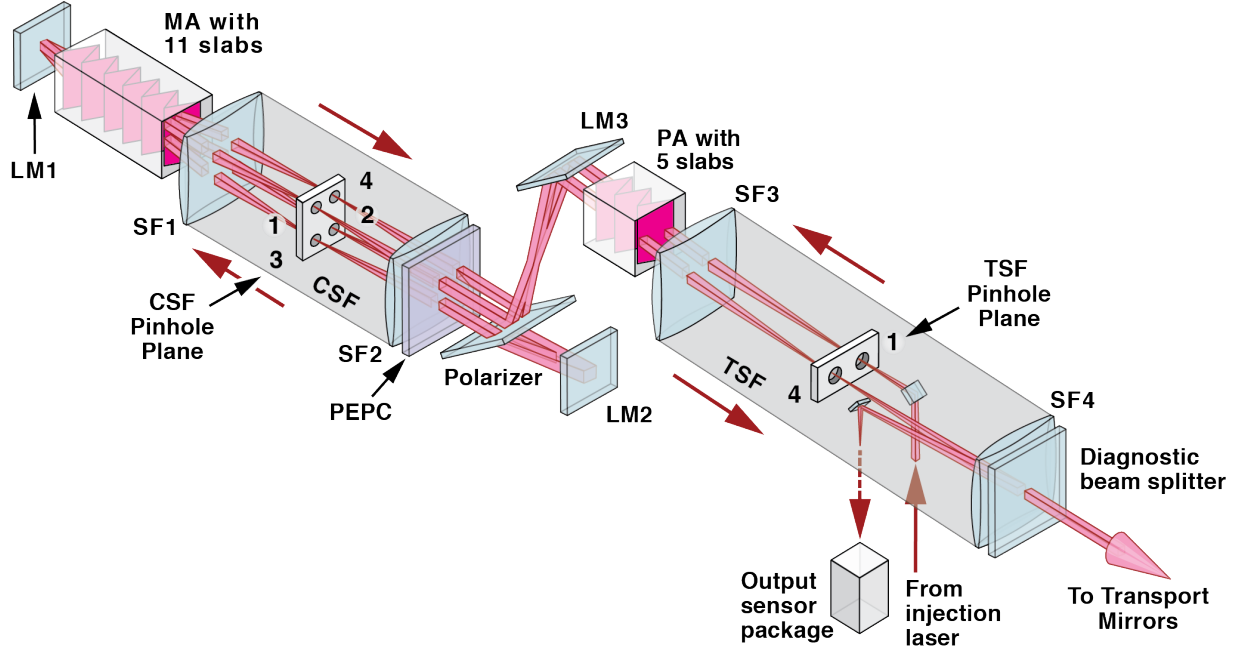


Fig. 8: Path of the light through one beamline of large 1ω amplifiers and spatial filters. The dimensions have been greatly exaggerated to allow better visualization of the angular multiplexing and PEPC switching concepts.³⁸

The pulse into the main laser (with P-polarization with respect to the slabs) is injected by reflection off a small mirror located near the plane of the TSF pass #1 focus. The injection focus at the TSF pass #1 pinhole is laterally displaced only 35 mm from the output TSF pass #4 “pinhole”; this placement is necessary for establishing the ~ 1 mrad angular separation of the multiple laser passes through the main laser. The beam is directed through the spatial filter lens, SF3, and into the five-slab power amplifier for its first step in high-energy amplification (see the red path in Fig. 6). After passing through the power amplifier, it is reflected by both LM3 and the polarizer through the not-yet-energized PEPC (see Section VI.C.1) polarization switch. The potassium-dihydrogen phosphate (KDP) crystal plate in the PEPC is oriented so as to not change the polarization state of the pulse when no voltage is applied. After emerging from the 23.5-

meter-long CSF, the beam is amplified once during its first pass through the eleven-slab MA section of the beamline, reflected once by the LM1 deformable mirror, and amplified again through the MA as it heads back through the CSF toward the PEPC. During the 280 ns propagation time from the beam's first encounter with the PEPC to its return to the PEPC, while the laser pulse is inside the MA, voltage is applied across the KDP crystal of the PEPC, converting it into a half-wave plate that rotates the polarization of the beam from P polarized to S polarized. With its new polarization, the beam is transmitted by the polarizer, reflected back towards the polarizer by LM2, and transmitted once again through the polarizer and the still-energized PEPC where its polarization is rotated back to P. The beam is then amplified during two more passes in the MA (with one more reflection by the deformable mirror between these passes). This time, while the beam is completing passes 3 and 4 through the MA, the PEPC voltage is returned to zero; by the time the pulse once again reaches the PEPC, the electric field across the crystal has decayed, and the pulse passes through with its polarization unchanged. The beam is then reflected by the polarizer and LM3 and sent on for its last pass through the five-slab PA, completing its high-energy amplification (and completing the path represented by red in Fig. 6).

The high-energy laser pulse makes its last pass through the Transport Spatial Filter and is then reflected by LM4, the first of two mirrors in the Switchyard followed by 2 or 3 more transport mirrors in the Target Bay on its way toward the target chamber. Finally, the last transport mirror, LM8, directs the beam radially toward the target chamber and through the FOA, where it is converted to 3ω and focused at target chamber center (TCC). A photograph of a 3D-printed model of the paths of beams destined to hit an indirect-drive target as they move through the transport section is included in Fig. 9. This model was printed during development of

concepts for the paths between the laser bays and the target chamber. Although the paths are correct, a number of other building features that exist today are not represented accurately in this model.

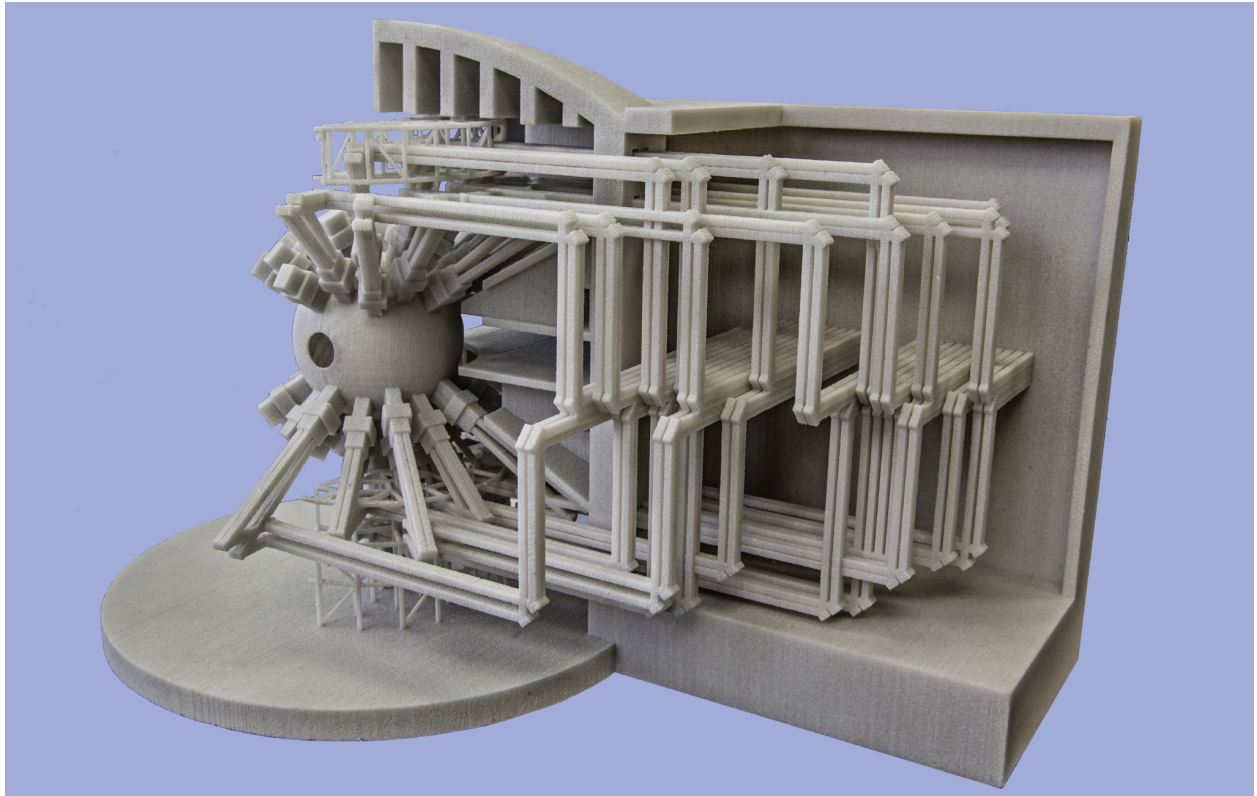


Fig. 9: A 3D-printed model of paths for beams moving out of a Laser Bay, into the Switchyard, and on to the Target Chamber, as configured for an indirect-drive target. The switchyard walls and beam enclosures are not shown.

III. FEATURES OF THE CONVENTIONAL FACILITY ARE ESSENTIAL FOR MEETING THE FR&PC

As seen in previous sections, the top-level requirements of NIF are met, in part, by architectural features of the building that support a laser configuration capable of meeting the primary criteria of the target, including the following:

- Two cones—inner cones from 21.2° to 33° and outer cones from 42.2° to 52.4°
- ≥ 8 -fold symmetry in azimuth
- Four-beam overlap to form f/8 quads

There are other less obvious ways the NIF building supports meeting the FR&PC as it provides the environmental, safety, and security controls that surround operation of the laser. Work to define these features of the building began after the optical parameters of the beamline had been defined.

With the levitated optical design of the laser beampath described in Section II in hand, optical configuration drawings could then be generated. During this process, ray tracing software was indispensable; it was used for development of alignment methods, for designs and locations of the laser diagnostics, and for mitigating (by providing beam dumps if necessary) ghost reflections from NIF optics that occur even with the very best of anti-reflection coatings. Locations, sizes, and tolerances for all optics in the system were provided to structural and mechanical engineers, who then developed the designs for mounting structures and enclosures. Engineering analysis yielded design options and identified construction costs for meeting laser position, thermal, stability, operability, maintainability, and cleanliness requirements as they were understood at that time.

The structure of the building and its foundations are also required to provide the very stable platform needed achieving and maintaining precision laser alignment. First, the building was designed to minimize its response to sources of vibration, and second, all of the optical components of the laser are carried on a large, one-meter thick concrete “optical table” that is mechanically isolated from the rest of the conventional facility. Heavy, rigid concrete structures residing on this optical table support the optical components and their individual mechanical

housings. Coupling of the space frame in the switchyard (that supports the heavy transport-mirrors) to the building structure was designed for minimum response to building vibration.³⁹

The target chamber itself and the floors around it contribute by supporting both personnel and diagnostic equipment. A flow-down methodology was used to establish stability criteria for all of the mechanical features of the building and its internal structures. Dynamic response analyses were used to allocate stability budgets across the mechanical systems. Stability budgets were consistent with meeting the criterion that the deviation in the position of all beams on the target shall not exceed 50 μm rms.⁴⁰

At all times during construction of the conventional facility that began in 1997 and was completed in September 2001, personnel safety was at the top of the list of priorities. Safety topics are addressed in more detail in the “National Ignition Facility Laser System Performance” article also in this issue of *FS&T*.

III.A. The Beampath Infrastructure System (BIS)

The enclosures and structures that support the laser hardware (without the optics present) and the process utilities that provide the appropriate environment for the laser light are together called the Beampath Infrastructure System (BIS) (Ref. 39). The BIS is often called the “exoskeleton” of the laser since it provides a protective shell and isolated environment for the sensitive internal components. This system is divided into bundles, each consisting of eight beams that are independently enclosed all the way to the switchyard wall. In the switchyard, the bundles of eight beams are split into two quads; the upper quads are reflected up while lower quads are directed down. All quads continue to be enclosed through the switchyards and up to the target chamber. The fully enclosed beampath ensures that the high-energy laser light cannot do unexpected damage to its surroundings; it limits the entry of stray contaminants into regions

where they could lead to degraded performance or optics damage over time, and it provides a suitable enclosure for the appropriate environment (clean-dry air, humidified-argon, or vacuum). All interior surfaces of the enclosures were “precision-cleaned” using methods and procedures specifically developed to assure that the number of particles and amount of organic residues were extremely low (see “Cleanliness of the NIF 1 ω Laser Amplifiers” also in this issue of *FS&T*). In addition, all materials exposed to the interior of the beam path were evaluated for outgassing and selected on the basis of their ability to keep the level of vapor-phase contaminants inside the beam path very low.

The beampath infrastructure system was installed during the years from 2001 to 2003, just as the conventional facility was being completed. Fig. 10 includes two photographs, one from early in its construction and the other when it was complete, empty, and ready to accept optics and diagnostics.



Fig. 10: The Beampath Infrastructure System Exoskeleton of the NIF laser. (a) BIS with the first of its large concrete support structures installed; (b) complete and ready for installation of LRUs.

A number of topics were of particular importance during the design and construction of BIS. In addition to ensuring that tight placement and alignment tolerances are maintained for its many large and heavy structures, a high level of attention was given to the use of materials that would be able to remain undamaged under exposure to flashlamp light and/or to ghost reflections of the laser beams. Also, materials used for fabrication of components in the switchyards and target bay were selected on the basis of reducing their future activation by neutrons produced during target experiments.

Before being brought into the NIF facility, all components that would be in the same volume as that of a propagating laser beam were first precision-cleaned in an off-site facility set up by AstroPak, a contractor hired for this purpose. AstroPak cleaned vessels, beam tubes, and mirror frames that would later be installed in the laser bays, switchyards, and the target bay. After cleaning, the parts were wrapped and stored until needed. A photograph of part of a Frame Assembly Unit being cleaned by AstroPak is included in a companion paper “Cleanliness of the NIF 1 ω Laser Amplifiers” also in this issue of *FS&T*. Frame Assembly Units (FAUs) are the structures that support the laser slabs and flashlamp LRUs.

Assembly techniques, referred to as “Fast Connections”⁴¹ were developed for delivery of an exceptionally clean exoskeleton. These techniques were in response to the question, “How do you assemble a clean beampath in a ‘dirty’ room?” Fig. 11 (a) shows triple-wrapped spatial-filter end vessels awaiting connection to their adjacent BIS enclosures and (b) the on-going installation of a “Interstage Beam Tube” that fits between the LM3s and the Power Amplifiers. Precautions taken to maintain cleanliness during installation of BIS hardware has paid off in reduced

maintenance of the operating facility. Again, see “Cleanliness of the NIF 1 ω Laser Amplifiers”, also in this issue of *FS&T*.



Fig. 11: (a) Spatial filter center and end vessels, triple wrapped and awaiting connection to adjacent BIS hardware (b) Photo taken during installation of a clean bundle-sized beam tube between the LM3s and the Power Amplifiers of that bundle.

The CSF center and end vessels shown in Fig. 11 had been cleaned off-site by AstroPak and sealed to maintain their cleanliness until they were ready to be connected to their mating beampath components. The assembly protocols used for connecting the very clean Class 1 (ISO Class 3) beampath and utilities in a stadium-size Class 100,000 (ISO Class 8) building were designed around the invention of several unique procedures for NIF and used three sizes of portable clean rooms. Local Class 100 (ISO Class 5) mini-environments held ambient conditions around activities for the 1200 individual flange-to-flange connections to Class 5,000 (ISO Class 6) and permitted appropriately garbed workers a maximum time of one hour to make each of the connections. While completing the connections, a small overpressure of clean air inside the

components was used to sweep out settling particles. Several work parties participated in each laser bay in a choreographed process. Once sealed, a filtered purge system maintained filtered air at an over-pressure in the beampaths of ~ 2.5 kPa. The supply systems for the clean dry air used for the flashlamp/laser slab volumes and for the argon used in the transport-mirror enclosures were both cleaned and include filters appropriate for meeting Class 1 standards.

Because the beampath infrastructure had to be ready to accept the laser, optics, and diagnostics hardware for the 1 ω sections of the laser (see section III.D), it had to include internal kinematic mounting assemblies ready to accept the kinematic hardware of each of the incoming LRUs. The two mating kinematic mounts, one in BIS and one for each LRU, position the optical components at their appropriate positions along the beampath. All laser bay components and diagnostics are brought to and installed in this structure using mini-cleanroom canisters carried by transporters, and once installed, are supported in place by their kinematic mounts. Mirror line replaceable units (LRUs) in the switchyard and target bay are installed using the clean-connection techniques described above. Necessary maintenance continues to use these same techniques.

III.B. Line Replaceable Units (LRUs)

The infrastructure system and the laser optics and diagnostics become the complete laser system when all of the optical components are installed as large opto-mechanical assemblies called line replaceable units (LRUs).⁴² There are over 40 different LRU types in NIF. Sketches of many of these along with their locations in the beamline are shown in Fig. 12. Each LRU has strict specifications with respect to cleanliness, alignment, and wavefront. All materials used in the construction of the LRUs were vetted for outgassing to assure that levels of vapor-phase contaminants inside the NIF beampath remained exceedingly low. Each LRU has kinematic

alignment hardware that can mate with the corresponding hardware in BIS. Requirements for the installation process itself were challenging. Abrasion has to be avoided because it generates particulates, and conventional, hydrocarbon-based lubricants could not be used because they produce vapor contaminants.

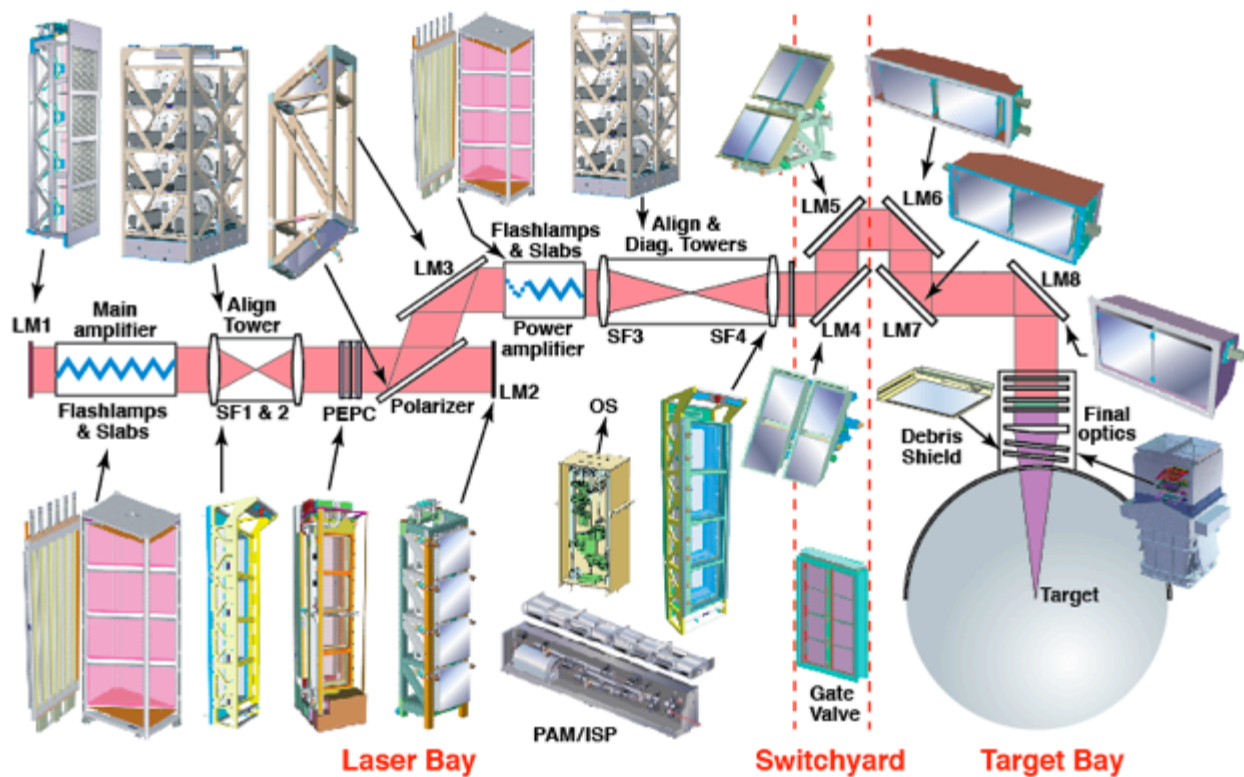


Fig. 12: Line Replaceable Units, LRUs, are the optical building blocks of NIF.

Assembled LRUs that are not frequently exchanged typically contain optics for up to four beams; they weigh up to 1800 kilograms and are about the size of a refrigerator. LRUs for optics may hold mirrors, lenses, laser glass amplifier slabs, and polarizers, as well as actuators and kinematic mounts. Other LRUs contain flashlamps and spatial filter pinhole assemblies. More detail on the much smaller LRUs used in the Final Optics Assemblies is discussed in Section VII.

III.C. The Optics Assembly Building (OAB)

NIF LRUs were assembled (and continue to be maintained), tested, and refurbished in on-site cleanroom facilities, many of them in the Optics Assembly Building (OAB) identified previously in Fig. 5.⁴³ In the OAB as optics are prepared for placement within an LRU, they are moved from station to station using handling and manipulating equipment designed to virtually eliminate human contact and to prevent chipping and any other type of damage to the optics caused by handling. More discussion of these activities is included in Section VI.B.3.

The OAB consists of a 400-m² Class 10,000 cleanroom with a high-pressure spray wash station and an ultrasonic cleaner for gross cleaning of mechanical parts, a class 1,000 area with large- and small-parts precision cleaners, and a 400-m² Class 100 cleanroom containing dedicated work-centers for assembling the different types of LRUs. Although each work-center is unique to the type of LRU it assembles, each generally consists of two major components, a rotating platform that supports the LRU frame at various angles and an optic insertion device capable of picking-up and precisely positioning each optic in the LRU frame. Once assembled and tested, the LRU is ready for transport and installation into the NIF laser system.

LRUs are carried between the OAB and the laser bays by autonomously guided vehicles, AGV robotic transporters. A transporter delivering a laser slab LRU is shown in Fig. 13. The transport and installation system consists of two major subsystems: canisters and the AGVs. Canisters are portable cleanrooms that carry the LRU during transport. Inside the canisters are mechanisms that dock to the NIF beampath and precisely lift and set an LRU on kinematic mounts inside the beampath enclosure. The canisters are designed to allow the insertion and removal of LRUs in a NIF beampath while preserving its very clean environment. For example, consider the transaction for replacing a laser slab LRU. After docking to the beampath, the

empty canister first equalizes its pressure to the pressure inside the beamline. This avoids mobilization of particles that may already be present in the beamline. The canister then removes the hatch cover with a precision motion that avoids allowing contamination that may have accumulated on the hatch cover from falling into the canister. An elevator inside the canister goes up, gently lifts the LRU to be removed, retracts the kinematic mounts using pneumatic cylinders, and lowers the now old LRU into the canister. The hatch cover is replaced with similar care and the canister is disconnected from the beampath. The transporter carrying the canister returns to its docking station in the OAB where it delivers the old LRU and picks up the replacement LRU. The transporter/canister then returns to the same beamline location, where the replacement LRU is lifted into place in a series of steps that are nominally the reverse of those described above. This time, after lifting the replacement LRU, the elevator gently lowers it onto its kinematic mounts in the beampath support hardware. The insertion steps are also completed without disturbing existing sediment or generating new particles.

The plug-and-play design provided by the LRUs gives the high-level architecture of NIF the ability to meet its requirements for both performance and routine operation. In addition, because LRUs are designed as interchangeable units, this same plug-and-play strategy also supports both necessary maintenance and desired upgrade possibilities.



Fig. 13: Laser slab cassettes are transported into the laser bay and inserted into the beam path using special portable cleanrooms carried by autonomously guided vehicles (AGVs).⁴⁴

The remainder of this paper is generally organized around the systems described in Fig. 7:

- The Injection Laser System is discussed in Section V
- The 1 ω Main Laser System in Section VI
- The 3 ω Final Optics in Section VII
- Shot Setup in Section VIII

In addition, background information on the laser design codes and the system-wide support provided by the Laser Performance Operations Model (LPOM) is included in Section IV, and a summary of how the entire optical system, including the target, is aligned is given in Section IX. The discussion of the Optics Recycle Loop listed in Fig. 7 is provided in a separate paper, “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold”, also in this issue of *FS&T*.

Sections of this paper will describe how each of these systems works independently and together to meet the NIF full-system requirements. Every one of these systems required

significant scientific and technological development before they could meet their responsibilities. Details about how well the entire system meets its requirements, including those met by the individual systems identified in Fig. 7, are also discussed in this issue of *FS&T* (see “National Ignition Facility Laser System Performance”). The focus of this article is on describing the hardware and the challenges the systems and subsystems faced in meeting their requirements.

IV. BEAM PROPAGATION CODES AND THE LASER PERFORMANCE OPERATIONS MODEL (LPOM)

The LPOM software⁴⁵ supports the ability of NIF to meet tight performance tolerances on quad energy, power, and power balance by calculating and defining the pulse shape parameters in the MOR and the beam-split values in the PABTS for each beam within a quad. It also calculates settings for the various laser diagnostics along the beamlines such as the best attenuation to be used for signal capture. More detail on how LPOM completes this task is given in Section VIII. LPOM also provides analysis and archiving capability for the laser performance data acquired for every shot, thus improving the understanding of laser operation under many different conditions over long periods of time.

At its core, LPOM includes a version of the laser propagation code that was originally used for the evaluation of beamline designs as they were considered for NIF. Propagation models rely on accurate metrology of the optical components in the beamline modeled. Accurate metrology data first became available for optics in the Beamlet physics test-bed. With this metrology data, propagation models were able to recognizably predict measured beam profiles. Fig. 14 compares predictions by Auerbach^{46, 47} with profiles for a “rocking curve” set of Beamlet measurements used to find the optimum tripler angle for frequency conversion. The experience gained during Beamlet modeling contributed to setting the specifications for NIF optics. The

Beamlet comparisons also provided invaluable reference material for setting up and interpreting measurements made during commissioning of the first NIF quad as it was tested in the precision diagnostics system (PDS).⁴⁸ With reliable models validated by testing in PDS, this code was incorporated into LPOM as discussed in Section IV.B. Section IV.A covers the development and use of these core physical optics codes.

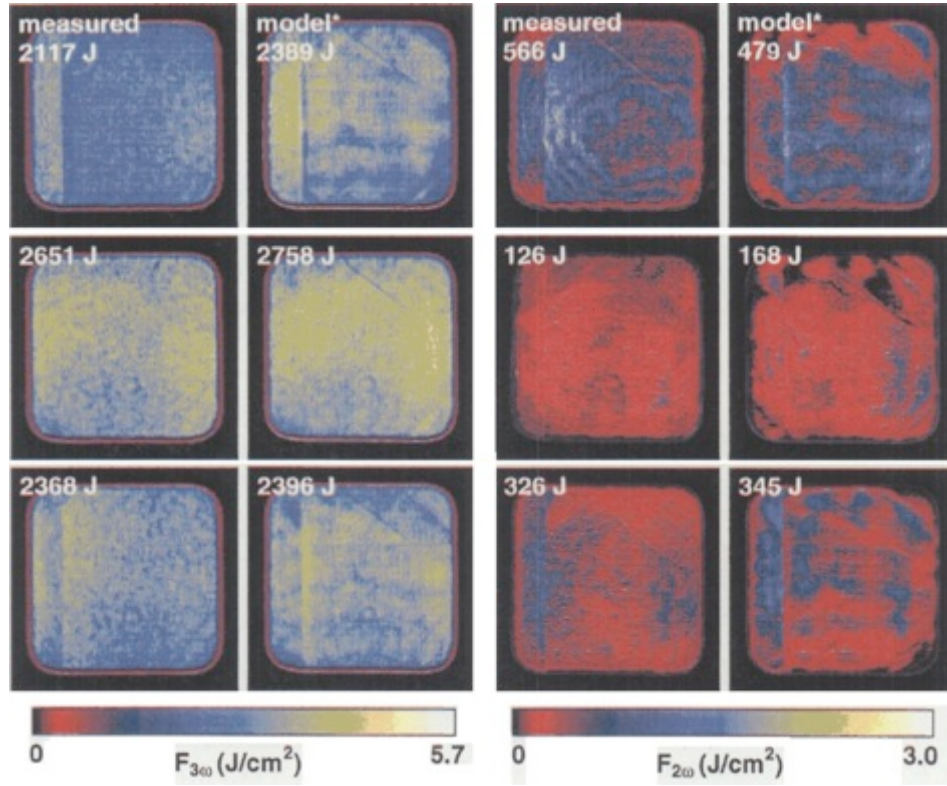


Fig. 14: Comparison of measured and modeled near-field fluence distributions for frequency conversion on three different Beamlet shots in which the tripler angle was varied while the doubler angle was held fixed at $220 \mu\text{rad}$. Drive irradiance at 1ω was $3.4 \pm 0.05 \text{ GW/cm}^2$.

Measured 3ω conversion efficiencies for flat-in-time pulses were, from top to bottom, 56, 73 and 66%.

IV.A. Laser Propagation Codes

At the near-visible wavelengths of 1.053 μm and 0.351 μm where NIF operates, diffractive effects can significantly affect propagation of the laser light. Laser beam intensity profiles computed with ray-trace codes alone have consistently failed to match observations precisely because nonlinear effects are typically not included. Gain saturation, intensity-dependent non-linear optical phenomena, and several stimulated scattering mechanisms join parasitic oscillations in complicating fusion laser system design (at LLNL, typically using Nd^{+3} in glass). Validated models for these processes must be self-consistently included in laser system simulations in order meet target requirements while at the same time safely managing these instabilities. Several categories of laser damage depend on the local intensity and/or fluence of the laser beam, the material of the optic, and the surface conditions of each optic. The laser beam presented to a given optic often depends on previous interactions of the beam with defects or aberrations on upstream components—that is, the beam profile that reaches the target carries with it the memory of every optical component it has encountered along its way. NIF profited from lessons learned during operation of earlier laser systems; a large number of potentially limiting problems were already understood and could be avoided.⁴⁹ The physical optics code, developed at LLNL, and most often employed for preliminary NIF simulations was Prop92, outlined in Fig. 15 (Ref. 50).

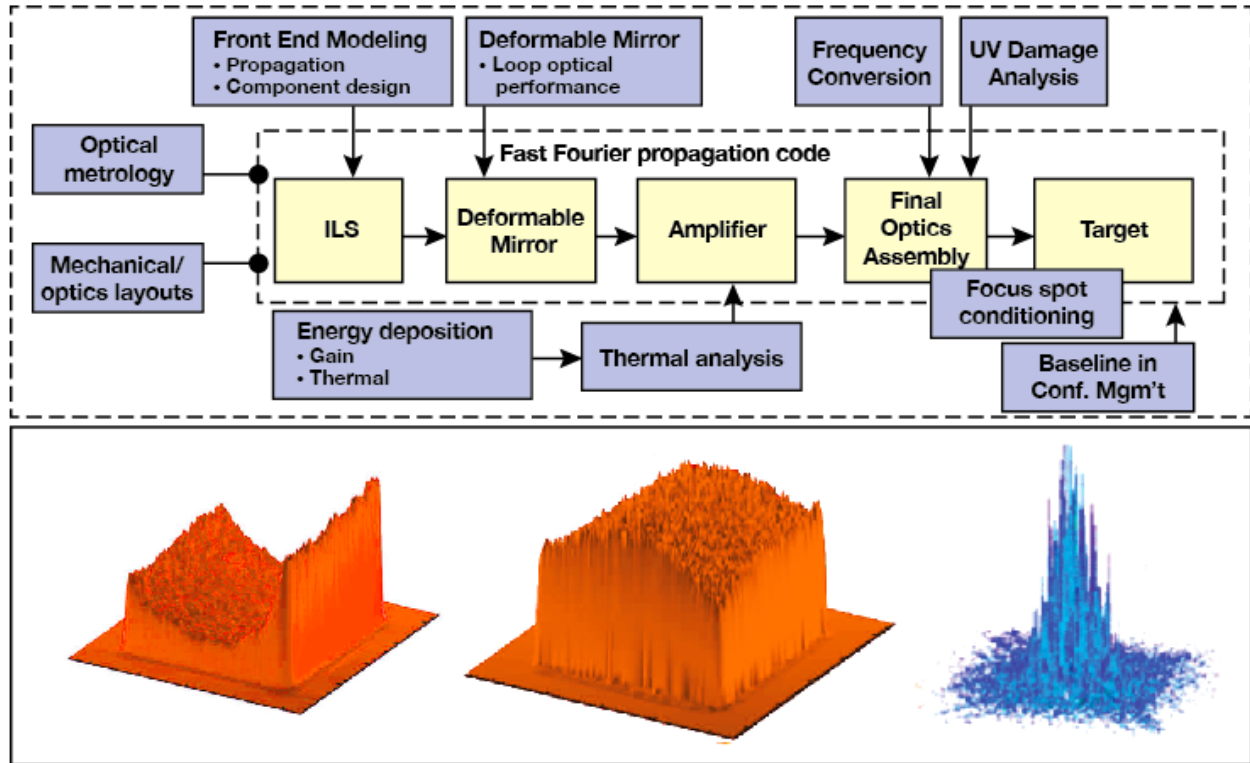


Fig. 15: NIF beamlines were designed using the physical optics code Prop92 to combine information from many sources for calculating beam profiles at selected planes along the path from the preamplifiers to the target chamber. It was used to identify safe operating regimes, relay-plane positions and the format of the conditioned beam presented to the target. The profile on the left is that for the beam as it enters the four-pass preamplifier on its way to the 1ω main laser chain; in the middle is the profile presented to the frequency converter; on the right is the focus at target-chamber center with no beam smoothing components in the beamline.

Prop92, a four dimensional (x,y,z,t) code, uses fast Fourier transform decomposition, added Maxwell phase, field recomposition (split-step) methods and Talanov⁵¹ transformations to deal with the many highly non-linear processes it must handle. When new phenomena were encountered during early NIF performance testing, it was possible to make fast and accurate

corrections because this in-house physical optics code was available for modification, thus delivering new understanding to the design team even as the final NIF engineering drawing package was being created. The process of laser modeling has been found to be an ongoing, resource-limited activity. In order to provide software that is sustainable and supportable for the NIF control system, the Prop92 Fortran code was rewritten and extended in JAVA, where it was renamed the Virtual Beam Line or VBL.

As each new target or target diagnostic is designed and tested, new and often stressing demands are made on the NIF laser. Currently available physical-optics modeling tools like VBL and MIRÓ⁵² are used to predict the fluence, intensity and the potential for damage to the laser for specifically requested output energy and power. If a similar configuration has been tested previously, and the laser was not damaged, the archived shot history in the LPOM database is a valuable asset for deciding to allow the proposed shot to go forward. During planning for NIF high priority was placed on being able to replicate the same shot time-after-time with extremely good repeatability. As NIF has been operated, however, requests for identical sequential shots have only rarely occurred. They can be entirely new pulse shapes, repeats of pulse shapes used many shots previously or precise changes to previously used pulse shapes. Tuning of ignition targets has thus required both repeatability and precise adjustment flexibility (see Section V.A The Master Oscillator Room). Requests for higher laser system agility are expected to continue into the future as users expand their views on experiments they would like to plan. VBL continues to be used as part of set-up for every shot on NIF. The complexity of the system and its non-linear response in both the temporal and spatial domains make use of a physical-optics code essential. Section VIII discusses the ability of VBL, working within LPOM, to define the output from the master oscillator needed for NIF to produce the 3ω pulse requested by a target designer.

Even though the modeling tools for shot set up are very good, they are not perfect, and occasionally preliminary test shots may be needed to establish and calibrate the performance for the specific 3ω pulse requested. Because NIF often operates above the laser damage-growth fluence on its final optics, it is important to be able to anticipate the beam fluence and intensity expected for every beam prior to the shot. A suite of damage identification and mitigation software tools, plus scheduling software, has been essential for responsible NIF operation. Laser damage has been managed in NIF through a combination of measurement, modeling, mitigation, and scheduling methods that are both unique and unprecedented in laser technology. (See “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” also in this issue of *FS&T*) The following section describes several of the services provided by the LPOM model.

IV.B. The Laser Performance Operations Model (LPOM)

IV.B.1. Overview of the Role of LPOM

Success for many of the NIF shots that are taken depends on obtaining precisely specified power waveforms from each of the 192 beams over a wide variety of pulse lengths and temporal shapes, while also meeting precise power-balance specification among the quads. Because the power-versus-time performance of each of the beams is slightly different due to differences in amplifier gain and optical transmission characteristics of individual beamlines, a computational model of the full laser system is necessary for accurately setting the input parameters for each beam. LPOM, with VBL at its core, has been developed to provide this function for NIF.^{53,54} More details on the logical steps involved in shot set-up are provided in Section VIII. LPOM is operated from the control room, where it communicates with a software supervisor that integrates it directly with the NIF Integrated Computer Control System (ICCS).⁵⁵ In addition to

supplying shot setup information. LPOM helps protect NIF equipment and archives shot data and analysis for future study. LPOM may also be run in an off-line mode (not in the control room) for pre-shot setup and target design studies.⁵⁶

As part of the setup process, LPOM maintains a current description of the system that includes the optical path, optical losses, amplifier configurations, and frequency conversion configuration for each beam, as well as a database of diagnostic measurements for laser energy and power at various locations along the beamline (see Fig. 16).

The VBL code continues the tradition established by Prop92 (in a more modern software environment) to provide detailed energy extraction and propagation information for NIF operation. VBL calculates the energetics (energy and temporal shape [power]) throughout the beamlines, based on the current optical properties of each of the NIF beamlines, to self-consistently determine the laser settings that will produce the required output temporal pulse. (see Section VIII for details) This code models energy extraction from amplifiers by solving a spatially-resolved version of the Frantz–Nodvik equation⁵⁷ while calculating the non-linear propagation of the laser pulse.

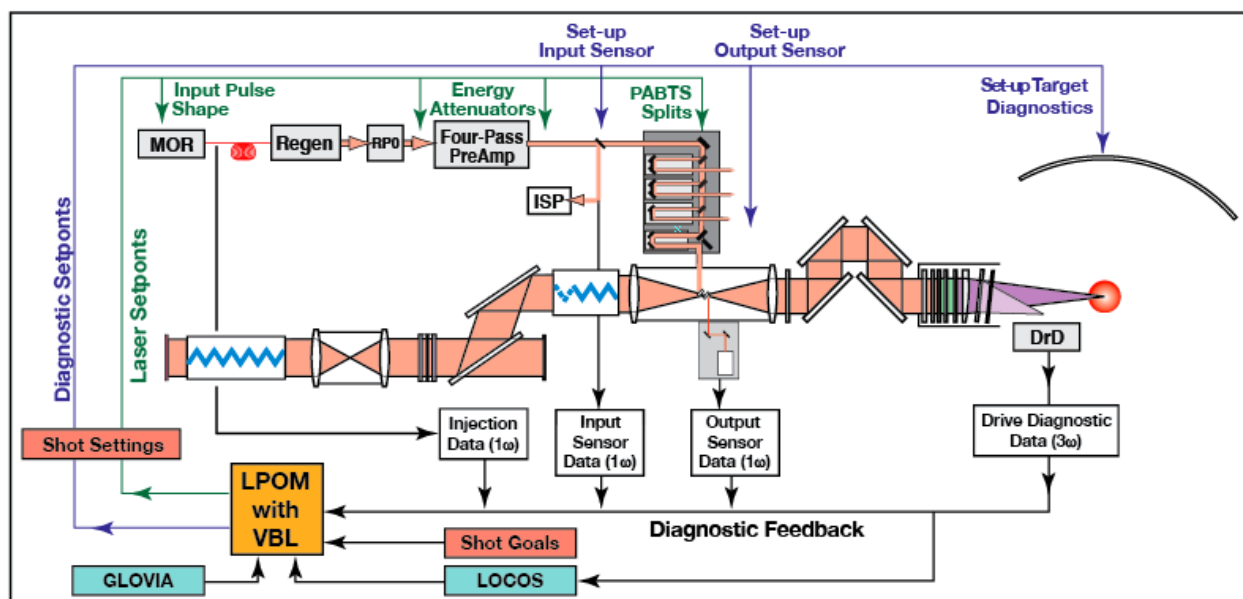


Fig. 16: LPOM contains a detailed model of each beamline. Propagation calculations using the VBL model provide predicted energy and power throughout the laser, information that is used for equipment protection and to configure diagnostics via ICCS. Data results are presented in a web-browser format, with a series of linked web pages that provide successive levels of detail for each quad (group of four beamlines).

This information on laser system configuration comes from metrology data that was measured interferometrically for one quad of optics and is now used as representative for the remaining quads. Other information is collected by diagnostics as the laser operates. For example, when the Final Optics Damage Inspection system (FODI) finds a damage site on one of the NIF final optics that requires a shadow to be placed by the programmable spatial shapers^{58,59,60} (located inside the PAMs) to prevent further damage of that site, LPOM uses VBL to compute the impact of the new shadow and the increase in output fluence that is needed from the four beamlines of that quad in order to meet user requirements for energy on successive shots. With this information, a quantitative prediction of the near-field beam modulation and far-

field spot size can be made. By maintaining an accurate description of the optical system, and by using a detailed physical optics code at its core, LPOM can precisely calculate the required settings for the Injection Laser System (ILS) that will produce the requested output energies and powers (see Section VIII).

Upon completing its setup calculation, LPOM has determined (1) the waveplate settings required by the splitting waveplates; (2) the attenuations for the input and output waveplates on the preamplifier module four-pass amplifier; and (3) the temporal pulse shape desired from the master oscillator. In addition, LPOM predicts the energy and power expected at each diagnostic location for the quad. These energies determine the attenuation settings necessary for each diagnostic device so that the shot can be accurately measured. These settings are uploaded to the ICCS shot database where they can be accessed by the ILS and Laser Diagnostics subsystems during shot setup. At this point, all systems are ready to implement these settings, in preparation for a shot.

In order to maintain an accurate model of each beamline, feedback from a suite of laser diagnostics is provided at the conclusion of each shot. The data from individual beams are used to determine the total power and energy and the power and energy balance on any given shot. When the predictions of the model begin to deviate from measured data, LPOM uses a set of measured data to modify or optimize the model parameters of the laser. In this way, LPOM continually acquires shot data for update of its energetics models (gains and losses in the main laser section, adjustable parameters for the frequency converter). Whenever an optic is removed and replaced at any location within the NIF laser system, LPOM must also be updated to accurately reflect the current configuration. For example, when final optics are exchanged for scheduled maintenance and mitigation processing, LPOM is kept informed of the location of any

shadow blockers or regions of the converters that must be conditioned. (More information on conditioning of crystals is included in Section VII.G.2.) Some beamlines carry restrictions on power levels their output components can support that change from time to time and, very rarely, a major 1ω component like a laser slab or a polarizer must be exchanged for another. The Location Component State (LoCoS) database keeps track of each NIF optic and provides the necessary data to keep LPOM up to date.

Real-time adjustments of the energetics parameters within LPOM allow it to predict total energies within 2% and to provide energy balance within the four beamlines to within 2% for shots over an energy range for each individual beamline from ~ 0.1 kJ to > 9 kJ at a wavelength of $0.351\text{ }\mu\text{m}$.

IV.B.2. LPOM Equipment Protection

Optimizing beamline performance is often a game of getting very close to, but not intruding into a non-linear operating space. Very accurate modeling is required for keeping the laser safe while keeping its performance high. Keeping the beamline within a safe zone is important because the high energy and high power carried along the beamlines also has a very real potential for self-damage of optical components.

LPOM works in cooperation with the Optics Recycle Loop to help safeguard NIF optics from optical damage. After calculating the fluence expected along the beamlines for a proposed shot, LPOM provides a pre-shot assessment to the BeamLine Integrated Performance (BLIP) Working Group responsible for monitoring the risk of laser-initiated damage to optics and to the NIF Shot Director (SD). This assessment includes a report on the feasibility of achieving the

proposed shot goals. LPOM provides additional post-shot support to the task of equipment protection by comparing the measured energies and powers to those predicted by the model.

The LPOM equipment protection module supports BLIP in their role of evaluating the risk of optical damage to the ILS four-pass preamplifier, the Preamplifier Beam Transport System optics, the main amplifier, and the Final Optics Assembly (FOA). The module has two components, both of which serve as administrative controls for equipment protection. The first part, called the Setup Assessment Code, checks the calculated system setup before the ICCS Laser Supervisory System implements the setup. The Shot Setup module compares the Shot Setup energetics calculations to preset fluence and intensity limit guidelines at the locations of key optical beamline elements. These tests evaluate the probability of optical damage initiation, beam filamentation and excessive beam spatial contrast. If all performance metrics are within prescribed limits, the system is declared ready. If either criterion (equipment protection or inability to meet the goals) is not satisfied, alerts are sent to the ICCS Laser Supervisory System and to the individual who has the lead responsibility for executing the shot, the Shot Director.

The second protection function, called the Setup Verification Module, evaluates the actual pulses generated during a series of rod shots prior to the initiation of a full-system shot; its role is to verify that the actual laser pulse and energy output from the ILS match predictions and will not damage the 1 ω main laser or exceed allowable damage expectations on the final optics. In addition, LPOM compares the measured near-field spatial profile with that predicted, and verifies that the energy splits among the beamlines of a quad agree with the requested set point. The Setup Verification code (via the Shot Director) can stop the shot cycle if there is a high probability of significant equipment damage or significant deviation from predicted results. If the

measured energies are acceptable, the Shot Director is alerted that the system is prepared for a primary shot.

Figure 17 shows a screen capture of the shot verification screen on the LPOM graphical web interface at the end of a low-energy shot. Metrics that fall inside or outside of prescribed limits are highlighted with green and red, as appropriate.

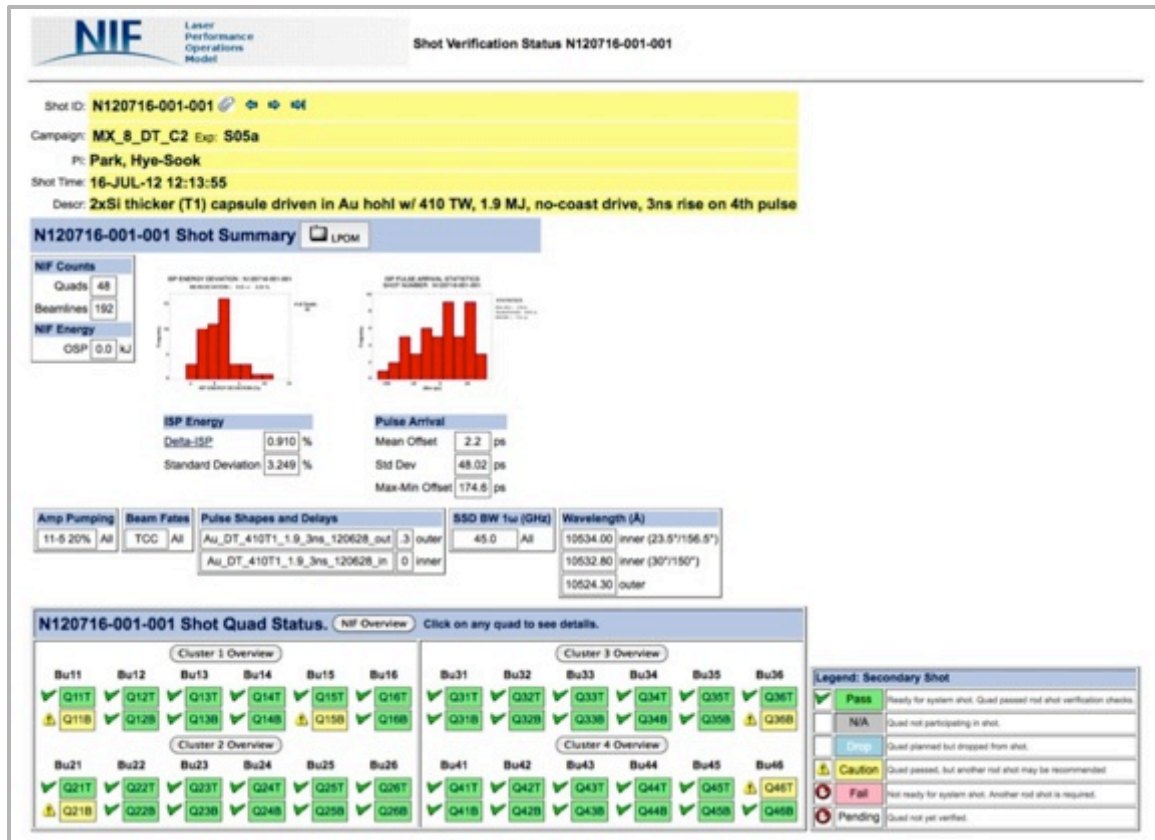


Fig. 17: During calculation of laser setup, LPOM compares fluences and intensities throughout the beamline against operational limits to minimize instances of optical damage. In addition, during a laser shot cycle, LPOM analyzes laser data to verify that the laser system is set up as required.

IV.B.3. LPOM Laser Performance Data Analysis and Reporting

The final functions of LPOM are performing post-shot data analysis and reporting laser performance. To do this, LPOM is directly linked to the Integrated Computer Control System (ICCS) shot database and upon request, it can quickly (within minutes) provide the NIF Shot Director and/or the user with a report that compares predicted and measured results, summarizing how well the shot met the requested goals. In addition, the LPOM data reporting system can access and display any near-field and far-field image taken at each of the laser diagnostic locations and provide comparisons with predicted images. Once completed, the results of the post-shot analysis are then immediately available from the LPOM web interface, while a subset of the analysis is presented to the Shot Director through a Shot Supervisor interface. A data analysis screen from the LPOM web interface is shown in Fig. 18.

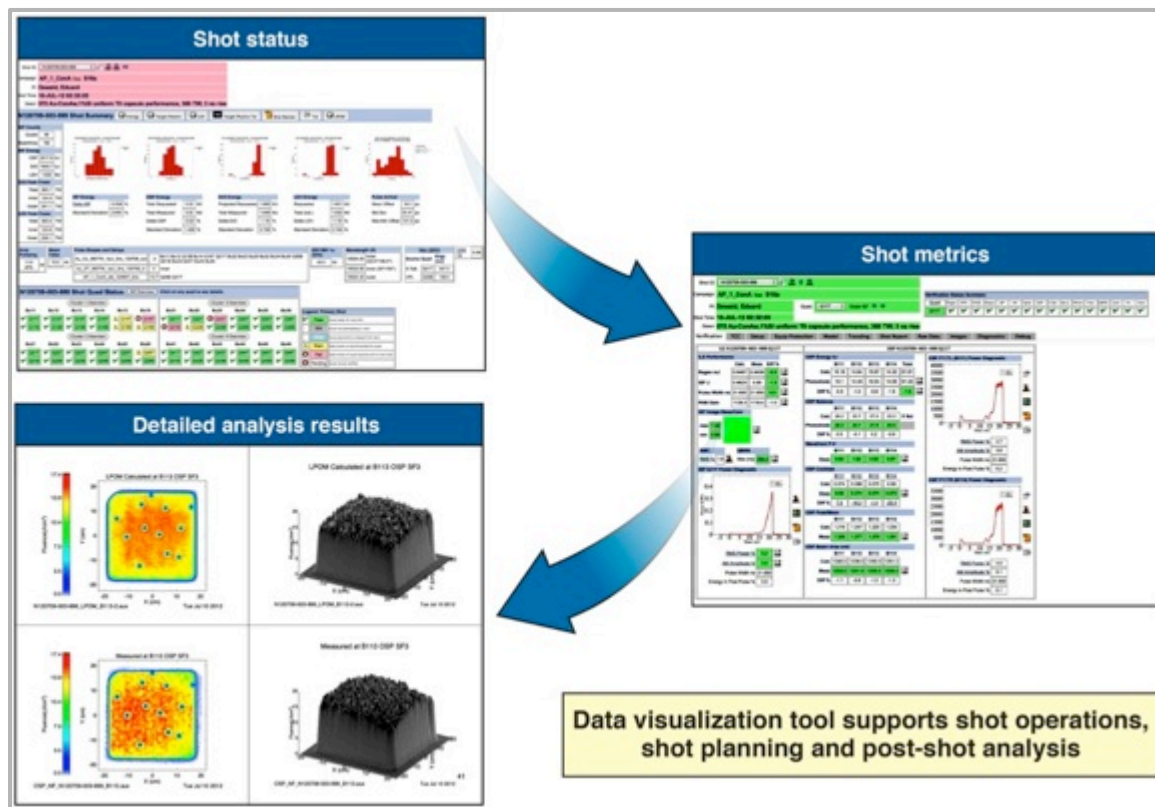


Fig. 18: After each shot, a web-based format enables the detailed laser performance for any beamline to be examined using a suite of data trending and analysis tools.

IV.B.4. Demonstrated NIF laser performance depends on LPOM

Since the beginning of NIF commissioning in 2003 up to the time of writing this section (February 2014), nearly 2400 system shots have been performed. In particular, a large number of high-energy shots with output pulses at 1ω , 2ω , and 3ω have been taken. During the course of these experiments, LPOM has solidly demonstrated its ability to accurately model laser energetics and ensure that precision laser pulses to target and experiments are conducted safely.

The NIF frequency conversion system has been operated up to energies of 10 kJ per beamline (making it by far the highest energy 3ω laser system in the world). NIF has displayed excellent agreement between measured and specified 3ω power over a wide dynamic range of operating conditions. The robustness of the VBL 1ω and 3ω models enables the system to accurately produce the precisely shaped 3ω temporal pulses required for ignition experiments, while at the same time meeting tight requirements for energy and power balance. In particular, VBL/LPOM was used to accurately predict the set points (shown in Fig. 19) for the 1.8 MJ, 500 TW shot taken on July 5, 2012. With LPOM, NIF routinely delivers exquisite precision for pulse shape, energy, power, and power balance in meeting user requests for shots on target.



Fig. 19: LPOM was used to safely set up NIF on July 5, 2012 for the 192-beam NIC milestone shot described above. Model fidelity also allowed VBL/LPOM to accurately set up NIF over the wide range of energies and powers required for the NIC campaign.

V. THE INJECTION LASER SYSTEM (ILS)

The Injection Laser System (ILS) is the front end of NIF. It has the key role of delivering a precisely shaped pulse, both temporally and spatially, while raising its energy from ~200 pJ at the master oscillator to as high as ~6 J, which is split and sent in four individual beams to the 1ω Main Laser (a gain of ~100 dB). Fig. 20 summarizes the primary responsibilities and the iconic view of the ILS in support of meeting the complete set of NIF requirements.

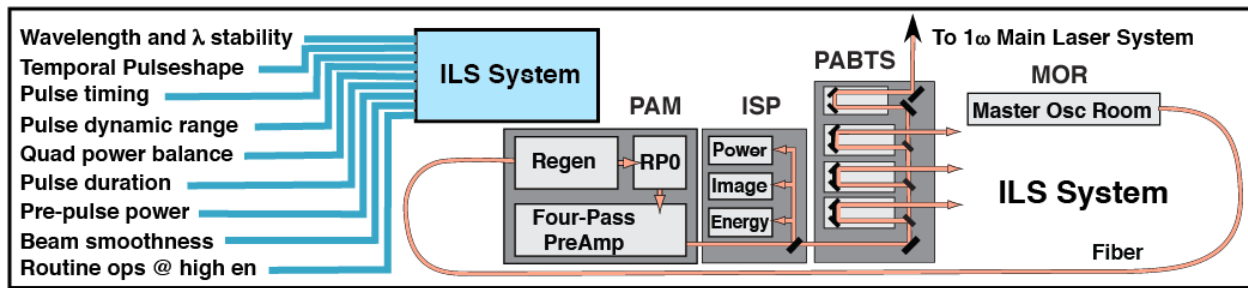


Fig. 20: Summary of the responsibilities and a schematic view of the Injection Laser System.

Science and technology development challenges presented to the ILS included:

- Building a master oscillator room⁶¹ that looks nothing like the bulk-optic tabletop layouts of the past. Instead it uses a new paradigm, telecom technology, taking advantage of the advances that have been made in electronic communications and adapting them to meet the needs of NIF, thereby expanding its precision and control to a level that had heretofore not been possible for an ICF laser.
- Ensuring that the ‘Fail-Safe’ modulator would not fail. A critical subunit of the MOR, the Fail-Safe modulator and its supporting electronics have responsibility for adding modulation to the beam in order to avoid one of the nonlinearities faced by the high-power beams at both 1ω and 3ω , stimulated Brillouin scattering, that is capable of creating very high side-scatter gain in the high-power optics.⁶² This unit is called “Fail-Safe” because, if it fails, it must leave the system in a safe condition. Even one shot taken at high power without sufficient modulation has the potential for destroying large optics; the vacuum-barrier lenses of the large spatial filters are of particular concern.
- Extending the design of the preamplifiers beyond the previous state-of-the-art into a regime where the design could be manufactured as an interchangeable LRU that can

deliver its performance over the broad wavelength range desired by target designers and that can operate with very good stability over both short- and long-term time scales. After several unsuccessful efforts to place a contract for delivery of the preamplifier units, a one-off factory (shown in Fig. 21) was set up at LLNL and used for almost three years for delivery of all the preamplifiers required for NIF, plus spares.

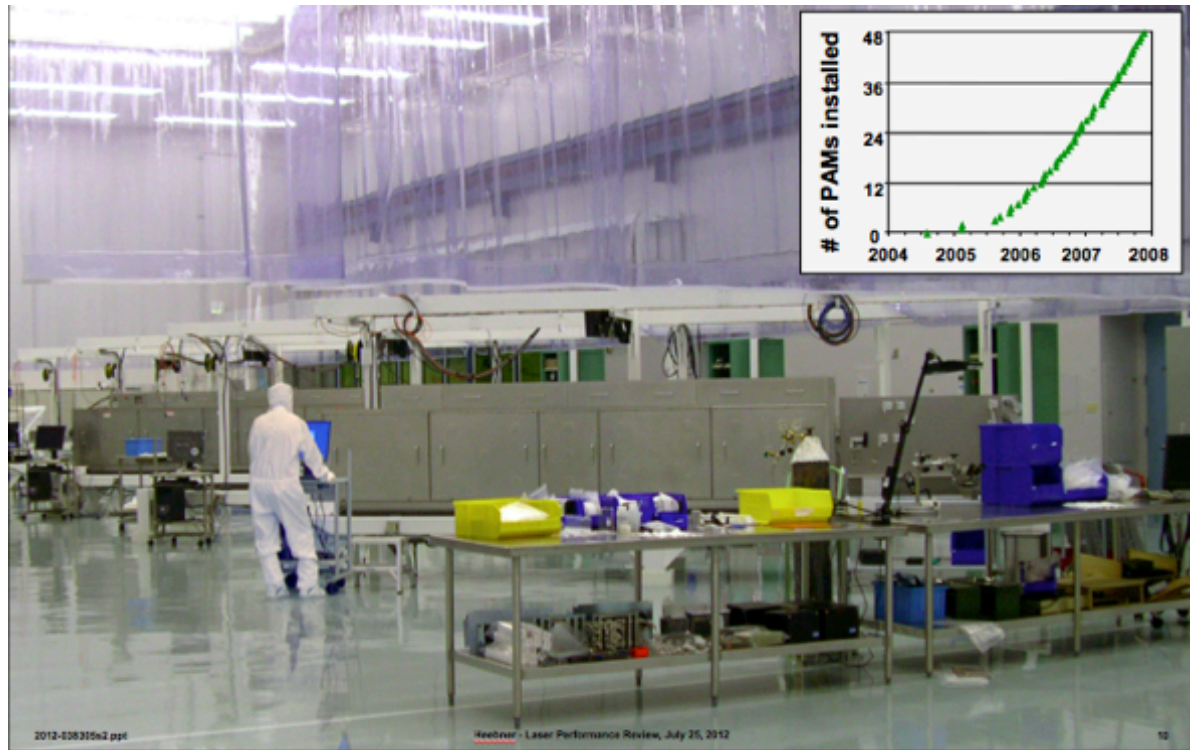


Fig. 21: The cleanroom PAM factory at LLNL set up for assembly and test of all of the NIF preamplifiers.

Photographs of the Master Oscillator Room and a PAM corridor are shown in Fig. 22. The racks of telecom equipment in the MOR and the trays that carry the fiber optics cables from the MOR to the PAMs can be seen in Fig. 22 (a). PAM LRUs are stacked two-high in PAM corridors of both of the Laser Bays. The NIF ILS combines state-of-the-art telecom fiber optics and integrated optics hardware with the modular preamplifier LRUs.

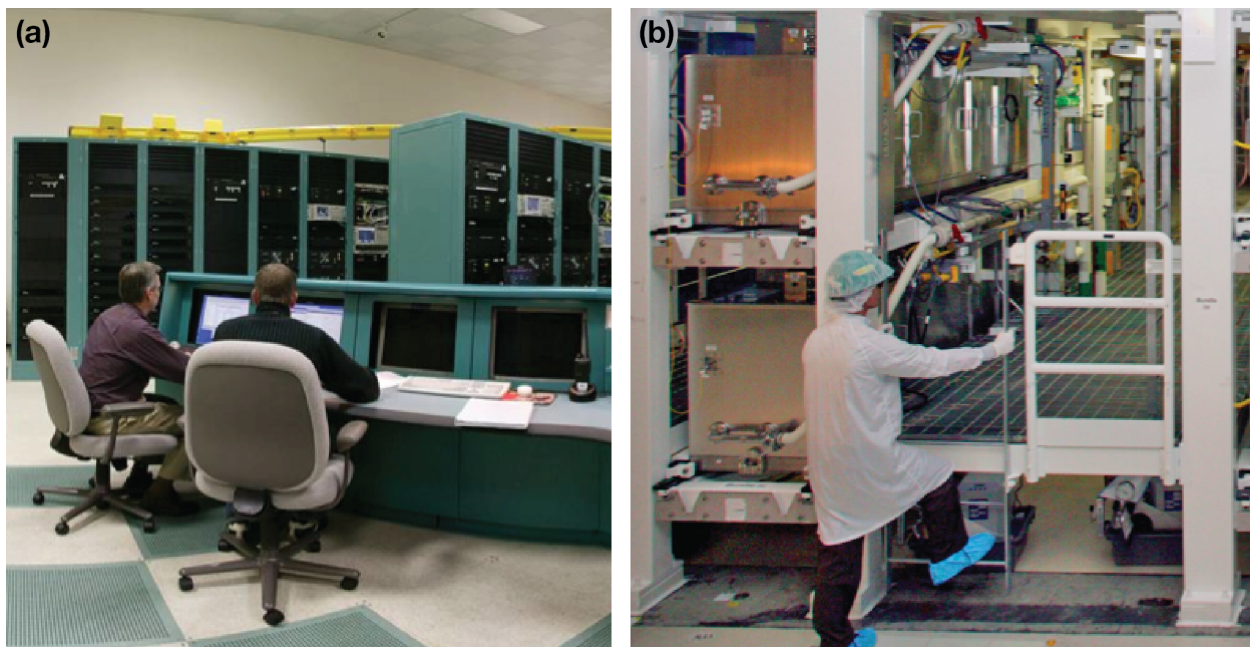


Fig. 22: (a) Photograph of the Master Oscillator Room (b) Photograph of a PAM corridor.

Specific examples of the precision and high gain provided by the ILS are summarized graphically in Fig. 23. Most of the gain, $\sim 10^{10}$, experienced along a NIF beamline is provided by the ILS.

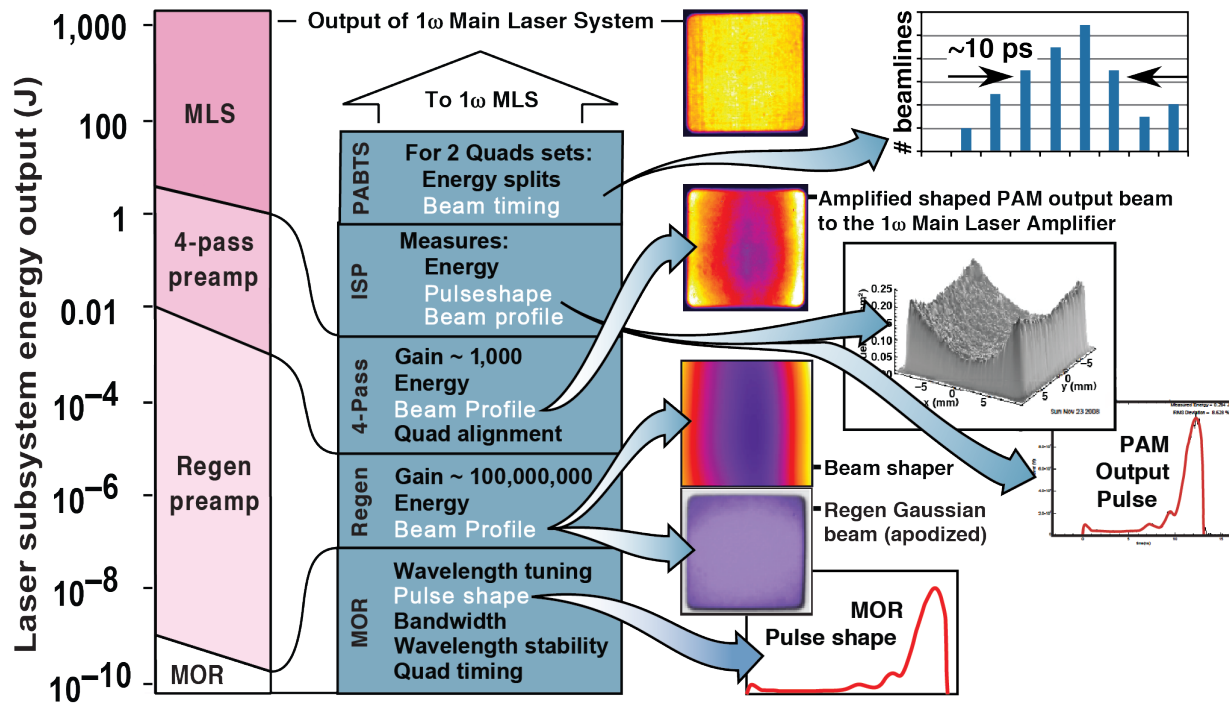


Fig. 23: Graphical summary of selected ILS parameters as delivered by each of the ILS subsystems. The slopes in the subsystem energy bar represent losses (such as for beam shaping) and the four-way split that occurs in the PABTS. Because of these losses, the net gain listed in the blue boxes is larger than the realized gain of the entire system. The amplified output from the 1ω Main Laser amplifiers that follow the ILS is also shown for reference.

V.A. The Master Oscillator Room (MOR)

A schematic of the Master Oscillator Room (MOR) as it was configured up until March 2014 is given in Fig. 24. This figure illustrates how the design leveraged telecom technology to take advantage of both its robustness and its precision. Text boxes along the top and the bottom of this schematic identify the function being accomplished at each step. Multiple arrows indicate the number of times each function is replicated per Master Oscillator. Currently, the MOR

includes three Master Oscillators and their sets of ancillary equipment to provide three independent tunable input wavelengths for the three cone-colors NIF users request.

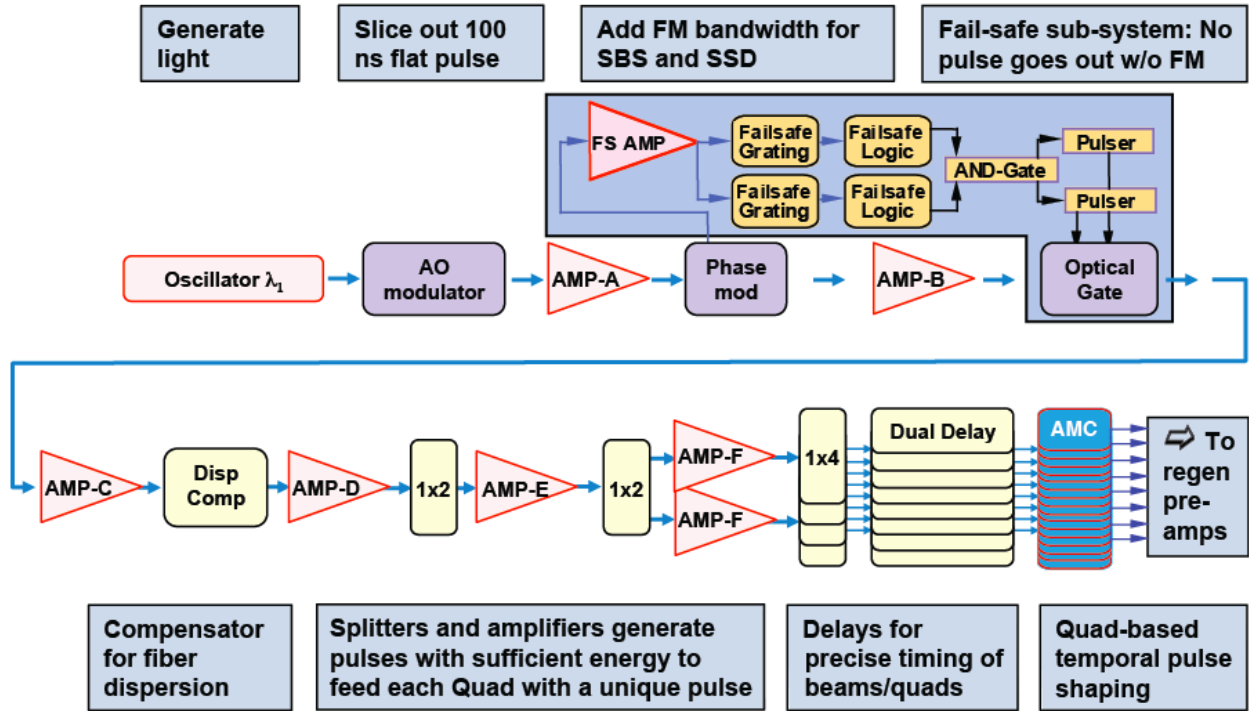


Fig. 24: NIF MOR provides 48 independently shaped and timed input pulses, one for each of the 48 quads. As shown here, these components produce pulses of one wavelength for 8 quads. This graphic describes the configuration of the MOR up until the time of writing. The configuration of the MOR was upgraded during April 2014. Experience gained during the past four years of operation motivated taking a more conservative approach for the fail-safe subsystem.

Rack-mounted chassis, some of which are pictured in Fig. 25, are configured to create 48 custom pulse profiles (one for each quad) each with an energy of ~ 200 pJ. The light begins in a wavelength-adjustable 10 mW cw (continuous wave) Yb-doped fiber oscillator. Wavelength tuning across many Angstroms can be accomplished by temperature tuning its Bragg grating reflectors. The wavelength stability of a master oscillator was discussed in “National Ignition

Facility Laser System Performance” also in this issue of *FS&T*. Three (3) and seventeen (17) GHz modulation (with variable modulation depth) is applied in a three-stage LiNbO₃ phase modulation system.

The three-GHz modulator is part of the fail-safe system for preventing Stimulated Brillouin Scattering, SBS, in the far downstream 1ω and 3ω optics. SBS can generate very intense Stokes waves that propagate transversely across these downstream optics. (Ref. 62) The paper, “Damage Mechanisms Avoided or Managed for NIF Large Optics”, also in this issue of *FS&T* discusses in more detail the havoc that can be raised in optics by transverse SBS. The input lens to the transport spatial filter, SF3, is particularly vulnerable. SBS Stokes light waves have reached damaging fluence levels on the bezels and vacuum sealing surfaces holding such optics in LLNL lasers, when, for any reason an operating modulator has not been present. Because both Nova and Beamlet suffered fractured vacuum barriers in these locations the three-GHz SBS fail-safe system has been elevated beyond equipment safety to a (low-level) personnel safety issue. The fail-safe system is doubly redundant and requires positive confirmation that the modulation is present based on agreement by two independent circuits (see the ‘AND-Gate’ of Fig. 24).

Frequency modulation at 17 GHz with a variable depth of modulation is also applied, most often in conjunction with a diffraction grating located in the four-pass preamplifier of the PAM, as part of the beam-smoothing requirement for the target, now called Smoothing by Spectral Dispersion (or SSD). More discussion about the “beam smoothing” capabilities of NIF and how they work together is included in Section VII.J.

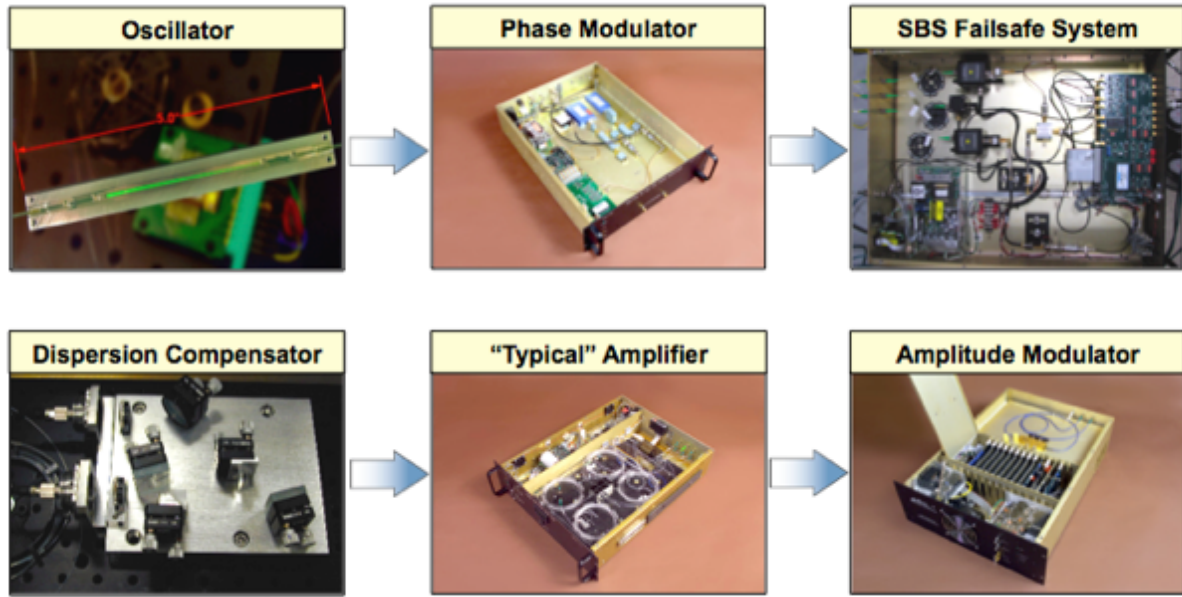


Fig. 25: Six key telecom chassis used in the NIF.

Compensation for normal fiber dispersion in the 450 m of fiber beyond the modulator is done with a Treacy compressor. Polarizing fiber is used throughout except in the amplifiers where single-mode fiber is used with polarization controllers and splitters⁶³ (Ref. 61). Each fiber channel contains six amplification stages based on a single, interchangeable, Yb-doped amplifier chassis design.

One of the flowdown requirements for the MOR was that it be able to deliver shaped pulses with lengths up to at least 20 ns. Motivation for this guidance can be seen in Fig. 26 (a) illustrating a pulse that was being studied as an ICF driver around 1992. The technique that was adopted to provide the necessary pulse shape control uses 140 variable amplitude impulse generators dedicated to each quad in the 48 independent Amplitude Modulation Chassis (AMCs). Example outputs from the first eight impulse generators are given in Fig. 26 (b). With

140 impulse generators spaced ~ 250 ps apart, NIF can support shaping of pulses up to almost 35 ns.

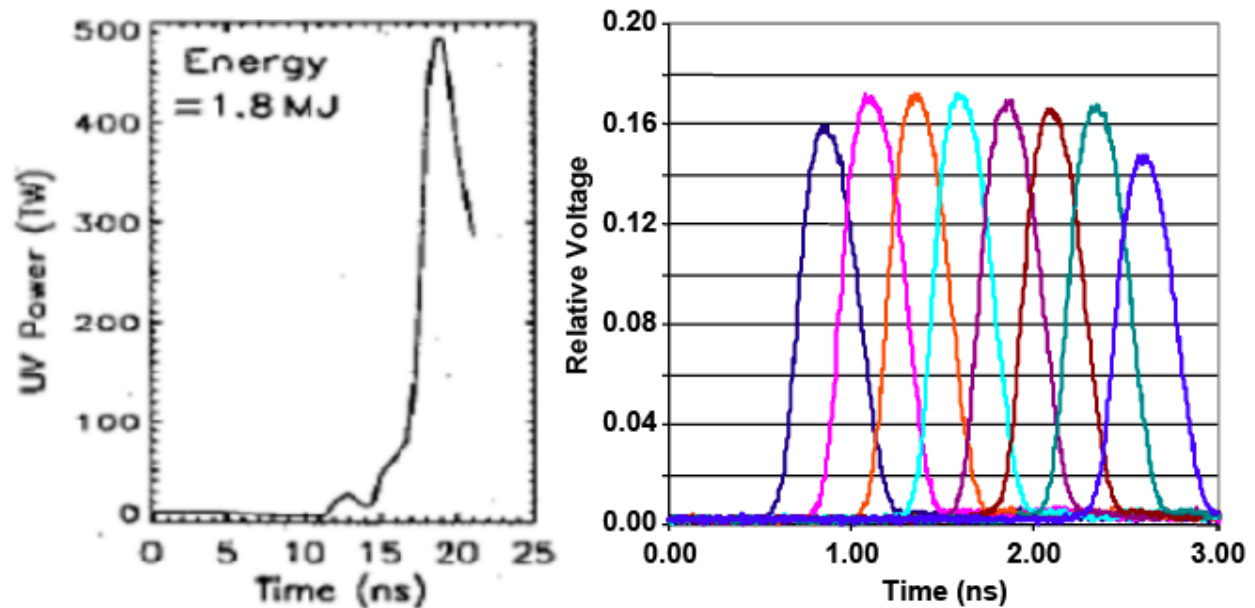


Fig. 26: (a) An example of a ~ 1992 calculation, as it originally appeared, in the *NIF Laser Design and Cost Basis Document*, of a igniting pulse shape being studied at the time of formulating the requirements for NIF. This pulse shape has been called the “Haan” pulse in recognition of its designer. (b) Optical pulses for the first 8 FETs on AMC#2; the amplitudes of the FETs are adjusted and added together to build a much longer shaped pulse, capable of producing a 3ω pulse similar to that shown in (a).

Examples of pulse shapes that can be produced in the MOR are given in Fig. 27. In addition to pulse shape control provided by the AMCs, the MOR can deliver short, approximately gaussian-shaped , ~ 88 ps impulses.

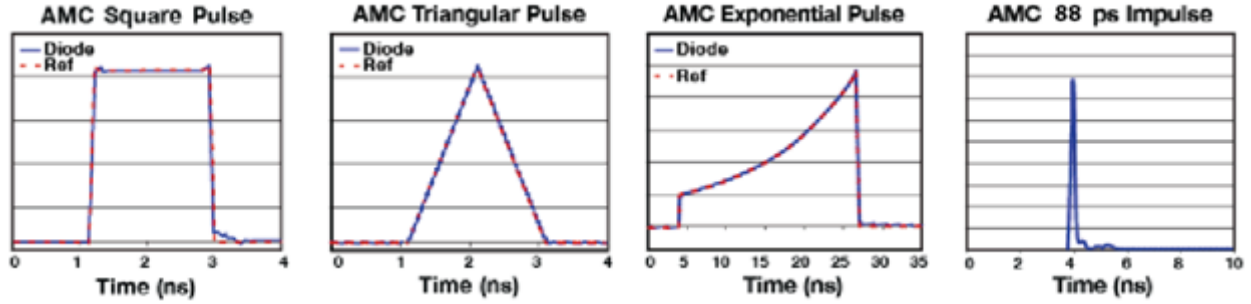


Fig. 27: Illustration of the broad range of pulse shapes that can be generated by a NIF 1ω Master Oscillator. (a) Square pulse, (b) Triangular pulse, (c) Exponential pulse, (d) 88 ps Impulse.⁶⁴

The very beginning of a pulse set up by the AMCs can rise at a rate from 10 to 90% of its height in ~ 100 ps. After a pulse is underway, the maximum rate of rise for an internal shape change is slower, taking ~ 400 ps to go from 10 to 90% of the rise. Pulse shapes with faster internal rise times have been considered by target designers. For a moderate investment, the AMC software and hardware could be modified to provide a capability for internal rise-time events with a time interval for change of ~ 100 ps. At higher cost, involving a complete change out of the AMC hardware, the rise time for an internal shape change of the AMC generated pulses could be reduced to ~ 10 ps.

The maximum output power that can be delivered by an AMC to its fiber is set at 200 mW to avoid problems with stimulated Raman scattering that could otherwise occur over long lengths of fiber. When constrained to this power level there is not always enough energy delivered to the downstream regenerative amplifier to drive it well into saturation. Fig. 28 illustrates the solution that keeps the AMC well below its power-level limit while still saturating the regen with a total input energy of 350 pJ. More discussion of the regen is given in Section V.B.1.

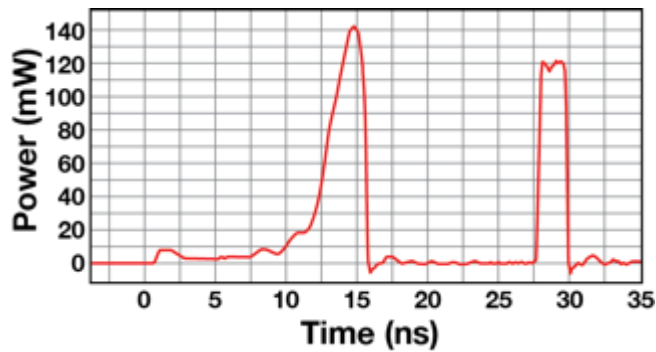


Fig. 28: An example of the pulse shape produced by an AMC for an ICF-like pulse followed by a post-pulse. The post-pulse is added to provide sufficient energy for saturation of the regenerative amplifier. The post-pulse is cut off using Pockels cells at the output of the regen and before the four-pass preamplifier.

Figure 16 includes a diagnostic link from the MOR. Data transmitted along this link includes the measured pulse shape for each AMC and a high-resolution measurement of any amplitude modulation that might be carried on each of the 48 beams from the MOR (one for each quad).

V.B. The Preamplifier Modules (PAMs)

Each PAM is a precision, two-stage, high-gain laser amplifier with very stable beam pointing attributes, excellent beam quality and a total gain of over 10 billion. The tight NIF requirement for full-laser-system power balance demanded that the 48 PAMs provide their high gain in an exquisitely stable and consistent manner. All PAMs also meet their other requirements for output energy level, pointing stability, and flexibility for responding to a wide range of requested pulse shapes.

Because PAMs were expected to require regular maintenance over the 30-year life span of NIF, very early on their interchangeability was set as a critical requirement for long-term

operation of the entire system. Prior to NIF, high-gain laser amplifier systems at the joule level were not common and those that did exist were individual units with idiosyncratic behavior resulting in inconsistencies that would preclude interchangeability. At one time, building 48 (plus spares) laser systems of such precision was deemed impossible, and a supplier that would agree to meet these specs could not be found. As discussed earlier, in order to provide the PAMs for NIF it was necessary to design, prototype and fabricate them at LLNL. Production, installation, and qualification of the 48 PAMs concluded in November 2007. Extra PAMs were built for ready-to-swap spares.

In NIF, the two stages of the PAM are held on opposite sides of a vertically oriented optical breadboard, as seen in the photographs of Fig. 29. The first-stage regenerative amplifier for each of the 48 PAMs is designed for operation at 1 Hz. Stability specs for energy, spatial pulse shape, temporal shape, and pre-pulse contrast must all be met at this rep rate. The regenerative amplifier provides a spatially Gaussian output pulse with energy that remains stable even though noisy fluctuations in its input energy may be present. As can be seen in Fig. 29, there is unfilled space at the end of the regenerative amplifier closest to the reader. This space has been reserved for the future use of hardware for the Direct Drive mission (Ref. 33).

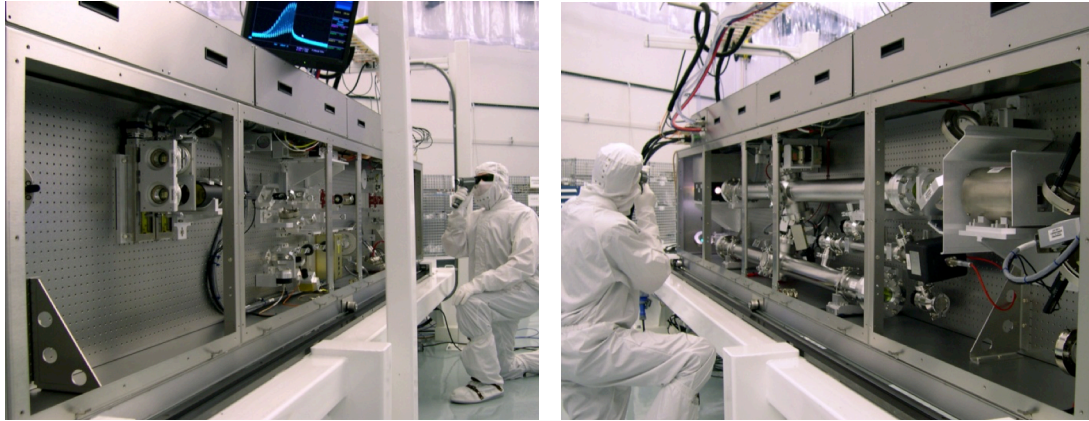


Fig. 29: The two sides of a NIF PAM are supported back-to-back to each other. The regenerative amplifier side of the PAM LRU is on the left; the four-pass preamplifier side is on the right.

V.B.1. The Regenerative Preamplifier (The “regen”)

A simplified concept for the laser-diode-pumped neodymium-glass regenerative amplifier is shown in Fig. 30 (a). The amplifier head contains pump diodes and a hollow-lens-duct concentrator that enables positioning of the rod at a dynamically stable location, where the mode size is insensitive to thermal lensing and surface-figure perturbations on the rod faces. The laser cavity is folded using mirrors to package its 45-ft length within a manageable volume (Ref. 61, 63). Figure 30 (b) also includes a photograph of the amplifier head assembly. Regen amplification takes place over 116 passes through the rod, with a single-pass small-signal net-gain factor of ~ 1.2 . Use of the post-pulse guarantees the regen gain is saturated for even the weakest inputs, leading to more stable regen output energy. Switching the pulse out at the peak of the energy buildup, where the saturated gain equals the loss, yields an output energy of ~ 10 mJ and a gain of ~ 100 million. The path length in the regen, after taking into account the multiple passes, is over half a mile and represents two-thirds of the total path length of the NIF beamlines.

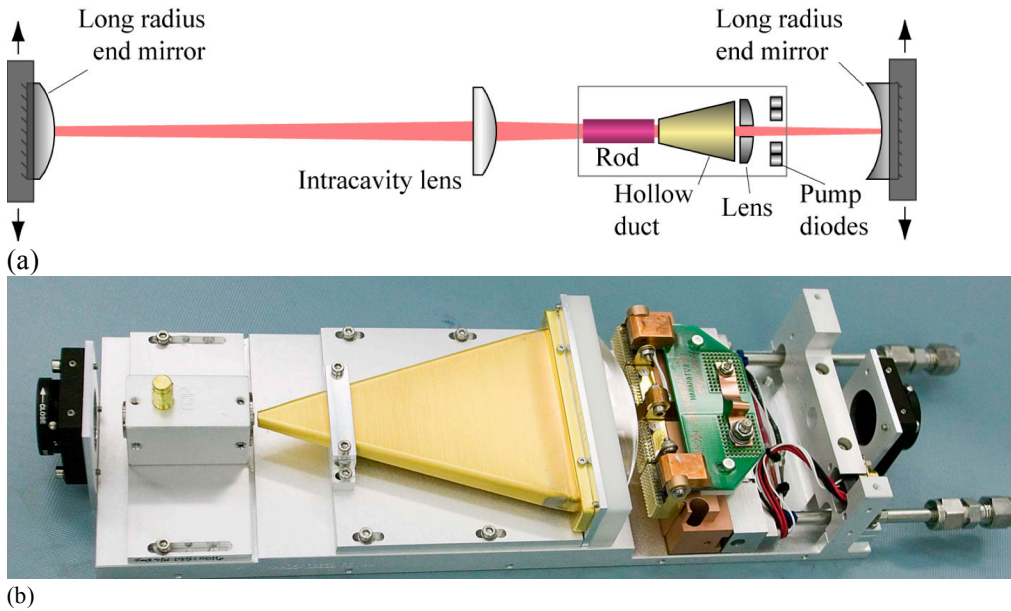


Fig. 30: (a) Unfolded regen resonant cavity. (b) Photograph of the hollow-lens-duct amplifier head assembly where a hollow-lens-duct, end-pumped geometry is used to concentrate 800-nm pump light from a 4-kW diode array into the neodymium-doped phosphate glass rod.

The specific design of the regen cavity was chosen because it requires a minimum of hardware complexity while still meeting its goals for stability, uniformity and reliability. Unfolded, the cavity consists of two curved end mirrors, a rod, and an intra-cavity lens. Numerous cavity configurations were considered and evaluated for:

- Beam-size stability and consistency (impacted by surface-figure errors)
- Steering alignment insensitivity (in the presence of vibrations and drift)
- Efficient energy extraction (optimally filling the rod with the beam size)
- Robustness against optical damage (ensuring that no focused beam “hotspots” would exist)

Meeting these goals was challenging because in an un-optimized cavity configuration, even weak focal lensing in the rod due to pump-induced thermal gradients and surface-figure errors can contribute to large changes in beam size. For many cavity designs, small changes in rod focal power can change the beam area by several percent, which proportionally changes the output energy. This sensitivity impacts both the stability of any one PAM and the uniformity across PAMs because shot-to-shot pumping variations can lead to beam-area instabilities and because surface-figure inconsistencies across manufactured rods can lead to disparities in the mode shape from PAM to PAM.

As a function of rod focal power, there are always two zones within a marginally stable laser cavity that can support geometrically stable light paths. Within these geometrically stable zones, there exists an optimal plateau where the change in beam size in the rod due to changes in the rod focal power is zero. One of these zones is less sensitive to beam decentering perturbations, while the other is less sensitive to beam-steering perturbations. Because the optics employed for folding the cavity are mirrors that unavoidably convert mechanical vibrations and drifts into tilt errors, we chose an optimal configuration in the steering-insensitive zone. The curvatures of the two end mirrors and focal power of the intra-cavity lens then became degrees of freedom that allowed optimization of the regen design within this zone while maximizing the energy-extraction efficiency and simultaneously minimizing hotspots that might occur as the result of an overly focused beam.

After settling on an optimized resonant cavity design, numerous iterations were made for improving the overall stability of the opto-mechanical mounts. The input pulse from the master oscillator is injected via an optical fiber positioned in a hardened, actuator-free sliding-plate mount. The folding mirrors are similarly adjusted without actuators but rather by nudge-rotating

their base along one axis and rotating wedged mirrors for steering corrections in the other axis. Finally, the cavity is precision aligned not with tip/tilt mounts but rather by translating weakly curved (4m, 5m radius) end mirrors. These improvements have resulted in precise initial alignment, elimination of actuator drift and backlash, and overall “set-and-forget” operation.

V.B.2. Mitigation of FM-AM Conversion⁶⁵

An earlier discussion about the MOR included a description of frequency modulation that is applied to the MOR beams for two purposes. One is for protecting large aperture downstream 1ω and 3ω optics from transverse SBS; the other is to provide bandwidth for beam smoothing on target. When the fundamental frequency of the light is changed by the modulator, the amplitude of the light is spread over a range of optical frequencies and optical wavelengths as shown in Fig. 31 where the amplitude vs wavelength spectrum can be seen for typical NIF modulation. Although the variation of amplitude with wavelength can be seen very clearly in Fig. 31, the amplitude of the beam as a function of time has remained undisturbed (at a location just after the position of the modulator). If there were no elements in the beamline with features that vary over the range of change in laser wavelength that accompanies the modulation, the amplitude along the beamline would continue to be stable with respect to time.

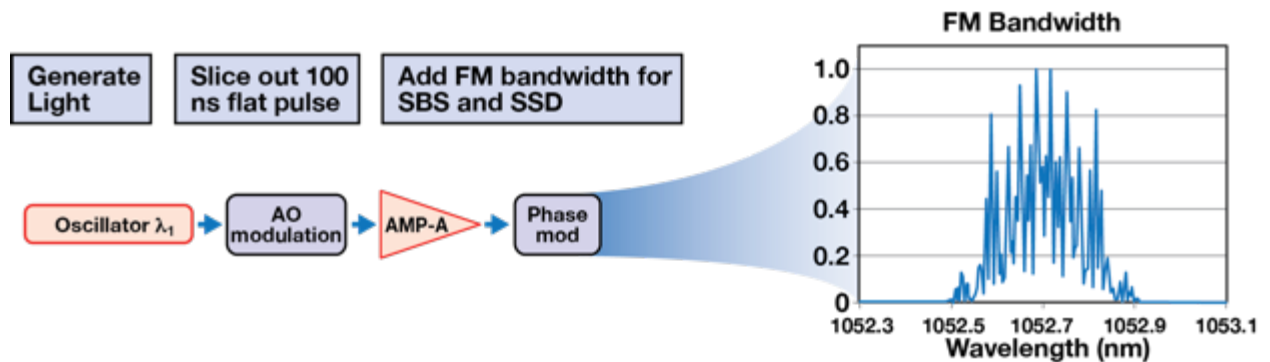


Fig. 31: Typical modulation spectrum applied to a NIF beam in the MOR.

However, if a modulated beam encounters any optical component with dispersion for either absorption/gain or change in the index of refraction, influencing phase—that is, with a response that varies as a function of the wavelength of the light—the frequency modulation will be transformed into very high-frequency amplitude modulation. When such high-frequency amplitude modulation is present, for those periods of time when the amplitude is high, the optical components in the beam are more vulnerable to the kind of damage that is a function of laser intensity (optical power per unit area).

One important example of a laser feature that varies with wavelength is the gain in the regenerative preamplifier. Because the light passes through the regen rod many (116) times the effective variation of its gain with wavelength becomes quite important. Figure 32 illustrates the net gain across the fluorescent linewidth of the regen. If the laser wavelength of the oscillator is tuned to line center of the regen and a frequency modulation is applied, (the case shown in blue) the temporal impact on the amplitude on the laser output is seen to be small; on the other hand if the MOR wavelength is tuned off center of the regen line, (the case in red) the amplitude modulation with time can become significant, high enough to limit the energy and power at which the laser can be operated. When NIF is asked to operate in the regime where optical damage is of concern, suppression of FM-to-AM conversion becomes very important. These conditions occur when the laser is operating at high power, a desirable condition for ICF because peak power is an important driver for the velocity of the imploding capsule.

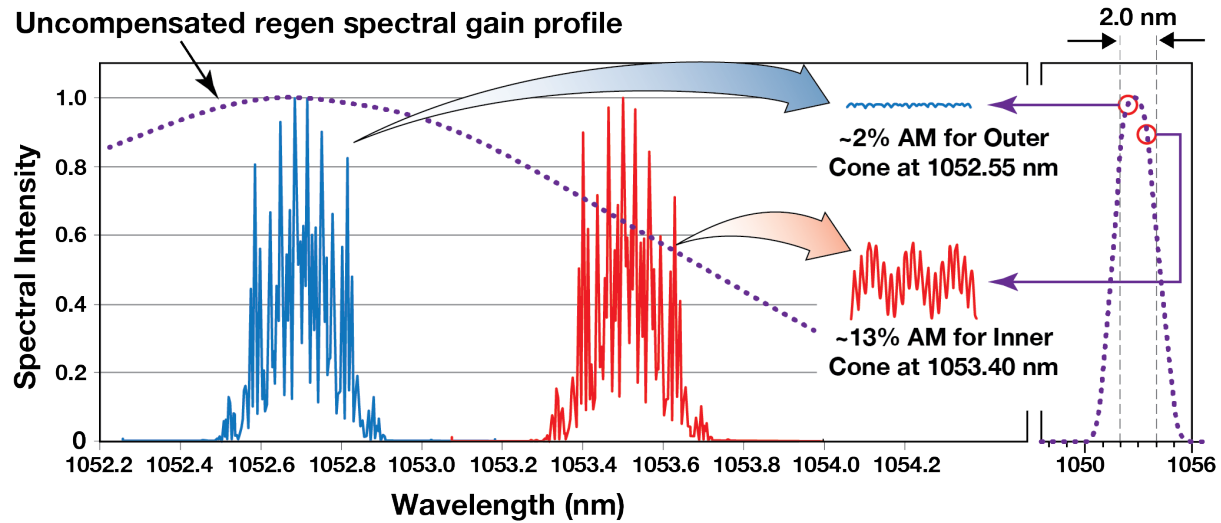


Fig. 32: (a) Impact of modulation on the beam produced by the master oscillator as a function of its wavelength within the effective gain bandwidth of the multiple passes in the regenerative amplifier. If the laser is asked to operate on the long wavelength side of the regen band, as the modulator drives the input to a shorter wavelength, the gain goes up and as the modulator drives it to a longer wavelength, the gain goes down.

In concept, compensation for a wavelength dependent feature of a laser component can be done by inserting another component with an equal but opposite wavelength dependent characteristic, thus nulling out the effect. Several techniques have been used during NIF in pursuit of this idea. In 2003 during the first target experiments on NIF with only one FOA installed on the target chamber, a bulk etalon in the MOR was used as an FM-to-AM compensator (Ref. 61). Prior to the addition of the compensator, FM-to-AM measured with a streak camera was found to be $\sim 30\%$; after compensation, stability was improved and FM-to-AM was reduced to $\sim 7\%$. In 2005, a transition was made to a PZT-tunable fiber-based etalon per cone. Later in 2010, with a need for higher peak power from the NIF facility, fiber-based AM compensators were installed on each quad. These correctors were fairly inexpensive but had

some major drawbacks like a need for adjustment after a wavelength change and potential drift during operations.

As work continued to move ahead on development of better FM-to-AM compensation, it became increasingly apparent that the methods being used for measuring the amplitude modulation were very cumbersome (the streak camera) or had inadequate bandwidth (~4.5 GHz scope) that at times gave misleading guidance.

Continuing work to reduce FM-to-AM conversion has thus been focused on two areas of development:

- Improved high bandwidth measurement of the AM, with emphasis on providing a measurement capability for all of the beams in NIF, at an affordable cost. Work continues to be active in this area
- Techniques for compensation, or equalization, of spectral amplitude and phase distortions inherent in some of the laser components, such as multi-bounce reflections from imperfect AR coatings, dispersion in the fibers and the example given above of the dispersion in the amplifier gain spectrum of the regen

Because the regenerative preamplifier is the individual element with the highest dispersion along the laser beamline, attention was focused on compensation techniques for this component. An idea that had first been explored for gain flattening across the bandwidth of a regenerative preamplifier for a short-pulse-laser was recognized as having great potential for use over the range of wavelengths being requested by ICF target designers in addition to reducing FM-to-AM conversion. Much like using the concept for an audio equalizer, a birefringent filter was added to

flatten the gain profile over a 2 nm tunable band around a point within the 1 ω fluorescent bandwidth of the regenerative amplifier.⁶⁶

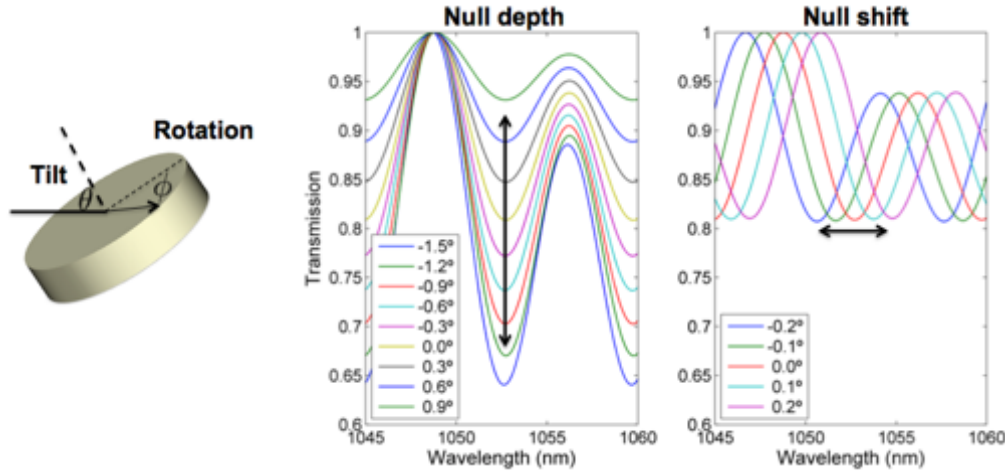


Fig. 33: Concept for regenerative gain-profile flattening with a birefringent filter.

The modification the birefringent filter makes to the spectral transmission of each pass of the regenerative preamplifier cavity is shown in Fig. 33. The only hardware modification required to achieve this response was the insertion of a thick quartz rotator into the existing regenerative amplifier cavity. On each pass through the cavity, the laser beam reflects off a cavity polarizer, double-passes the quartz rotator and again reflects off the same polarizer. The effect of the quartz is to modify the polarization state of the beam in a spectrally periodic manner. The polarizer in turn manifests this periodicity in the spectral transmission. By adjusting the rotation and tilt of the quartz's crystal orientation with respect to the polarizer, one of the transmission nulls can be tuned both in center wavelength and depth. When the shape of the filter response matches the inverse of the gain shape, the effective gain for the amplifier is flattened.

In the spring of 2012, all of the regenerative preamplifiers in NIF were retrofitted to give performance similar to that presented in Fig. 34 (a). The specific operating wavelengths shown in

this figure are those at which NIF was operating on July 25, 2012. A photograph looking down the bore of one of these birefringent filters is included in Fig. 34 (b).

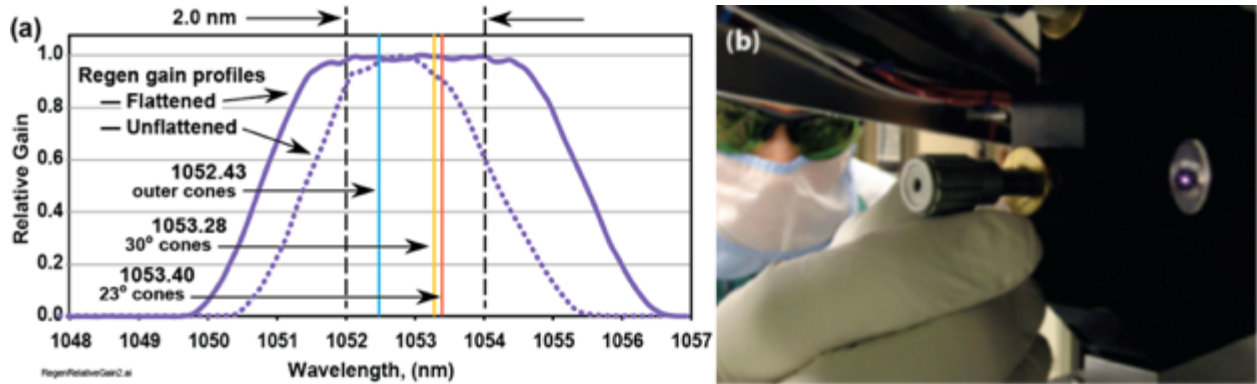


Fig. 34: (a) Flattened gain profile and tuning range of the regenerative preamplifiers currently in NIF compared with the dotted black unflattened profile. Specific wavelengths shown were for operation on July 25, 2012 (b) Photograph of birefringent filter alignment.

It should be noted here that the full 2.0 nm tuning band shown in Fig. 34 cannot (at this point in time) be accessed for NIF operation because another limit, one set by capturing the THG back-reflection is somewhat narrower, restricting the net tuning bandwidth to about 9.6 Angstroms at 1ω .

V.B.3. Masks and Programmable Beam Shaping

Immediately following the regen and before the four-pass preamplifier, the output TEM_{00} Gaussian beam profile from the regen is linearly expanded by a factor of 20 and spatially reformatted (at relay plane RP-0) using a serrated apodizer mask to become a soft-edged square beam. It has been recognized since 1972 that better extraction efficiency from the large amplifiers can be obtained when diffractive ringing (intensity spikes near the edges of the amplified beam) is avoided.^{67,68,69} Better amplifier filling can be achieved when the injected beam has soft intensity edges. In NIF, a second shaping mask (also at RP-0) is used following

the soft-edge apodizer for pre-compensation of non-uniform small-signal spatial gain profiles in both the four-pass preamplifier and the NIF Main Amplifiers. This beam-shaping mask uses a randomized pattern of chrome dots on a glass substrate to form the shaped envelope. Examples of these static masks are provided in Fig. 35.

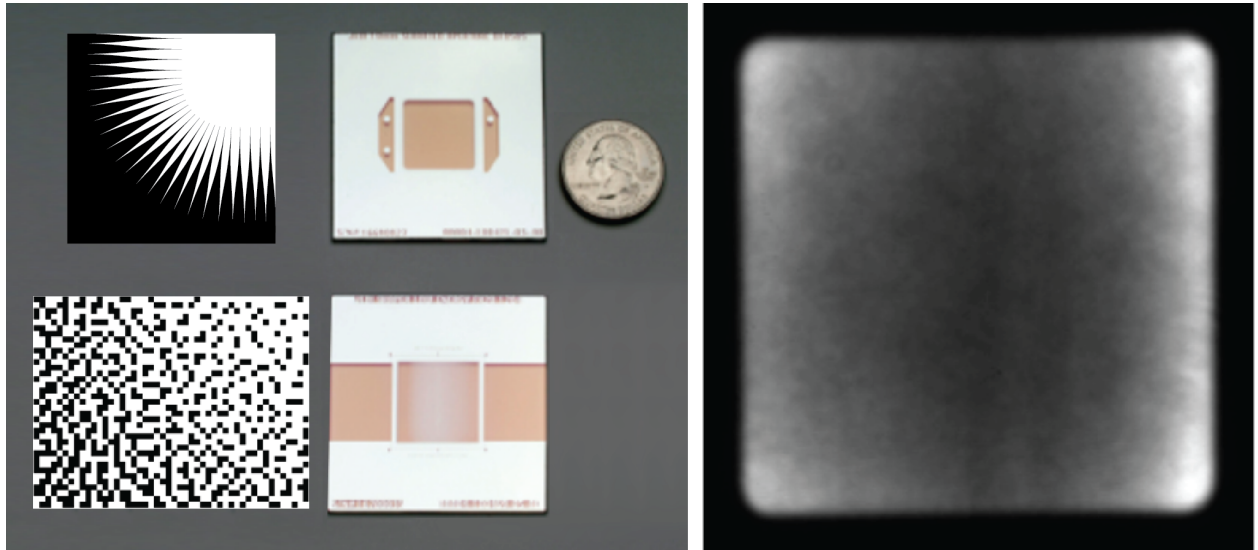


Fig. 35: Top-left: Serrated mask for soft-edge cropping of the Gaussian TEM_{00} beam from a regenerative preamplifier with a magnified view of a serrated corner of the mask. Bottom-left: Chrome-dot mask that shapes the gain-profile pre-compensating pattern, with a magnified view of a section of the pseudo-random pattern of dots that forms the envelope of the mask. If a more regular pattern of dots is used, Moire patterns develop in the laser beam profiles. Right: Composite effect of the static masks. All of these masks must be filtered by $\sim 100 \mu\text{rad}$ spatial filters (first pass of the TSF) in order to achieve the desired beam profile.

A third mask, a programmable mask under computer control, was introduced at this location in 2010. A photograph of the regen side of the preamplifier with a schematic of the regen, including the Programmable Spatial Shaper (PSS) is shown in Fig. 36. The PSS can

dynamically adjust the beam shape to compensate for higher-order gain non-uniformities of the downstream amplifiers and very importantly, as shown in Fig. 37, it can dynamically introduce shadows for protection of downstream locations where there are flaws that are susceptible to laser-induced damage growth or other optical damage.^{58, 59, 70} Protection of downstream flaws adds very significantly to the ease of operation of the entire laser as discussed in “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” also in this issue of *FS&T*.

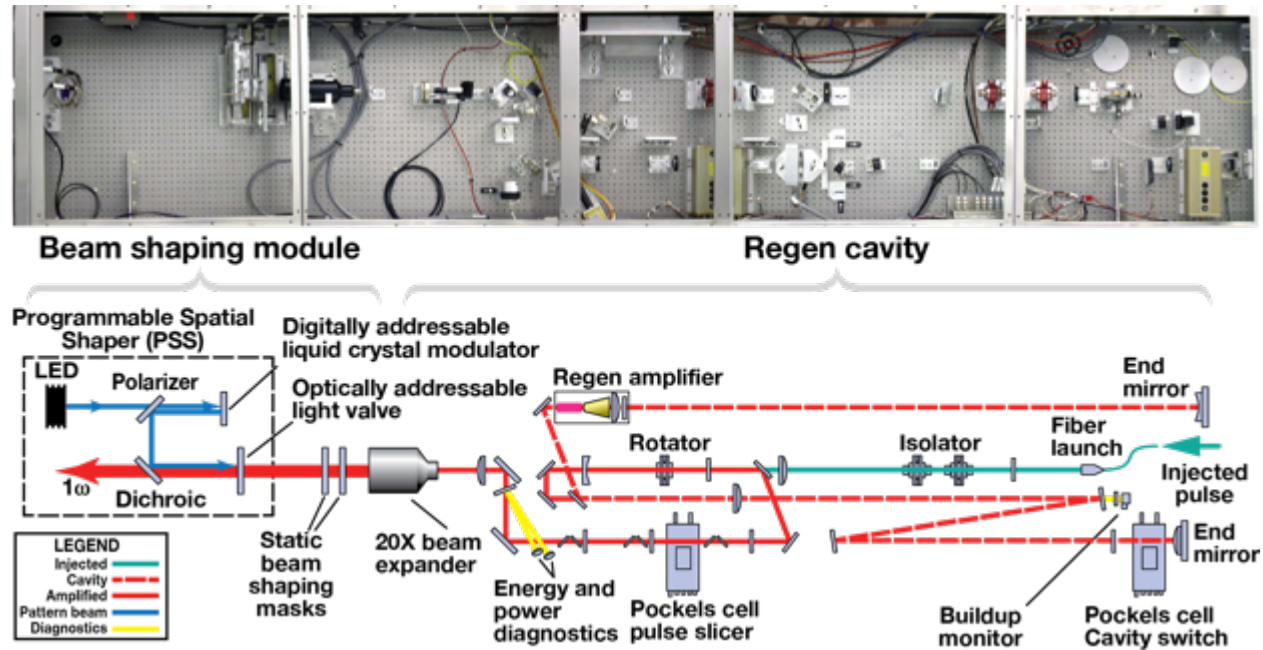


Fig. 36: PAM first-stage preamplifier and layout of the beam-shaping module. (Upper) Photo does not include Programmable Spatial Shaping assembly on the far left. (Lower) Schematic of the regenerative preamplifier and beam shaping masks, including the components for programmable spatial shaping.

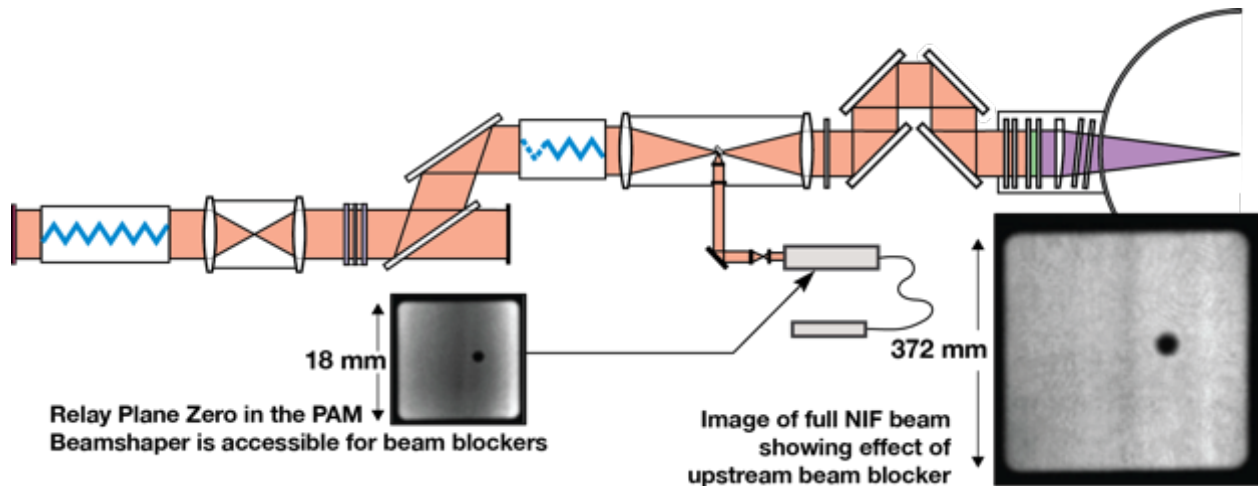


Fig. 37: Small obscurations or “blockers” can be placed in the low-fluence, low-intensity region at RP-0 to shadow and protect specific sites on downstream optics subject to much higher fluence and intensity. The protecting shadows have to be large enough to avoid having their spatial frequencies clipped off by the spatial filters. Avoiding nonlinear intensification of edge effects by requiring soft edges on the blocker profiles leads to a minimum fractional area of each downstream shadow of $\sim 0.3\%$.

The PSS uses a two-stage liquid crystal spatial light modulator to perform its function. In the first stage, a pixelated pattern is imprinted onto an incoherent blue light source using a conventional liquid-crystal light modulator, as found in a projection television. In the second stage, that pattern is transferred from the incoherent illumination to the coherent 1ω beam using a liquid-crystal analog light valve. The resulting patterned beam is free of spurious pixelization artifacts. Figure 38 illustrates a photograph of a PSS in a NIF regenerative preamplifier.

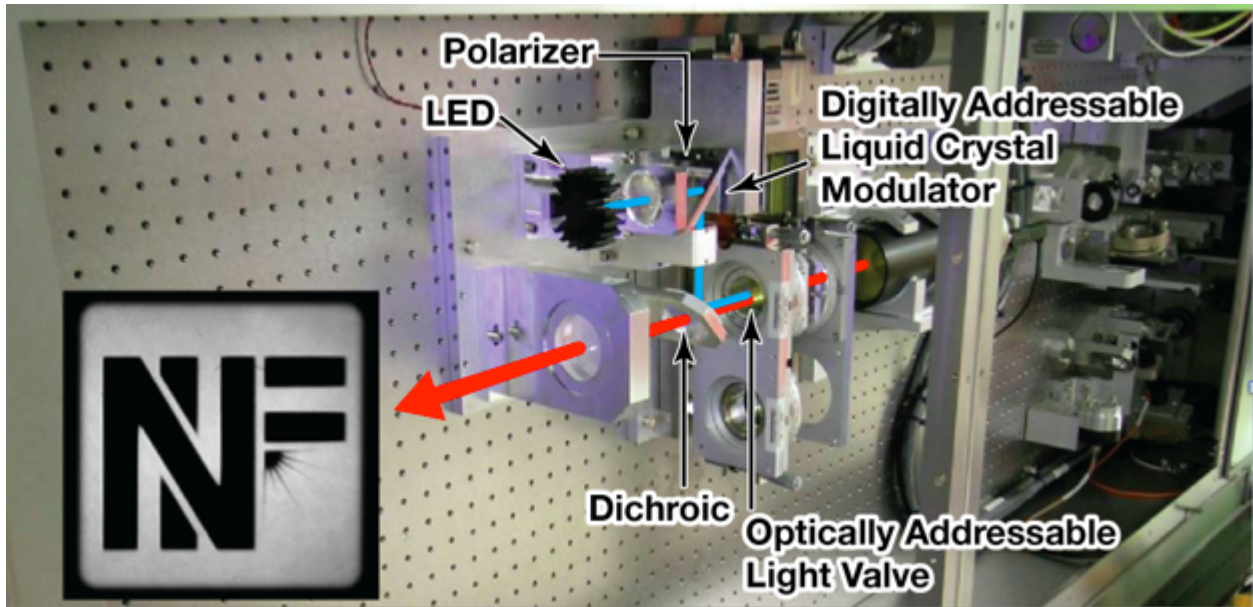


Fig. 38: Programmable Spatial Shaper (PSS) package. The package implements a two-stage liquid crystal spatial light modulator. In the first stage, a pixelated pattern is imprinted onto an incoherent blue light source using a conventional liquid-crystal light modulator, as found in a projection television. In the second stage, that pattern is transferred from the incoherent illumination to the coherent infrared beam using a liquid-crystal analog light valve. The fidelity of imprinting an arbitrary black-and-white pattern onto the transmitted laser beam is shown in the inset. In this case the NIF logo (black portions are masked; lighter portions show laser light proceeding unmasked).

After leaving the PSS the shaped beam is passed through a hole in the vertical breadboard that supports the regen on one side and the four-pass preamplifier on the other, then it moves through a Faraday rotator and into the second, the four-pass, preamplification stage of the PAM.

V.C. The Four-Pass Preamplifier

To maintain alignment of the 48 PAMs for the planned 30-year life of NIF, hand-off from the regen-and-mask side of the vertical breadboard to the side housing the four-pass preamplifier is facilitated by 10 actuated control points. These control points are capable of automatically correcting any misalignments in centration of the beam on the 20x expander, and pointing and centering into and out of the four-pass preamplifier (Ref. 61, 63).

The four-pass flashlamp-pumped Nd:Glass preamplifier provides an amplification factor of approximately 1,000 bringing the energy up to ~6 J. During the design and prototyping phase of the four-pass preamplifier priority was given to avoiding the possibility of parasitics (unwanted self-oscillations due to inadvertent feedback above the 0.01% level) and pencil beams (undesired amplification of reflections from transmitting surfaces, i.e., ghosts, clipped by spatial filter pinholes). Vacuum Relay Telescopes (VRTs) are used to relay and re-image the shaped beam through the four passes of the preamplifier rod. A quarter waveplate and polarizer enable the last two passes through the rod after reflecting from either an end mirror or diffraction grating. The dispersion of the diffraction grating is one element of the system that provides beam smoothing on the target.

Each VRT uses angular multiplexing through a four-element pinhole array, much like the large main amplifiers, with lenses that are tilted to suppress unwanted reflections from entering the pinhole array and creating amplified pencil beams. The orientations of the tilts were strategically chosen to keep net wavefront distortions below 0.5 waves peak-to-valley. Care was also taken to wedge or tilt remaining optical components and to baffle any mechanical components that could give rise to stray reflections that could result in parasitic oscillations or pre-pulse on the target. As shown in Fig. 39 the PAM delivers nearly diffraction-limited performance.

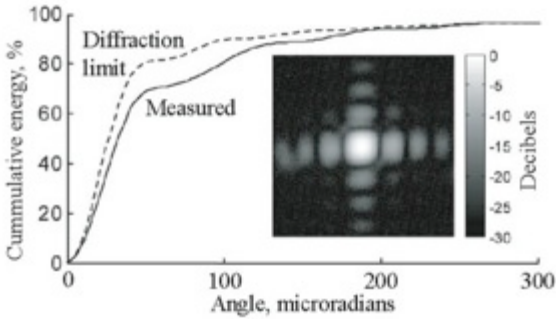


Fig. 39: Output far-field cumulative angular energy from the four-pass preamplifier compared with the diffraction limit for a perfect square beam. The inset displays the raw far-field spot data displayed on a logarithmic scale. The cross-pattern is close to the textbook, ideal focused intensity pattern associated with a square laser-beam profile.

All mounts in the four-pass preamplifier were carefully screened and pretested for optimum pointing stability. Measurements have consistently validated a pointing stability below 10 μ radians rms. Accelerated lifetime tests were performed on motorized components expected-to-be-frequently exercised during the projected 30-year NIF lifetime and only those devices that passed these tests were chosen. A photograph and schematic of the four-pass preamplifier are included in Fig. 40. The 0.98 μ m reference source is provided locally by a diode laser that assists in both positioning the preamplifier beam on its end mirror and alignment of this preamplifier with the 1 ω cw alignment beam from the ISP.

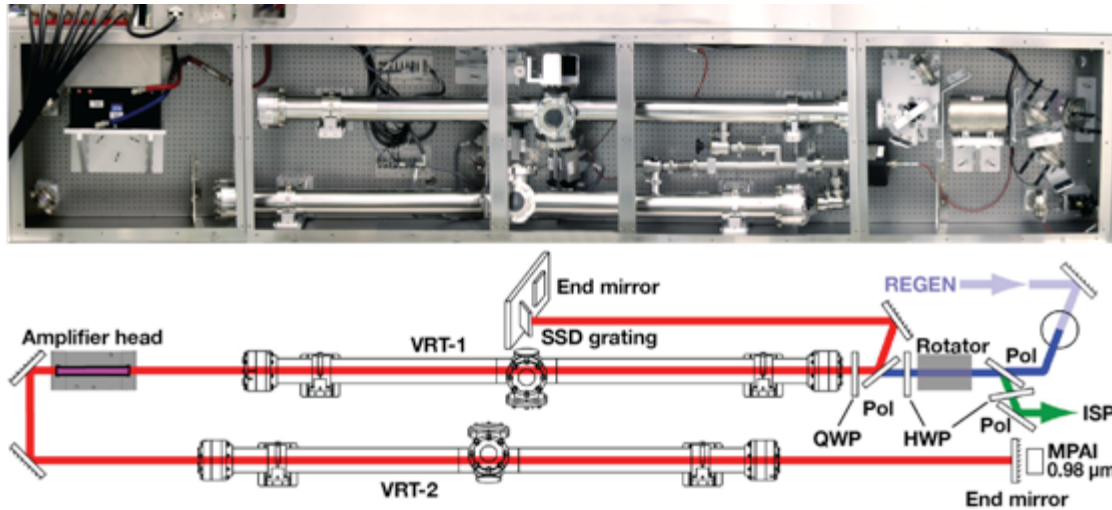


Fig. 40: PAM second stage four-pass geometry. Following the regen and beam shaping module, light is injected (on-line in blue) through a Faraday rotator into the four-pass amplifier (on-line in red). The Vacuum Relay Telescopes (VRTs) image the shaped beam through the system. A quarter waveplate (QWP) and polarizer (Pol) enable the last two passes through the rod after reflecting from a choice of end mirror or diffraction grating. The output from the four-pass preamplifier is sent to the ISP, the Input Sensor Package. Most of that light is sent through the Transport Side of the ISP and then on to the PABTS.



Fig. 41: A photograph of a PAM LRU being readied for installation in the region below the Transport Spatial Filters. The two sides of the PAM, seen earlier in Fig. 29, the regen and the four-pass preamplifier, are supported back-to-back to each other in the LRU.

One of the PAM LRUs is seen in Fig. 41 just before installation in its rack below the Transport Spatial Filters in one of the laser bays. This LRU houses a vertically oriented strongback breadboard centered along its length. One side of the breadboard carries the regen, the other supports the four-pass preamp.

The system of 48 PAMs has met its stringent set of requirements. A shot-to-shot rms energy stability of 1% is achieved when operated near maximum energy output in the saturated regime. The nearfield contrast (spatial noise) of its beam profile is around 3.5%, and the overall beamshape is well within the required $\pm 10\%$ deviation from a prescribed shape.

V.D. Input Sensor Package (ISP)

After leaving the PAM LRU, the beam is sent to the Input Sensor Package (ISP). Greater than 99% of the delivered light is sent through the transport side of the ISP and then on to the PABTS. On its way, it passes through a turning mirror where $<1\%$ of the beam energy is sampled and sent into the diagnostic suite of the Input Sensor Package (see the diagnostic side of the ISP in Fig. 42). The ISPs provide functionality for all of NIF, as well as characterizing the PAM output for every quad. Each ISP provides:

- The 1ω cw alignment laser, a key source of light for multiple functions in the Main Laser and the Output Sensor Package (see section VI.C.8)
- Images for co-alignment of the incoming PAM beam (near-field and far-field spatial patterns) with the 1ω alignment laser
- An insertable reflector that can redirect the light from the 1ω cw alignment laser into a single-mode fiber that carries light to the pass #4 pinhole plane of the transport spatial filter where it serves as the near-diffraction-limited source for wavefront measurement and close-loop adjustment of the deformable mirror actuators. (see Section VI.C.9)
- Measurement of the 1ω energy from the PAM
- Measurement of the 1ω temporal pulse shape of the PAM. This pulse shape, together with the energy measurement gives the PAM power versus time during the pulse
- Measurement of the 1ω beam fluence profiles for the PAM

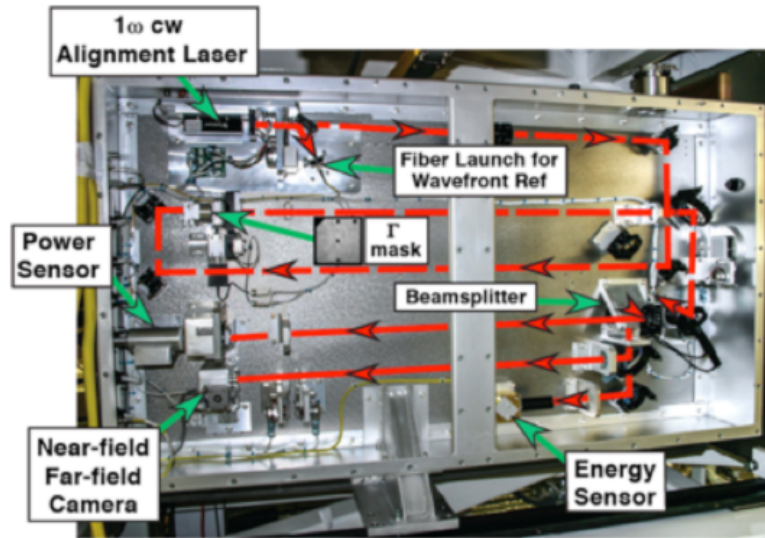


Fig. 42: Diagnostic Side of the ISP. The Transport Side of the ISP is located on the opposite side of the diagnostic box seen here. Light is passed between Transport and Diagnostic sides through two holes in the breadboard (follow the arrows, on-line in red). Light from the Transport side is transmitted through a <1% splitter and enters the Diagnostic side at the green arrow that also points to a beamsplitter. Via beamsplitters and mirrors, the light then propagates to the Power sensor, the Energy sensor and the ISP camera capable of measuring both near field and far field. There is also a Quad Back-Reflection Sensor (a diode and integrating sphere) that is incorporated with the Faraday-Rotator Isolator on the Transport side.

ISP measurements are important for both validating and normalizing LPOM numerical models for laser performance and for ensuring that each laser beam is properly configured prior to propagation into the 1ω Main Laser System. On the basis of LPOM calculations, ICCS adjusts the attenuation in the path to the sensors of all 48 ISPs to ensure that good data is collected for every shot.

V.E. Preamplifier Beam Transport System (PABTS)

Before leaving the transport side of the ISP, the PAM output beam encounters a Faraday-Rotator Isolator designed to protect the PAM from target back-reflections. It then enters the structure of the preamplifier beam transport system (PABTS). The functions of the PABTS are to optically split the beam leaving each PAM/ISP into four beams and to relay these beams, properly sized and mode matched to the main amplifier system. The pulse energy entering the PABTS can be set from milli-joules to more than a joule by controls within the PAM, including a rotatable-half-wave plate at the PAM output (see Fig. 40). The energy ratios between beams are adjustable within the PABTS by use of the rotatable-half-wave plates that precede each polarizer beam-splitter as identified in Fig. 43.

Rotating the linearly polarized beam (by rotating the half-wave plate) going into each polarizer changes the ratio between the transmitted “P” polarization and the reflected “S” polarization and provides control over the fraction going into each MLS beamline. During early testing it was found that available dielectric coated polarizers allowed up to 1% of the unwanted “S” polarization to be transmitted along with the desired “P” polarization, compromising the ability of the controls to achieve the desired splitting ratios. Initial measurements showed that the beams transmitted by the two polarizers identified (by P-2) in Fig. 43 had up to 8% more energy than the beams reflected by the subsequent polarizers (P-3) when the wave plates were set for 25% for each of the beamlines. Analysis identified “S” polarization leakage of the P-1 polarizer as the principal cause of this loss; the desired performance was recovered by coating this optic on both surfaces, i.e. a double polarizer for this location. The intensity of forward-going internal reflections is negligible, and those going to the reflected path are directed out of the beam path by an appropriate wedge in the polarizer substrate.

During shot set-up, as directed by LPOM, ICCS adjusts the PABTS rotatable half-wave plates to provide the requested beam splits. A timing adjustment is also built into the PABTS for each beam in the form of an adjustable length trombone as shown schematically in Figures 20 and 43. These are used to adjust the relative timing of the four beams coming from each PAM. (More information on timing control is given in “National Ignition Facility Laser System Performance”, also included in this issue of *FS&T*.) Changes to the timing of each four-beam group, each “quad,” are implemented in the MOR.

Each one of these beams is relayed to its corresponding large aperture amplifier in the 1ω Main Laser System. Relay plane 8 (RP-8) is imaged to RP-9 by vacuum relay telescope-1 (PABTS VRT-1) and RP-9 is relayed to RP-10 by PABTS VRT-2. Finally a combination of

upper injection mode-matching optics, the transport-spatial-filter input lens, and the cavity spatial filter relays RP-10 of each beam to the corresponding deformable mirror in the main laser.

V.F. Summary Overview of the NIF ILS

The hardware and control systems for the ILS as they exist today meet all of their original flowdown requirements and a number of new flowdown requirements that evolved as the concepts of interest to target designers matured since the time of the NIF Laser Design and Cost Basis Document in 1993 (Ref. 29). As for all of the NIF systems, the goals of the ILS focused on both shot-by-shot performance and support for routine operation over the projected life of NIF. Tables II and III summarize how specific features of the ILS cover each of these sets of responsibilities.

TABLE II: Summary of the primary shot-by-shot performance responsibilities of the NIF ILS system.

	Functional Responsibility	ILS Design Response
Performance	Bandwidth for SSD & SBS	Frequency modulator and Failsafe system
	Temporal pulse shaping	Amplitude modulators for each of 48 quads
	Wavelength agility	Multiple (3) tunable oscillators
	Gain up to multi-Joule level	2-stages, providing a net gain of 10^{10}
	Beam spatial shaping	Edge apodizer Gain compensating mask
	Timing, energy ratios	Provided by PABTS
	Performance diagnostics	High bandwidth, 6 GHz transient digitizer, Tektronix 70604; ISP energy, pulshape, beam profile

TABLE III: Summary of routine operations responsibilities of the NIF ILS system.

	Functional Responsibility	ILS Design Response
Routine Operation	Pointing stability	Stable and/or automatic optics alignment
	Long-term wavelength stability	Temperature-tuned master oscillator
	Suppression of FM-to-AM	Extended bandwidth regen preamplifier via intracavity birefringent filter
	Programmable downstream shadowing of specific sites	Programmable Spatial Shapers (48X) Integrated computer control of PSS with FODI (see <i>Optics Recycle Loop</i> , this issue)

V.G. Leaving the ILS

A pulse from the ILS is injected into the 1ω Main Laser System near the focus of a Transport Spatial Filter by a small injection mirror held within the clean vacuum environment of the spatial filter. These small mirrors are shielded from light and debris scattered by their surroundings and have been kept virtually maintenance free by holding the fluence levels they handle to less than 2 J/cm^2 . The location of the injection mirrors and their fluence beam profile is shown in Fig. 44.

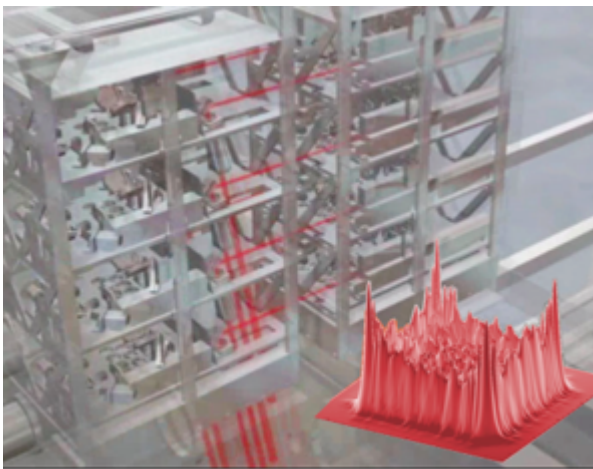


Fig. 44: The input beams to the 1ω Main Laser System come up from the PAMs that are housed below the transport-spatial-filter structures, to be reflected by a small injection mirror located near the Transport Spatial Filter (TSF) focal plane. Here, a profile of a typical beam at the injection mirror is overlaid on a perspective CAD drawing of their locations inside the TSF.

VI. THE 1ω MAIN LASER SYSTEM (MLS)

The 1ω Main Laser System (MLS) provides the muscle and endurance of NIF. It accepts the low-energy low-power output from the ILS and delivers it amplified by a factor of approximately 50,000 to the final optics for frequency conversion, focusing, completion of beam smoothing and delivery to the target.^{71,72} The 192 Main Laser Beams were operationally qualified up to 4.2 MJ of 1ω energy on Sept 24, 2008. The MLS can provide peak power of over a PW and support temporal pulse lengths that can range from ~ 0.1 to 33 ns while at the same time meeting the tight ICF requirements for power balance and focal spot size. The responsibilities carried by the MLS, as identified in Fig. 5, are repeated here in Fig. 45 along with the schematic of a single beamline in the MLS. As seen from this figure and with reference to Fig. 2, the MLS occupies a large fraction of the NIF facility. It should be noted that one of its top-level goals was meeting all of its performance requirements with rugged, extremely reliable hardware. Because minimum maintenance was believed important and achievable for this system, high reliability was demanded (and verified) for each of its many components.⁷³

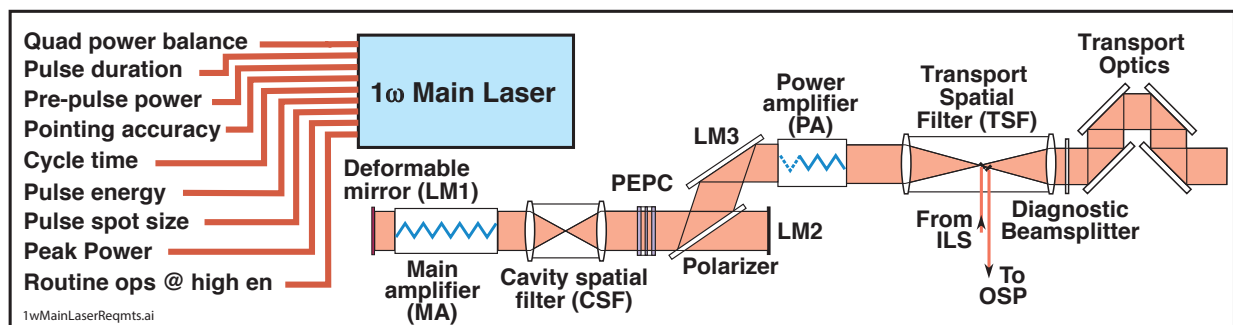


Fig. 45: Responsibilities and a schematic diagram of the components of the 1ω Main Laser System.

The 1ω MLS was required to meet economic and performance criteria many times more demanding than those of its Nova predecessor, as summarized in Table IV. Although each of these challenges was considered feasible, significant scientific and technology development was necessary for their realization.

TABLE IV: Science and technology challenges faced by the 1ω Main Laser System with comparison to values for the Nova laser.

Requirement	Factor	Response
Better use of building volume	$\sim 10x$	Use compact arrays of large amplifiers
Reduce component count	$\sim 5x$	Eliminate intermediate amplifiers, use 4-pass design packaged in compact arrays
Enable large-aperture four pass architecture	First demo on Beamlet	Develop the transparent electrode Plasma Electrode Pockels Cell LRU
High volume production of high-quality optics	Never before done	Develop relationships with optic suppliers, introduce new finishing technology
Decrease laser glass cost increase production rate	$\sim 5x$ $\sim 20x$	Develop continuous-pour glass melter, fast finishing
Increase 1ω operating fluence	$\sim 2x$	Hafnia/silica coatings, Mirror conditioning Improve optical specifications
Improve beam quality	$\sim 5x$	Adopt ISO 10110 standard for surface specifications, Develop adaptive optics
Higher energy density power conditioning modules	$> 10x$	Abandon ignitron switches and engineer new flashlamp driver modules
Increase electrical efficiency	$\sim 3x$	Optimize amplifier packing, improve reflector design, eliminate inefficient isolators

VI.A. Critical concepts established by pre-NIF laser developers

Understanding the design strategy for a high-energy Nd:Glass optical beamline expanded rapidly with the design, construction and operation of the six lasers built at LLNL from 1972 to 1984 and seen in the photographs of Fig. 46 (Ref. 12).

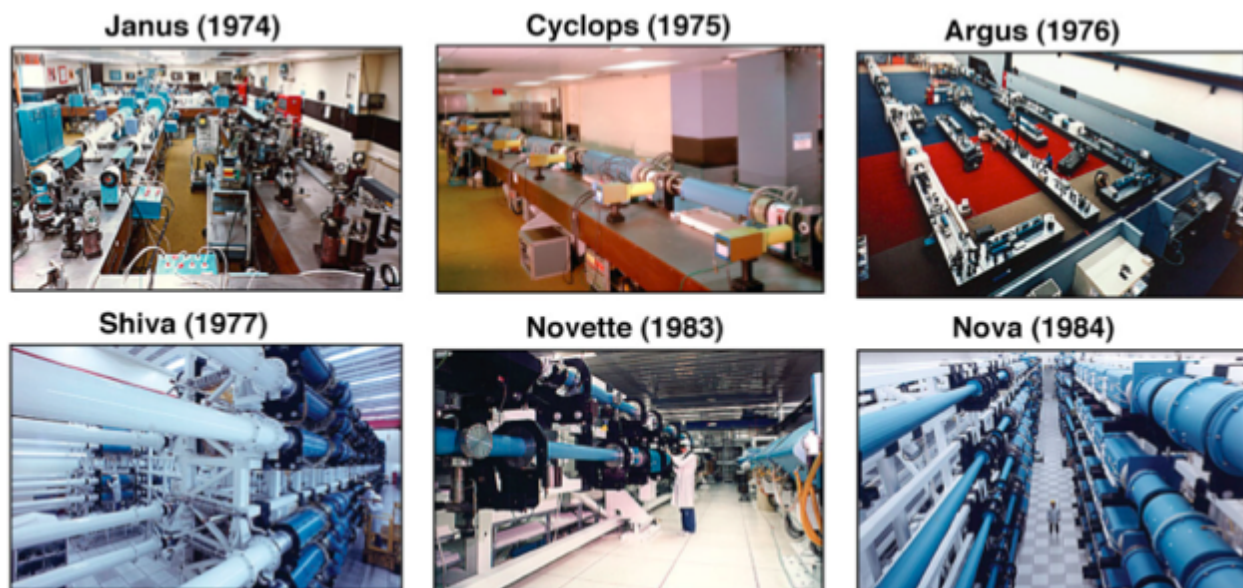


Fig. 46: Photos of pre-NIF large aperture glass lasers at LLNL.

These lasers provided platforms for development of the concepts required for delivering high-beam-quality, high-power, high-intensity beams from large 1ω amplifiers. The 1ω output energy from these systems increased from less than a hundred Joules from Janus in 1974 to more than 120,000 Joules from Nova in 1987.

Lessons learned from Janus, Cyclops and Argus:

- For reduction of optical damage at 1ω , all pre-NIF beamline designs used amplifiers with increasing diameter as the beamline fluence increased along the amplification path. The magnification for each segment was selected to keep the output fluence for the larger amplifier about the same as that for the preceding smaller amplifier. Incremental increase of the beam size from the low-power, low-energy front-end components into the first amplifier, and from amplifier segment-to-segment used magnifying Keplerian telescopes. The four-pass architecture of NIF avoids the need for resizing the aperture along the

amplifier chains but still uses the lessons learned with Keplerian telescopes for reduction of optical damage.

- Good energy extraction with low optical damage requires keeping the spatial contrast low within the laser slabs and at all high-fluence surfaces.⁷⁴ Spatial contrast is defined in Fig. 47(a):

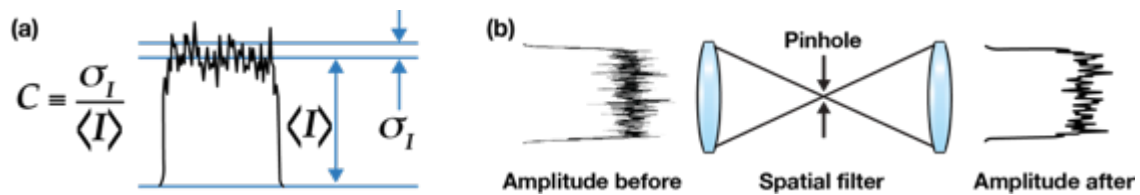


Fig. 47: (a) Intensity lineout across a laser beam, and definition of spatial intensity contrast. (b) Concept and benefit of spatial filtering (Ref. 71).

- The near-vacuum environment required by the high-intensity focus of the lasers in the Keplerian telescopes (see Fig. 47 (b) provided a location for placing “pinholes”. Functionally, the pinholes allow spatial filtering of high-frequency optical noise, thus reducing (improving) the spatial intensity contrast of the transitting beam. Cyclops was the first laser to take advantage of this spatial-filtering feature.⁷⁵
- The concept of relaying the high-quality image of one near-field plane to improve the uniformity of the downstream laser profile at optical surfaces at another near-field plane was first introduced in a retrofit to Argus (Ref. 49) (see Fig. 48).⁷⁶

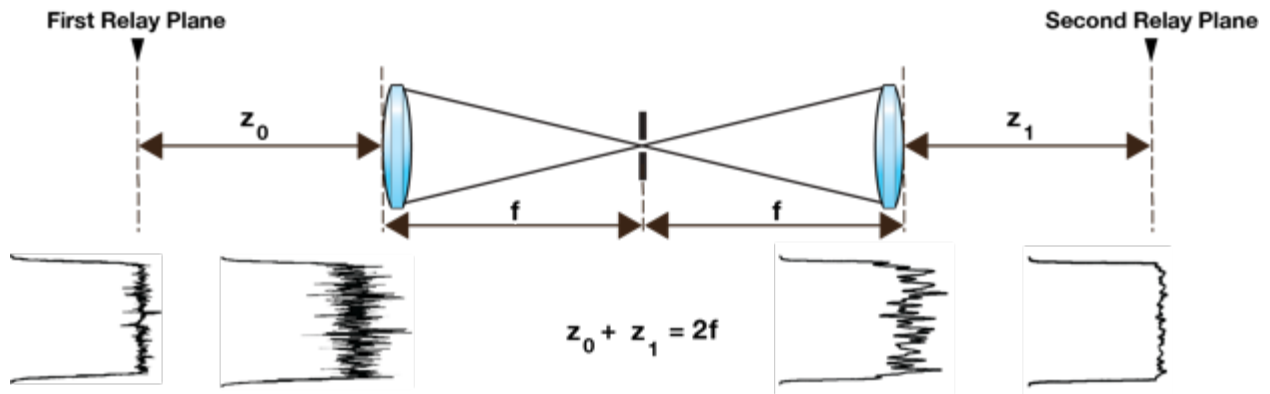


Fig. 48: Relay imaging concept used throughout the NIF laser beamlines, from RP-0 in the PAM, forward, including in the large amplifier chains. Note that $z_0 + z_1 = 2f$. This relationship set the length of the NIF building.

The economy of compact laser arrays with only one-size amplifier was learned from the studies of large ICF laser systems (identified in the timeline of Fig. 2) completed during the years from 1983 to 1986.^{77,78} Figure 49 reproduces a compact array designed as part of the LLNL MultiMegaJoule Laser Design of 1984. From the start of work on the NIF laser design, the compact arrays of 1ω amplifiers were configured into the bundles and clusters shown in Fig. 49. Implementing these arrays then became a challenge that was spread across all of the mechanical and electrical teams charged with delivering LRUs that could operate within these confined volumes.

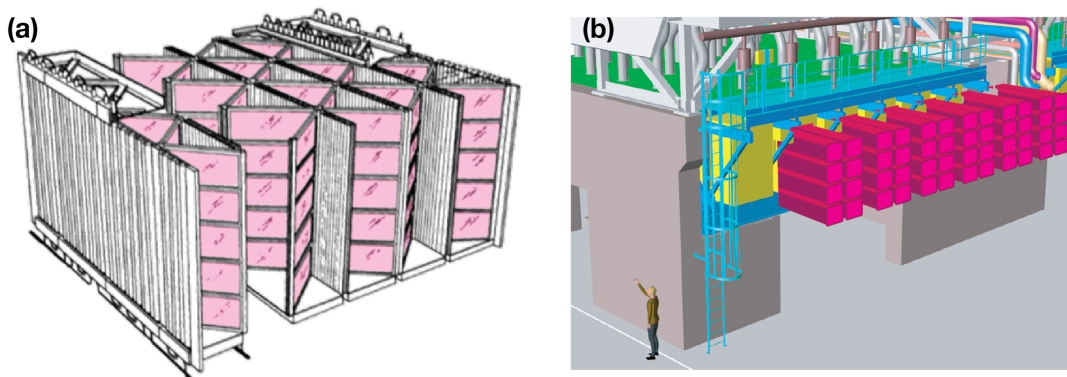


Fig. 49: Comparison of compact laser array architectures (a) Architecture with a 5-high amplifier stack identified as having low capital cost in the MultiMegaJoule Laser Design published in 1984 (Ref. 77) (b) CAD drawing showing the tight packing of NIF large amplifiers with eight beams per bundle and six bundles per cluster.

Two facilities shown in Fig. 50 were built as joint efforts with the French CEA (Commissariat à l'Energie Atomique et aux énergies alternatives) to explore the physics and engineering of the next generation of large 1ω amplifiers. On the left in Fig. 50, the Amplifier Module Prototype Laboratory (AMPLAB)⁷⁹ was a four-slab-high, three-slab-long and one-slab-wide amplifier segment used for study of a number of critical NIF amplifier features, including amplifier gain and phase profiles, flashlamp reflector concepts and hardware, cleanliness, and somewhat later, the Fast-Connections techniques essential for assembly of the large hardware for the Beampath Infrastructure System of NIF. Following the guidance gleaned from the MultiMegaJoule Laser Design study illustrated in Fig. 49, both AMPLAB and Beamlet had square-aperture laser beams. On the right side of Fig. 50, Beamlet had a 2 x 2 beam configuration similar to that now found in a NIF quad, but for reasons of economy, Beamlet had only one of the four apertures populated with laser slabs. The other three beamlines were filled with architectural glass.

As the physics prototype of NIF, the near-full-scale 11-7 configuration of Beamlet was well positioned to test and validate a number of critical concepts and hardware components for its NIF successor. The hard-aperture diameter of Beamlet optics was 37 cm compared to that for NIF of 40 cm.

Lessons learned from Beamlet:

- Perhaps most importantly, Beamlet demonstrated for the first time that the four-pass architecture proposed for NIF was realizable for large-aperture beams. This architecture was made possible because Beamlet incorporated a large aperture, transparent plasma electrode Pockels Cell (PEPC). (see Section VI.C.1) With this configuration NIF would be able to use only one size amplifier instead of many different sizes as had been used in pre-NIF lasers.^{80,81} In NIF the 2 cm x 2 cm output beam from the Injection Laser System is expanded without amplification to match the 37 cm x 37 cm aperture of the large amplifiers
- The layout of the Beamlet beamline in the Bldg 391 Highbay (seen in Fig. 50) provided a flexible base for evaluation of several beamline geometries, including the “L-turn” and “U-turn” options. These two geometries were of interest because it was hoped they could eliminate the cost and development time required for the large 1ω polarizer and PEPC that are now included in the NIF design. LLNL did not elect to build one of these geometries for several reasons, including that they were difficult to keep clean, they did not pack well into the small volume deemed acceptable for NIF and their requirement for high 1ω fluence on a small mirror (80 J/cm² average, 200 J/cm² peak)
- With its successful use of a deformable mirror, Beamlet was able to demonstrate output wavefronts with quality never before achievable at this scale⁸²
- Beamlet was the first laser to demonstrate quantitative agreement between the physical-optics codes used for its design and experimental measurements of its performance (see Section IV and Fig. 14)

- Development of the cone pinholes used in the spatial filters of NIF was an outgrowth of two (pre-cone) pinhole closing events on Beamlet that seriously damaged its transport mirrors. The cone pinholes now operate with very high reliability in NIF⁸³
- Beamlet was also used to experimentally identify the limits on phase pushback, ΔB , introduced by non-linear effects along a beamline. The intensity in Beamlet was driven to higher values than are now allowed for NIF, illustrating the importance to NIF of staying away from this regime. (more information on ΔB can be found in Ref. 84)
- Diagnosis of the Beamlet wavefront added significantly to our understanding of the importance of reducing the scale of imperfections on optical surfaces, particularly those in the spatial frequency band associated with small-tool finishing (~ 2 cm). In addition developing economical procedures for slab finishing using a planetary lap was validated on Beamlet
- The good uniformity of the frequency converted Beamlet beam made it possible to measure the Transverse Stimulated Raman Scattering (TSRS) gain cross-section in 80% deuterated DKDP with a precision that has still not been replicated. (This value was needed for the design of the triplers and polarization optics in the Final Optics Assemblies)⁸⁵ (Also, see the “Damage Mechanisms Avoided or Managed for NIF Large Optics”, also in this issue, for more information on this measurement.)
- Experience with optical damage on Beamlet fused-silica and crystal optics was a strong motivator for developing a better fundamental understanding of optical damage mechanisms and for practical implementation of the concepts described in the “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” paper also in this issue of *FS&T*⁴⁷

- Beamlet was also a first article for NIF from the viewpoint of gaining operational experience. It provided broad understanding of the directions that should be taken for system robustness and operability.⁸⁶ It was used to explore the entire power-energy range important for meeting the requirements of the NIF missions



Fig. 50: AMPLAB (on the left) and Beamlet (on the right) predecessors of large NIF amplifiers.

VI.B. Assembly and Installation of the Main Laser Components

The 1 ω MLS contains 6208 large optics. Assembly of these optics and associated hardware required dedicated facilities and a team of scientists, engineers and technicians. Figure 51 shows facilities in the north-east quadrant of LLNL dedicated to this purpose, including Building 381, Building 391, the Optics Processing Facility (OPF) and the Optics Assembly Building (OAB), part of the NIF building described earlier in Fig. 2.

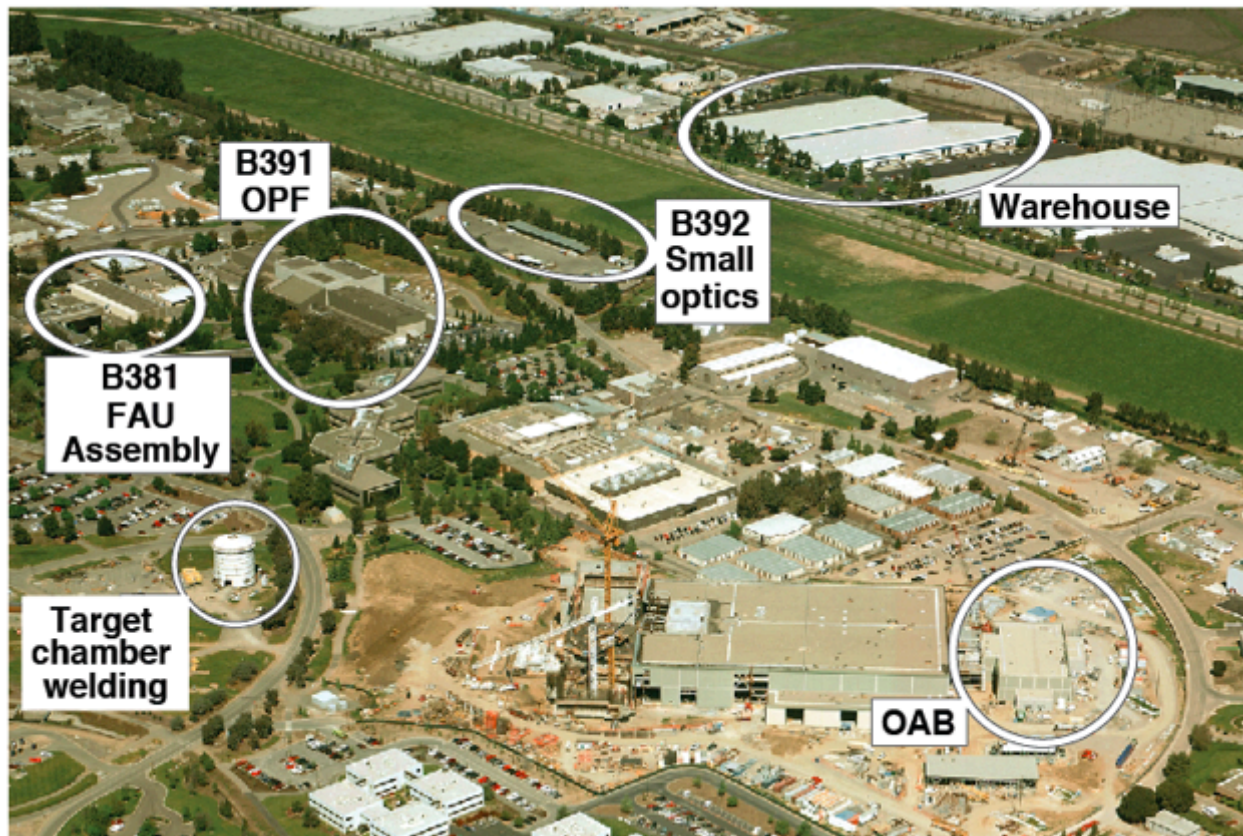


Fig. 51: Buildings in the north-east corner of LLNL were used for acceptance, interim storage, cleaning, coating, and assembly of Main Laser System components. (Note: A recycled storage tank was used to house activities for constructing the target chamber. Here, welders assembled large pre-fabricated curved “plates” to form the precision sphere of the target chamber.)

VI.B.1. Frame Assembly Units (FAUs)

Building 381 was originally built for the Argus laser; its second occupant was Novette, followed next by the Beamlet laser. It was put into service for NIF as space for assembly and internal alignment of the Frame Assembly Units (FAUs), the housings that now support the slab and flashlamp LRUs. Although the flashlamp windows—the windows that separate the flashlamps from the slabs—were originally designed to be line-replaceable units, early on it was

decided to integrate them directly into the FAUs as they were being assembled in Building 381. This had the advantage of allowing certification of proper sealing of the windows in each individual FAU and eliminated the need to install the windows later in the laser bays of NIF. This strategy was possible because the clean optic processing capabilities of the Optics Processing Facility (OPF, discussed in 6.2.2) were available for flashlamp-window processing and assembly in time to meet the FAU schedule.



Fig. 52: Photographs of work underway in Bldg 381 during assembly of the Frame Assembly Units.

Two photographs of activities as the FAUs were assembled are included in Fig. 52 (Ref. 39 and 42). Section VI.C.3 includes another picture of an assembled FAU being prepared for transport. After assembly and alignment in B381, FAUs were moved to the Laser Bays in custom transporters as shown in Fig. 53 (a). Figure 53 (b) is a photograph of a delivered FAU being lowered into place in one of the laser bays.



Fig. 53 (a) Transporter delivering an already internally aligned FAU. (b) An FAU being lowered into place in the laser bay.

VI.B.2. Optics Processing Facility (OPF)

Upon receipt, all of the large optics for NIF were first routed through the Optics Processing Facility (OPF). The OPF is divided into two class-100 processing areas, one dedicated to crystals and the other for the various types of glass. The optics processed included those for both the Main Laser System and the Final Optics Assemblies: amplifier slabs, mirrors and polarizers, lenses and windows, KDP crystals and flashlamp windows. Within OPF, a typical workflow path for an optic included: receipt, inspection, cleaning, inspection, AR coating, inspection, assembly of sub-units, inspection and finally shipment to Building 381 or to the OAB for assembly into an LRU.



Fig. 54: OPF stations for cleaning incoming optics.

As seen in Fig. 54, equipment is set up in OPF for automatic cleaning (toluene ultrasonic, aqueous ultrasonic, and hand-assisted aqueous washing). The OPF also includes stations for applying sol-gel anti-reflection coatings and for post-processing these coatings (see Figs. 55 and 56).

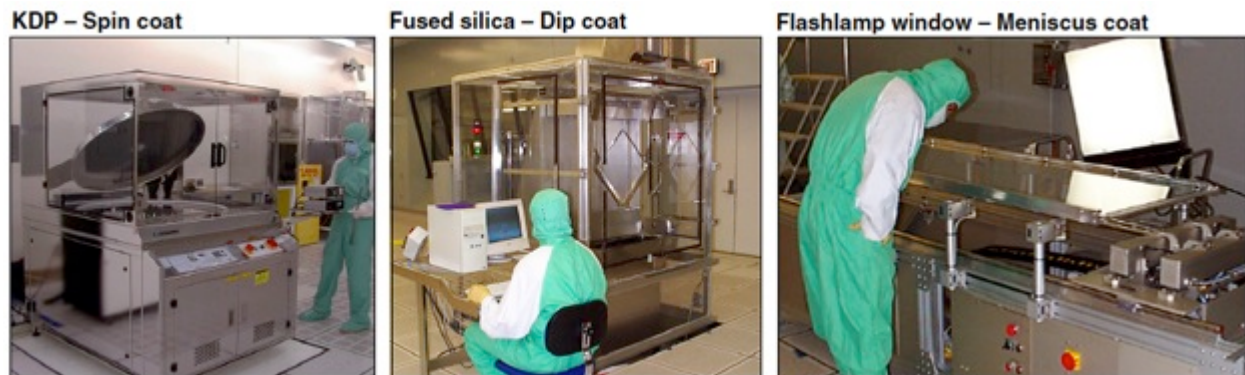


Fig. 55: Sol-gel coaters used for producing high-damage resistance, very high transmission coatings.



Fig. 56: Ammonia/water vapor curing chamber in OPF.

Sol-gel antireflection coatings for the flashlamp windows and the large transmissive optics of NIF, (fused-silica, crystal optics and the disposable debris shields) were first reduced to practice at LLNL in the early 1980s in support of Novette and then Nova.^{87,88} These coatings are based on single-layer quarter-wave porous silica technology. They have many advantages when considered from the viewpoint of a high-fluence, high-intensity NIF beamline. They have high damage thresholds, low manufacturing costs using equipment kept available locally and under the control of the facility they support, and they can provide outstanding anti-reflection properties at their use wavelength ($<<0.25\%$ reflectivity per surface). However, as seen in Fig. 57, they have a very porous structure with large surface area ratio, on the order of 100:1, and can readily adsorb vapor borne contaminants. If contamination occurs, the pores of the coating are gradually filled, and the transmission of the coating is reduced.

All sol-gel solutions are synthesized on-site by the NIF program using high-purity precursors and solvents. The coatings for the NIF glass optics are post-treated for 16 hours in the station shown in Fig. 56 with ammonium-hydroxide vapor to provide a “hardened” coating that

is both more strongly adherent (“tougher”) and less susceptible to vapor-phase organic contaminants.⁸⁹

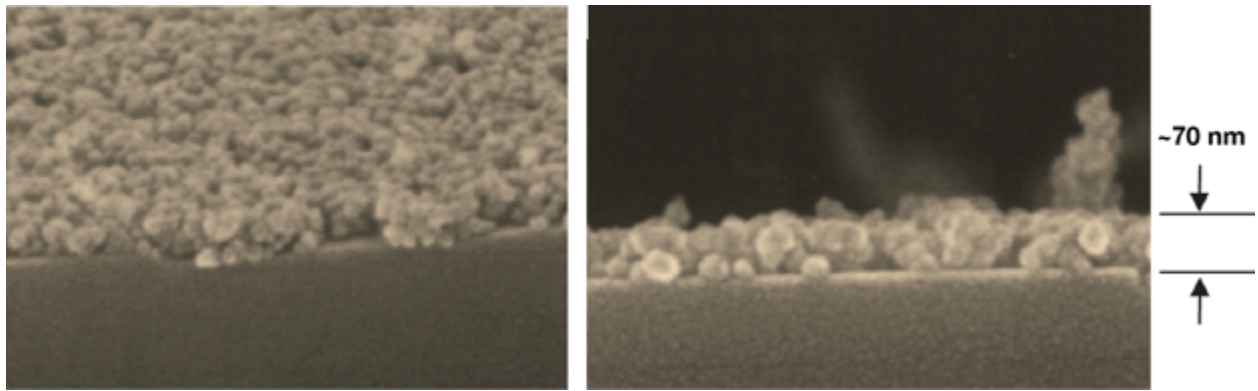


Fig. 57: Scanning electron microscope images of a sol-gel anti-reflection coating.

All spin-coated optics for NIF, including all of the crystals and the un-etched side of the grating debris shield (discussed in Section VII) use a sol-gel solution that has been treated with hexamethyldisilazane (HMDS).⁹⁰ In this process HMDS reacts with the ~20 nm colloidal silica surfaces to form a very hydrophobic trimethylsilyl ($-\text{Si}(\text{CH}_3)_3$) surface. The HMDS treated coating resists vapor contamination of the pores and prevents etching of the KDP crystal surface induced by the condensation of water.

All materials of construction that are used in the NIF beampath were rigorously vetted for outgassing to assure that, in operation, the level of vapor-phase contaminants remains sufficiently low that it does not pose a risk to the sol-gel coatings. Because of a higher rate of vapor transport, the risk of contamination is much higher in an evacuated volume. Section VI.C.7 on the topic of the Large Spatial Filters describes techniques that are used to reduce this risk.

VI.B.3. The Optics Assembly Building (OAB)

The primary responsibility of the OAB was to assemble the large LRUs of the MLS and load them into clean canisters for delivery to the laser bays or switchyards. Mechanical parts for LRU assembly were first cleaned in the OAB or were received from vendors as already precision-cleaned components using cleaning protocols provided by LLNL. Processed optics from OPF and their corresponding mechanical parts were assembled on dedicated work-stations for each type of LRU (Ref. 43). After assembly, optics installed in the LRUs were tested for wavefront quality, stress-induced birefringence, alignment and other features specific to the LRU.

The LRU alignment verification system (LAVS) is one of the several large-scale LLNL-designed verification systems used in the OAB. LAVS was used to verify that each optic was correctly positioned in its LRU frame. LAVS consists of an ultra-stable steel structure with docking locations for the different types of LRUs. A robotic arm at the center of this structure can accommodate video, ultrasonic and auto-collimator-based metrology tools. The optics were precisely scanned in three dimensions to ensure their x, y and z positions relative to the LRU frame were within tolerance, and that they were oriented at the correct pre-alignment angle. The position tolerances varied by LRU but were typically 1.0 mm in the x, y, and z directions, and 1.0 mrad in angular tilt. Pre-aligning the position of the optics prior to installation decreased the time required to perform on-line alignment and activation of the laser. The wavefront verification system (WAVES) is a Hartmann sensor-based diagnostic capable of measuring the wavefront distortion across the full aperture of a large optic in an assembled LRU. This system verified that mount-induced wavefront distortion was within tolerance. The tolerance also varies by LRU but ranges from 0.10 to 0.25 waves (peak-to-valley).

Once these tests were satisfactorily completed, the LRUs were loaded into canisters and transported to their destinations in the Beam Path Infrastructure (Ref. 42) as described in Section III.C. Figure 58 is a photograph of an LM1 mirror being loaded into its LRU.



Fig. 58: An LM1 being loaded into its LRU. The deformable mirror actuators can be seen through the coated surface of the mirror that is highly reflective at 1ω , yet transparent in the visible.

VI.C. Descriptions of the Main Laser System Components

VI.C.1. The Plasma Electrode Pockels cell (PEPC)

Operation of the four-pass architecture described in Section II.A was first validated by its successful demonstration in the Beamlet test bed, a demonstration enabled by the first operation of a large aperture transparent electrode half-wave rotator, the Plasma Electrode Pockels cell (PEPC) and an even larger (~ 40 cm x ~ 80 cm) polarizing mirror. Demonstration of the PEPC and thus of the four-pass configuration set the stage for the entire architecture of NIF. The first demonstration unit of the PEPC in Beamlet used a single aperture non-conducting housing,

leaving further development for packing into an LRU to be completed during the NIF Project.^{91,92,93,94,95}

Switching of the beampath within the Main Amplifier (MA) is accomplished by this combination of the PEPC and the polarizer. The polarizer mirror reflects 1.053 μm light if it is horizontally polarized and transmits that light if it has vertical polarization. When the PEPC is not energized, it does not affect the polarization of the beam that passes through it, but when it is energized, it rotates the polarization by 90 degrees. Section II steps through the sequence of events experienced by a beam as the combination of the PEPC and the polarizer makes four-pass amplification possible.

Each PEPC aperture contains a 1-cm thick potassium dihydrogen phosphate (KDP) plate, cut normal to the z-axis of the crystal and installed in a partial vacuum cell between two fused-silica windows. Glow-discharge plasmas are ignited in the low pressure He-filled spaces on the two faces of the crystal. The plasmas must have an electron density low enough not to absorb, reflect, or diffract the beam as it passes through the cell, yet a conductivity that is high enough for uniformly charging the opposing crystal faces to the switching voltage of ~ 15 kV in about 100 ns. Growing the large, ~ 43 cm KDP boules from which the PEPC crystal optics were cut was another of the development challenges faced by the NIF team. This work is described in Section VII.G together with the work to grow the KDP and deuterated KDP (DKDP) for the doubling and tripling crystal plates.

Although the concept of a PEPC had existed for some time before NIF,⁹⁶ there were serious doubts about whether its transparent electrodes could maintain the uniformity required for good extinction of the undesired polarization across the entire clear aperture of the beams. Additional design challenges were placed on the NIF PEPC because its entire mechanical

structure had to be streamlined to fit within the clean, metallic confines of an LRU. Vacuum seals and high-voltage feed-throughs are potential problem areas in such compact high-voltage assemblies. Special care had to be taken to mitigate current-pinch effects in the low-pressure plasmas. A weak simmer discharge is used to initiate the plasma. A multi-kilo-ampere capacitive discharge (15 μ s FWHM) boosts the electron density in preparation for the much larger longitudinal voltage pulse (300 ns FWHM) that appears across the crystals. Two techniques, one magnetostatic and the other electrostatic, are employed to achieve the required plasma uniformity. About 40% of the switching pulsed plasma current is routed around the glow discharge; simultaneously, the metal housing of the cell is driven to a potential slightly lower than that of the anode. Figure 59 shows a photograph of a four-aperture PEPC plasma superimposed on a CAD drawing of a PEPC LRU.⁹⁷ The uniformity of this plasma is adequate for reaching an extinction level of 300:1, enabled by the simmer phase and spreading circuitry.

By far the largest loss in the 1ω amplifier beamline is that due to bulk absorption in the KDP material of the PEPC switch. This loss, which is due to intrinsic KDP absorption of $\sim 6\%$ per pass at $1.053\ \mu\text{m}$, was accepted at the time of the design of the NIF beamlines because rapid growth KDP had become readily available and any of the alternatives, principally DKDP, were far more expensive and risky to obtain on the required schedule. (A test of a low-loss DKDP PEPC was completed in Beamlet that showed that this material works as well, albeit at a different pulsed voltage.)⁹⁸

Early reviewers often identified the PEPC as a high-risk subsystem; however, the Beamlet PEPC turned out to be the single most reliable component in that system. During the first years of NIF operation, the PEPCs did fall among the top ten causes for delays in operations; however, during the last three years, the PEPC gradually moved far back in the

Pareto chart of lost-time causes. Although some corner stress-induced birefringence issues continue to be monitored for the PEPC, they are likely to be of the same level of importance as for the stress-induced birefringence of all of the large square spatial-filter lenses.

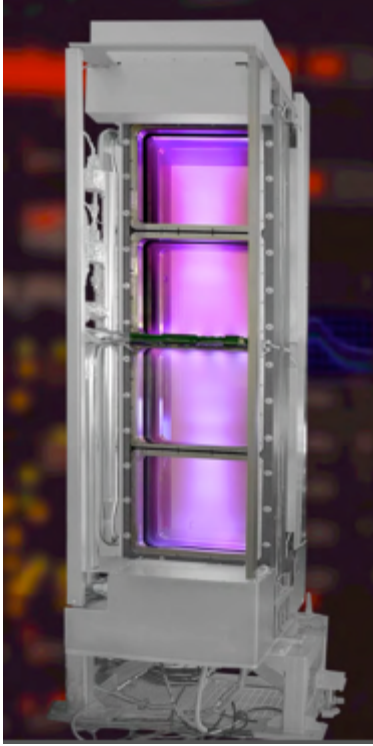


Fig. 59: Plasma emission from a NIF PEPC LRU.

VI.C.2. Optics

The NIF laser is not only the world's largest laser, it is also the largest optical system ever built. The 1ω amplifiers contain 6208 large-aperture optics (~ 0.5 to 1.0 m) as summarized in Table V.

TABLE V: Summary of the number and types of large aperture (~ 0.5 to 1.0 m) optics used in the 1ω Main Laser System

Optic	# req'd	Key Material(s)
Amplifier slabs	3072	Phosphate glass
Mirrors and polarizers	1600	HfO ₂ /SiO ₂ coating on BK-7
Windows and lenses	1344	SiO ₂
Crystals	192	KDP
Total	6208	

Manufacturing the NIF optics required an extensive optical materials and process development effort that began in 1995, followed by several years of activities for design and construction of optics manufacturing facilities and start-up (“pilot”) operations. Accomplishing this was possible because LLNL partnered with a group of well-known optical materials and optics fabrication companies located around the world. This approach built on a 25-year tradition of working closely with the private sector to develop and manufacture the optics needed for the high-energy laser systems constructed at LLNL. The companies participating in supplying NIF optics are shown in Fig. 60.

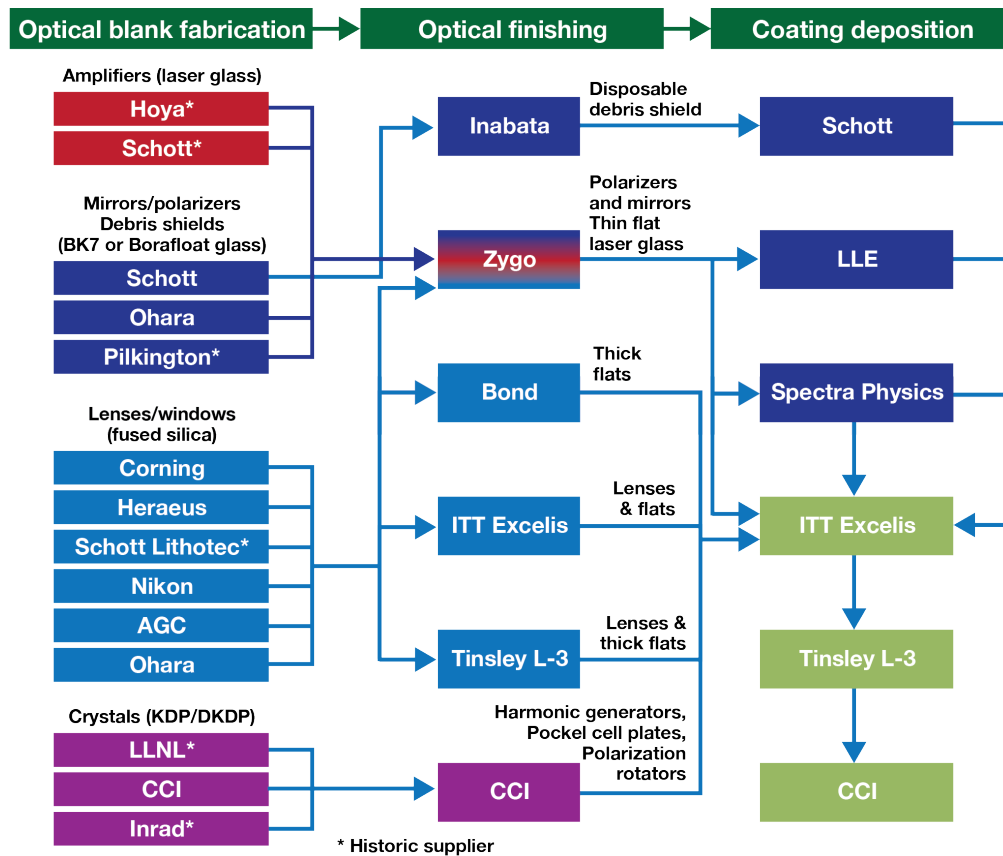


Fig. 60: Optics suppliers participating in delivery of the large optics for NIF.

VI.C.3. Laser slab production

Two of the economic challenges for the MLS were to decrease laser glass cost by a factor of 5 and to increase slab production rate by a factor of 20. Acquisition of the laser slabs was a joint effort with Commissariat à l'Energie Atomique et aux énergies alternatives (CEA), which also needed slabs for their planned Laser MegaJoule (LMJ) facility. Achieving these cost improvements had to be accomplished while also meeting tight homogeneity and quality requirements for the bulk glass material. The 54 slab passes, four passes through eleven slabs in the MA and two passes through five slabs in the PA, impose tight requirements on the level of allowed slab distortion.

Meeting these goals led to the first-time adoption of a continuous pour technique for production of the phosphate glass needed for the high-energy laser amplifiers; ~150 tons of this glass were needed for NIF alone. (The CEA laser, LMJ, requires a similar amount of glass.) Figure 61 outlines the steps of the continuous pour process that was implemented by both laser glass companies, Hoya and Schott.^{99,100}

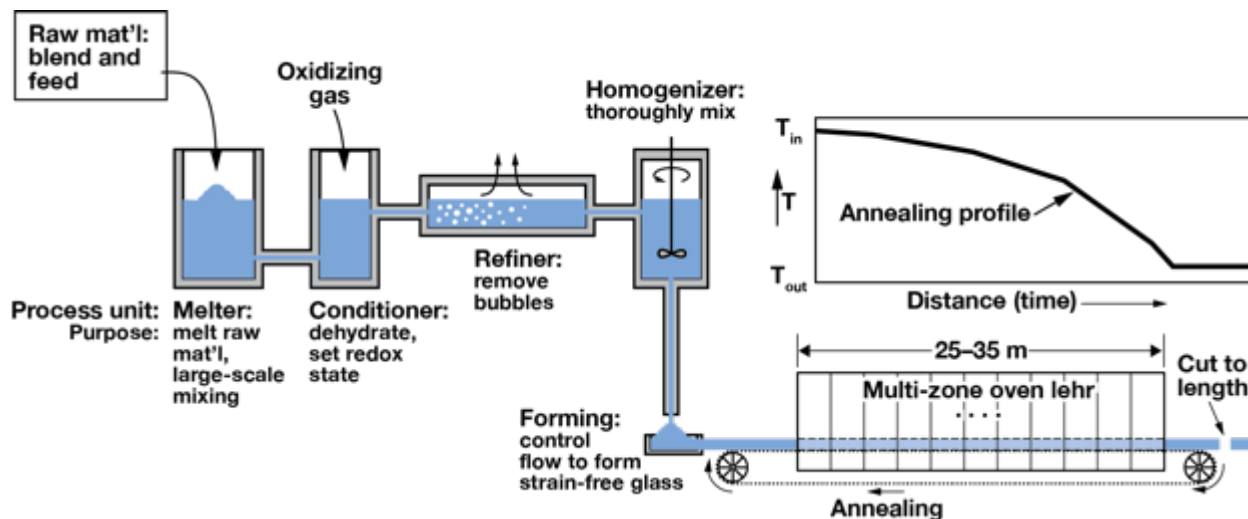


Fig. 61: Melting, forming and coarse annealing of the continuous-pour processes used for laser glass production by both Hoya and Schott.¹⁰¹

The viscosity of these glasses becomes adequate for mixing and pouring at ~1000 C. At such temperatures, the glass is chemically aggressive; dissolving small quantities of the platinum used to line the melting system. In addition platinum vapor can form platinum particles in cooler regions of the melter system often resulting in metallic Pt⁰ inclusions in the bulk of the glass. Such inclusions are problematic because they can absorb the high-fluence laser light, resulting in laser damage.

The technical improvements needed to make continuous melting successful are a result of a six-year, joint R&D effort between LLNL, Schott and Hoya. The specific technological developments include:

- 1) **Pt-inclusion removal:** Microscopic metallic Pt particles ($\leq 10\mu\text{m}$) in the laser glass can absorb laser light and cause fracturing of the glass (laser induced damage). Research on their formation and dissolution has led to a redox-controlled process for minimizing the number and size of inclusions in the glass.^{101,102, 103, 104, 105} Specifically under oxidizing conditions and in the presence of chloride ions, which are formed in-situ by the addition of chlorine containing gases such as Cl_2 or CCl_4 , the metallic (Pt^0) is oxidized and dissolves into the glass matrix. Spectroscopic evidence strongly suggests that this is due to the formation of the highly stable hexachloroplatinate anion, where each Pt^{4+} ion is surrounded by six chloride (Cl^-) ions within an octahedrally symmetric coordination sphere
- 2) **OH removal:** Hydroxyl (OH) groups in the glass quench the fluorescence of the Nd^{3+} ion and reduce the laser output energy. Research on the chemical mechanism of OH removal (dehydroxylation) using reactive gas bubbling, raw material pre-drying using rotary calciners and the incorporation of this information into numerical process models led to a 10-fold reduction in the OH content of continuously melted glass (Ref. **Error! Bookmark not defined.**).^{106,107} Figure 62 illustrates the dramatic improvements in the glass OH content that has been achieved
- 3) **Fracture prevention:** Phosphate laser glasses are prone to fracture due to their low fracture toughness and high thermal expansion. Finite element heat transport and stress analysis combined with the identification of various stress sources and research in crack

growth led to improvements in the annealing and fabrication processes that eliminate fracturing^{108, 109, 110}

- 4) **Impurity minimization:** Metal-ion impurities (such as Fe^{2+} and Cu^{2+}) at levels $\gtrsim 10$ parts-per-million level can increase the optical absorption of the glass above acceptable limits. New analytical techniques, such as inductively coupled plasma mass spectrometry (ICPMS) were used to quantify impurity levels. This information was combined with research on the absorption characteristics of these impurities and led to much improved specifications and quality control procedures for both the laser glass and the raw materials^{111,112}
- 5) **Homogeneity:** Laser glass requires a refractive index uniformity (i.e., optical homogeneity) of about one-part-per-million, requiring advanced forming technologies
- 6) **Quality assurance:** A number of unique quality-assurance tools have been developed to inspect large optical glass plates at a high rate. These tools include large-aperture (24-inch) phase-measuring interferometers and large-aperture laser damage testers¹¹³

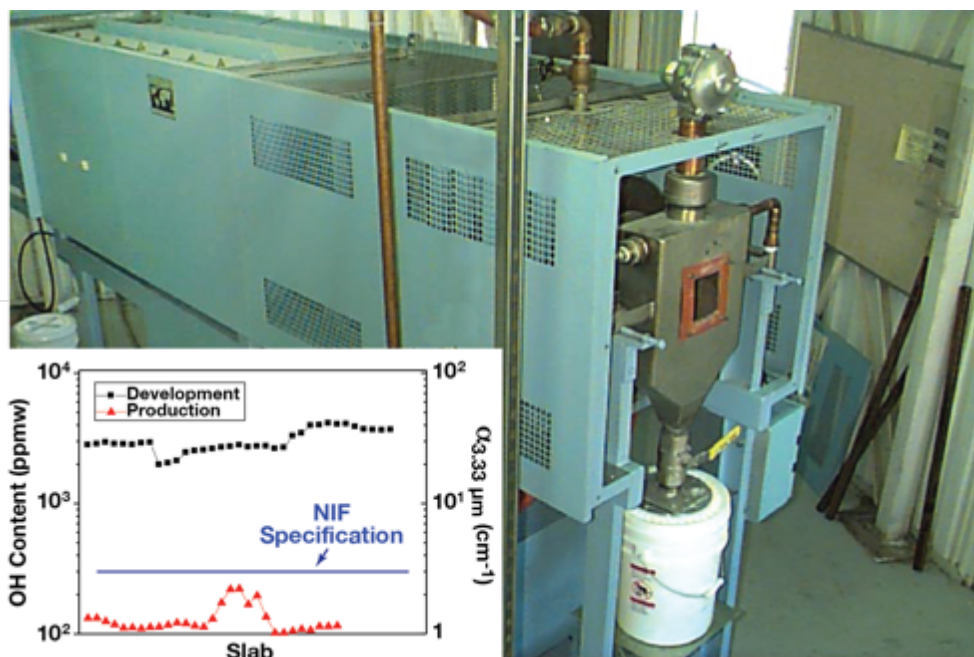


Fig. 62: Graph of OH content, in ppmw (parts per million by weight) and OH absorption coefficient (of the hydroxyl stretching band at $3.3 \mu m$) for randomly selected laser glass slabs showing a nearly 50-fold reduction in this contaminant comparing an early development run and a production melt campaign. Photograph shows an early calciner test underway at LLNL. Optimization of the calciner configuration for drying raw materials is a first step in reduction of the OH content.

The photograph in Fig. 63 (a) depicts a strip of phosphate glass as it exits the coarse annealinglehr of the continuous glass melter system at Hoya. Figure 63 (b) is a similar photograph taken at Schott.

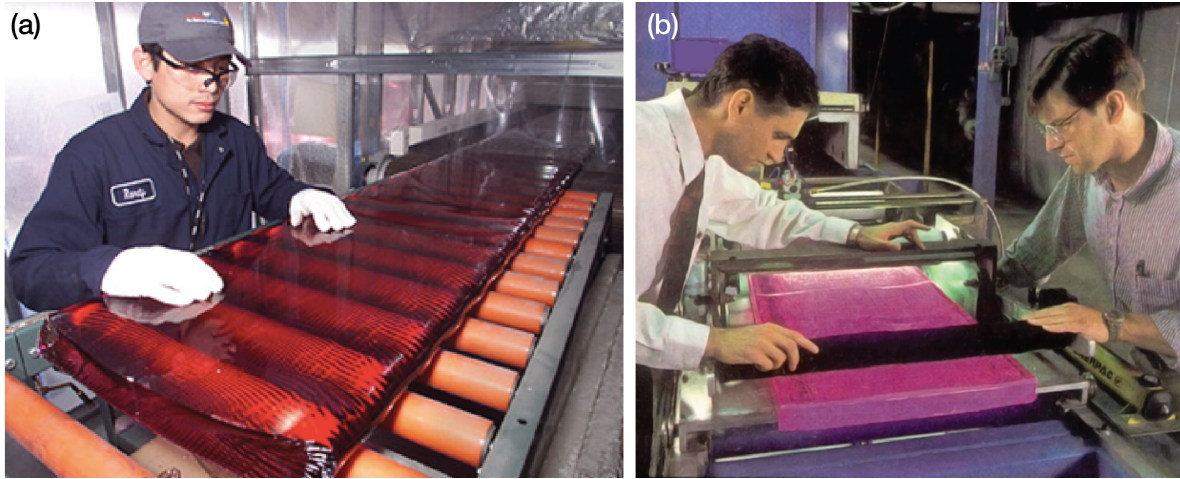


Fig. 63: Photograph of laser glass leaving the lehr, annealing oven, (a) at Hoya and (b) at Schott.

The total length of the strips of glass required by NIF is about 2 miles. After coarse annealing and being rough-cut to size, the glass slabs were laser damage tested and inspected. The slabs were then fine annealed and assessed for residual strain-induced birefringence (<10 nm/cm). After additional sizing operations each slab was ground and inspection polished in preparation for its first interferometric measurement of internal homogeneity. Slabs meeting specifications were then packaged and sent to the finishing vendor where the edges were ground to final dimension. After cleaning, copper-doped edge cladding for suppressing amplified spontaneous emission (ASE) was applied to each edge using a special index-matched epoxy adhesive.¹¹⁴ (More about ASE is given in Section VI.D.2.) The faces of each slab were then ground to final form and optically polished. Figure 64 shows a final amplifier slab undergoing visual inspection and another slab being mounted into its LRU structure. The blue-green copper doped cladding is readily visible on the edges of the amplifier slab. To prevent degradation of the optical surface due to weathering (water vapor reaction with glass surface) each slab was

packaged using molecular-sieve desiccants.¹¹⁵¹¹⁶ The goal of this packaging protocol was safe storage of the slabs (such as spares) for up to 30 years.

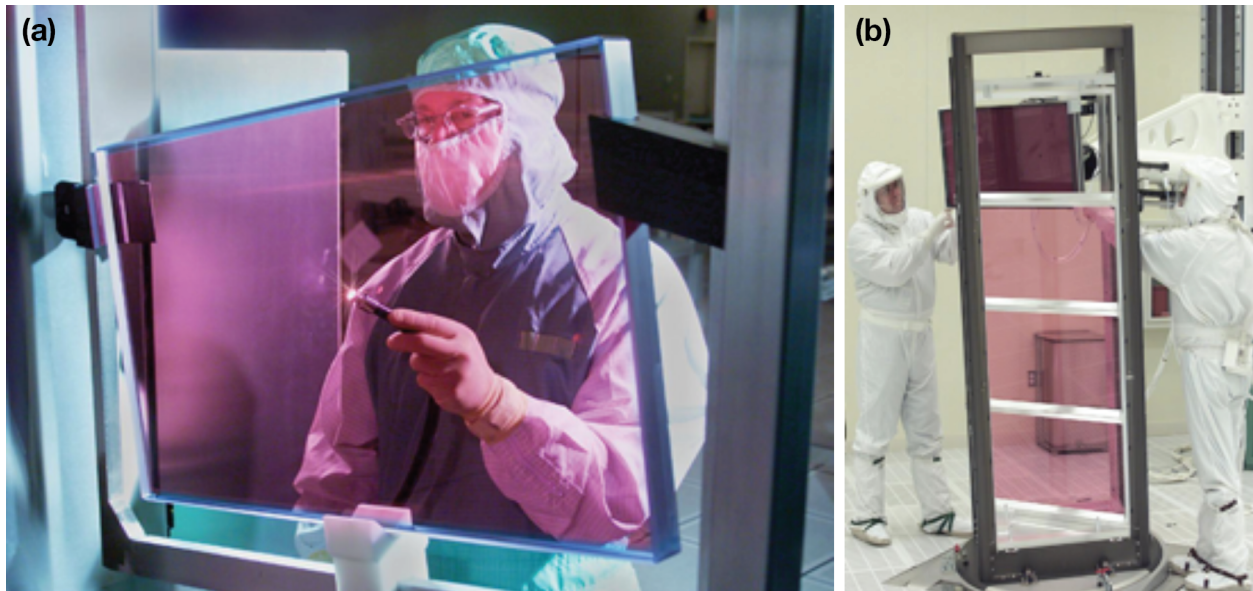


Fig. 64: (a) Photo of a finished amplifier slab, note the blue-green edge cladding; (b) Photo of an amplifier slab LRU being assembled at LLNL.

When finished, each of the large 1 ω amplifier slabs has a mass of about 42 kilograms and measures 46 cm x 81 cm x 4 cm. When installed, the amplifier slabs are mounted at Brewster's angle to minimize Fresnel surface reflection losses and to enhance the pump efficiency of the surrounding flashlamps as shown in Fig. 65.

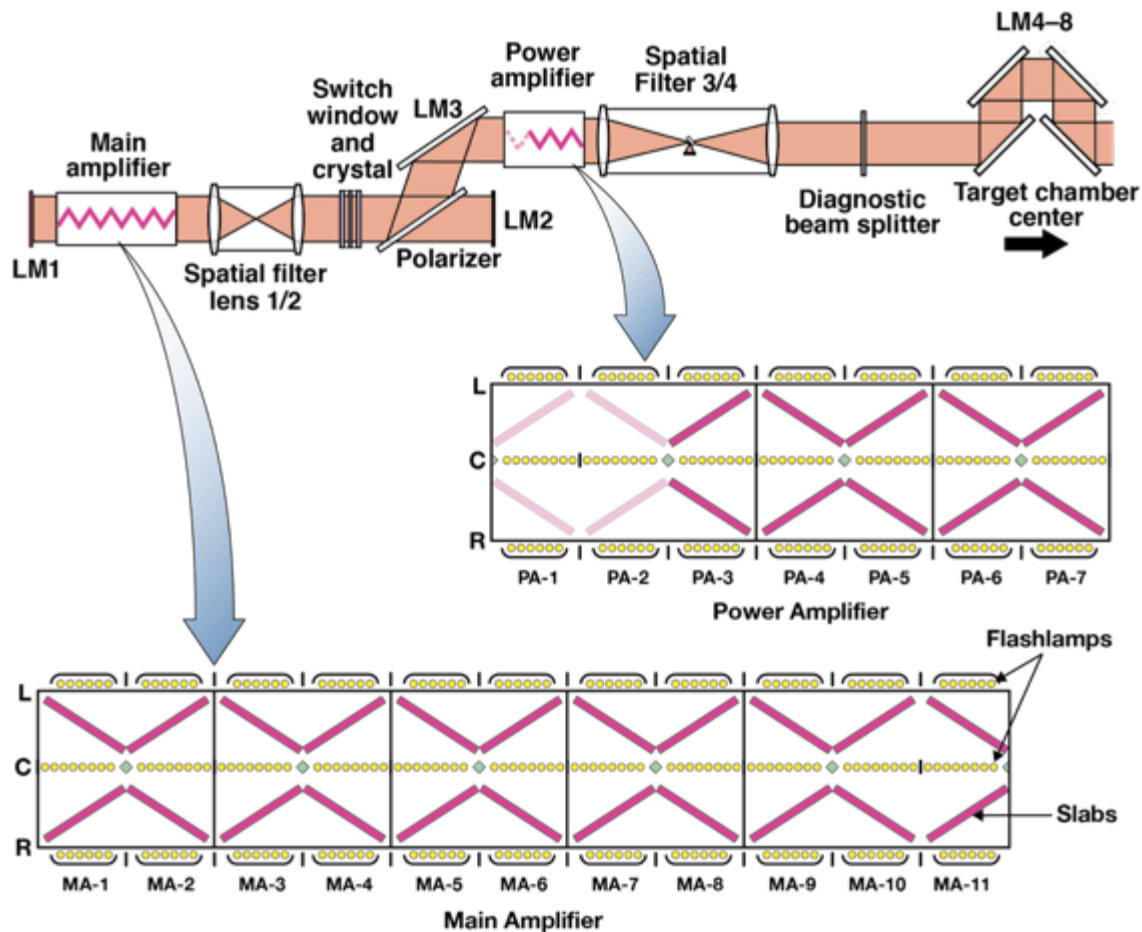


Fig. 65: The lower part of this graphic shows laser slabs in the large 1ω amplifiers as seen when looking down from the top. Note that in the iconic view, there are no slabs in positions PA-1 and PA-2, and as shown, the amplifier is in what is referred to as an 11-5 configuration. Adding slabs to locations PA-1 and PA-2 locations would result in an 11-7 configuration. (Ref. 99)

Each of the 192 NIF beamlines is capable of accommodating up to 18 amplifier slabs, a maximum of 11 in the Main Amplifier (MA) and 7 in the Power Amplifier (PA). The iconic beamline at the top of Fig. 65 includes an identification of all of the large 1ω optics in a single NIF beamline, specifically illustrating the orientation, location, and labeling of the amplifier slabs. Adjacent slab locations alternate between two mirror-image configurations (referred to as “even” and “odd”). To maximize the slab lifetime and laser performance,

each slab with its unique properties is selected for specific amplifier locations. (Ref. 99) Some key issues that drive the selection rules include: 1) maximizing the amplifier slab life that could be limited by growth of platinum pre-initiated damage sites in the glass; 2) maintaining a reasonable gain balance between beamlines; and 3) minimizing the beam “walk off”.

Based on off-line laser testing of platinum damage sites initiated by the scanning QA process, there is a possibility that initiated sites can grow beyond their original post-scan size during subsequent use in the NIF laser. The probability of damage-growth increases as a function of laser fluence. Growth of such a site to 3-4 mm could cause an intensity spike that could initiate damage on downstream optics. In addition, the scattered light from such damage sites increases the fluence on the low-pass pinhole in the spatial filter and raises the risk for pinhole closing. The Large Optic Inspection System (LOIS) that is described in Section VI.C.8 is used to monitor platinum damage sites in the slabs; thus a site that begins to grow can be detected, and its slab can be replaced before the site grows to a problematic size. To date no slabs have needed to be replaced as the result of platinum damage growth.

One factor that can affect the gain balance of the amplifiers is that two different glass compositions are used; each has a slightly different emission cross-section ($3.9 \times 10^{-20} \text{ cm}^2$ for LG-770 and $3.6 \times 10^{-20} \text{ cm}^2$ for LHG-8). Thus variations in the number of slabs of each glass type can result in beam-to-beam gain variation. To maintain gain balance, our goal was to use the same number of slabs of a particular glass type in each beamline.

VI.C.4. Lenses, Windows and Mirrors of the 1 ω Main Laser System

In addition to the laser slabs and the Pockels cell crystals, the 1 ω MLS includes 384 Pockels cell windows, 960 lenses and 1600 mirrors (including the polarizers). Lenses and

windows used >30 tons of fused silica and mirror substrates used ~100 tons of BK-7 glass. Each of these optics have specifications for low loss, high damage resistance and good wavefront quality (wavefront quality means surface figure for mirrors and both surface figure and homogeneity for transmissive optics). The polarizer is unique in that it is both a reflective and a transmissive optic.

Porous silica anti-reflection coatings have been developed over the past 30 years at LLNL for use on fused silica and KDP optics (Ref. 87). These low-loss sol-gel coatings were chosen rather than multilayer coatings because they have superior laser damage resistance. The AR coatings used for the fused silica optics are post-processed with ammonia and water vapor to reduce their adsorption of organic contaminants and increase durability (Ref. 89). The KDP optics are coated with a hydrophobic silica sol-gel which also exhibits low adsorption of organic contaminants.¹¹⁷ These coatings are discussed further in Section VII.I. Fig. 55 provides photographs of the sol-gel coating equipment used for processing of NIF optics.

Being able to handle the high energy and power of the propagating 1ω beams also requires good damage resistance of low-loss high-reflectivity mirrors. Years of developmental work and facilitization of private-sector companies has resulted in technology for multilayer dielectric coatings that can meet the variety of wavelength-discriminating and angle-of-incidence specifications of NIF mirrors and polarizers. Meeting the damage-resistance specifications for the polarizer and high-reflectivity mirrors in the 1ω laser was achieved by “conditioning” the coatings after they had been applied to their large-aperture substrates. During conditioning a relatively low energy laser was focused and raster scanned across the face of each mirror, pre-initiating nodules (which are contaminant particles on the substrate surface or caught between layers of the coatings to form dome-like structures). Three separate scans of the mirrors step the

conditioning fluence up to just below the peak operational fluence of the mirrors. By pre-initiating these sites in a controlled step-wise fashion it is possible to raise the damage resistance of the entire optic while maintaining its quality for use in the beam path.¹¹⁸ The mirror coatings are highly reflective at 1.053 μm but transmissive at the third harmonic, 0.351 μm . The support and alignment fixturing behind the LM-8 transport mirrors is protected from damage by target backscatter at ~ 0.35 μm by darkening the BK-7 glass substrates using the 1.17 and 1.33 MeV gammas from a Cobalt 60 radiation source.^{119, 120}

The polarizer was a particularly difficult optic to design and fabricate; it has to work in both reflection and transmission and it has a complex multi-layer dielectric coating that requires good damage resistance in both reflection and transmission. It reflects the full energy of the output of the four-pass amplifier into the power amplifier. The risk of damage to the polarizer limits the allowable 1ω energy out and thus establishes a restriction that must be considered during shot set-up calculations. For some pulse shapes, if more 1ω energy were to be desired, increasing the gain in the power amplifier by installing additional slabs in the PA-1 and PA-2 (see Fig. 65) locations could reduce the load on the polarizer while increasing the output energy from the 1ω MLS.

Fortunately for the NIF Project, a new class of mega-pixel-camera phase-measuring interferometers became available as the wavefront requirements for the surface figure of NIF optics were being established.¹²¹ In some cases, taking advantage of this new technology required development of large-aperture interferometers specifically for NIF optics. The availability of these tools allowed NIF to specify and perform metrology on large optics at levels of precision higher than were possible for previous systems. This enabled measurement of phase aberrations over the range of spatial frequencies described in Fig. 66 corresponding to ranges

that are accessible by specific diagnostic instruments (Ref. 71). The specifications used for the large optics of NIF are expressed in terms of their 1-D Power Spectral Density (PSD). The fractional area of the optic that is sampled by a diagnostic is a function of the size of the feature being studied. The entire optic is tested using a transmitted wavefront measurement when evaluating the rms gradient or PSD-1 specification. Much smaller regions of the surfaces are sampled for evaluation of meeting the PSD-2 or roughness specifications. For these two, sets of nine samples in a 3 x 3 tic-tac-toe pattern are typically measured for each surface.

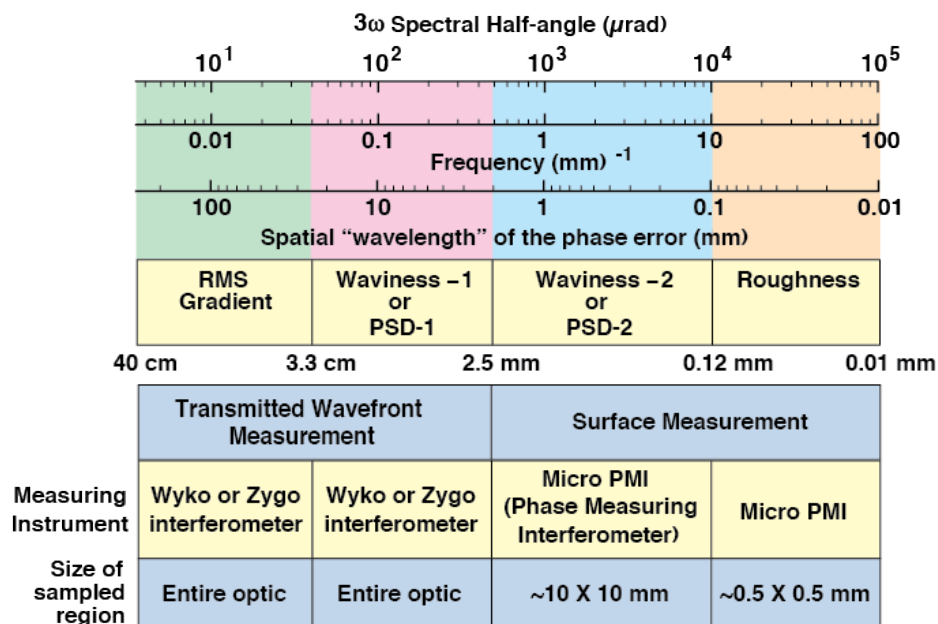


Fig. 66: The spatial frequency or spatial wavelength ranges used to specify the optical quality required of NIF optics. The different ranges are delineated from each other based on the diagnostic instruments used to measure features in each range.

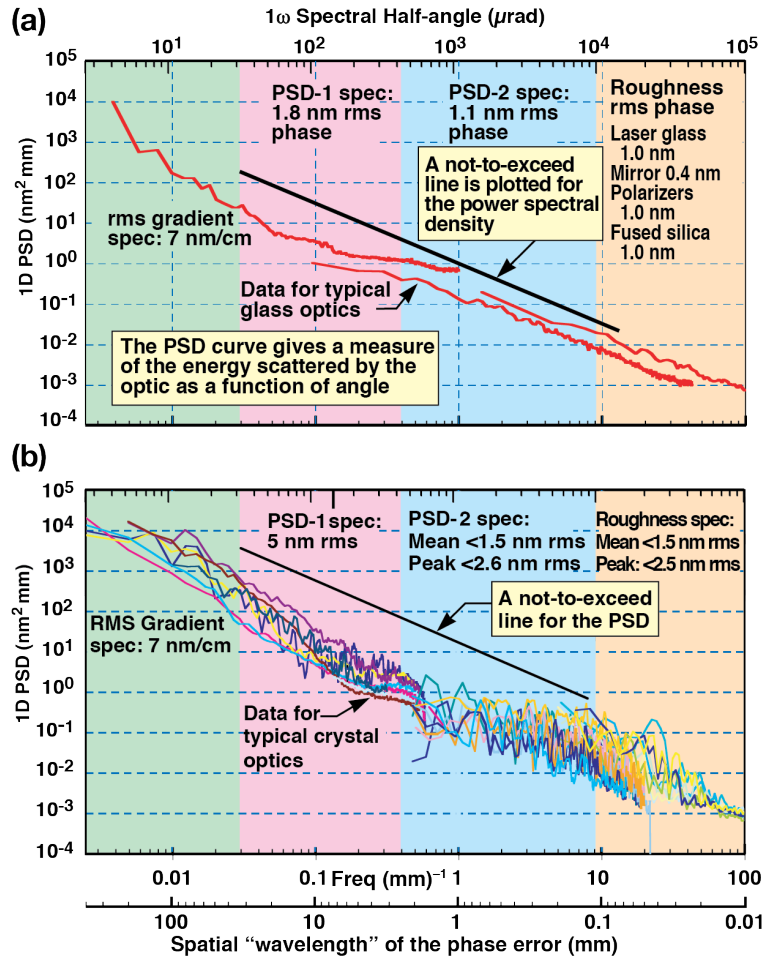


Fig. 67: (a) Specifications used for the large glass optics of NIF expressed in terms of their 1-D Power Spectral Density (PSD). There are two types of specification for the PSD-1, PSD-2, and roughness ranges, a specification for the rms value over a spatial area and a not-to-exceed value. Both are a function of spatial frequency. (b) The same as (a) but for crystals (Graphics from Ref. 71).

The wavefront specifications for large NIF glass and crystal optics are shown in Fig. 67 (a) and (b). PSD power laws for large optical systems were first introduced by the Laser Interferometer Gravitational-Wave Observatory (LIGO).¹²² These concepts were validated by LLNL for use on NIF and applied to measurements made both by LLNL and supplier

companies.¹²³ The large optics subject to these metrology requirements include laser slabs, transport mirrors, the fused-silica optics for use at both 1ω and 3ω and the crystals used at either 1ω or 3ω . Significant development was necessary to achieve the PSD specifications particularly for optics using small-tool finishing technologies. In Fig. 67, the rms gradient specification is represented by the value <7 nm/cm. Both a not-to-exceed line and rms values are specified for the PSD and roughness regions. Figure 67 also presents the maximum fraction of the light that is scattered within each region for an optic that meets the specification.

With this new technology for setting optical specifications for large optics, it was possible to relax historically tight peak-to-valley specifications and instead to rely on the deformable mirrors to compensate for errors introduced in the low-spatial-frequency RMS-gradient band, while still meeting the NIF requirement for focal spot size. Studies that were carried out in the late 1990s using an assortment of methods, including statistical optics, had concluded that the gradient of the wavefront is more important than the peak-to-valley specification for controlling the minimum spot size that can be achieved at target chamber center. The results of these studies were found to be consistent with the ISO standard 10110.¹²⁴ Relaxing the peak-to-valley specification resulted in very significant cost saving for NIF large optics.

The actual spot size desired for NIF is different for differing missions. Spot-size goals for its various missions were formally reviewed in *NIF Laser System Performance Ratings* (Ref. 124). The original spot size requirement for the indirect drive ICF mission, included in the NIF Functional Requirement and Primary Criteria document, (Ref. 28) is that the laser output should be delivered into a 600- μ m-diameter circle. As concepts for ICF targets matured, the spot size

goal changed to ellipses with different dimensions for different NIF cones; dimensions are now in the range from ~1.2 mm to 1.8 mm by ~ 1 mm.

VI.C.5. Housing the flashlamps and the amplifier slabs

A Frame Assembly Unit (FAU) that will eventually accept the flashlamps and slabs is seen being readied for installation in the NIF facility in Fig. 68 (a). (Ref. 39) Figure 68 (b) provides a photograph of a flashlamp window just before being installed into an FAU; installing the window was one of the steps in constructing the FAU. Photographs of other FAU construction steps are seen in Fig. 52. After construction of each FAU was completed, they were installed in NIF (See Fig. 53 (a) and Fig. 53 (b))

Amplifier slabs are loaded into slab LRUs as shown in Fig. 64 (b). The slab LRUs are then carried by a portable cleanroom canister and installed into one of the FAUs already installed in NIF. The FAUs also accepted flashlamp cassettes (Ref. 42) that are discussed in the next section. The combination of hardware seen in Fig. 69 includes an FAU that houses two slab LRUs and three flashlamp-cassette LRUs. There are two flashlamp cassettes between the walls and the slab LRUs and a middle flashlamp cassette in between the two slab LRUs. Flashlamp windows separate the independent volumes of the slabs and the flashlamps.

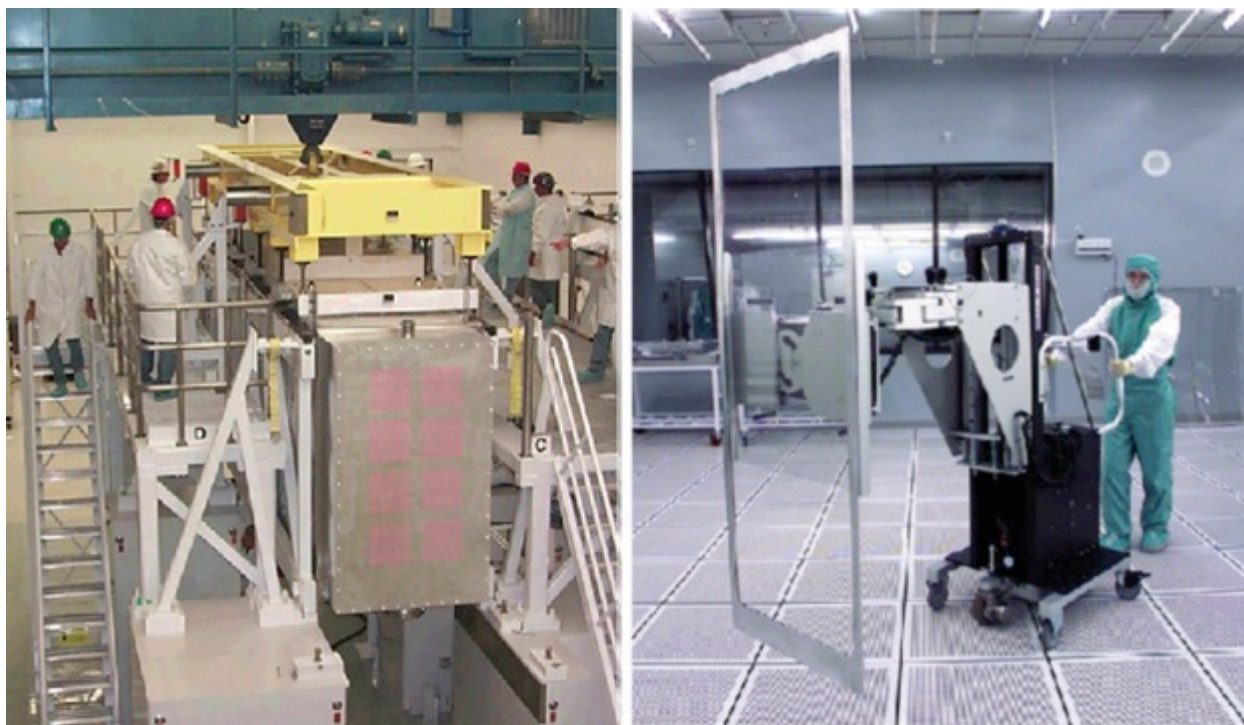


Fig. 68: (a) Frame Assembly Unit (FAU) Bus being prepared for shipping from its off-line assembly building; here protective sheet metal covers the end of the FAU. The locations of future laser apertures have been ghosted in for help in orienting the reader. (b) Flashlamp window assembly being transported for installation in a FAU.

Individual gas flow is provided for both the slab LRUs and the flashlamp cassettes installed in the FAUs. In an early design, gas flow was provided only for flashlamp cooling. Following a decision to divert part of this flow to the slab LRUs for purge of aerosol contaminants from the region of the slabs, cooling of the slabs was also realized as a side benefit. Flow for both the flashlamps and the slabs is initiated a short time after every laser shot. The “Cleanliness of the NIF 1ω Laser Amplifiers” article in this issue of *FS&T* discusses flashlamp- and-aerosol induced obscuration damage that had been observed in all previous ICF lasers at

LLNL. With the cleanliness procedures and precautions used during design, fabrication, and construction of all of the hardware and enclosures of the large amplifiers, and with the vertical purge flow pictured in Fig. 69, this problem has in large part been avoided in NIF.¹²⁵

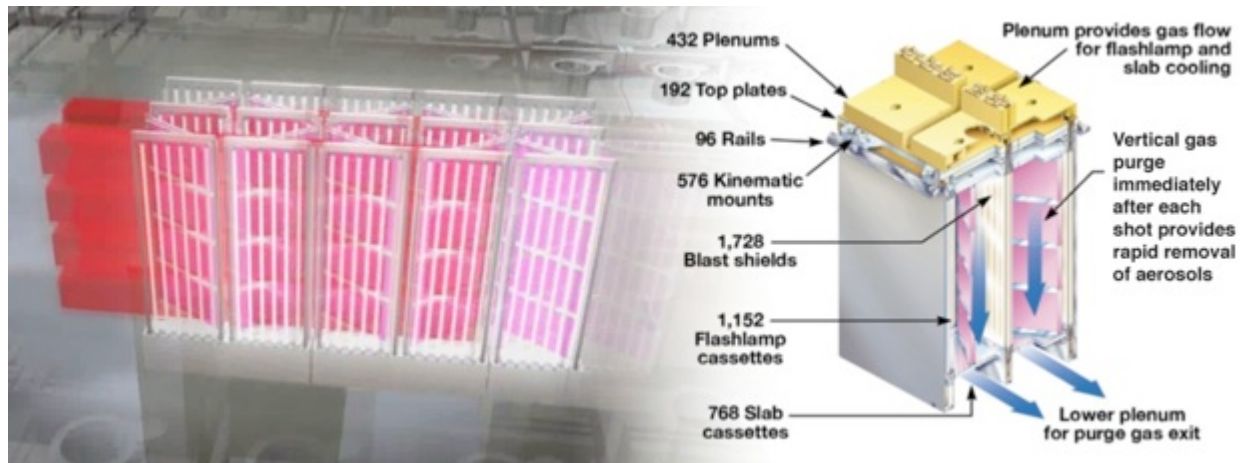


Fig. 69: (a) An artist's view of ~ 15 ns (~ 15 foot-long) laser pulse moving through a large amplifier. (b) Laser slab and flashlamp LRUs housed within their FAU support structures with identification of the major components and the vertical-purge-flow path.

The left hand side of Fig. 69 gives an artist's view of a multi-nanosecond (~ 15 foot-long) laser pulse moving through an amplifier chain. In this view, the flashlamps are interrupting the view of the transiting laser pulse. The right hand side of Fig. 69 illustrates the locations of the laser slab and flashlamp LRUs within an FAU housing and identifies the vertical path of the purge flow.

The reliability of the large NIF amplifier units is very much higher than for previous lasers. Lessons learned from NIF predecessors, such as, how to eliminate risks for flashlamp explosions and how to design the flashlamp windows (that separate the flashlamps from the slabs) made important contributions to this improvement. Other critical improvements were

made during the design of NIF, including concepts for low-distortion slab support and the protocols for amplifier cleanliness. On average, about 7% of the Nova slabs had to be replaced every year. Now after millions of slab shots on NIF, no slabs have failed due to aerosol damage, and only 13 slabs total have been replaced for any reason. Achieving and maintaining slab cleanliness has been key to maintaining this level of reliability. Slab surfaces continue to be monitored by the Large Optics Inspection System (LOIS) for possible damage to their surfaces.

VI.C.6. Flashlamps and their Power Conditioning Systems (PCS)

Xenon-filled flashlamps with ceria-doped (UV-absorbing) fused-silica envelopes energize the Nd^{3+} ions in the laser glass; the pulsed-power conditioning systems (PCS) energize the flashlamps. In addition to its key role in providing the input energy that drives the high-energy amplification process, the PCS plays a very specific role in meeting one of the Primary Criteria for NIF, the criterion for power balance between quads. More details regarding power balance are given in the “National Ignition Facility Laser System Performance” article in this issue of *FS&T*; emphasis is given here to the contribution the PCS makes by maintaining a very high level of accuracy in the shot-to-shot and module-to-module energy it delivers. The PCS specification for shot-to-shot repeatability is <1% rms with a flowdown power supply voltage accuracy of 0.05%. Meeting this flowdown requirement is an important factor in meeting the power balance criterion.

There are almost 8 miles of ~6-foot long 4-cm diameter lamps in NIF. These flashlamps were manufactured by PerkinElmer using high-quality Ce-doped quartz envelopes made by Hereaus. Design of the flashlamps for NIF benefited greatly from the experience gained from all previous ICF laser systems, all of which also used flashlamp-pumped amplifiers. Fig. 70 (a) is a schematic of a PCS module including its flashlamp load. Fig. 70 (b) is a photograph of an outer

flashlamp cassette. Energy to the lamps follows a path that begins at the top of one lamp and returns through an adjacent lamp as seen in Fig. 70 (a).

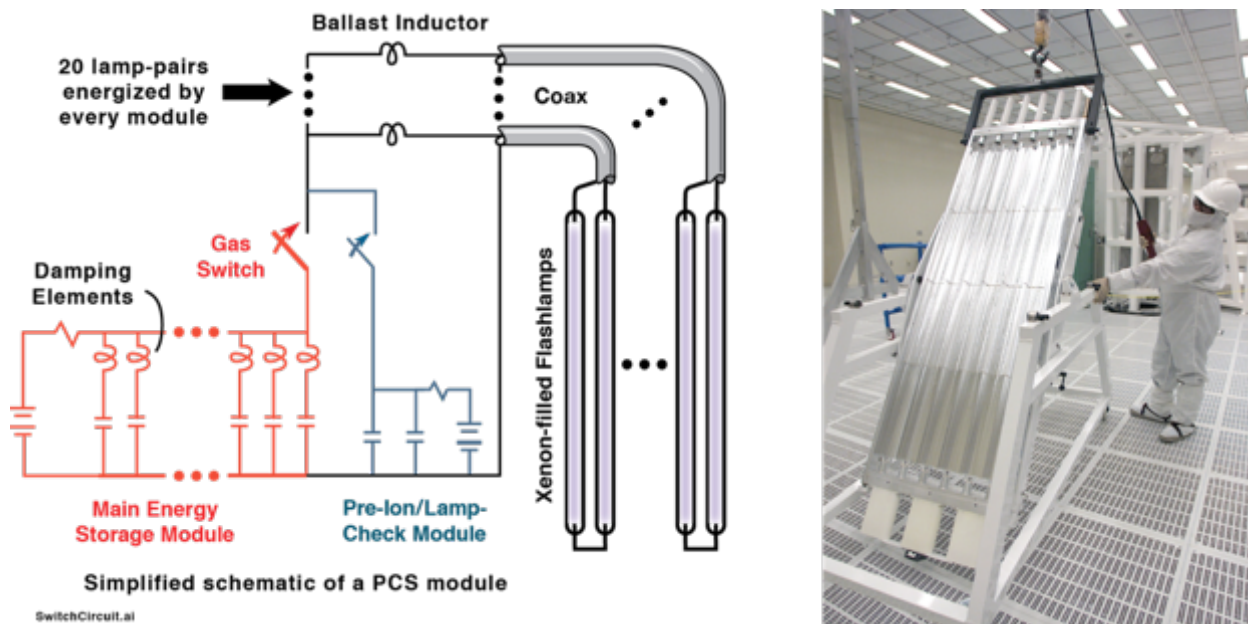


Fig. 70: Photograph of an outer flashlamp cassette next to a graphic of the flashlamp position in a schematic of a Power Conditioning Module.

The PCS drives the nearly 8000 flashlamps in NIF. Each of its 192 modules is capable of storing ~ 2 MJ before delivering that energy in a critically damped 0.5-MA, 400- μ s current pulse to 20 pairs of flashlamps.¹²⁶ The main pulse is preceded in time (300 μ s) by a relatively low-power pre-ionization pulse that prepares the xenon gas for the main pulse. Pre-ionization causes the arc to develop more uniformly within the lamp bore, which in turn increases lamp lifetime, reliability, and efficiency. Each main discharge is followed by a low-power “lamp check” pulse that verifies the health of the lamps before forced air cooling of the laser begins. Both the main and pre-ionization/lamp-check (PILC) circuits rely on high-pressure gas switches to initiate the lamp discharges. The flashlamps in NIF have been extremely reliable. At the time of writing,

only three of the nearly 8000 flashlamps in NIF have failed. These were infancy failures, which occurred during commissioning or soon after NIF began operating. One of the lamps simply quit working; the other two failed explosively. The cause of the explosions was suspected to be breakdown at one of the electrodes. In response, the PILC voltage was lowered, and since that time there have been no more flashlamp failures.

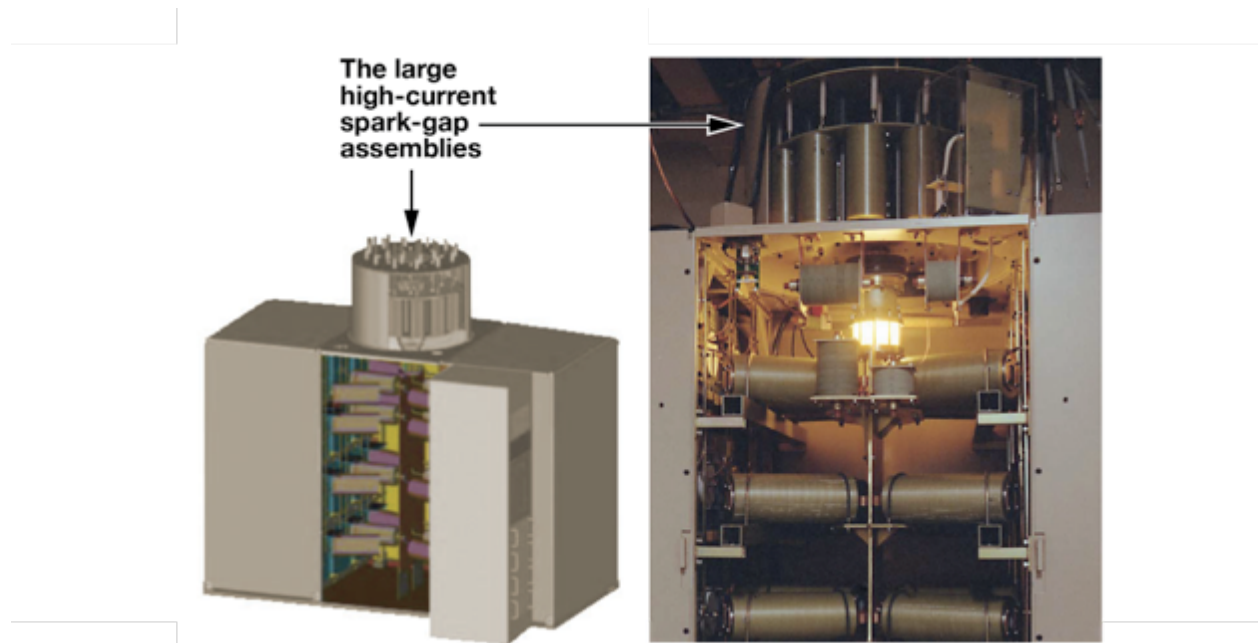


Fig. 71: CAD drawing and photograph of a single PCS module.

A CAD drawing of a single module is shown in Fig. 71, adjacent to a photograph of one of these modules with its door open. The photograph captures a discharge in the main switch. During a shot sequence, the PCS system is remotely controlled from the NIF control room. PCS operators monitor the performance of the system, which is controlled by the software shot-supervisor layer that communicates through front-end processors to embedded controllers (in the individual modules) over fiber optic links. Before a system shot, the operators verify the

participation of the PCS modules; during the shot sequence the PCS system performance is relayed to the operators through top-level and lower-level Graphic User Interfaces (GUI), which are part of the NIF Integrated Computer System (ICCS). The ICCS software allows the PCS system to be operated in two distinct modes: automatic and manual. The automatic mode is used for system shots and executes well-defined sequences necessary for the shot. The manual mode allows troubleshooting and independent operations. Each bundle of power conditioning units has all the required controls hardware and software, utilities and other elements of the infrastructure required to operate as a completely separate and autonomous unit. (While it is possible to operate a subset of a bundle, the emphasis is on operating this grouping as a fundamental unit.)

PCS modules occupy four individual 1150 m² capacitor bays. One bay is shown in Fig. 72 (a); power moves from the modules to the flashlamps through a set of coaxial cables as shown in Fig. 72 (b). Each capacitor bay supports one cluster of 48 beamlines with 48 power-conditioning modules (not correlated on a one-to-one basis with each other). NIF amplifiers are now set up in an 11-5 configuration, but there is room to add 2 slabs/beamline, going to an 11-7 configuration. Each PCS bundle has a reserved location for a ninth module that would be used to drive the flashlamps pumping the additional slabs.

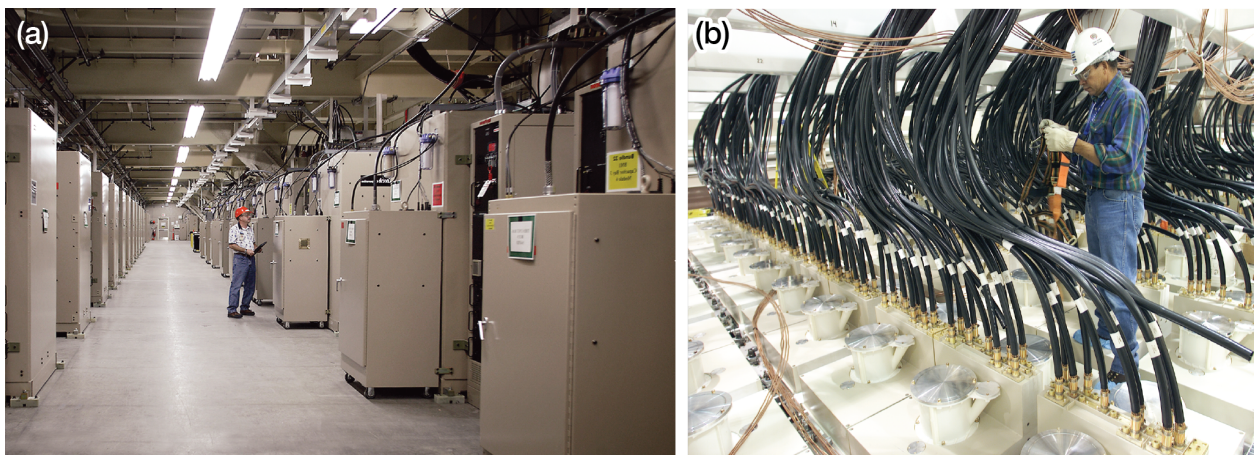


Fig. 72: (a) One of four fully populated NIF Capacitor Bays. (b) Coaxial cables leading from the PCS modules to the top connections on the flashlamps. Note that the worker is standing on top of an FAU.

As the design for the power-conditioning system for NIF began, it faced an uphill challenge. The volume available for power conditioning in the NIF building is about four times the volume used for this same purpose in Nova, but the delivered energy per pulse is about 25 times higher. Thus NIF needed a stored-energy volume density roughly 6 times higher than for Nova. Some of this came from increased stored-energy density in the capacitors, but much of it came from increasing the number of flashlamps that could be switched (or fired) by one PCS module. The circuit shown in Fig. 70 was designed to meet this goal: to energize 20 lamp-pairs compared with one lamp-pair for a Nova module. The large high-current spark-gap assemblies shown in Fig. 71 were developed at the company L3 Communications to make this possible. Maintaining the current balance between this large number of parallel low-resistivity loads (the flashlamps) required keeping all other resistance (the coax cables, for example) in the energy delivery circuits as low (physically large) as possible and use of balance inductors along each energy delivery path.

During the first several years of PCS fabrication many failure modes appeared. The failures were often related to design flaws in the mechanical assembly, in particular at connectors, and explosions were not uncommon. In 1999, a tiger team consisting of explosive containment and ES&H experts as well as PCS personnel was assembled to examine the shrapnel containment problem. Design solutions were identified and verified through analysis. Changes were implemented in the design packages; an updated RAM analysis of the system was completed and additional data was gathered from a variety of sources on component-level

reliability. Subsequent review of the complete PCS system advised that a combination of the design modifications and use of qualified components would enable the system to meet its requirements for reliability and availability.

The PCS team has been a very reliable partner in supporting NIF as a user facility, operating three shifts per day, seven days a week, shooting up to 6 times per day. The PCS has participated in more than 2400 system shots since 2007 with availability and reliability performance as given in Table VI. The reliability goal was originally set at 92.01%; as seen in Table VI, the PCS exceeded that goal for all three years of NIC.

TABLE VI PCS System availability and reliability

Yearly Average for PCS		
Year	Availability	Reliability
2009	96.39%	86.83%
2010	96.98%	95.15%
2011	93.31%	94.66%
2012	93.98%	95.67%

The availability of the PCS system is kept at a high value by having tested working spares for most components in all four capacitor bays and by having PCS trained operators/maintenance workers available around the clock. It should be noted that the availability data takes into account both reactive and preventive maintenance that occurs between systems shots. While the PCS system sits idle for a large fraction of the time (coming into play only during the last 3 minutes of a multi-hour system-shot sequence) it must be ready to support shot operations on any shift. Due to the architecture of the laser, having a single module down in a bundle of eight beamlines is almost certain to keep the entire bundle out of a shot, thus penalizing the system heavily for any failures. The effort of the support team has kept the NIF

PCS modules performing well, with good reliability. Between start up and the time of writing (Spring 2014), the PCS system had 3 significant explosions. In each case, a capacitor shorted and the other 19 capacitors discharged into the failed capacitor. In each case, as prepared for by the safety features engineered into the module housing, the explosion was contained. Module recovery averaged one week. It has not yet been necessary to remove any of the modules for servicing. Modules are not considered line replaceable units. All maintenance and recovery tasks have been completed in situ. During module down time, experiments on NIF have continued without that bundle in operation.

The work to bring the PCS performance up to and beyond its original design requirements was a team effort, with contributions from many collaborators, including Sandia National Laboratories and numerous industrial partners, L-3 Communications (formerly Physics International), Ktech, American Control Engineering, General Atomics, Universal Voltronics, and ICAR. Primary responsibility for fabrication, initial testing, and installation of the system fell to Raytheon Technical Services of Chula Vista California.

VI.C.7. Large Spatial Filters

Two large confocal spatial filters, evacuated Keplerian telescopes with pinholes at their foci, strip high-frequency spatial noise from the 1ω beamlines and image relay the propagating beams to the target chamber. The Cavity Spatial Filter (CSF) has two fused-silica lenses, each with a focal length of 11.6 m, and lies totally within the four-pass amplifier. The Transport Spatial Filter (TSF) has 29.7 m focal length lenses. All of the lenses are equi-convex with slight aspheric corrections on one side for reduction of low-order Seidel aberrations. The lenses are coated with a quarter-wave sol-gel anti-reflection layer with 50% porosity giving an effective refractive index of refraction of 1.23 ± 0.02 and a single pass transmission of $>99.5\%$.

In an evacuated environment, such as that present in the spatial filter enclosures, contaminants are more rapidly transported in the gas phase than at ambient pressure. This increases the potential for the sol-gel coatings to become contaminated and consequently lose their anti-reflective properties. The interiors of the vessels were precision cleaned prior to installation, and the probability of contamination during NIF construction was minimized by scrupulously observing cleanliness protocols that included *in-situ* cleaning of the interiors of the vessels.¹²⁷ A rigorous material qualification program was implemented to assure that all materials used inside the vessels met stringent ultra-low outgassing requirements. Furthermore, silica gel getters were placed and continue to be kept in large (50 cm) trays at the bottom of each of the spatial-filter structures to adsorb residual semi-volatile contaminants, thus providing ongoing protection of the transmission properties of the sol-gel coatings.¹²⁸

The spatial-filter-lens focal lengths had to be measured to very high accuracy, about one part in 10,000, in order for the beamlines to reach the wavefront flatness demanded by high-power frequency conversion. In addition, maintaining acceptable magnification (1:1) and recollimation of the spatial filter telescopes in the long master- and power-amplifier sections required very accurate spacing of the two lenses of each telescope. Individual alignment shims were custom fabricated with thickness dimensions that were matched to measured back focal lengths for each of the lenses to achieve the necessary recollimation precision, while still fitting within the tight confines of the lens-LRU housings. It was possible to relax the wavefront specifications for these lenses (for significant cost savings) because other optics in the beamlines had come in with wavefront quality somewhat better than their original specifications, allowing the margin to be allocated to the more difficult-to-fabricate lenses.

A photograph of pinhole choices that can be made for the Cavity Spatial Filters is seen in Fig. 73. The stainless steel pinholes are supported by a position-controlled, rotating plate that allows different pinhole combinations to be placed accurately without breaking the vacuum environment of the spatial-filter enclosures. Different pinhole combinations are available for selection by the operators for use during laser operation and for use with the LOIS diagnostic. As of February 2014, all of the pinholes installed in the CSF have an angular cut-off of 200 μrad . The entry pinhole cut-off for the TSF is 100 μrad and its exit pinhole has a cut-off of 150 μrad . “Washer” pinholes are used for the low-energy passes through the spatial filters. Cone pinholes, with the shape seen in the inset of Fig. 73, are used for the last pass, which has to carry a higher energy and intensity load of rejected light. Cone pinholes were chosen to avoid two problems, pinhole closure and long-term pinhole erosion. Pre-NIF pinhole designs had suffered from one or the other or both. Pinhole closure occurs when the trailing end of a pulse is cut off by the blow-off plasma formed by the leading edge of that same pulse. Pinhole erosion occurs when the accumulated amount of material blown off the edges of the pinhole by the plasma of multiple shots has become large enough to open up the pinhole and thus change its angular rejection (Ref. 71).¹²⁹

The cone pinhole reduces the early time blow-off by distributing the rejected light over a large area and reflecting much of this light at the grazing-incidence surface of the cone. Cone pinholes are regularly inspected and now after many shots in NIF, all are functioning normally. Indeed, one reason for the multiple pinhole sets on the filter wheel was to provide on-line spares in case the pinholes were eroded out of specification, but these extra sets have not had to be used because the cone pinholes have proven to be very robust.

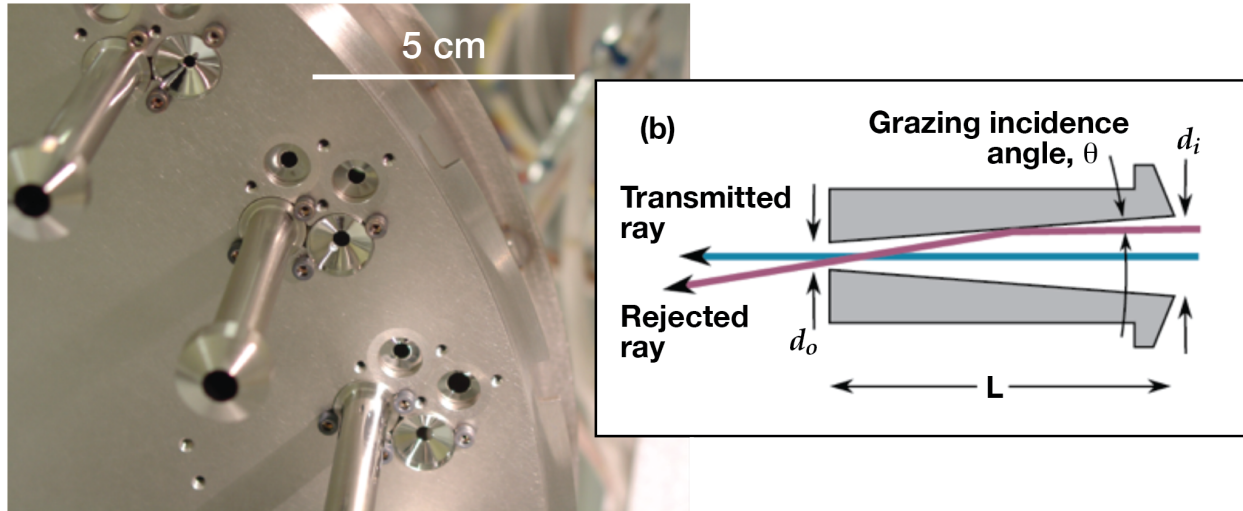


Fig. 73: Description of the CSF pinholes (a) Photograph giving a view of the CSF pinhole wheel; this image includes three of the possible sets of pinhole combinations that can be rotated into position at the location of the CSF focus (b) Schematic of the cone-pinhole concept.

As somewhat-faintly seen in Section V (Fig. 44), the region around the focal plane of the TSF is crowded. During design and construction of NIF this region was referred to as the war-zone because it involves so much functionality that was competing for space in the same small volume. Components in each beam in this region include:

- Optics to direct the beam from the PABTS to its injection mirror in the main laser path
- Injection mirror and its protective hardware
- Pass-1 and pass-4 pinholes (four choices)
- Insertable beam splitter cube near the pass-4 pinhole to intercept the $1.053 \mu\text{m}$ alignment beam and direct it toward the OSP during preshot alignment
- Insertable fiber launch carrying a $1.053 \mu\text{m}$ beam for the output pointing and wavefront reference
- Insertable fiber launch carrying a $0.375 \mu\text{m}$ beam for alignment to the target

- Beam dump to capture CSF pass-2 light from PEPC leakage or a PEPC malfunction
- Pick-off mirror that receives the light sample from the diagnostic beam splitter, located just past the TSF, and directs it to the Relay Optics
- Relay Optics to transport alignment and diagnostic beam samples (for both the main beam and for wavefront correction) to the Output Sensor Package (OSP) located below the Transport Spatial Filters of the beamlines

VI.C.8. Diagnostics for the 1ω Main Laser

The diagnostic beamsplitter (DBS) located just past the TSF as seen in Fig. 65 reflects $\sim 0.1\%$ of the output light and provides a sample of the Main Laser output to all diagnostics of pulsed light in rod shots and system shots where the energy in the beam is greater than a few mJ. The DBS is also used with the 1ω cw alignment beam while closing the adaptive optic loop to adjust the deformable mirror actuators (see Section VI.C.10). Because it is this beamsplitter that directs a light sample into the 1ω diagnostics system, calibration of laser performance measurements at 1ω depends on accurate knowledge of the spatial profile of its reflectivity. The spatial profile is measured after sol-gel coating and after it has been stored in a clean, dry atmosphere for 6 months to allow its coating to stabilize. The light sample from the DBS is sent back toward a pick-off mirror near the TSF focal plane that redirects the sample down into a set of diagnostic packages below the Transport Spatial Filters. For each beam, diagnostics include an energy-measuring diode within an integrating sphere in the relay optics section, followed by the Output Sensor Package.

The Output Sensor Package (OSP) is configured from the control room of NIF for a number of different functions, including:

- Alignment of the 1ω beams (Alignment procedures are discussed in Section IX)
- Measurement of the 1ω temporal pulse shape This pulse shape, together with the energy measurement gives the power versus time during the pulse
- Measurement of the 1ω beam fluence profiles
- Measurement (by the Hartmann sensor) and with the deformable mirror and ICCS, adjustment of the integrated wavefront along the path from the Input Sensor (ISP) to the final spatial filter as described in Section VI.C.9
- Inspection of the main beam optics with the Large Optics Inspection system (LOIS) for identification any optical defects that may have resulted from previous shots

The Hartman sensor consists of an array of small lenses located in a demagnified relay plane of the near-field of each laser beamline, specifically the plane of the LM1 deformable mirror. These lenses are located in front of a CCD camera by a distance equal to the focal length of the lenses. If a perfectly flat wavefront is presented to the Hartman sensor, its CCD camera will produce an image with a perfectly regular array of spots. If the wavefront is not flat, the x, y location of the focused spot of each of the lenses will move by an amount that represents the angular error in the wavefront at the location in the near-field of the corresponding lens. The Hartman sensor relies on being able to stitch adjacent errors together to make a phase screen that covers the entire near-field aperture. For this technique to work, the angular errors between lenses has to be relatively small compared to a wavelength. The NIF Hartman sensors have lens arrays with a pattern that matches the array configuration of the NIF deformable-mirror actuators (see Section VI.C.9). Although the reconstructed phase surface is not required for closed-loop operation of the deformable mirror, the rms gradient can be found from the locations of the

Hartmann spots. The system is capable of responding to wavefront errors as large as 15 waves and as small as one twentieth of a wave of 1ω light.

A photograph of the OSP is included in Fig. 74.

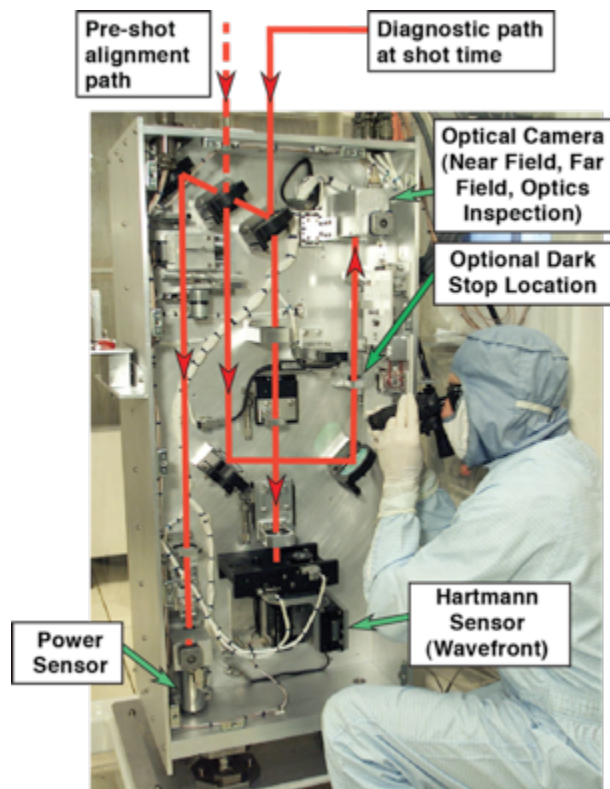


Fig. 74: The Output Sensor Package can be configured as an alignment sensor, a shot diagnostic or as LOIS for 1ω optics inspection.

The TSF pinhole wheel, besides carrying a selection of 100, 150 and 200 μrad pinholes and other alignment aids, has positions dedicated for use by LOIS during inspection of optics along the same multipass path as followed by the pulsed beam at shot time. If LOIS collects an image that indicates the presence of a damage site, several different combinations of pinholes are available for help in isolating and identifying the specific optic on which that damage site is

located. The software used by LOIS for site identification is similar to that described for use with the Final Optics Damage Inspection (FODI) system and described in “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” also in this issue of *FS&T*. To date, LOIS has found two damage sites on laser slabs. An example of the image for one of these sites is given in “Cleanliness of the NIF 1ω Laser Amplifiers” also in this issue of *FS&T*.

VI.C.9. Adaptive Optics for the 1ω Main Laser System

The deformable mirror at LM1, the Hartman sensor in the Output Sensor Package (OSP), and the Integrated Computer Control System work together to adaptively correct for wavefront distortions lying in the gradient regime identified in Fig. 66. This deformable mirror system is capable of correcting for:

- Prompt pump-induced distortion of the slabs by the flashlamp light
- Residual figure errors, inhomogeneities, and off-axis beam aberrations in optics
- Residual thermal distortions in optics

Pump-induced distortion is introduced by heating of the laser glass as the flashlamps are fired. As shown in Fig. 75, flashlamp heating results in a very slight S-shaped curvature of the slabs that subsequently results in a W-shaped distortion of the phase front of a beam passing through the slabs (Ref. 71 and 79). Because the NIF beamlines contain many slabs in a multi-pass configuration, the pump-induced peak-to-valley phase departure, plus residual thermal distortion for the entire beamline, can be as high as four to six waves.

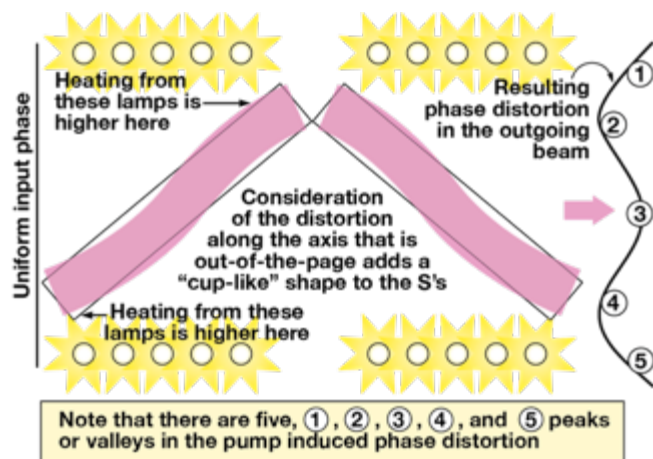


Fig. 75: Looking down from the top: an exaggerated view of the distortion that is introduced in the laser slabs when they are illuminated by the pulse of light from the flashlamps.

A NIF deformable mirror, shown in Fig. 76, has a “hex-pack” actuator pattern optimized for correcting low-spatial-frequency errors expected for NIF optics, to the level needed to meet NIF specifications for focusable energy and power. Thirty-nine precision lead-magnesium-niobate (PMN) actuators (Ref. 79) installed on the rear surface of the substrate can modify the surface topography of the mirror (i.e. its shape over “wavelengths” greater than 15 cm) to correct for optical aberrations within the main laser system up to the pass-4 pinhole in the TSF (Ref. 71 and 121). Particular emphasis in the choice of actuator locations across the deformable mirror aperture was placed on correction of pump-induced distortion. Note the seven columns of actuators across the center of the mirror that match the excursion features of the W-shaped pump-induced wavefront distortion. Each of the individual actuators has a stroke range of almost four waves at $1.053\ \mu\text{m}$. Because the deformable mirror is used twice in the multi-pass architecture, and because as a reflector the impact on wavefront for each use is twice the motion of the mirror, the total range for wavefront correction held by the mirror is ~ 15 waves. Because

the correction actually needed from the mirror in NIF is four to six waves, considerable stroke margin is still available.

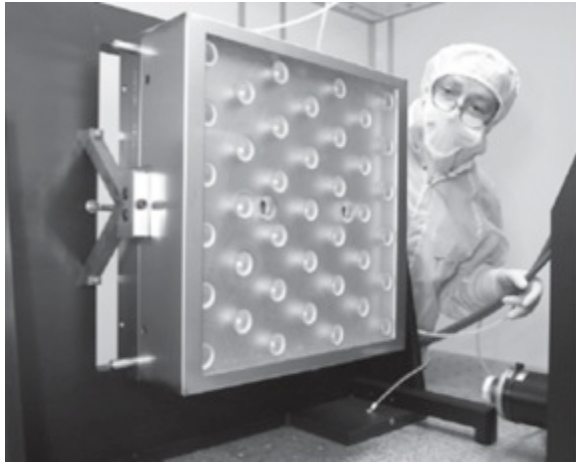


Fig. 76: Deformable-mirror optic, LM1, with its 39-actuator attachment points.

When mounted in NIF, the mirror is positioned at the end of the main amplifier cavity with the actuator orientation as shown. Another photograph of an LM1 is included in Fig. 58 during assembly of an LM1 LRU. Early in the commissioning of NIF, the wavefront distortion for each NIF beamline was measured for various configurations of flashlamp-explosion-fraction energy and the number of slabs pumped. The prompt-distortion corrections needed for each deformable mirror were saved as ‘static’ files that are now available to be applied to the actuators of that deformable mirror as system shots are taken.

The sequence for alignment of a beamline on target in preparation for a system shot has to be accomplished during a time when the flashlamps are not firing, thus at a time when no pump-induced correction should be applied. When alignment is complete, and before a full system shot is taken, the pump-induced correction needs to be applied to the deformable mirror actuators in order to correct for the four to six waves of distortion that could result in

damage to the main laser optics and that would surely interfere with proper focusing of the beam on target.

The sequence that allows both precision alignment of the beamlines and application of the pump-induced corrections during the shot is described in the following: As part of the early alignment process for a shot, a 1.053 μm reference beam from a single-mode fiber, pointed toward the target chamber, is inserted into the TSF pass #4 pinhole plane. A sample of the nearly perfect diffraction-limited wavefront from this source is reflected by the diagnostics beam splitter (DBS) located just after the TSF output lens (SF4) and directed to a Hartmann sensor in the Output Sensor Package (OSP) (see Sections 6.3.8 and 6.3.9, and Fig. 74). The resulting Hartmann image is recorded as the “reference” phase-front of an ideal point source at the TSF pinhole (in effect, this ignores any aberration contributed by SF4). The fiber is next withdrawn to allow the 1 ω alignment beam from the ISP to be recorded by the same Hartmann sensor. The cw (continuous wave) alignment beam from the ISP carries with it wavefront aberrations that were imposed by the optics along its multiple passes through the beamline (now including SF4). During this process, a small half-wave rotator is inserted into the CSF pinhole plane to mimic the role played by firing the PEPC. The adaptive optic control software then adjusts the actuators of the deformable mirror until the alignment beam wavefront best matches the reference wavefront. It is in this step that residual errors in figure, homogeneity errors, and off-axis beam aberrations are corrected. Once this point has been reached, alignment of the laser can be completed.

After alignment has been completed (see Section IX), the pump-induced correction is added to the closed-loop correction acquired in the step described above; the mirror figure is

then "frozen" and remains unchanged through the rest of the shot cycle. Any subsequent rod shots and the system shot have this total correction applied.

The manner in which the mirror actuator positions are now set in NIF is less complex than expected by the designers of this sequence, based on their experience gained during operation of Beamlet. In response to needs defined by Beamlet operation, the NIF adaptive optics software was designed to allow correction of air turbulence and residual flashlamp-induced distortion from previous shots in a closed-loop fashion, up until less than a second before shot time. This relatively short time is approximately the inverse of the Greenwood frequency of the air turbulence in the NIF beampath. The software is also able to accommodate changes in the pump-induced corrections that might happen over time.

In fact, with the active slab cooling that occurs as a side benefit of the vertical flow of clean dry air in the slab cavities originally instituted to avoid flashlamp-induced obscurations on the slabs and the threat of damage to spatial-filter lenses, buildup of residual thermal distortion in the slabs does not occur for shot cycle times regularly experienced for NIF. In addition, conditions in NIF have been found to be more stable than conditions in Beamlet, and over the first 7 years of NIF operation no change has been needed for the pump-induced correction.

VI.C.10. The Transport Mirrors

The top-level responsibility of the Transport Mirrors is to turn the beams from the close-packed linear arrays of 1ω amplifiers into beams that are directed radially toward the center of the target chamber. The path lengths within the transport-mirror section have to be kept the same (within some allowable difference) to provide for simultaneous arrival of the beams at target

chamber center. The allowable differences between path lengths is set by several features of the beamlines including: the time-location of the AMC-quad pulse generated in the MOR, within its ~ 100 ns pulselength window, the temporal separation between pulses of two quads in the same bundle (set by the time constants of the bundle-common PEPC electronics), and the range of adjustment of the optical trombones in the PABTS. This requirement for simultaneity, along with the need to keep the polarization of each beam appropriate for frequency conversion in the subsequent final optics and the need to relay image the RP-0 plane close to the location of the final optics, required the lengths of the transport-mirror paths to be approximately 70 m.

Whenever a high-intensity beam moves through a Raman active gas, such as nitrogen or oxygen, the light can interact with and be scattered by the rotational modes of the gas in a process known as stimulated rotational Raman scattering (SRRS).¹³⁰ It is of critical importance (that is, necessary for transmission of the light) to keep the SRRS gain to a value less than would scatter 1% of the propagating light. Since the SRRS gain coefficient is a linear function of the “Intensity times the Length” along its dangerous path, known as the “IL product,” the higher the intensity the greater the risk of SRRS loss. Because a path length of ~ 70 m in air cannot be tolerated at the 1ω intensity levels designed for NIF, it was necessary to enclose the transport-mirror beampath and fill it with a noble gas. None of the noble gases are Raman active; argon was chosen for NIF. Because argon is heavier than air, great attention has been given to monitoring oxygen levels outside of the enclosures in regions of the building where argon could accumulate and where breathable air is an absolute necessity. In addition, work continues for developing more time-efficient procedures for making sure that at shot time the interconnecting enclosures are always adequately filled with argon, and not contaminated with air.

Transport mirrors are required to maintain very good optical figure across their 40 cm clear apertures as they are held in their in-use position in a beam path. In order to meet their wavefront specification, their thickness has to be an appreciable fraction of their transverse dimension. Figure 77 is a photograph of a transport mirror in position for a wavefront-error test. This photograph also has reasonably good visibility of the backside three-point support configuration of the mirror. The spacing between mounting locations was designed to minimize the gravitational-induced distortion of matching upward- and downward-facing mirror pairs.

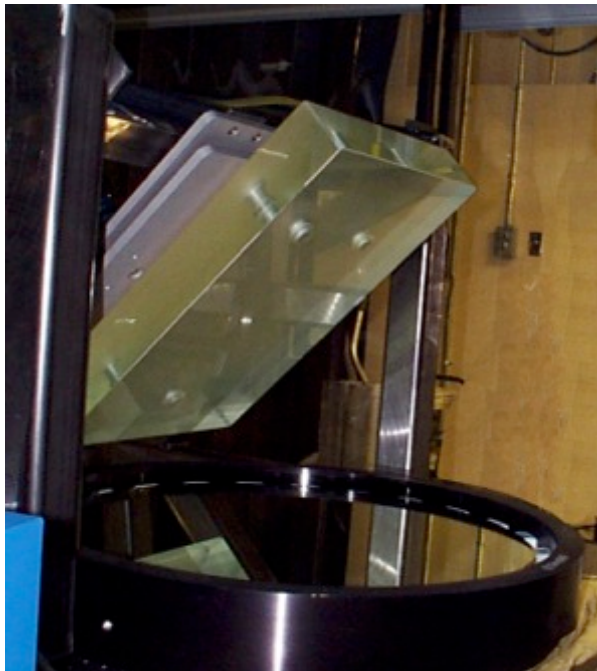


Fig. 77: Test assembly of a transport mirror supported by ‘expansion lugs’ fitted into holes drilled into its back side, ready for completion of a wavefront-error test.

Up-facing mirrors along the transport-mirror path provide an undesirable but convenient surface for collection of particles that may be inside the argon beam enclosures. Figure 78 is a photograph of a “gas knife” at the top edge of a transport mirror (see the black arrow). The gas knife is designed to produce a wall jet that delivers bursts of argon that flow at ~ 55 m/s across

the mirror.¹³¹ This jet is more than 95% effective at removing settled particles within the potentially damaging size range.¹³² The red arrow points to a 250 μm slit orifice along the length of the knife, the exit nozzle for the argon. The mirror support structures and actuators behind the LM4 mirrors can be seen through the mirror coating that is reflective at 1ω , in the infrared, but transparent in the visible.

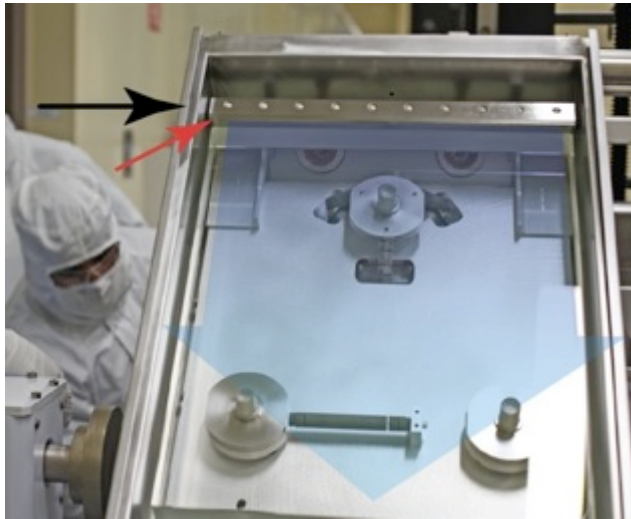


Fig. 78: An argon gas knife on a transport mirror. Flow direction is from top to bottom as shown by the wide light-blue arrow.

VI.D. Performance of the 1ω Main Amplifier System

VI.D.1. Amplifier gain profile

As discussed many times previously, the amplifier slabs are pumped by banks of flashlamps oriented vertically around the two sides of a slab LRU. The manner in which the light from these flashlamps is absorbed by the Nd^{3+} ions in the slabs establishes the gain profile in the 1ω amplifiers (Ref. 79). From Fig. 79 and Fig. 69, note that light from the middle flashlamp cassette pumps two vertical sets of slabs, the ones shown in Fig. 79 and the ones that are to the

left of the middle bank of flashlamps, but not seen in this figure.

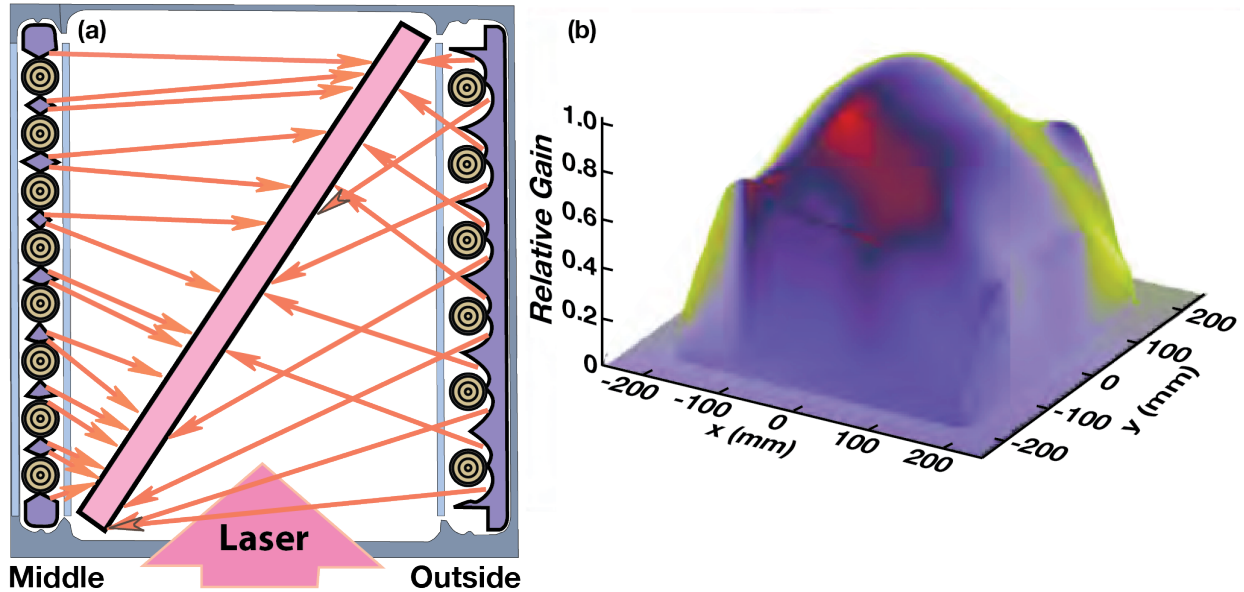


Fig. 79: Calculations of the gain profile of the slabs in the 1ω Main Laser System (a) Geometry of flashlamps and slabs used in the gain-profile model (b) Calculated gain for 54 slab passes through the amplifier. Creating a main-laser-system gain of 50,000 with uniformity of ~ 1.5 peak-to-mean, as is routinely achieved in NIF, requires the gain-profile uniformity of each slab to be better than 1%.

Creating a high level of gain-profile uniformity across the slabs depends on the shape of the reflectors behind the flashlamps for the outside flashlamp cassettes and the shape of the “diamonds” between the flashlamps of the middle cassettes. These shapes were designed using a ray-trace model that had been under development at LLNL for approximately 12 years (from 1986 to 1998). This model was built for predicting the fate of light from flashlamps used to pump Brewster’s angle slabs (Ref. 79). The intent of the involute shapes seen in Fig. 79 is to direct a higher-than-average fraction of the flashlamp light toward the long ends of the slabs. The additional light compensates for amplified spontaneous emission (ASE) that can deplete the

energy stored in this region (more about ASE is given in Section VI.D.2). These shapes are so important because they ultimately determine the efficiency for converting the 1ω light to 3ω and the spatial profile of the 3ω beam. With 54 slab passes in an amplifier chain, the output uniformity of the amplified beams depends on the 54th power of the gain distribution of each slab. With the good gain uniformity that was achieved for the NIF beamlines, it was then possible to fabricate the gain-profile compensation masks such as the one shown in Fig. 35 with a transmission profile that is the inverse of the net amplifier gain profile (Fig. 79 [b]). The goal of the pre-compensation chrome-dot mask is to present a fully-amplified 1ω beam to the frequency converter that is as flat as possible. A flat-fluence profile at the frequency converter is important not only for ensuring good conversion efficiency but also for keeping 3ω optical damage to a minimal level.



Figure 80: Aluminum sheet involutes used behind flashlamps of the large 1ω amplifiers.

Acquisition of these reflectors of flashlamp light was accomplished at a cost much lower than originally anticipated because a technique originally developed for the lighting and CRT industries could be adapted to the NIF application. Aluminum sheet was first silver-plated and

over-coated with a non-organic protective layer. It was then bent into the precise shape required without breaking the protective overcoat layer.¹³³ Figure 80 is a photograph of one of the shaped involutes manufactured for NIF. Maintaining the integrity of the overcoat layer is important for avoiding tarnish and loss of reflectivity of the silver in the presence of air. This technique had an immediate effect on improving the long-term performance of NIF because it allowed the use of clean-dry air (not the much more expensive dry nitrogen) for purging of aerosols from the laser-slab region immediately after every shot. This purge significantly reduces subsequent contact of the aerosols with the slabs and prevents the level of flashlamp-induced obscurations on NIF slabs that had been a significant cost center for operation of earlier ICF-scale lasers.

VI.D.2. Absence of Parasitic Oscillations

The presence of parasitic oscillations has always been of big concern whenever a laser storage medium is held in an excited state for times longer than a few optical transits along its beam path. This concern exists for NIF because the excited state lifetime of the Nd ions and the length of the flashlamp pumping pulse are both ~ 0.5 ms. When such a condition exists, it is possible for either resonant (parasitic oscillation) and or non-resonant (amplified spontaneous emission, ASE) to deplete the excited medium. Internal ASE is largely defeated within the slabs by using absorbing cladding around their edges. The light blue-green edge of the slab seen in Fig. 65 is the cladding of copper-doped phosphate glass. Historically, several strategies have been used to avoid parasitic oscillation. The first is never to allow the net gain in an amplifier stage (in NIF this would be the four-pass MA) to exceed between 14 and 16 per pass. Whenever a gain over about 14 exists, special precautions have to be taken. These precautions include inspecting the design of the amplifier enclosure and eliminating any “shiny” surfaces that could exist on opposite sides of the excited medium (for example, screw heads holding the mounting

frame of an optic or even any small dig-like defect very near a pinhole). In addition, any time there is a mirror at one end of a laser beampath, (as there is with LM1 behind the MA) the gain that has to be suppressed to avoid parasitic oscillation is ~ 200 , and any downstream surface with a reflectivity of over half-of-one percent can become very dangerous. Reflecting objects in the focal plane of a spatial filter are of particular concern because of the inherent retro-reflective nature of this configuration. As part of the effort to avoid problems with parasitics, a quarter-scale CAD drawing of an entire beamline was set up in one of the in-construction NIF corridors and teams of reviewers would study this drawing, looking for any suspicious situations. Several candidates were found and designs were modified. As NIF was brought into operation, its pump energy was raised gradually and all beamlines were monitored for the possible existence of parasitic oscillation. Two parasitic events were found involving spatial filter assemblies; these led to modifications to the hardware. Subsequent tests with step-wise increases in pump power found no further problems; the relatively smooth beam profiles of the ASE profiles given in Figure 81 are indicative of no parasitic modes. In addition, external ASE measurements made with a detector in the ISP showed a signal in very good agreement with modeled expectations. Had a parasitic mode been present, it would have been evident in the ISP measurement.

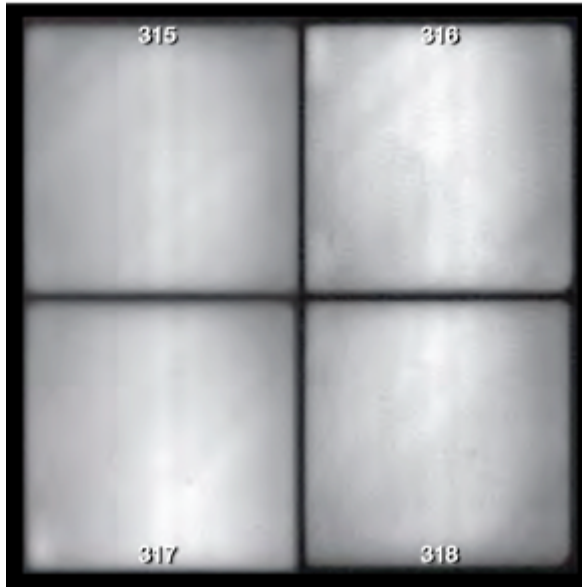


Fig. 81: Near-field images of amplified spontaneous emission from fully-amplified in the main laser system taken with the OSP camera show no signs of parasitic lasing action.

VI.D.3. Contrast of a 1ω Beamline vs. Output Energy

The spatial fluence contrast of a 1ω beamline was measured in the Precision Diagnostic System (PDS) (Ref. 48). Saturation of the gain in the amplifiers reduces the peaks in the fluence profile of the beam, with the effect that the standard deviation of the fluence variation across the beam is reduced. Figure 82 (a) summarizes the time-integrated fluence contrast measurements made for one of the first beamlines brought into operation in NIF, compared to the flow-down requirement that had been established for the 1ω amplifier chains. Fig. 82 (a) also includes a solid black curve showing the saturation of the amplifier gain versus fluence. The contrast given in Fig. 6.4.3 (a) illustrates that as the energy of a beamline is increased, the beam will look more uniform. This behavior is consistent with expectations for a clean, saturating amplifier, operating far-away from any non-linear regimes. As NIF is operated, fluence profiles for every beam are regularly collected at the OSP. Figure 62 (b) gives an example of these measurements.

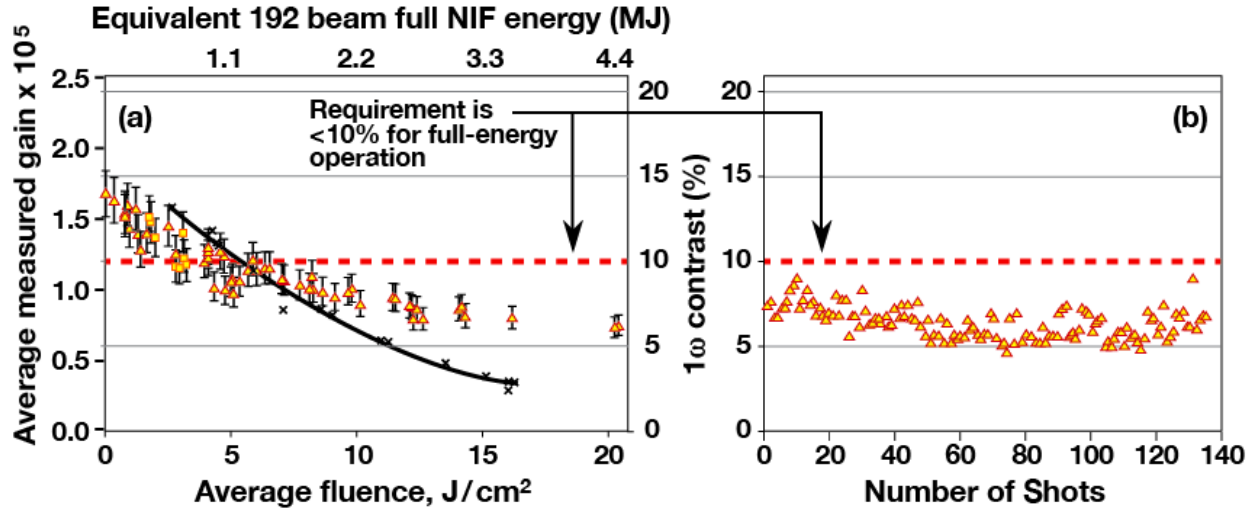


Fig. 82: (a) Saturation reduces fluence contrast in the 1ω beamlines (Ref. 48) (b) Contrast of B132 for shots with energy between ~ 12 and 18 kJ for the time frame from Nov, 2011 to Mar, 2014.

VI.D.4. Near-field and Far-field Beam Profiles at 1ω

Both near- and far-field images for 1ω energy and power were collected using the NIF Precision Diagnostic System (PDS), with results for the near field given in Fig. 83. Additional information on 1ω near-field performance is provided in Haynam et al. (Ref. 48). The uniformity of the near-field images is important because better uniformity means better frequency conversion efficiency and lower damage rates in the following 3ω section of the laser. The corresponding 1ω far-field profile is described in Reference 48. The quality of the far-field spot at 1ω (without beam smoothing) is important because it has a large impact on the corresponding spot size at 3ω , and the 3ω focal spot must meet criteria described by the Functional Requirements of NIF. The companion document “National Ignition Facility Laser System

Performance” also in this issue of *FS&T* describes the results for 3ω that are significantly better than required.

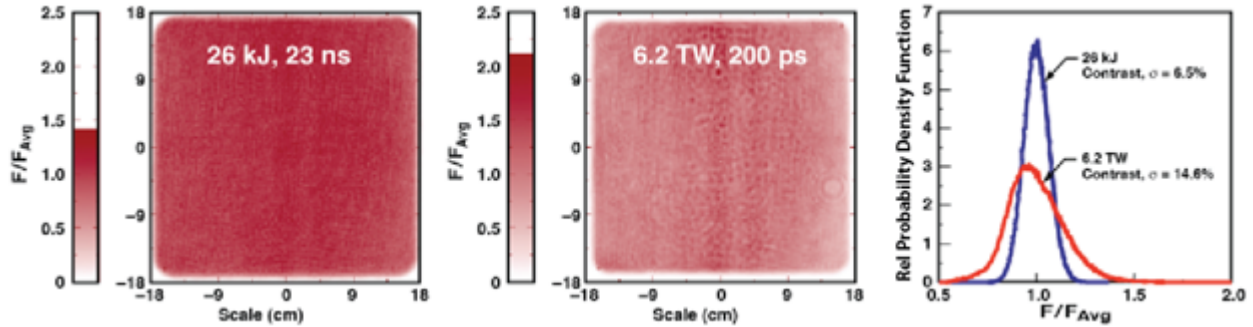


Fig. 83: Near-field beam profiles measured for an amplified 1ω beam operating at high energy (26 kJ per beam) and high power (6.2 TW per beam) The right-hand graph gives the relative probability density function of the fluence for these two cases¹³⁴

VI.D.5. Beam pointing stability

The transport mirrors LM5 and LM8 are used in tandem to point the beams to the target. As the designers for target experiments specify different pointing locations for their individual shots, these two mirrors keep the central ray of an output beam at the center of its final focusing lens while maintaining its pointing to the target location as requested. The accuracy with which this is accomplished (better than required) is described in “National Ignition Facility Laser System Performance” also in this issue of *FS&T*. Coordinated moves of the LM5 and LM8 mirrors and the frequency conversion crystals allow a range of pointing angles such that the light can be focused over a range of distances from TCC in a plane normal to its line of sight, as needed, for example, to point at a target diagnostic backlighter.

VI.D.6. Energy delivered

As each of the 1ω bundles was brought into operation, the graphic of Fig. 84 was used as a poster-size scorecard. Bundles were turned red in this graphic, one at a time, until all of them had been operationally qualified. All bundles had passed all tests by September 24, 2008, providing the ability of the system to deliver 4.2 MJ of 1ω energy.



Fig. 84: The 192 1ω laser beams of NIF have produced output energy of 4.2 MJ.

VI.E. Summary overview of the 1ω Main-Laser System

The 1ω Main Laser System delivers on its flowdown requirements as a partner in meeting the full system requirements of NIF. This success is based on a combination of designed-in features and procedures that were used during construction and that now continue into operations as shown in Table VII for performance and Table VIII for routine operations.

TABLE VII: Functional responsibilities of the 1ω MLS for meeting NIF laser performance.

	Functional Responsibility	1 ω MLS Design Response
Performance	Target irradiation symmetry	192 beams, grouped as closely-packed clusters, delivered in mapped quads
	>19 kJ/beam @ 1 ω	Nd:Glass with 40 x 40 cm ² hard apertures
	ICF Ignition shaped pulse (400:1)	Media w low n ₂ , 4 to 5 J/cm ² saturation fluence
	Spatial contrast across beams <10%	Image relay, good optics, pinholes
	Spot size at target <500 μ m @ 1/e	Deformable mirror, low-phase-gradient optics
	Power balance <6% @ 1 ω	Stable power supplies, flashlamps
	Pulse simultaneity <30 ps @ TCC	Switchyard layout requires ~70 m Argon path
	Beam pointing stability <6 μ rad	Heavy concrete and spaceframe structure

The 1 ω MLS maintains the precision and quality of the input beams from the PAMs and delivers high energy and power to the FOA for frequency conversion. Good beam quality from the full-aperture 1 ω amplifiers is maintained in the form of low fluence contrast that leads to keeping the 3 ω contrast low, reducing damage initiation on FOA optics and ensuring high frequency conversion. Low 3 ω contrast also keeps the edge roll-off of the conditioned and focused 3 ω beams small. The 1 ω laser has not been a limiting factor of the cycle time of the facility between shots because of the rapid thermal recovery of the flashlamps and slabs and the wavefront control provided by the deformable mirror.

TABLE VIII: Functional responsibilities of the 1 ω MLS for meeting the needs of routine operations.

	Functional Responsibility	1 ω MLS Design Response
Routine Operations	>250 shots per year, <8 h turn-around	24/7 operation, cool lamps & slabs with CDA
	Minimum maintenance cost	LRUs, OAB, Clean transporters
	- Build an extremely clean system	Cleanliness — Scrub, seal, flash, monitor
	- Maintain internal cleanliness	- Vertical flow of CDA across slabs - Air knives across up-facing mirrors - Sol-gel getters in spatial filters - Beam dumps for ghosts
	- Self-diagnosis of obscurations	Large Optics Inspection System (LOIS)
	- Protect from counter-propagating light	The target, opposing beams, crosstalk
	Provide performance diagnostics	OSP

NIF was designed with the goal of a 30-year operating life, while requiring minimum maintenance. Failure modes that had been observed for all previous large 1 ω laser amplifiers were reviewed and used as guidelines for avoidance of these same failure modes in NIF. Reliability and availability studies were completed for all of the actuator control systems that had been selected in early design activities and those with unacceptable failure rates were replaced by more robust components. Good engineering practices were followed, and if none were extant, new practices were developed. As discussed, cleanliness was given very high attention during all fabrication and assembly steps all along the beamlines.

VI.F. Continuing vigilance for keeping the 1 ω Main Laser System ‘Safe’

As stated at the beginning of this section, the 1 ω Main Laser System supplies the muscle and endurance of NIF. It is a solid piece of equipment. Keeping it that way, however, requires vigilance for staying within safe operating bounds. The following are areas in which vigilance is particularly important:

- The vertical gas purge across the slabs is turned on immediately after every shot

- ΔB , the phase-pushback due to the non-linear index of refraction (Ref. 84) and variations in the high intensity across a beam, is kept below 1.8 radians between spatial filters for every shot
- Shots are never fired without the SBS fail-safe system operational
- Argon pressure in the beam enclosures is kept stable and above ambient atmospheric pressure for all high-power shots. Stratification of residual oxygen and argon within the beam enclosures is held within acceptable bounds
- Monitoring the beampaths is continued between shots for the presence of dangerous obscurations
- A low-risk posture is taken for every target shot that could lead to back reflections dangerous to the 1ω system (The last mirror that turns the beam toward target chamber center, LM8, is vulnerable to optical damage by 3ω back-reflections) This risk could be significantly reduced in the future if a “blue-blocking” Ce-doped fused-silica optic were to be located in the FOA in the space between the target chamber vacuum window and the tripler frequency-conversion crystal

VII. THE FINAL OPTICS ASSEMBLIES (FOA)

The 48 Final Optics Assemblies (FOAs) (each with optics for one quad of four beams) accept the amplified 1ω light from the MLS; they convert it to the third harmonic at 3ω with energy as high as 2.0 MJ and focus it with high precision (Ref. 48, 134). Often most of the NIF beams are focused onto a primary target, with several beams reserved for focus onto x-ray creating backlighters used for target diagnostics. As modeled and expected, the FOAs preserve

the precision for pulse shape, timing, pointing, etc. that was imposed on the 1ω beams. The partnership responsibilities of the FOA and its schematic are provided in Fig. 85.

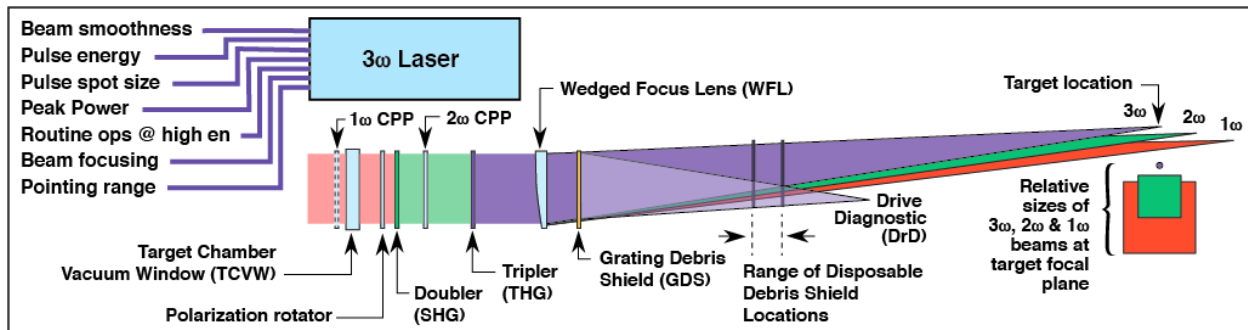


Fig. 85: Responsibilities and a schematic of the components of the Final Optics Assemblies. Note that in this graphic the location of the focus for each of the wavelengths has been vertically offset for clarity. They actually fall on a common horizontal line parallel to the axis of the light in the FOA.

Each FOA consists of a fixed-hardware interface to the target chamber and four integrated optics modules (IOMs) that house the final optics. The IOMs are precision opto-mechanical systems that combine a number of critical functions into a single compact package: frequency conversion, focusing, color separation, diagnostic beam sampling, vacuum isolation and shielding from debris created by imploding targets. A view of several FOAs on the target chamber can be seen in Fig. 86, a frame from the movie, *Star Trek Into Darkness*, which was filmed in NIF during a facility maintenance period in 2012.

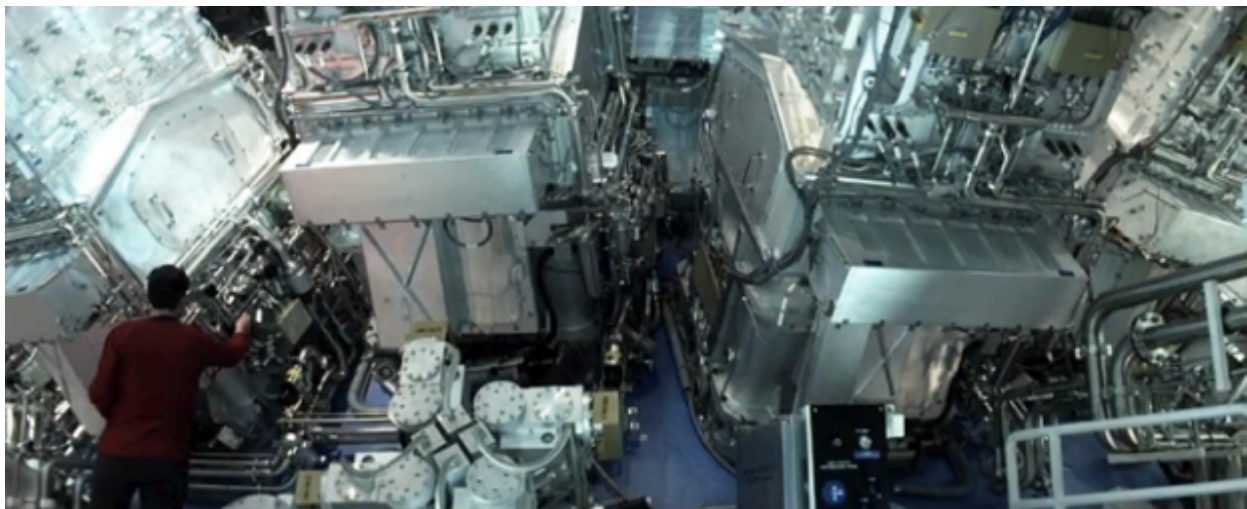


Fig. 86: Two FOAs can be seen in the center of this image, a frame from the movie *Star Trek Into Darkness*. Two more FOAs can be partially seen on the side edges of the frame. The person seen in the frame is Bruno Van Wonterghem, Deputy Program Manager for NIF Operations (Permission granted by Bad Robot).

VII.A. Top-level Goals for the NIF FOAs Established by Experiments in Earlier Laser Systems

The discussion in Section VI.A focused on contributions made by earlier ICF systems for understanding high-energy amplifier designs. It is also true that every one of these systems also served a parallel purpose, as target shooters, where they built LLNL experience in laser-driven experiments with ICF targets. The requirements for the NIF FOAs can be traced directly back to the results of these experiments. When it was found that targets used in the 10 kJ Shiva system (operating at 1ω) were not producing a significant number of neutrons from ablative imploding targets even though the targets were absorbing most of the input light, attention was given to much smaller experiments in Argus and later to multi-kilojoule experiments in Novette with beams that had been frequency-converted to 2ω , 3ω and even 4ω . These experiments

demonstrated plasma behavior significantly more favorable for shorter wavelength light (Ref. 7). Attention was then turned toward building the scaled-up Nova laser capable of operating at 3ω . A system operating at 4ω was not pursued because light at the fourth harmonic was found to be far more difficult to produce and deliver than light at the third harmonic.

The NIF FOAs follow the path set by Nova, delivering 3ω light at the shortest wavelength that can practically be provided by a system that is also capable of meeting the full set of ICF requirements, including those for output energy and peak power. Meeting the target need for high energy and high power in a near-UV wavelength ($0.351\ \mu\text{m}$), brings with it the challenges placed by coming closer to the UV absorption band-edge of many materials that might be considered for use as optical or coating materials. As the wavelength moves closer to the band-edge of these materials, there is a greater likelihood of optical damage as a function of fluence and intensity.

Because optics damage was expected to be an important and perhaps limiting issue for NIF operations, high priority was placed on designing a system that could be maintained with rapid turnaround time. Figure 87 gives a top-level view of decisions made as part of the evolution of the NIF FOA design that centered around reducing or being able to gracefully respond to optical damage. The article entitled “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” in this issue of *FS&T* describes techniques and procedures that were developed for operating at a fluence level over twice the threshold fluence for damage growth on the optics,¹³⁵ while at the same time incorporating the ability to be incrementally responsive to improvements in the resistance of the optics to damage initiation, as these improvements could be achieved. Routine operation in this regime had not been attempted before NIF.

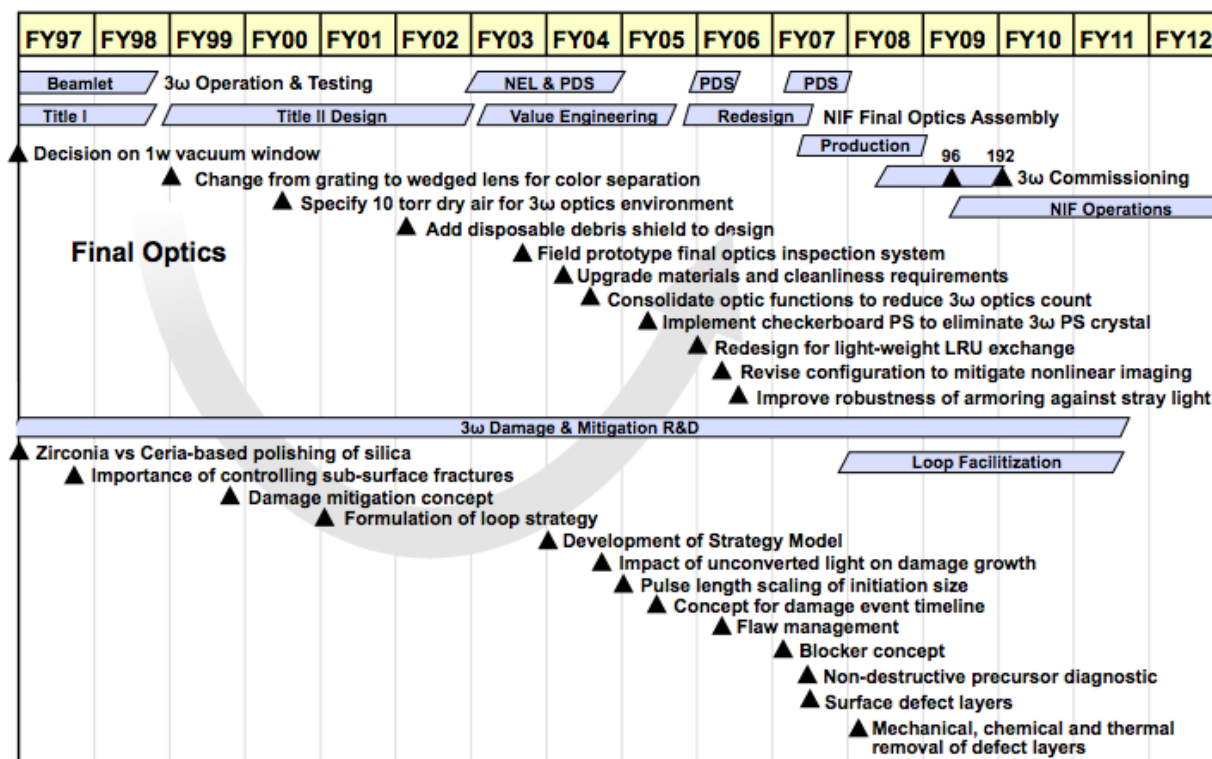


Fig. 87: Timeline for the development of concepts and decisions made in the evolution of the FOA design related to reducing or gracefully responding to the impacts of optical damage.

VII.B. Assembly of the Integrated Optics Modules (IOMs)

IOMs to be used in the fixed FOA hardware were among the last of the large pieces of hardware to be fabricated and assembled for NIF.¹³⁶ The decision to set up a special assembly area for this hardware in building 490 at LLNL was based on several factors: our experience with the PAM factory, our experience with fabrication of many other LRUs in the OPF and OAB, and acknowledgment of the constant high level of cleanliness and quality control that would be needed during assembly.

A 280 m², Class 100 clean room, called the IOM Factory, was constructed to meet the needs for clean fabrication of the IOMs, including a number of unique assembly stations and

materiel-handling equipment. Each IOM weighs about 400 pounds, without its optics installed. All of the subassemblies that would eventually hold the optical LRUs had to meet stringent location and angular positioning requirements within the IOMs. A photograph of one station in the IOM Factory is shown in Fig. 88. After assembly, test data was taken on every IOM to verify that all of its requirements had been met, such as those for cleanliness, alignment, and vacuum integrity. Testing was done prior to shipment of the IOMs to the target area and installation onto the target chamber.



Fig. 88: Assembly of production FOA integrated optics modules in a temporary factory set up at LLNL.

VII.C. Description of an FOA beamline

The FOA design represents an integrated solution to a large number of performance, operational, and environmental requirements. The FOA optical configuration, shown schematically in Fig. 85, is designed to deliver the required functionality with the fewest possible optics. It is desirable to have fewer optics because this keeps the total optical thickness in the 3ω

section smaller and exposes a fewer number of optics to 3ω light. (Ref. 136) With the quality of optical finishing available for silica components delivered in 2013, some damage initiation still occurs. There is growth of the initiated sites because the mean 3ω fluence in the FOAs is often over the threshold for 3ω damage growth (~ 3 to 4 J/cm^2). During routine shots taken in July of 2012, (See “National Ignition Facility Laser System Performance” also in this issue of *FS&T*) the FOA optics saw over 10 J/cm^2 mean 3ω fluence, with a similar fluence for the sum of the residual $1\omega + 2\omega$ light, which is often important for growth, in addition to the 3ω light.

Today, as NIF is usually operated, the optics in an IOM include a 1ω target chamber vacuum window, a polarization rotator crystal (only on two of the four beams in each FOA), a 2ω Continuous Phase Plate (CPP), doubler and tripler frequency-conversion crystals, the wedged focusing lens, a 1-cm-thick main debris shield that also serves as a diagnostic pickoff for measuring energy and power, and a thinner disposable debris shield (DDS) for protecting the optics from target blow-off. The DDS Cassettes can hold ten individual disposable debris shields (either 1-or-3-mm-thick) that can be exchanged from the control room, as desired.

VII.D. FOA Optics Production Challenge

Procurement of the large optics for 3ω was part of the procurement package for all of the large optics for NIF. Because achieving good damage resistance for 3ω optics is more difficult than at 1ω , our work with the suppliers of 3ω optics extended for a longer period of time and included a higher level of technical cooperation between the suppliers and LLNL optical finishing scientists. (Ref. 121)

As reported in Section VI, there are 6208 large optics in the 1ω MLS. As seen in Table IX, the Final Optics add another 1440, bringing the total number of NIF large optics up to 7648

when in an 11-5 configuration. Just as in the MLS, each FOA beam is square with a nominal clear aperture of $37\text{ cm} \times 37\text{ cm}$. The effective beam area is $\sim 1250\text{ cm}^2$.

TABLE IX: lists the optics in an FOA for any one shot. Change out of some of these optics happens quite frequently for two reasons. One, NIF often operates above the optical damage threshold for growth, and two, target debris is continually contaminating the disposable debris shields.

Optic	# req'd	Key Material(s)
Vacuum windows	192	Fused Silica
Half-wave rotators	96	KDP or DKDP
Doubler crystals	192	KDP
Continuous Phase Plates	192	Fused Silica
Tripler crystals	192	DKDP
Wedged Focus Lens	192	Fused Silica
Grating Debris Shield	192	Fused Silica
Disposable Debris Shields	192	Borosilicate Float glass
Total	1440	

VII.E. Fused-silica optics

All of the fused-silica components in the FOA (except for the target chamber vacuum windows) are fabricated from inclusion-free synthetic silica for reasons that are discussed in Section VIII.L. In addition to the target chamber vacuum window (TCVW) there are three other fused-silica optics in the FOA, the 2ω continuous phase plate, (2ω CPP), the wedged focus lens (WFL) and the grating debris shield (GDS). All of the substrates for these optics are fabricated by one of the several companies that supplies 1ω and 3ω optics for NIF (see Fig. 60).

VII.E.1. Target Chamber Vacuum Window (TCVW)

Each $1.053\text{-}\mu\text{m}$ beam from the main laser enters its IOM through a 4.3-cm thick fused-silica vacuum window. This window provides safe separation of the argon-filled beampath at

atmospheric pressure from the near-vacuum interior of the IOMs. The quality of the surface finish for the TCVW is similar to the quality of the surface finish for all of the 1 ω optics.

The TCVW receives special attention because it is one of the optical vacuum barriers of NIF. Optical windows under stress from an atmospheric load can fail suddenly if a damage site on the vacuum side grows to a critical size. A catastrophic failure of the TCVW could vent the NIF target chamber through its beamtube with serious consequences. To prevent this from happening, the TCVWs are thick enough to have both low stress and large critical flaw size. If the extremely unlikely case of TCVW failure should occur, the argon-side beam tubes have rupture panels that would open to prevent the beampath from collapsing.

During NIF operation TCVWs are regularly inspected for optical damage. Monitoring of the windows is done after every shot using a camera-based subsystem referred to as SIDE (Side Illumination Damage Evaluation). With a resolution of 1 mm, SIDE is well able to identify a site long before it can grow to a critical-flaw size of greater than 13.9 mm. In operation, SIDE uses multiple small sources of light to illuminate two of the orthogonal window edges of each TCVW with light that propagates internally through the bulk of the optic. If a damage site is present, it will scatter some of this light into the camera located ~3 m upstream of the window. With aid of a wedged beamsplitter, one SIDE camera is able to monitor two TCVWs. The SIDE system alternately illuminates each of the two windows to provide unique camera-image-to-window correlation. There are 96 SIDE cameras in NIF and they can all be operated in parallel, thus SIDE inspection of the TCVWs can be done very quickly. Because analog CCDs are less susceptible to neutron damage than their digital counterparts, the analog SIDE cameras are robust in an environment where neutrons can be generated. Fig. 89 captures installation of the last LRU in NIF, a SIDE camera/shutter assembly going into quad 45B.



Fig. 89: Installation of the last LRU to go into NIF, (other than those for the final optics) a SIDE camera/shutter assembly for Quad 45B. This SIDE assembly will be placed into the beam enclosure just above the floor on which one of the installers is kneeling, about 3 m upstream from the location of the TCVWs (indicated by the arrows, black with white surrounds).

A backup inspection system is available for the TCVWs if the SIDE cameras degrade in the environment of a high-neutron-yield shot. Backup is provided by the Final Optics Damage Inspection (FODI), described briefly in Section VII.K and in more detail in the “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” article also in this issue of *FS&T*. FODI is regularly used to inspect transmissive optics in the FOA and the mirrors located between the TCVW and the last spatial filter lens, SF4. If called upon, it can also inspect the TCVWs. FODI regularly completes its serial inspection responsibilities inbetween shots while it is positioned at the center of the target chamber. During low-yield shots, FODI is located within its positioner just outside the target chamber. For high yield shots, where neutron damage to its camera is a real concern, the FODI instrument is removed from its positioner and

stored outside the target-bay shield walls where its camera is well protected from neutron degradation.

VII.E.2. Continuous Phase Plate (2ω CPP)

Once in the FOA, the next fused-silica optic to be encountered is the 2ω CPP, a key component of the hardware used for beam smoothing and conditioning. (The KDP crystal doubler just precedes the 2ω CPP, and in half the beams a polarization rotator also precedes the KDP crystal doubler). Spatial beam smoothing is a method of introducing spatial incoherence in the near-field beam to produce a larger, more controllable focal spot in the far field (at focus) with reduced peak intensities at the target plane. The manner in which the beam smoothing and conditioning components in NIF work together is discussed in Section VII.I. Here the discussion will focus around the technology used for CPP fabrication¹³⁷ that has now been used to fabricate over 300 phase plates for use on NIF and the OMEGA facility at the Laboratory for Laser Energetics in Rochester, NY.

CPPs have one plano surface that is produced using the same optical fabrication processes used for other NIF 3ω surfaces. The second CPP surface introduces a set of pseudo-random phase aberrations to control the size of the focal spot on the target and the energy distribution within the focal spot. NIF CPPs can deliver over 99 percent of their incident light into the conditioned spot. Nova and Beamlet used less efficient discrete random and kinoform phase plates that were fabricated using photolithographic techniques.¹³⁸ The stepped contour patterns of these phase-plate types led to step-edge modulation and resulting damage on downstream optics; as a result, kinoform phase plates were not acceptable for the higher fluence and intensity conditions of NIF.

NIF phase plates are manufactured using magneto-rheological finishing (MRF®, a registered trademark of QED Technologies, Inc.), a technique pioneered by QED Technologies and jointly developed with LLNL. In the early nineties, after work with the Soviet Union had become easier for western nations, the inventor of MRF, William Kordonski, and several of his colleagues from the Luikov Institute of Heat and Mass Transfer in Minsk, were invited to work at the Center for Optics Manufacturing at the University of Rochester with Steve Jacobs and Don Golini. Golini subsequently founded QED Technologies. MRF is an advanced optical finishing process combining interferometry, precision equipment, and computer control. It utilizes a sub-aperture polishing tool (or removal function) generated by the interaction of a magnetic field and an iron-based MR fluid containing microscopic abrasive particles such as ceria or nano-diamonds. Because this type of machine polishes only a small part of the entire optic at a time it is well suited for figuring the phase aberrations specified for a CPP. The MRF tool removes material from an optical surface when the optic is positioned at a fixed distance from a moving spherical wheel. An electromagnet located below the wheel surface generates a magnetic field in the gap between the wheel and the optic. When the MR fluid is delivered to the wheel, it is pulled against the wheel surface by the magnetic field gradient and becomes a sub-aperture polishing tool, as shown in Fig. 90.

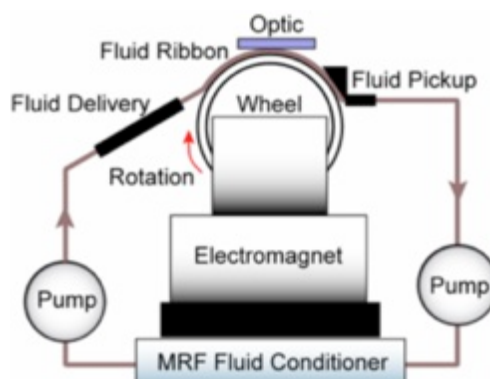


Fig. 90: (a) MRF polishes optics by creating a sub-aperture polishing tool using magnetic media and an electromagnet. Material is removed in the area where the optic is immersed into the fluid ribbon. Surface polishing is accomplished by rastering or rotating the optic over the ribbon. The fluid is continuously recycled. (b) close-up photograph of the tool surface with an optic undergoing raster polishing.

Computer algorithms determine a “schedule” for varying the translation velocity of the optic as it sweeps through the polishing zone, in either a rotating or raster pattern. Because the polishing tool effectively doesn’t change, MRF is a deterministic polishing technique, and because interferometric techniques are used to accurately characterize the amount of material that should be removed on the next pass at each location on the optic surface, it makes efficient delivery of high-precision parts possible. Meeting these location-dependent, topographical polishing goals is enabled with an easily adjusted polishing tool that conforms to the optical surface.

The MRF process achieves high removal rates with negligible normal load at the surface of the optic, leading to little subsurface damage and thus to good resistance to laser-induced surface damage. In addition, the smooth surface contours of NIF MRF-polished phase plates eliminate surface features that could lead to downstream optical damage.

CPPs fall into the category of diffractive optics; they take advantage of the apparent bending of light waves in response to small topographical changes on an optical surface. Fig. 91 illustrates an example of the computer-generated topographical features of a CPP that can provide the far-field energy contours specified by target designers. This near-field topography is key to providing detailed control of the laser beam shape at the target plane. As will be seen in

Section VII.I, it can be designed to convert a square or circular laser beam footprint to an elliptical or circular spot of prescribed lateral dimensions.

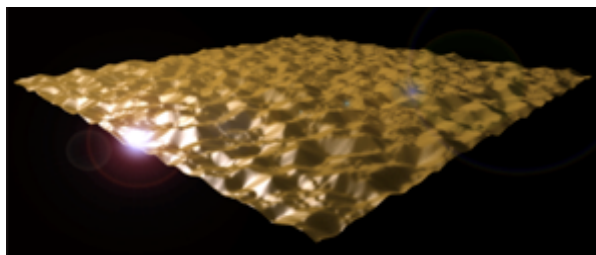


Fig. 91 Computer calculation of a continuously varying topographical CPP pattern fabricated using MRF. This pattern has an $8.6\text{ }\mu\text{m}$ peak-to-valley imprint on a $43\text{-cm} \times 43\text{-cm} \times 1\text{-cm}$ fused silica substrate.

Stringent specifications for the surface pattern of a CCP are set in keeping with meeting the stringent requirements for the NIF focal spot. A sharp edge-roll-off is necessary for the far-field spot in order to keep a beam from unintentionally impinging upon critical components in the target area and for establishing the proper projection angles onto targets for indirect drive. The required edge-roll-off is described as a high-order super-Gaussian, of order greater than ~ 7 . In addition the illumination uniformity within the focal spot is generally specified to be better than 5%. This specification has the goal of eliminating high intensity areas within the spot that could reduce the hydrodynamic performance of the target.

VII.E.3. Wedged Focus Lens (WFL)

The final focusing lens of NIF is probably the single optical component that has most often been redesigned, going through five design generations, including one grating-Fresnel-lens-like version. The design of the lenses now in NIF is shown in Fig. 92. This Wedged Focus Lens (WFL) is the highest value optic in NIF. Its surfaces are post-processed at LLNL using an

Advanced Materials Processing (AMP) technique to improve its resistance to damage initiation. The lens is an off-axis plano-convex aspheric design with a 7.7 m focal length at 3ω . Conceptually, each lens can be thought of as cut from a much larger lens, with its vertical midline common with the midline of the much larger lens, as seen in Fig 7.5-4 (b). Use of a wedged focus lens with a thick side of ~ 4.5 cm allows the four beam apertures in each FOA to be arranged in close-packed 2×2 arrays with ghost foci deflected to off-axis locations between the beams where they are intercepted by beam dumps. It also serves the important function of angularly dispersing the unconverted 1ω and 2ω light away from the target (see Fig. 85 shown earlier for the relative size and position of each of the three 1ω , 2ω and 3ω beams). This pattern corresponds to focal lengths for the 1ω and 2ω light of 8.16 m and 7.92 m, respectively.

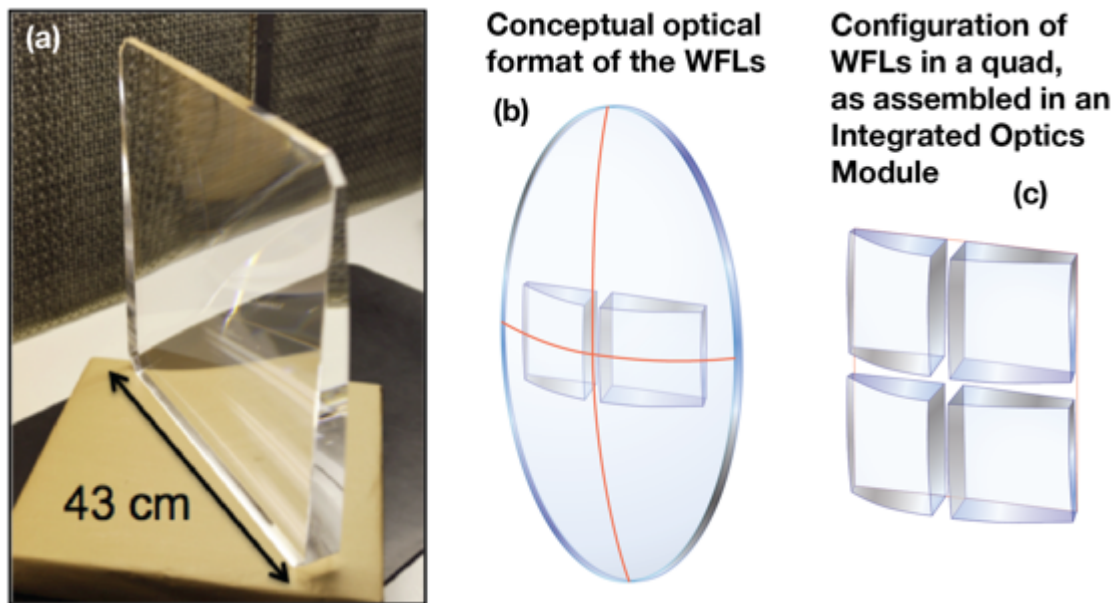


Fig. 92: Off-axis Wedged Focus Lens (a) Photograph (b) Conceptual view of the surface figures of the off-axis plano convex design (c) Two sets of two lenses each with the optical format shown in (b) are stacked to configure the four WFLs of one quad.

CAD drawings of the optical configuration of a NIF quad are the basis for the graphics in Fig. 93. In Plan view, the beams are parallel as they approach the IOMs. In the Elevation view the beams approaching the IOMs are pointed directly at target chamber center.

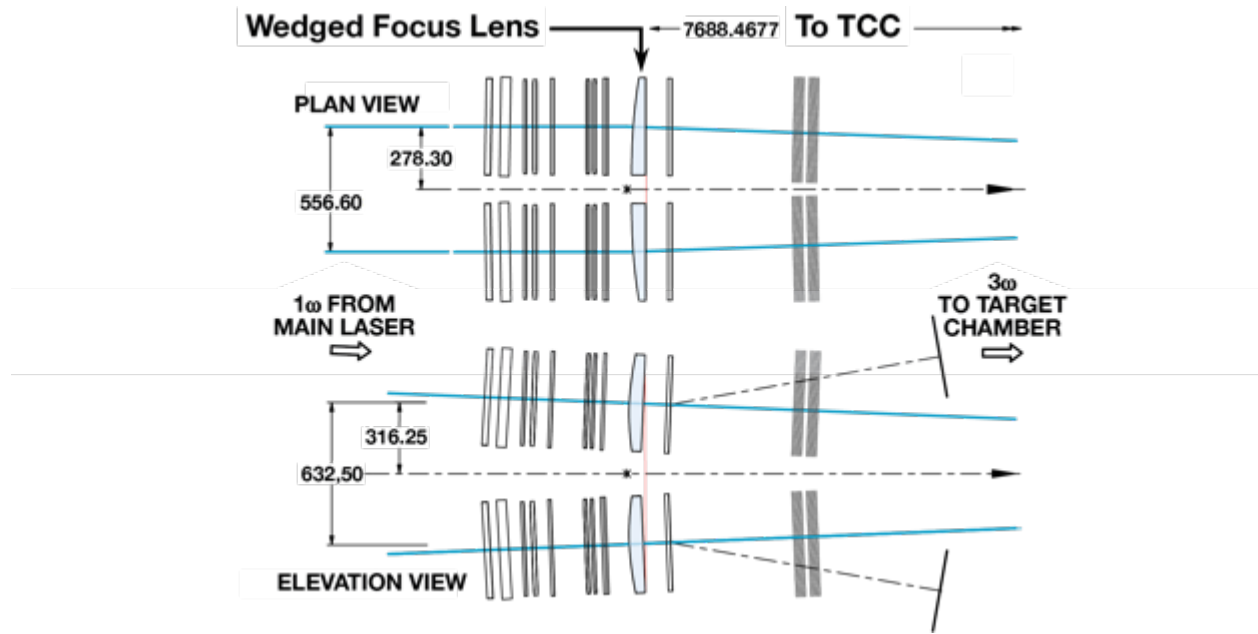


Fig. 93: Focusing characteristics of the WFLs in the quad of one FOA. Note that the path of the central ray of each beam has a different profile in Plan and Elevation views.

Stepper motors are provided for moving the WFLs along the line of their beam axis pointing toward target chamber center, enabling the 3ω light to be focused over a range of distance on either side of TCC, as discussed in “National Ignition Facility Laser System Performance” in this issue of *FS&T*. Each beam has an individual focusing range.

VII.E.4. Grating Debris Shield (GDS)

The grating debris shield (GDS) serves several functions. As its name implies, it is a backup debris shield, specifically for protection of upstream FOA optics from a highly energetic debris fragment that might be headed toward an FOA. It is thicker than the disposable debris

shield that sits between it and the target. It also serves as the vacuum barrier between the very clean IOM environment at 10 Torr clean dry air (See Section VII.H) and the evacuated target chamber. In addition, it has the very important role of providing the light sample for diagnosis of the 3ω light going toward the target. After receipt of a GDS blank from the supplier, both of its surfaces are post processed with AMP (advanced material processing, see the “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” also in this issue of *FS&T*). One side then receives a HMDS sol-gel anti-reflection coating (crystals receive a similar coating, see Sections 6.2.2 and 7.9) and the other side is imprinted with a shallow, ~ 15 nm grating using holographic lithography. It is this shallow grating that diffractively supplies the light sample for beam diagnosis.

The GDS fabrication process is similar to that used at LLNL to produce the large gratings used around the world in short-pulse laser applications. During exposure of the photoresist with 3ω light the optic is placed in a location where interference fringes are formed between a large $f/21$ weakly converging wave and a spherically diverging wave originating from the same source. (see Fig. 94) This geometrical relationship replicates the geometry the finished GDS will see when it weakly diffracts a converging wave into the Drive Diagnostic (DrD) aperture while transmitting most of the 3ω light on its way to the target, that is, the exposure configuration replicates the in-use configuration. Because the two interfering waves used for exposure are not perfectly uniform, the etched grating will also not perfectly meet its design request; a calibration surface map is therefore generated for each GDS before it is put into use in NIF.

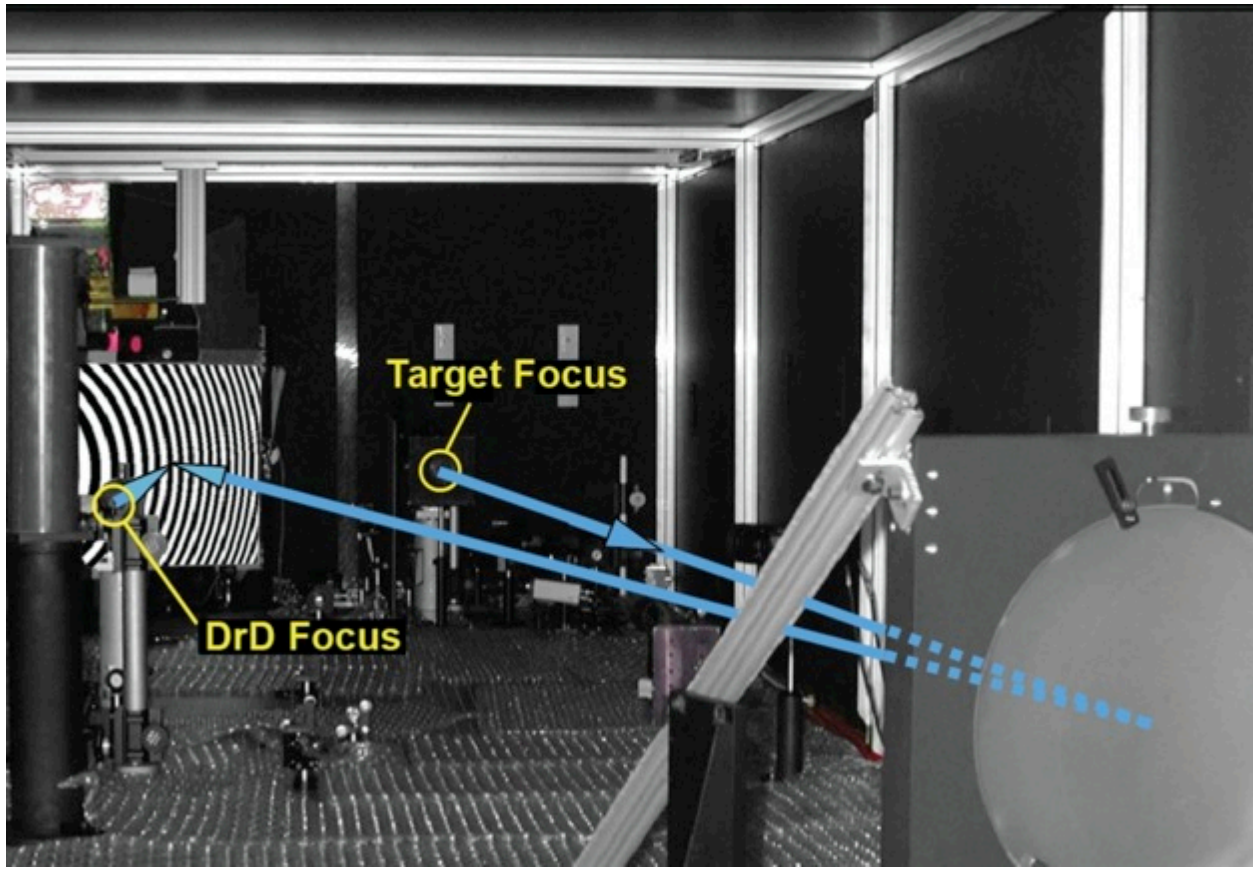


Fig. 94: Photograph of the exposure chamber for the photoresist of the GDS. The large mirror on the right edge of the picture illuminates the GDS with an $f/21$ wave replicating the geometry of the NIF beam as it focuses toward the target. The source of the spherically diverging wave identified as the DrD focus in this picture is the same distance from the GDS as the distance to focus at the DrD in the geometry of NIF. The size of the fringes on the GDS are exaggerated.

VII.F. The crystal optics in an FOA, KDP and DKDP

VII.F.1. Crystal Growth and Finishing

This section will cover production of all of the crystals needed for NIF, including the switch crystals in the 1ω MLS and the frequency converters and polarization rotators in the FOA. The KDP and DKDP crystals used in NIF are negative uniaxial crystals. They gain their

non-linear properties because two of their crystallographic principal axes have indices of refraction that are equal and larger than the index of refraction of their third principal axis. In the literature, this third, and unique principal axis, is often referred to as the “c” axis or as the “z” axis. We use “c” in this article to avoid confusion with the coordinate system used in NIF. The same crystal material can be used for different purposes by orienting the crystallographic axes at different angles with respect to the propagating light.

There are two types of frequency conversion crystal optics in NIF: second harmonic generators (SHG, or doublers), and third harmonic generators (THG, or triplers). The second harmonic generator doubles the frequency of a predetermined amount of the incident infrared (1ω) light. This 2ω and the remaining 1ω light are then mixed in the tripler to form the 3ω light. In addition, half of the beams have KDP Polarization Rotators (PRs) that are part of the NIF capability for beam smoothing. The frequency-converting crystals used with the half-wave rotating PRs are aligned as appropriate for the polarization of the light from the PRs. This 50/50 configuration makes it possible for half of the beams to be delivered to the target in a polarization orthogonal to that of the other half of the beams.

One of the challenges for building NIF was developing the growth technology capable of producing the large crystal boules that could yield the 42 cm single-crystal optics needed at both 1ω and 3ω while also meeting the NIF goals for cost and schedule. Nova had used 27 cm x 27 cm square KDP crystal optics for both doubling and tripling in 3 x 3 arrays for coverage of its round 72-cm-diameter clear-aperture beams. The Nova crystal optics were cut from “conventionally” grown boules that take approximately one year to grow, with growth rates on the order of 1.5 mm/day. By the end of Nova construction, Cleveland Crystals Incorporated (CCI), (now a Gooch & Housego Group) was able to grow KDP and DKDP boules large enough

to yield 30 cm square finished crystal optics. The initial crystal optics for Beamlet were even larger, at 37 cm, but were still conventionally grown. With the success of Beamlet and the expectation of NIF construction, LLNL intensified its attention to crystal growth and production technology.

Crystal growth takes place when small (2 to 3 cm) seed crystals are placed in tanks containing warm, saturated aqueous solutions of the specific salt (KDP or DKDP). As the temperature of the solution is reduced, the concentration of KDP/DKDP above its equilibrium solubility provides the driving force for crystal growth.

Dr. Natalia Zaitseva, a Russian scientist, came to LLNL in the mid 1990s after pioneering techniques for increasing the growth rate of this family of crystals. High growth rate requires constant replenishment of KDP-rich solution at the growing face. Rotation of the crystal within its water-based growth solution became an essential feature of the rapid-growth approach. Continuation of her work at LLNL led to rapid growth of >40 cm crystal optics, with growth rates of ~1 cm/day.¹³⁹ By late 1998, however, although large crystals could be grown, the yield was still unacceptably low.

The main production challenge for rapid growth of KDP was growing boules large enough to yield doubler crystals for NIF. Figure 95 illustrates the relationship between boule orientation and the manner in which crystal optics can be cut from the boules. PEPC switch crystals require the smallest size boules, with material yield possible from boules with base dimensions as small as 43 cm x 43 cm. The orientation of polarization-rotator optics in the boule is similar to that for switch crystals. In order to produce doublers, however, the crystal boules must be larger, at least 51 cm x 51 cm x 51cm for minimum yield.

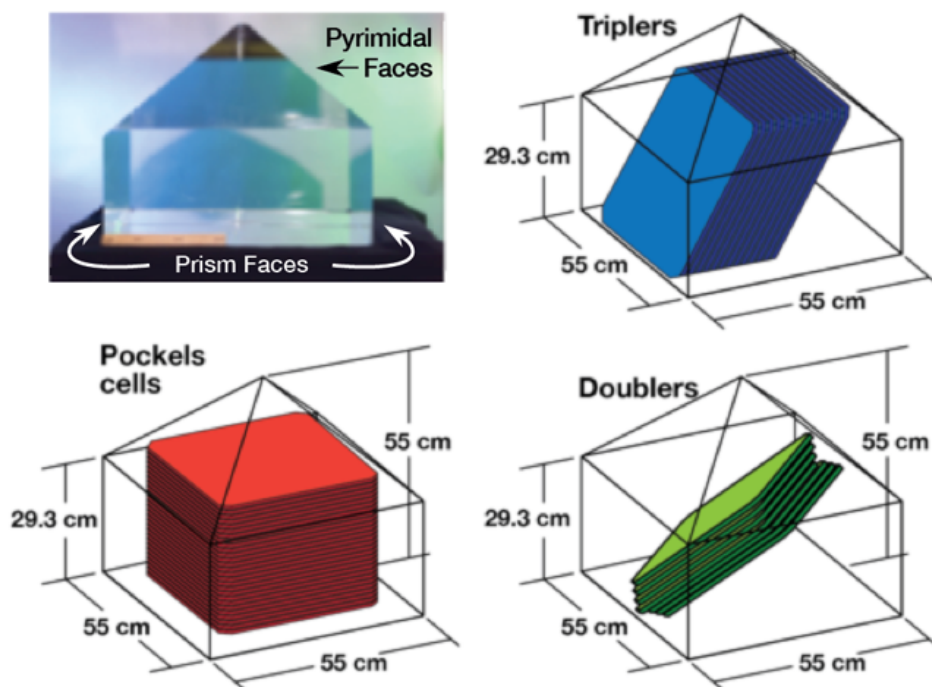


Fig. 95: Orientation of finished NIF crystal optics relative to their parent single-crystal boule.

The vertical direction of the growing boule is parallel to the principal “c” axis of the “crystal.”

During 1998 the rapid-growth technology was being transferred to CCI and Inrad (who both subsequently delivered boules for PEPC switches and frequency-converting doublers that are now used in NIF) and work at LLNL focused on improving the yield of growth runs.

The technical advances needed for growing KDP boules with high yield (both in terms of optic-yielding boules and a larger number of optics per boule) using the rapid growth process were a result of a sustained R&D effort by both LLNL and CCI. Disciplined procedures were established to ensure run-to-run repeatability, precise control of the declining tank temperature profile, reagent purity, and tank conditions. In addition significant advances in a number of specific technical areas were made, including:

- 1) Preventing Secondary Nucleation:** Secondary nucleation (i.e., formation of secondary KDP crystals) within the solution growth tank system is detrimental because they will grow, migrate, and dislodge other crystals that can eventually contact the main growing boule, prematurely ending the growth run. Locations for secondary heterogeneous nucleation include cracks and joints within the crystal growth system and impurity particles (either already present within the growth system or migrating in from the external environment). Three modifications to the crystallizer (seen in Fig. 96) were important in reducing the number of secondary crystals formed during growth, including: (a) fluorinated (i.e., Teflon-like) coatings on the growth platform and liners of a similar material on the glass tank interior wall reduced the number of sites where heterogeneous nucleation crystal could grow; (b) a continuous solution filtration system (CFS) reduced the number of impurity particle seeds present in the tank; and (c) improved sealing of the growth system and overpressure of the tank atmosphere significantly reduced the entry of external particle seeds from the surrounding environment.¹⁴⁰ With the Teflon-like coatings, the rotation rate could be increased, thus also supporting a faster growth rate.
- 2) Minimizing Liquid Inclusions:** During crystal growth, small (micron-sized) pockets of solution can form on the growth face leading to bulk liquid inclusions that form unacceptable scattering sites in the final fabricated optic. Trapping of solution to form these inclusions is due to poor mass transfer and/or pinning of elementary growth steps by the presence of impurity metal cations.^{141,142,143} Better control of the solution mass transfer to the crystal face was found to reduce liquid inclusions.^{144,145} Better control was provided by (a) modifying the platform rotation rates as a function of the different face sizes of the growing boule, (b) rapidly alternating the direction of rotation, thus

accelerating the flow across the crystal faces and (c) reducing the solution impurity cation concentration (by using the fluorinated coating & liner barriers, higher purity raw materials and use of ethylenediaminetetraacetic acid (EDTA) as an impurity getter).

3) Controlling Crystal Habit: Depending on the optic type (Switch Crystal, Doubler, or Tripler), the size and aspect ratio of the final boule determines the number of optics it yields. The final aspect ratio is governed by the overall relative growth rate of the prism and pyramid faces of the crystal. Several key mechanisms and behaviors became to be understood that led to developing techniques for controlling the final crystal aspect ratio. These concepts included: (a) the influence that metallic cations have on the growth rate of prism and pyramid growth faces, (b) the influence of the dislocation number density at a growth face on the growth rate and (c) the influence of temperature on the asymmetric growth rate of these faces.¹⁴⁶ The resulting aspect-ratio-control techniques included: (a) using starting seeds with different aspect ratios to influence the final aspect ratio of the boule, (b) minimizing uncontrolled impurity levels (described above) and introducing a controlled level of Al^{3+} impurities during the growth run, and (c) incorporating an auxiliary tank of additional salt solution that could be fed into the main crystallizer tank, thus allowing a smaller temperature drop and reduced variations in prismatic and pyramid growth faces during a growth run. In addition, a mathematical model for predicting the final aspect ratio of the boule based on its observed aspect ratio at ~10 days into its growth was developed as a aid for process adjustments during the growth run.^{145,147,148,149,150}

4) Preventing Boule Fracture: KDP has low fracture toughness ($\sim 0.1 \text{ MPa m}^{0.5}$) and high thermal expansion coefficient ($\sim 4 \times 10^{-5} \text{ K}^{-1}$), resulting in poor thermal shock resistance;

hence it is very prone to fracture. The boules were particularly susceptible to fracture at the end of a growth run when they were removed from the growth tank. At that time, the temperature differences between the interior of the crystal and its faces was the result of two contributing factors, a rapid drop in the temperature of the thermal environment around a boule as it was moved from the warm growth tank into the cooler room and a drop in the temperature of the crystal surfaces due to heat loss as residual salt solution evaporated from the faces of a recently removed boule. Boule fractures were ultimately prevented by reducing the rate of the temperature drop as the boule was brought to room temperature and by maintaining a high humidity environment around the boule until room temperature was reached.^{151,152}

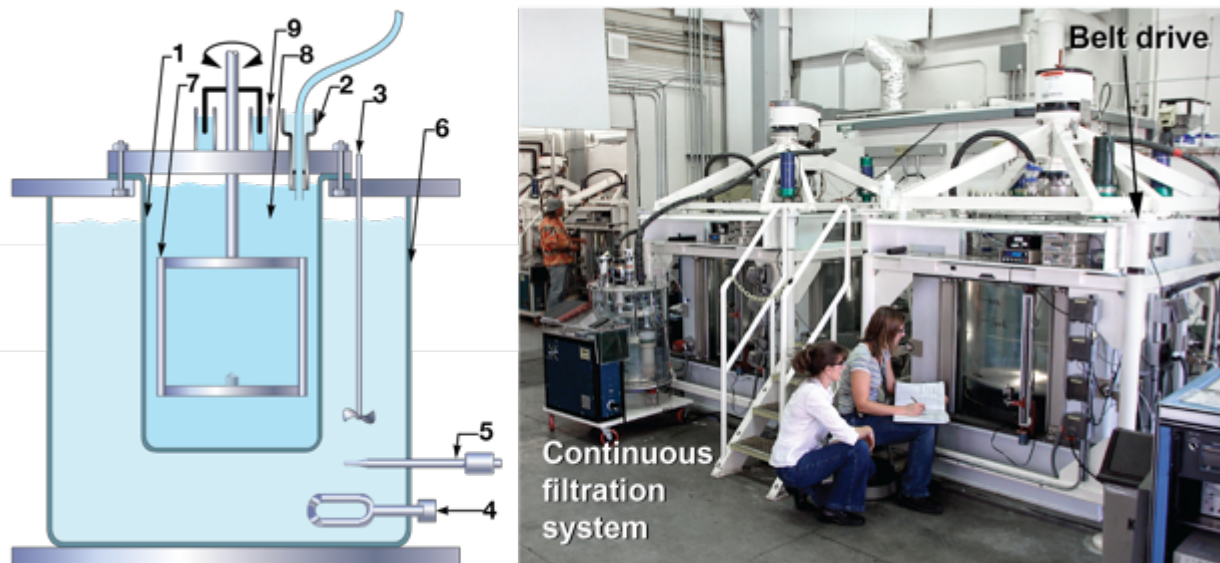


Fig. 96: (a) General schematic of a crystallizer used for rapid crystal growth: (1) growth tank; (2) water-cup seal, part of the continuous filtration system for the salt solution (3) stirrer, important for keeping the water temperature uniform (4) heater; (5) thermocontroller; (6) water bath; (7)

platform with the seed; (8) growth solution; (9) water cup seal (b) Two 1000 L rapid-growth crystallizers at LLNL, with Terry Land and Rebecca Dylla-Spears.

By the year 2000 a single growth vendor had been selected and growth tanks at both LLNL and Cleveland Crystals Incorporated (CCI) were put into production for growing enough crystals in time to meet the NIF schedule. The boule in the photograph of Fig. 95 was harvested from its tank in January 2000. After growing for 52 days, it weighed in at 701 lb (a mass of 319 kg), with dimensions of 66.9 cm x 52.9 cm x 59.4 cm, yielding 14 doubler optics. A photograph of five harvested rapid-growth KDP crystal boules is shown in Fig. 97.



Fig. 97: Large KDP crystals awaiting further cutting and finishing for use as polarization rotators or frequency doublers in NIF. As production began, Ruth Hawley was the group leader for KDP Rapid Growth/Pilot Production.

A significant parallel effort to use rapid-growth technology for production of tripler crystal boules of ~70% deuteration was also undertaken at Livermore. Although partially successful in producing NIF-sized boules, the resulting material did not routinely meet all NIF specifications, and the process was judged to be unsuitable for commercialization in time to meet

the needs for NIF. In the end, all of the DKDP material used in NIF for triplers and for some of the polarization rotators was grown using conventional slow-growth techniques.

KDP and DKDP crystals are not finished using the grinding and polishing techniques used for glass optics. Rather, crystals are first cut to just over their final size on a bandsaw as shown in Fig. 98.

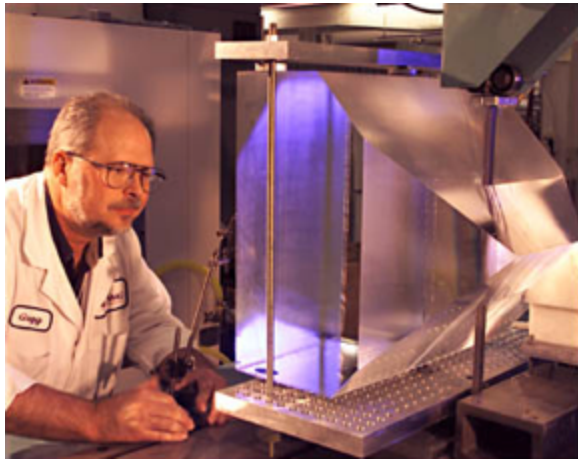


Fig. 98: Bandsaw cutting of a large KDP single-crystal boule.

Next they are finished with a single-point diamond tool set in a flywheel to skim cut the entire surface of the optic. Experience with this approach was first gained by LLNL engineers and transferred to CCI for delivery of the crystal optics for Nova. Early Beamlet crystal surfaces had visual evidence of diamond-turning tool marks,¹⁵³ with irregularities large enough to result in damage to downstream optics. With NIF 3ω fluence levels more than 10 times higher than for Nova, the engineering partnership between LLNL and CCI was renewed. LLNL contributed in the area of precision engineering including design of new machines and of upgrades to existing finishing machines directed toward improving machine tolerances.¹⁵⁴ With these improvements, the optical quality of the finished surfaces was dramatically improved; the power spectral density

(see Fig. 67) was improved by a factor of ten, significantly reducing the threat of damage to optics downstream from the crystals.

VII.F.2. Bulk Damage and Laser-Conditioning of Crystal Optics

Bulk damage is the occurrence of small voids distributed throughout the interior of a crystal optic, each of them surrounded by modified material. The voids are the result of laser illumination of crystals that have not previously been subjected to laser light. The diameter of the voids is pulselength dependent, with diameters of $\sim 3\text{ }\mu\text{m}$ typical for pulselengths of 3 to 5 ns. Bulk damage is observed to occur in both KDP and DKDP crystals during their initial exposure to 3ω fluences of $\sim 3\text{ J/cm}^2 \pm 1.5\text{ J/cm}^2$. If the number of bulk damage sites reaches $\sim 10^6$ in a NIF optic, the obscuration level is considered to be unacceptable. Fortunately, the 3ω fluence at which bulk damage will initiate can be substantially increased with use of a process known as laser conditioning. In a manner similar to that described in Section VI.C.4 for mirror surfaces, conditioning of the crystals^{155,156,157} is accomplished by raising the fluence in a step-wise fashion up to near the fluence expected for NIF operation. Crystal optics used in NIF have been conditioned both off-line before installation in NIF and on-line as the NIF output energy was increased over a number of system shots.

In 2002-2003, an off-line laser conditioning protocol was developed that utilized an XeF excimer laser operating at 351-nm with a pulse width of $\sim 8\text{ ns}$. From 2004 to 2009, nearly all of the switch crystals for NIF were off-line conditioned prior to installation, using the raster-scanned excimer laser with peak fluence steps of 3, 6, and 9 J/cm^2 . Although a number of doubler crystals were also off-line conditioned using the excimer laser with peak fluence steps of 3, 5, and 7 J/cm^2 , we did not learn much about the effectiveness of this conditioning protocol

because these doublers were also on-line conditioned with their accompanying tripler crystals that were installed at the same time.

The most commonly replaced crystal optics during operation of NIF are the DKDP triplers. Although conditioning with the excimer laser has been effective for switch crystals that are used at 1ω and possibly effective for doublers that experience both 1ω and 2ω , this protocol has been ineffective for protecting triplers at 3ω . Being able to off-line laser-condition crystal optics has been a long-time goal for NIF operations. Without off-line conditioning, triplers must be on-line conditioned using dedicated shots in NIF with step-wise increases in fluence to ensure they do not experience excessive bulk damage when the system is operated at higher fluence. In addition, because NIF now regularly operates with programmable spatial shapers in place, records have to be kept and compensation shots may have to be taken for crystal optics that were on-line conditioned while the shadow of a shaper was in place to protect other optics that were in use in the beamlines as those crystals were on-line conditioned. During 2003 and 2004, an experiment designed to search for an optimum off-line conditioning protocol for tripler crystals identified that 3ω pulse lengths in the range from 200 to 900 ps were especially effective.¹⁵⁸

In 2004, work began on the design and construction of a sub-nanosecond laser (SNL) that could deliver >30 mJ per pulse at a repetition rate of >200 Hz, with a user-selectable, flat-in-time pulse width between 350 ps and 800 ps at 3ω . The SNL hardware delivered, with ~ 50 mJ per pulse, a repetition rate of 300 Hz and a user-selectable pulse width between 400 ps and 800 ps, was ready for pilot operation by the end of 2006 and a report of its performance was completed in 2007. (Ref. 159) In 2007 a protocol that included fluence steps at 1.5, 2.0, 2.5, 3.0, 3.5 J/cm² was developed and used for conditioning of 9 tripler crystal optics, preparing them for immediate use in NIF. For the past 6+ years, however, operation of the SNL laser has been on-hold. This

delay was first of all the result of a delay for its need. On-line conditioning of all of the crystals initially installed in NIF was accomplished as NIF was brought up, step-wise, to full-energy performance. A second contributor to this delay was the subsequent constraints associated with early operation of the NIF facility as it faced new challenges associated with shots on a nearly every-day basis. Now that NIF has become a regularly operating user facility, the need for off-line conditioning of tripler optics has once again come to the fore, and it is now being used in a production mode to condition triplers in preparation for their installation on NIF. From late 2013 to early 2014, twelve (12) tripler crystals for NIF were off-line conditioned using the SNL laser. The average power from the SNL laser as it is now operated is 15 W. The temporal pulse shape of this laser is shown in Fig. 99 (a), and Fig. 99 (b) illustrates the uniformity of the spatial footprint that can be applied to the surface of the crystal being conditioned.

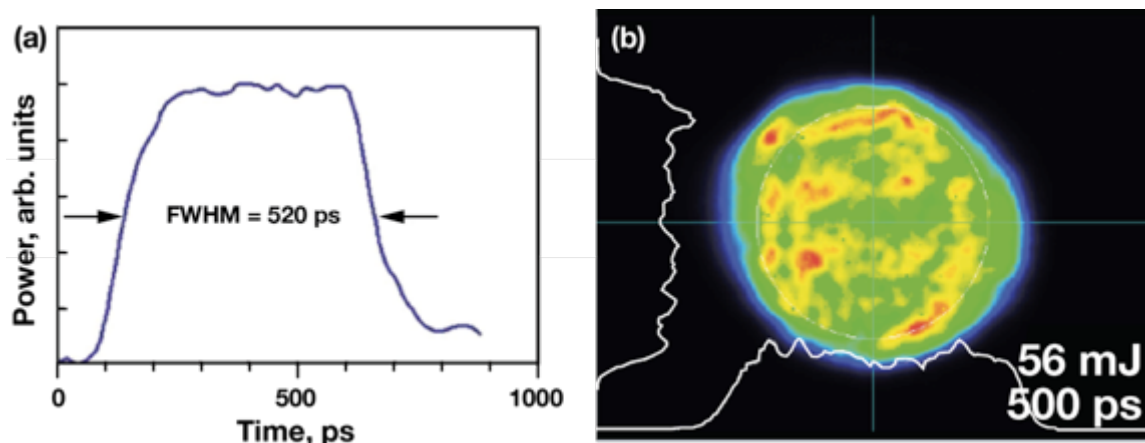


Fig. 99: Characteristics of the SNL laser now being regularly used to off-line condition triplers crystals for use in NIF (a) ~ 500 ps flat-in-time pulse length (b) an example of the spatial footprint that can be applied to the crystal surface. The contrast over the central portion of this footprint is calculated to be $\sim 11\%$.

The conditioning protocol for triplers uses five fluence steps, requiring a total of approximately one and a half million SNL pulses for conditioning of one tripler. Good conditioning uniformity thus also requires good pulse-to-pulse energy stability. In regular operation the SNL laser has a 1σ pulse-to-pulse stability of $\pm 5\%$. A photograph of the laser is included in Fig. 100.



Fig. 100: The SNL ~ 500 ps laser developed for off-line conditioning of tripler crystal optics for NIF, with its developer, John Honig.

VII.G. Frequency Conversion

Since well before Nova, two configurations for frequency conversion were being modeled at LLNL. One was designated as Type II/Type II; the other Type I/Type II. These two optical configurations are shown in Fig. 101. The choice for Nova was Type II/Type II because the models available at that time indicated that it could provide higher frequency conversion efficiency.^{160, 161} In practice, however, as Nova operated, it was found difficult to reach the predicted theoretical efficiency of $\sim 80\%$; the maximum efficiency demonstrated during Nova

operation was only $\sim 43\%$. After significant analysis directed toward understanding why the Nova performance was poor, the strongest hypothesis was that stress birefringence in the spatial filter lenses was depolarizing the 1ω light coming from the highly polarizing Brewster angle slabs. This amount, when combined with the polarization sensitivity of the Type I/Type II scheme was enough to account for the poor performance.¹⁶²

Work to improve the models for frequency conversion continued during the time of Nova operations and the Type I/Type II scheme became the initial choice for Beamlet.¹⁶³ After continued improvement was demonstrated by evolutionary changes made during several generations of the Type I/Type II hardware for Beamlet, this scheme became the choice for NIF. (Ref. 47)

The NIF frequency converter is a cascade Type I/Type II sum-frequency generation design (two 1ω photons form a 2ω photon in the doubler; a 1ω photon and a 2ω photon form a 3ω photon in the tripler). It consists of a 1.1-cm-thick Type-I KDP doubler and a 0.9-cm-thick Type-II deuterated-KDP tripler, optimized to achieve $>80\%$ peak power conversion efficiency to the third harmonic at a 1ω drive irradiance of 3 GW/cm^2 . (Ref. 136)

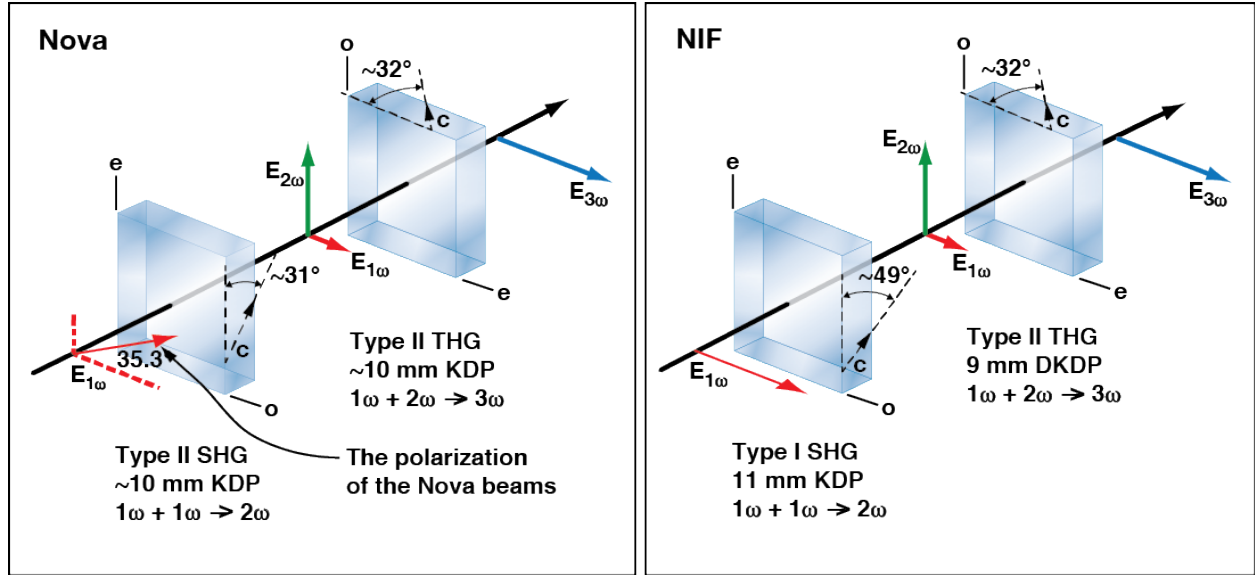


Fig. 101: Schematic of Type I/Type II and Nova Type II/Type II (Ref. 164) frequency converter configurations. The index of refraction along the extraordinary electric-field polarization (containing a component along the crystal c-axis) varies with crystal tilt angle around the ordinary field polarization (perpendicular to the crystal c-axis) and allows angular phase matching between wavelengths in the crystal. In a Type I doubler two photons having ordinary polarization with respect to the crystal will combine to form one photon with double the frequency and extraordinary polarization. In Type II conversion, two photons having orthogonal polarizations will combine to form one photon with the sum of the original frequencies and extraordinary polarization.

The NIF frequency converter represents an optimized design. The Type I/ Type II phase-matching scheme was chosen for reasons of material size availability as well as for its relative insensitivity to 1ω electric-field depolarization. This design balances optimizing conversion efficiency over the full dynamic range of the drive pulse from < 0.3 to $> 3 \text{ GW/cm}^2$ with $\sim 80\%$

peak power efficiency, while maintaining acceptable operational tolerances for angular errors, crystal thickness variations, and the spectral bandwidth of the delivered 1ω light.

Figure 102 illustrates the 3ω conversion efficiency for the NIF frequency converter described above as a function of internal-doubler-tuning angle for several 1ω intensity levels. Note that as the intensity goes up the sensitivity of conversion efficiency to tuning angle also goes up.

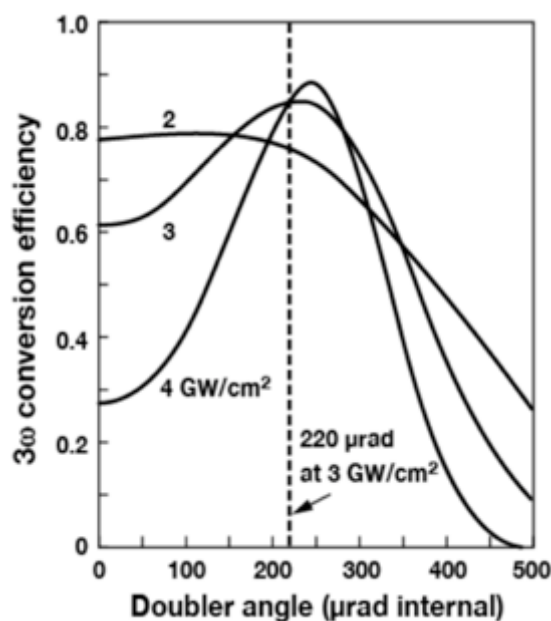


Fig. 102: 3ω conversion efficiency of the Type I/Type II frequency conversion scheme of NIF can be managed as a function of 1ω input intensity by angle-tuning of the doubler.

NIF operates today with a “mixed fleet” of converter crystals with different thicknesses. Concern for having crystals thick enough to allow for refurbishment led to decisions for cutting some of the crystals just beyond their optimal thickness. As NIF has operated, the need for crystal refinishing has not been as high as originally anticipated, and the mixed fleet continues. Thickness of doublers ranges from 11 mm to 14 mm while triplers may be 9 or 10 mm thick.

NIF's frequency conversion scheme has been very robust, able to respond to LPOM set-up instructions with little or no fine adjustment needed. Many target experiments call for a different "tune" for each converter assembly and the models and hardware continue to prove themselves daily.

VII.H. The environment of the FOA

An optically transmissive "vacuum barrier" for entry of each laser beam into the target chamber is required for separation of the atmospheric pressure of the target bay from the much lower pressure inside the chamber. NIF elected to put this barrier, a ~4.3-cm-thick plate of fused silica, in the 1ω section of the beampath for two reasons: the damage resistance at 1ω is many times higher than at 3ω and the non-linear index of refraction that can lead to filamentary damage in the output optics is 3 times smaller at 1ω than at 3ω . This choice of location for the barrier places all of the frequency-conversion and beam-conditioning hardware inside the IOM held by the fixed hardware on a target chamber port.

Early testing in Beamlet revealed that laser irradiation of crystals with sol-gel coatings in the hard vacuum of a simulated target chamber led to a new set of issues. Several types of surface degradation appeared, described variously as, "etch pits," surface roughening and loading of the coatings with vapor contaminants. (Ref. 89) ^{165, 166}, Search for the root causes of this degradation led to an understanding that these effects can all be mitigated if the crystals are held in an environment of clean dry air (CDA) at a pressure of at least 1 Torr. We now believe the etch pits were due to high humidity conditions during pump down and that the rapid organic contamination was due to rapid transport of organic compounds that occurs in vacuum. Maintaining such an environment around the crystals then incurred the need for a second barrier, one between the low-pressure CDA and the much harder vacuum of the target chamber. Because

this pressure standoff is much lower, the barrier can be thinner, thus reducing the path-length impact of its non-linear index of refraction.

The practical, optimized design solution selected for the IOMs is shown in Fig. 103(a). The pressure within the IOM is held at 10 Torr, safely above 1 Torr and safely in a regime that keeps the stress within the “window” between the target chamber and the IOM below the maximum allowable design stress for NIF optics of 500 psi. This “window” is the 1 cm thick grating debris shield (GDS). The GDS serves as a cleanliness barrier and a secondary vacuum barrier in addition to its optical responsibilities. The IOMs are purged to keep vapor contaminants from building up inside the IOM and to remove some of the particulates that might be mobilized by the incident or reflected laser light during a shot. The plumbing hardware required for implementation of the design in Fig. 103(a) is seen in Fig. 103(b). This plumbing system is located on the side of each FOA, very close to the target chamber. The blue color of the target chamber wall can be seen in the lower right corner of Fig. 103 (b).

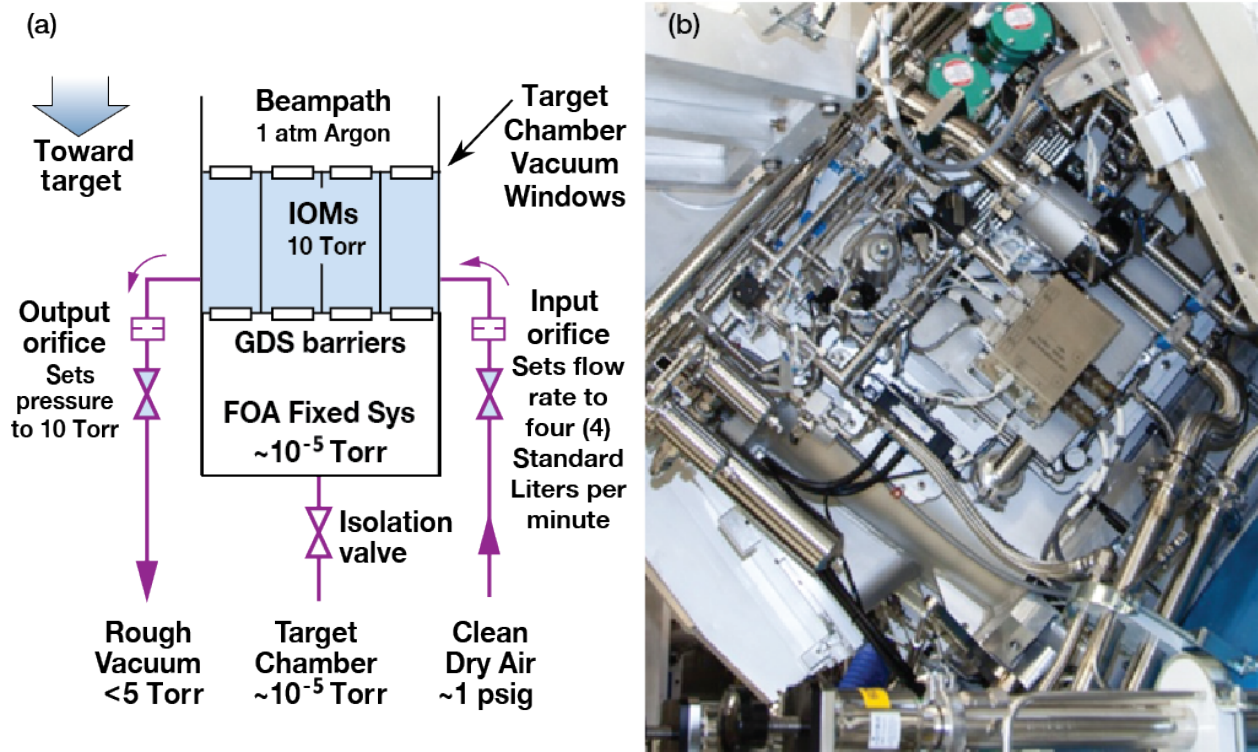


Fig. 103: (a) Pressure and gas characterization of regions around the FOAs (b) Plumbing for the utility distribution panel on the FOAs in NIF that provide the functionality described in (a). The two green Solon switches near the top of the photograph actuate a normally open, usually closed valve that maintains a safe pressure differential across the GDS barriers.¹⁶⁷

VII.I. Sol-gel coatings in the FOA

The sol-gel coatings for the 1 ω CPP, TCVW, and wedged focus lens are similar to those used on other dip-coated glass optics in NIF. They are post-treated with ammonium-hydroxide vapor to provide a “hardened” coating which is both “tougher” and less susceptible to airborne organic contaminants (Ref. 168). Because KDP crystals are hygroscopic, additional protection from water vapor that may be in their environment has to be provided. NOVA conversion crystals,¹⁶⁹ made of KDP for both doublers and triplers, received a two-layer coating comprised

of a thermally cured dense methylsilicone layer topped with the porous silica sol-gel. This coating strategy provided $<1\%$ reflection loss at both 1ω and 2ω for the SHG exit and THG input surfaces while also protecting all four surfaces against surface degradation by ambient humidity. For NIF, the use of deuterated KDP (which decomposes below the temperature required to cure the methylsilicone layer) and the higher 3ω fluence necessitated development of a modified (hexamethyldisilazane) HMDS-treated sol-gel coating (Ref. 89 and 90)^{170,171,172} to eliminate the need for the thermally cured methyl silicone on the THG surfaces. The HMDS-treated sol-gel provides a hydrophobic coating that is highly resistant to airborne organic contaminants and protects sol-coated KDP surfaces from degradation when exposed to ambient and low pressure environments up to $\sim 70\%$ relative humidity. The non-polar solvent used to spin-coat the HMDS-treated sol-gel also enabled the substitution of a UV-cured methylsilicone layer for the thermally cured methylsilicone in the two-layer compromise coating for the SHG exit and THG input surfaces. This same two-layer compromise coating is also utilized for both surfaces of the 2ω CPP (where both 1ω and 2ω are present) to achieve the desired anti-reflection properties at both wavelengths.

The HMDS-treated sol-gel is also spun-coat onto the input (non-diffractive) surface of the GDS. The exit (diffractive) surface is left uncoated to provide a stable diagnostic. If coated, surface tension of the sol-gel on the grating surface would produce a non-conformal coating that would effectively round the edges of the steps. This in turn would have three impacts: 1) reduce the diffraction efficiency (which can be compensated for by etching deeper grooves); 2) degrade the diffraction efficiency uniformity due to the existence of coating non-uniformities, and 3) reduce the stability of the diffraction efficiency due to the sensitivity of the effective refractive index of the sol-gel coating to humidity and airborne contaminants.

Results of the development effort for NIF coatings are given in Fig. 104. Active purging of the IOMs with 10 Torr dry air keeps coating contamination low and transmission high.

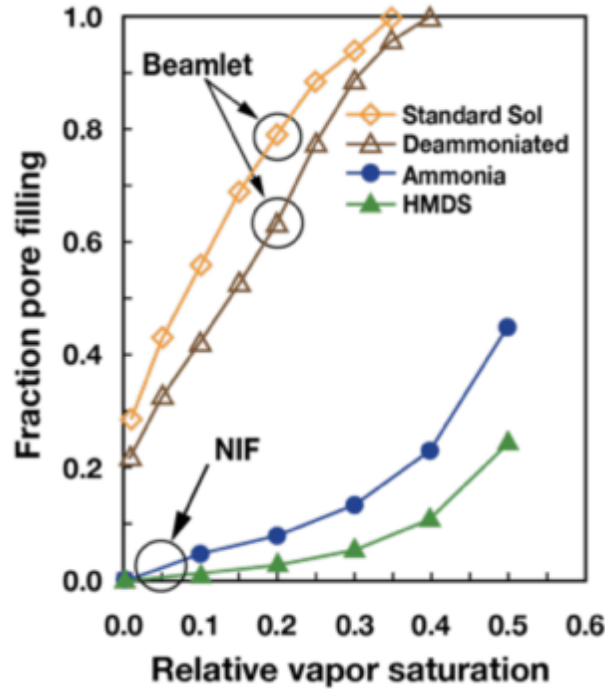


Fig. 104: Sol-gel coated FOA optics are preserved in a 10 Torr clean-dry-air environment to maintain their anti-reflection properties and high damage thresholds (Ref. 136).

VII.J. Focal Spot Smoothing by Spectral Dispersion (SSD)

Section V.A included identification of a location where modulation is imposed on the low-power beams created in the Master Oscillator Room (MOR). This modulation serves two purposes, one for protection of downstream optics from Stimulated Brillion Scattering that can occur when the intensity in these optics is distributed over a very narrow spectral line width. The second, of interest here, is for Smoothing by Spectral Dispersion (SSD), one element of the beam conditioning techniques NIF provides for the target, as very generally prescribed by the NIF Functional Requirements. In addition to the modulator in the MOR and a grating in the four-pass

preamplifier, other hardware that participates in meeting this requirement is located in each IOM as seen in Fig. 105.

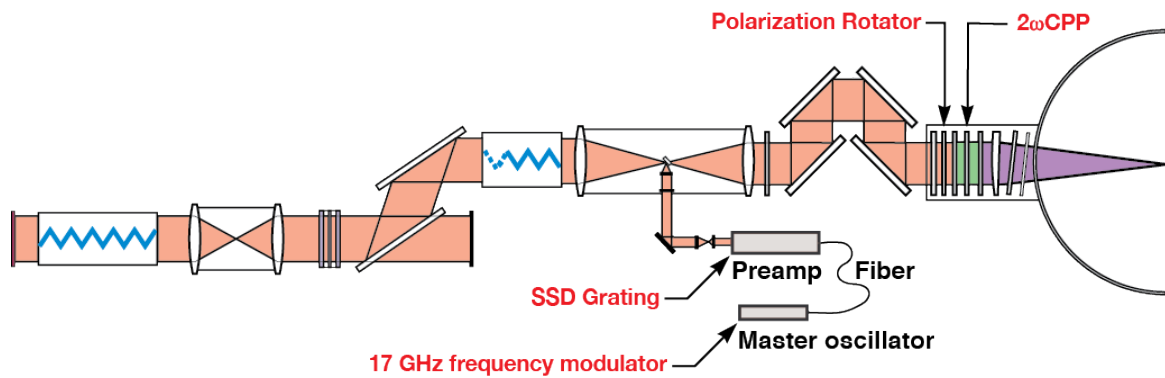


Fig. 105: Beam conditioning components (with functionality in red) for NIF are distributed along the beamlines; the modulators are in the Master Oscillator Room (MOR); a grating that adds angular dispersion as a function of the modulation resides in the four-pass section of the preamplifier; a continuous phase plate (CPP) and polarization rotator are housed in the final optics assembly, just before entrance into the target chamber.

Without a CPP present in a beam, as indicated in the upper right hand corner of Fig. 106, an individual focused NIF beam will produce a small, high contrast (100% modulated) intensity profile consisting of speckles whose size ($\sim 14 \mu\text{m}$) is set by the diffraction limit of the beam aperture, $\sim 37 \text{ cm}$. The probability density function for the intensity of these speckles is exponentially distributed. The dimensions of this profile are defined as the “focal-spot-size” of a NIF beam. If this high-intensity profile were directed toward a target it would drive unwanted laser-plasma interactions. The CPP is added to the beamline to increase the diameter of the spot on the target. The CPP and the SSD frequency modulation imposed on the beam (in the ILS) work together to reduce the time-averaged peak intensity of the light as the beams are focused at the target.^{173 174} Reducing the intensity brings it into line with long-held projections for the

highest intensity that would be acceptable at the Laser Entrance Hole (LEH) of between 3×10^{14} and 1×10^{15} W/cm² (Ref. 175). Lowering the time-averaged intensity reduces the likelihood of Laser Plasma Interactions (for example, backscatter, which can cause part of the laser light to be reflected rather than absorbed by the target).

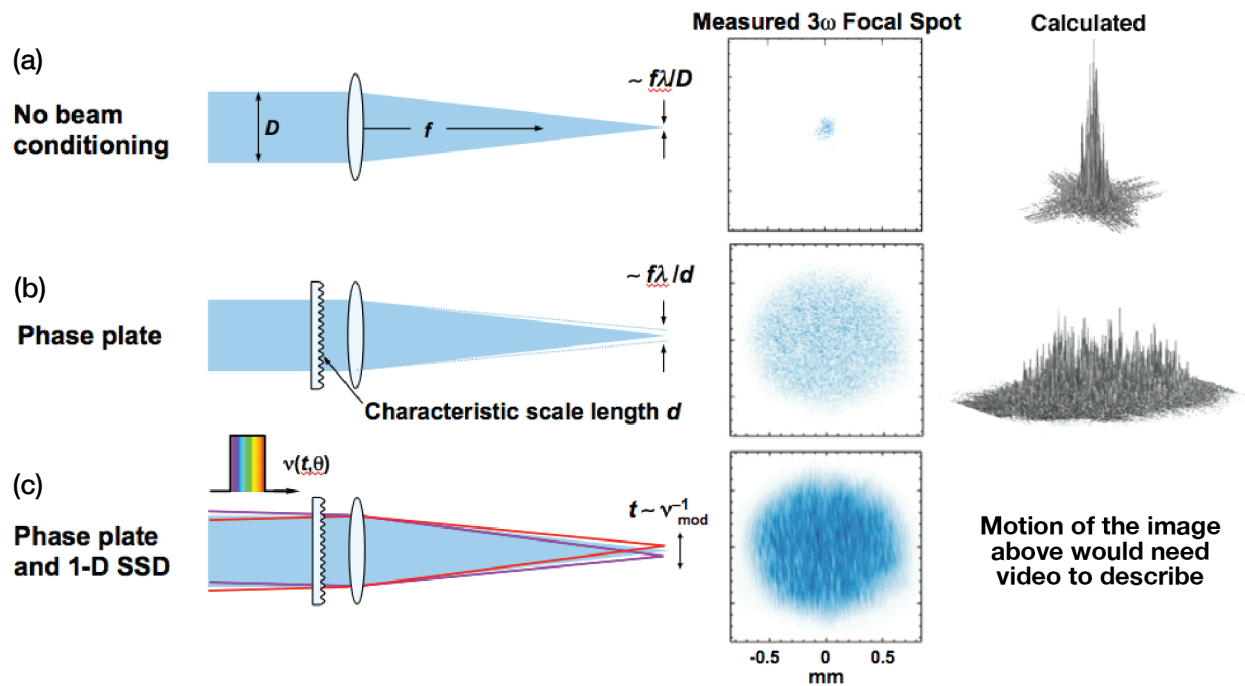


Fig. 106: Illustration of two concepts for beam conditioning: (a) Beam focus with no conditioning (b) The focused beam with a CPP and (c) The focused beam with a CPP and Smoothing by Spectral Dispersion (SSD) accomplished with a grating located in the preamplifier module and modulation applied in the MOR. Streaks in the measured 3ω focal spot are the result of the SSD modulation with the grating installed. It is noted here that the size of the unconditioned spot primarily affects the edge roll-off of the CPP-broadened spot.

A simplified explanation about how a CPP works as a continuous aggregation of small “lenses” is provided in Fig. 107. NIF users have had several sets of CPPs fabricated for NIF. The ones in bold in Table X are those that are installed in the FOAs as of February 2014.

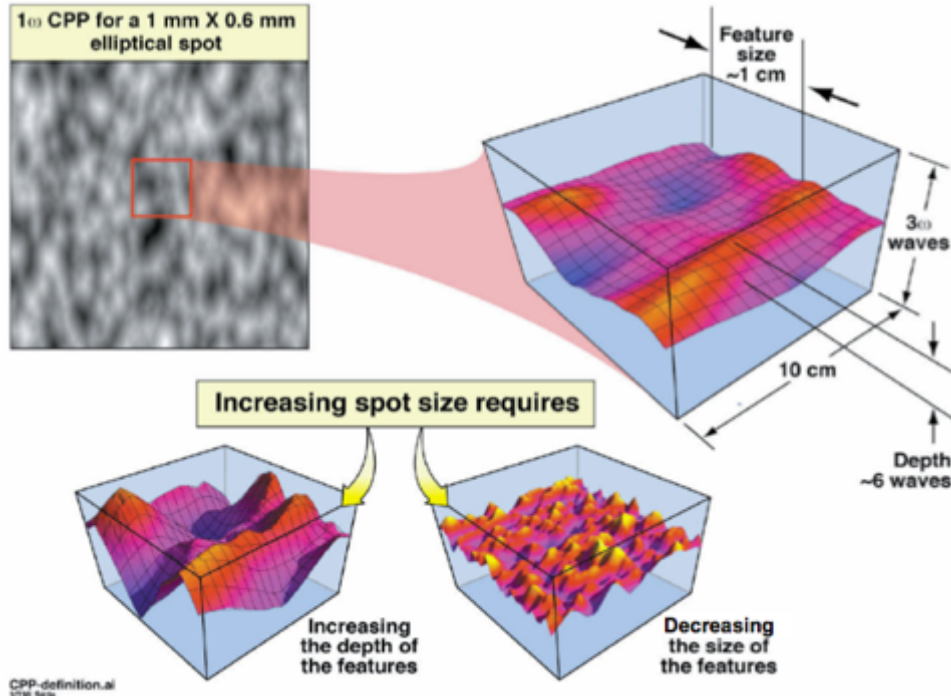


Fig. 107: A gray-scale description of the phase variation introduced into the optical-path-length profile of a CPP (top left). An exploded perspective view of how the phase of the transmitted beam is affected by the CPP (top right). A description of how a CPP can be modified to increase the spot size by increasing the average gradient of the phase of the beam (bottom).

TABLE X: Listing of the CPP sets that are available for use on NIF. The CPPs in bold are currently (2014) the ones in the system.

Location	Quantity	Major Diam (μm)	Minor Diam (μm)	Ellipticity
50 deg (Outer)	64	1186	686	0.58
44.5 deg (Outer)	64	1270	734	0.58
30 deg (Inner)	32	1648	1180	0.72
23.5 deg (Inner)	32	1764	1262	0.72
Storage	64	1394	806	0.58
Storage	32	1936	1386	0.72
For back-lighter quads	8	400	400	1.00

When a CPP is introduced into a NIF beamline it can affect the performance of the frequency converter. As the spot size introduced by a CPP is increased, the pseudo-random phase “error” introduced by the CPP impresses an increasing divergence onto the beam in order to match the size of the requested spot at the focus, 7.7 m away. Fig. 102 indicates that the conversion efficiency at 3ω will be reduced as the angular error at the doubler is increased. It also illustrates how sensitive this effect is to the intensity of the 1ω light. The 1.936 mm spot size given in Table X represents a maximum half-angle divergence of $\sim 120 \mu\text{rad}$. If light with this divergence were presented to the doubler, the conversion efficiency for that light would be significantly reduced. The effect of the CPP on conversion efficiency for experiments often being requested now (2014, with large spot size) is most pronounced when it is used in the 1ω CPP slot. To accommodate large spot size as well as several other requests received from different users, the FOA has been provided with several alternative positions for the CPP as shown in Fig. 108. For recent shots, the CPPs have almost always been placed in the 2ω slot.

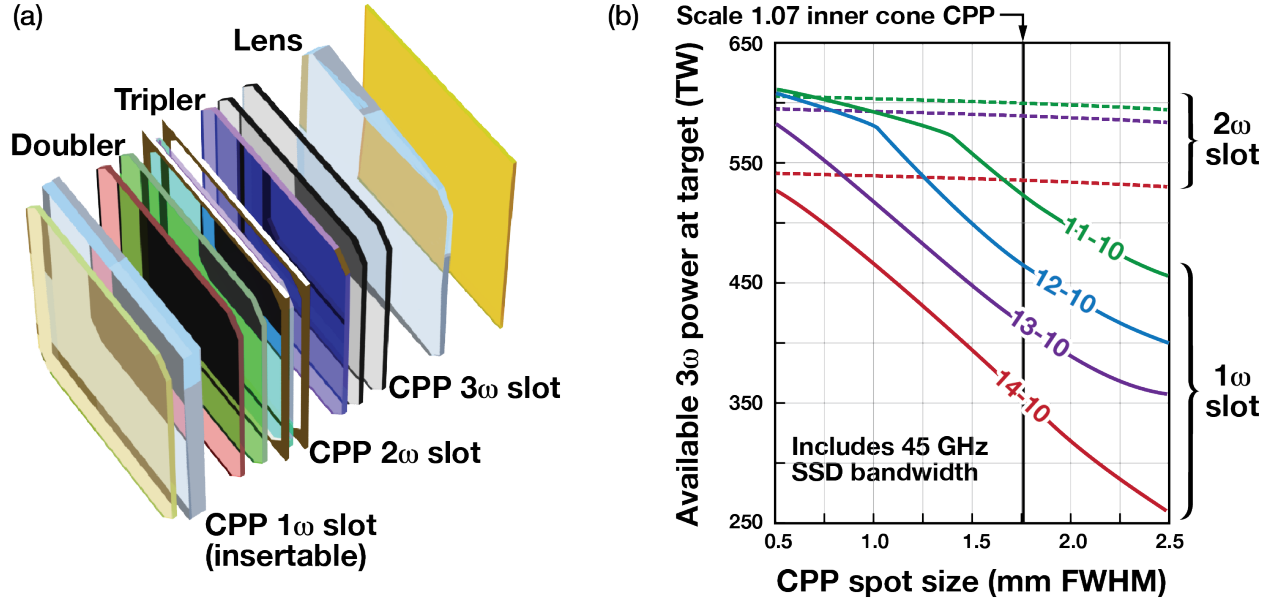


Fig. 108: (a) Available positions for a CPP in an as-built FOA (b) Impact on available power at 3ω as a function of the slot position, the combination of crystal thicknesses (doubler-tripler in mm) and the desired spot size at TCC.¹⁷⁶

In order to further reduce the effective instantaneous intensity on the target plasma by a factor of the square root of two, while keeping the delivered energy high, each quad on NIF delivers two of its 3ω beams with one polarization and the other two with polarization rotated by 90 degrees from the other two. Half-wave plates that rotate the polarization are in two of the four FOA apertures for every quad. Placing the rotator-polarization plates in the 1ω rather than in the 3ω section means that, for those beams, the doubler and tripler crystals also have to be rotated by 90 degrees. Although the polarization rotators could be put into the 3ω location, the 1ω location is preferable because at 1ω , the wave plates have Stimulated Raman Scattering and Stimulated Brillouin Scattering gain coefficients that are lower by two thirds, and when located in the 1ω section, the rotator crystals are also less prone to optical damage.

In addition to the beam conditioning provided by a single beam, as defined by the *Laser Design Basis for the National Ignition Facility* (Ref. 1), an early requested feature of the NIF beam smoothing strategy is inherent in the quad and cone-based architecture of the laser. The four beams in a quad are focused on the target with an $f/8$ “quad f-number.” Typically, the foci of the four beams (with two different polarizations) are overlapped on the target. In this region, where the total number of speckles is conserved, there are four times the number of speckles of an individual beam, the speckle “diameter” is reduced by a factor of two and the speckle length is reduced by slightly more than a factor of four. When the foci of multiple quads in a cone also overlap in a target plasma, the scale size of the intensity patterns of the lasers on the target is further reduced. To a very high degree, NIF beams are internally coherent and coherent with each other. Their overlapping behavior is largely determined by this coherence. The interactions of these conditioned coherent beams with the plasma facilitates energy transport and smoothed energy deposition on target surfaces.

VII.K. FOA Support of the Optics Recycle Loop

A number of features of the FOA design are in direct support of the Optics Recycle Loop discussed in much more detail in the “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” article also in this issue of *FS&T*. These features include:

- Edge lighting of the optics
- Fiducialization and registration of optics
- Rapid exchange of FOA optics LRUs

The first two (described here) work in concert with the in-situ final optics damage inspection system; the third is discussed in Section VII.N.

With high resolution, the FODI camera records a dark-field image of light scattered by damage sites on an FOA optic. In order for the FODI software to calculate the location of the site and to identify the optic on which it is located, sufficiently uniform illumination must be provided individually to fiducialized optics. Figure 109 (a) provides a photograph of an edge-lit fiducialized optic. Figure 7.11-2 includes a photograph of one corner of an FOA LRU with identification of the diffuser bar that provides the edge-lit illumination.

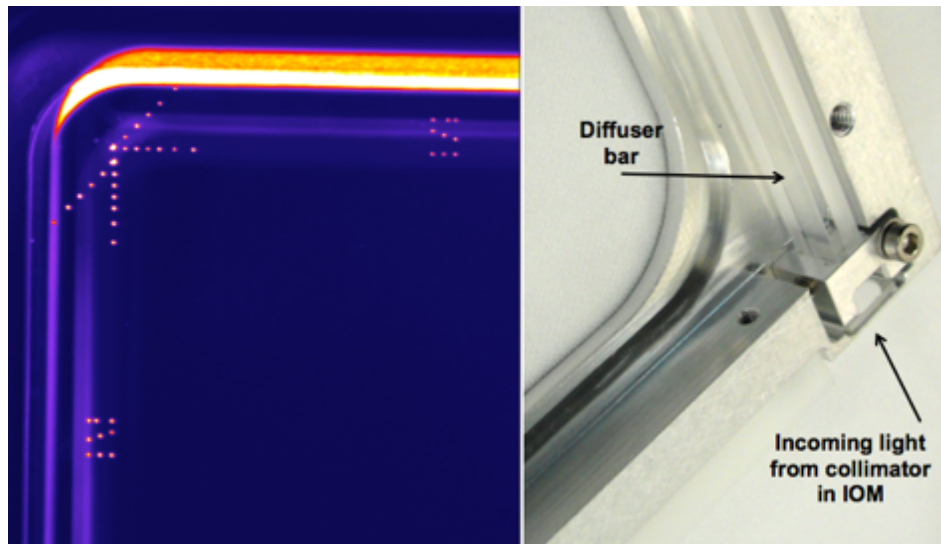


Fig. 109: (a) CO₂ laser inscribed fiducialization spots on an FOA optic, located outside of the clear aperture of the laser beam, but within the viewing field of the FODI camera (b) Corner of an FOA LRU allowing the diffuser bar for edge illumination to be seen.

With edge illumination, the light injected at the proper angle into the edge of the optic is confined by total internal reflection between the two faces of the optic. A defect on the surface of the optic disrupts the total internal reflection and causes light to be scattered from that location. A percentage of this scattered light is collected and imaged by FODI. In the FODI image of the optic, any defect will appear as a bright spot against a dark background. The light used to

illuminate the optics is provided by a single 800-nm light source, coupled to a fiber network through a 1:N fiber-optic switch. As different IOMs are inspected by FODI, the computer-controlled switch selects the fiber for illuminating the optics within the corresponding IOM.

VII.L. Drive Diagnostics (DrD)

In addition to their role as a backup debris shield, the grating debris shields, (GDSs) have one side that is etched with a low-efficiency ($\sim 0.1\%$ to 0.3%), shallow (~ 15 nm) transmission grating that diffractively samples the 3ω pulse exiting the Final Optics. It feeds this sample to the Drive Diagnostics package shown in Fig. 110. The GDS diffraction efficiency is measured off-line and each 3ω calorimeter is calibrated off-line at its use angle. With these calibrations, reliable measurements of the 3ω input to the target can be made even when the disposable debris shields are coated with a moderate amount of material.

Each DrD employs a modular, extensible LRU-based design (see Fig. 111):

- Every NIF beam has a vacuum-side package with a calorimeter for energy measurement of each incident 3ω pulse.
- As currently configured, 57 of the beams, including at least one in every quad, also have optics for reflecting $\sim 8\%$ of the light going toward the calorimeter and rerouting of this light to the DrD air-side-optics package.

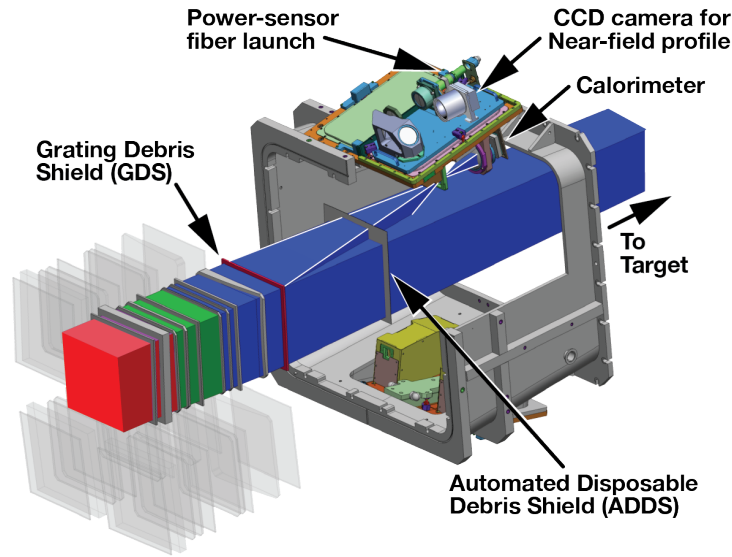


Fig. 110: The optics and beams in one IOM are highlighted while optics of the other three IOMs are ghosted in. A small fraction of the 3ω light going toward the target is diffracted into the diagnostic aperture of the Drive Diagnostic package (referred to as the DrD).

The relationship between the vacuum-side and air-side packages of the DrD is illustrated in Fig. 111. A beam sample provided by the GDS as it is directed toward the calorimeter on the vacuum side is seen in Fig. 111 (a). Additional vacuum-side components that can redirect $\sim 8\%$ of the incoming GDS light to the air-side package are also seen. An air-side package, such as that shown in the drawing of Fig. 111 (a), has two functions. One is to send an optical signal out of the target bay to a more sheltered environment for recording of the 3ω power trace. The power-sensor fiber launch in the air-side package collects and homogenizes the collected light to provide a valid signal for the power measurement. Special doped-silica optical fiber that resists neutron darkening¹⁷⁷ carries the 3ω pulse samples out of the target room and beyond the shield walls to instrumentation racks where 60-ps-response-time diodes, transient digitizers and computer interfaces are located. The optical signals from many air-side units are multiplexed on

a single digitizer with multiple channels at different gains. With the aid of computers, the signals from different channels are stitched together to improve the dynamic range and thus the accuracy of the power measurement. Fig. 111 (b) is a photograph of a typical air-side assembly holding only a fiber launch unit.

As seen in Fig. 111 (a), the air-side can also support use of an optional near-field camera. There are currently four DrDs instrumented for monitoring 3ω near-fields at the equivalent of the front surface of the wedged focus lens. These four units are portable and can be moved to any desired beamline. Together, the vacuum- and air-side packages provide measurements of incident pulse energy for every beam, a temporal pulse shape for at least one beam in every quad and (as of 2014) four near-field 3ω beam profiles for every NIF target experiment.

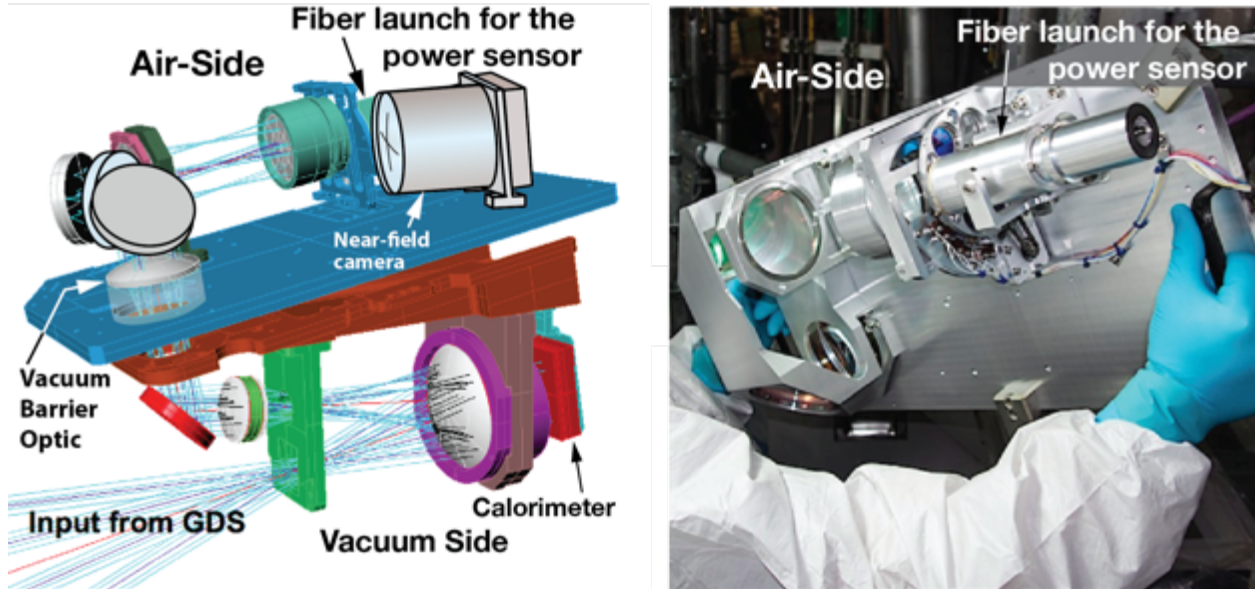


Fig. 111: (a) The vacuum side of the Drive Diagnostic includes a calorimeter for measuring the energy of each 3ω beam. The air-side assembly contains optics for the fiber launch that feeds the fiber leading to the power sensors. The air-side can also accept an optional near-field camera. (b)

Photograph of the air-side of a DrD with its Fiber Launch assembly. This unit is shown being removed from a NIF beamline to be retrofitted with a camera for collection of near-field 3ω images.

VII.L.1. Drive Diagnostics are also Target Diagnostics

The DrD power sensors also provide service as a target diagnostic. Laser heated plasmas can backscatter incident laser light by means of Stimulated Brillouin Scattering (SBS). Since SBS scattered light is typically shifted by only a few Angstroms, its wavelength lies within the detection bandwidth of the DrD. Spectral discrimination against 1ω or 2ω is performed with a 1mm thick UG11 filter, AR coated for 351, in front of the 3ω -power-sensor vacuum photodiode. Measured average transmission of the filters is: 4% at 1ω , 0% at 2ω , and 90% at 3ω .

Light reflected from the target returns to the final optics about 50 ns after the incident pulse has passed. About 4% of this light is then reflected by the doubler crystal and sent back toward the target where, just as for the original outgoing signal, it is sampled by the GDS grating, arriving at the Power Sensor approximately 54 ns after the initial pulse.¹⁷⁸

Calibration of these SBS back-reflected signals relies on comparing the DrD reflected light signals collected for two NIF quads, Q31B and Q36B, with measurement of the same source of back-reflected light by the independently calibrated, room-sized FABS detector systems for these two quads. The FABS data supplements the off-line calibration of these sensors and confirms that the DrD captures a valid time resolved sample of most of the light scattered back into the 57 NIF beamlines that have power sensor pick-offs. As a result, the DrD system collects valuable data on target absorption and the angular distribution of SBS from targets. An example of a back-reflected signal captured by one of the DrD power sensors on shot

N120925-003 is given in Fig. 112 where the back-reflected pulse is superimposed on the truncated signal of the initial outgoing pulse that appeared ~54 ns earlier.

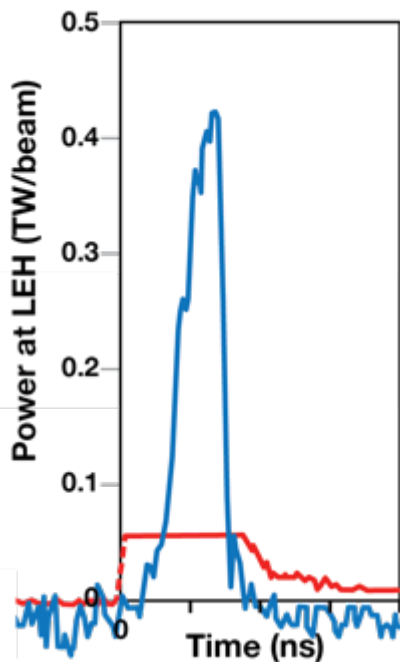


Fig. 112: The blue line is for the signal of a back-reflected beam received ~54 ns after receipt of the (red) off-set truncated signal from the main outgoing pulse.

VII.M. Automated Disposable Debris Shield (ADDS) System

The Automated Disposable Debris Shield (ADDS) system has proven to be the primary means of protecting the FOA optics and their environment from debris generated by targets.

Photographs of the ADDS and its ten-shield cassette are given in Fig. 113.

The disposable debris shields (DDS) protect the FOA optics from debris generated by the target or ancillary equipment near TCC that is “vaporized” during a shot. The DDS spools are located between the IOMs and the target chamber. The DDS spool and ADDS units are part of the FOA. In keeping with the shape that can be seen on the right-hand photo of Fig. 113, a DDS spool is sometimes referred to as a “doghouse.” In the left-hand photo of Fig. 113, disposable

debris shield cassettes are being inserted into a feed mechanism that sits just outside of the DDS spools. Each DDS housing accepts two DDS cassettes per beamline, each of which holds five automatically insertable debris shields.

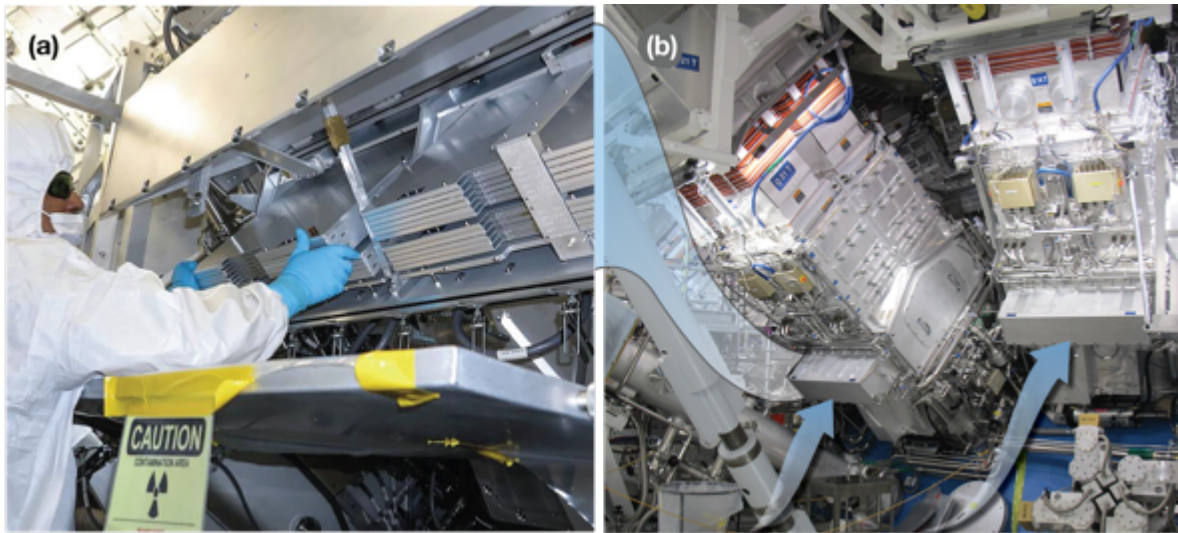


Fig. 113: Photographs of the ADDS (a) A five-shield cassette being loaded into the ADDS holder (b) Arrows point to ADDS holders on the debris shield spools at a location just before light enters the target chamber.

Debris shields are typically used for at least two or three high-energy shots, but can be used more often if their transmission allows. Prior to every shot, a model in LPOM calculates the expected transmission of each DDS based on the shot history of that DDS. The LPOM model used to provide guidance on when a DDS should be replaced was developed and calibrated by earlier measurements made in NIF. In those measurements, the transmission of a DDS was measured by comparing the intensity of the cw alignment beam, as recorded by the target alignment sensor (TAS), with the DDS slot empty and with a DDS in place. According to Schott, the supplier of the DDSs, the mean transmission of pristine DDSs is 98.5%. Figure 114 presents

a comparison of measured DDS transmission with projections of LPOM. A disposable debris shield is replaced when its transmission falls below 94.5%, a 4% loss from its pristine state. The model continues to be checked with repeats of the procedure described above.

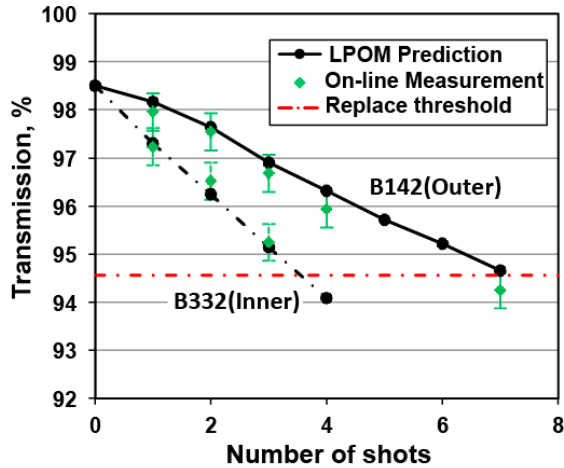


Fig. 114: Comparison between LPOM predicted DDS transmission and on-line measurements.

VII.N. Prototyping of the IOM Design

The average 3ω fluence (energy per unit area) operating point demanded for the NIF FOAs is more than an order-of-magnitude higher than the operating point for Nova—greater than 9 J/cm^2 for NIF compared to $\sim 0.8 \text{ J/cm}^2$ for Nova. Previous to NIF, ICF lasers at LLNL—and around the world—generally failed to perform routinely at their design points even though their design points involved fluence levels considerably below those for NIF. Attention given to delivering the large increase in fluence performance that was demanded from NIF led to completion of a comprehensive risk-reduction and design-verification program for the IOMs that started with NIF Early Light (NEL) in 2003. Figure 115 (a) is a photograph of the first operating prototype FOA on the NIF target chamber. At that same time, another prototype IOM, virtually identical to those on the target chamber was also being tested in the Precision Diagnostic System

(PDS). A schematic view of the 560 m² PDS laboratory is given in Fig. 115 (b) (Ref. 48). The transport optics used to move a beam from Quad 31B to PDS were also very similar in wavefront quality and damage resistance to those now used in the Switchyard and Target Bay. A broad suite of performance diagnostics was available on PDS, including the ability to measure beam characteristics at a plane equivalent to that at target chamber center.

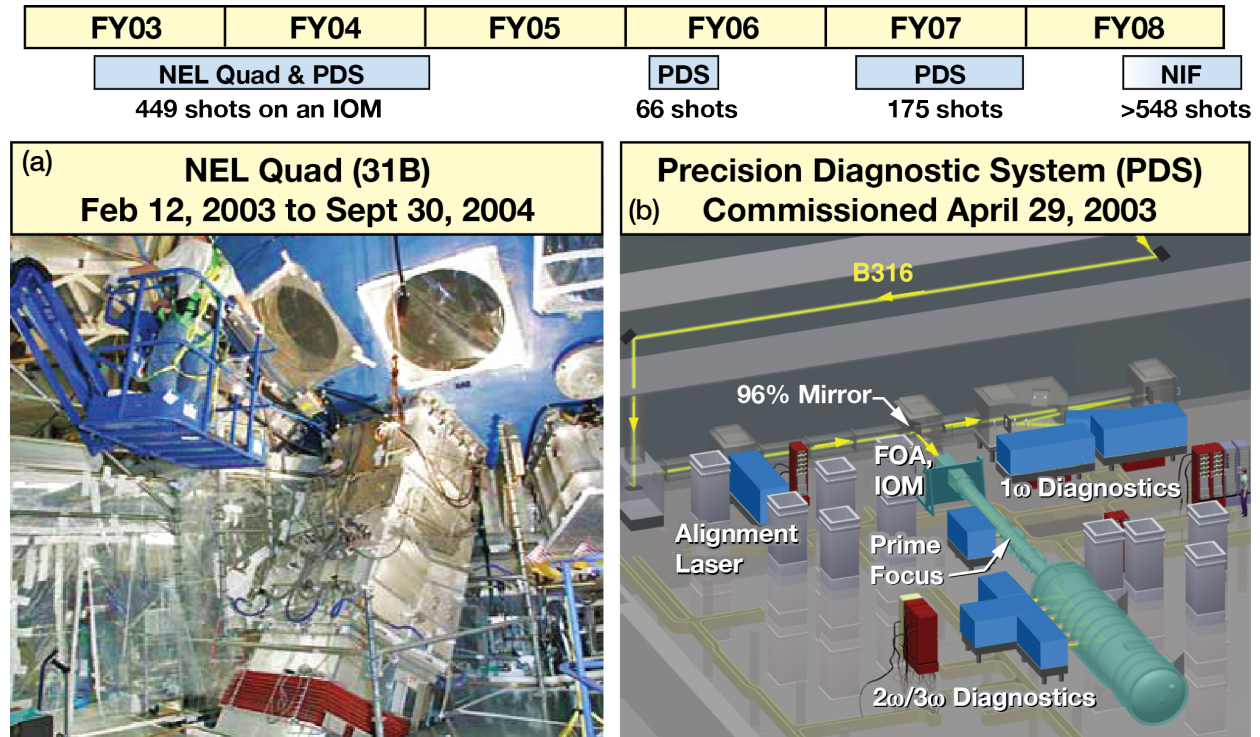


Fig. 115: (a) NIF Early Light FOA housing four IOMs (b) The Precision Diagnostic System (PDS). (Ref. 72)

Very significant changes were made to the laser, and particularly to the design of the IOM opto-mechanical design, in response to the results of these early tests in NEL and PDS.¹⁷⁹

- It was found that an accumulation of small flaws in the ILS was leading to intensification at locations in the laser spatial profiles far downstream in the IOMs resulting in damage to

the crystals. In response, to limit the range of spatial frequencies that could enter the MLS and then the IOMs, the TSF pass 1 pinholes were changed from 200 to 100 μrad

- Better understanding was gained of the impact of 3ω damage initiation and growth on IOM operability. This understanding led to changes in both the design of the IOMs and to more support being given to facilities that are described in the “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” article, also in this issue of *FS&T*. The effort to reduce the number of optics in the IOM to the absolute minimum led to combining the previous Main Debris Shield and the Sampling Grating optics into the one optic now used and called the Grating Debris Shield (GDS)
- Initiations that were found on the focus lens and main debris shield at intensified locations associated with upstream coating flaws or other phase objects (lenslets, sleaks) led to an overhaul of our understanding about how intensification leading to optical damage (also called fratricide) can occur in the 3ω section of the NIF laser. Over half of the large growing sites on the WFL were found to be associated with upstream flaws. A new criterion for designing the locations of optics in the IOM was based on recognition that nonlinear imaging was the cause for initiation and growth of these sites. Our propagation code was significantly upgraded for analyzing the combined impact of multiple wavelengths existing simultaneously within the frequency conversion and fused-silica optics. In addition, new criteria were added for restricting the number, size and location of small phase objects in nearby upstream optics, the target chamber vacuum window and the 1ω CPP. These new criteria made it necessary to change the quality of the fused silica used in these optics from Corning 7980 to inclusion-free fused silica purchased from both Schott and Hereaus. New procedures were also added for inspection and resolution of

coating flaws found on nearby upstream optics. These procedures are discussed in the “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” article, also in this issue of *FS&T*

- An on-axis plasma spark caused by focus of a primary ghost from the backside of the focusing lens (used at that time) led to damage of IOM optics for pulse durations longer than about 7 ns. In response, the on-axis lens design was changed to the off-axis design with a plano output surface described in Section VII.E.3
- It was found that contamination and/or damage to optics was caused by reflected or stray light incident on metal surfaces that had not been adequately hidden or armored. Avoiding this issue was accomplished by redesigning the optical configuration to remove large plate tilts and to simplify optical armoring. (Optical armoring uses low-cost architectural glass to protect non-optical surfaces from ghost reflections and other scattered light.) These observations drove development of new much faster and more powerful ghost analysis tools used for redesigning the opto-mechanical design of the IOMs and their frame armor
- Severe damage was found on the GDS in a pattern that followed its grating profile for shots that involved long shaped pulses with energies above ~1.3 MJ. This damage is believed to be caused by Stimulated Brillouin Scattering (SBS) within the GDS along a zig-zag path that involves total internal reflection at the two faces of the GDS. A practical work-around solution for suppressing this type of damage was implemented quickly and effectively by using the available 17 GHz SSD modulator to add 45 GHz bandwidth to every beam. The laser is now protected from failure of the 17 GHz modulator in the MOR by the addition of Fail-Safe circuitry similar in function to that for the 3 GHz modulator described in Section V.A.

- A backward reflected grating order from the GDS focused laser light on the side wall of the argon beam tube about a meter in front of the TCVW. Identification of the source of light for this wall damage created a need for installation of new beam dumps. This installation required great care as 192 ~10” holes were drilled in the already-clean beampath wall. Two of the top-hat-shaped “cans” for holding these beam dumps can be seen just above the red retractable beam tubes of Q45B (that look like bellows) and to the left of the hard hat on the kneeling worker in Fig. 89. The top-hat shaped “cans” can also be seen in one of the figures in Section VII.O.

In addition to these changes that were made in order to meet the original NIF requirements, a number of changes were implemented for meeting new needs identified as target designs had matured over the years since 1994.

- Requests were received for spot sizes on target that were larger than had previously been made. These requests required a CPP with an angular bandwidth that exceeded the angular bandwidth of the Type-I doubler. This need was met by providing a new slot for a CPP between the two harmonic generator crystals. A CPP in this slot is referred to as a 2ω CPP
- The first polarization-smoothing scheme requested was found to be severely limited by transverse stimulated Raman scattering in the 3ω polarization scrambler crystal (PS). This limit was avoided by changing to a quad-based checkerboard polarization pattern¹⁸⁰ utilizing Polarization Rotator crystals (PR) in the 1ω section of the FOA. More detail on the limits of polarization-scrambler crystals is discussed in the “Damage Mechanisms Avoided or Managed for NIF Large Optics”, also in this issue of *FS&T*. This change also

involved devising an alternate alignment scheme for the converter crystals in the beams with the PR crystals

- A new request was received for wavelength-tunable operation of some cones with center wavelengths shifted by several angstroms from that of other cones. Two-color and later three-color configurations were requested. The response to this request meant that the flexibility of the frequency conversion crystal alignment scheme had to be expanded. Separate tip/tilt carriages for the doubling and tripling crystals are now provided

After observation of fratricide in the 3ω section of the IOMs, (damage on the focusing lens and the main debris shield at locations directly downstream from flaws that were found on upstream optics), analysis of pseudoscopic intensification in the 3ω section of the NIF laser was immediately given high priority. A not-previously reported mechanism was identified; this mechanism is referred to here as “sum-frequency generation”. With this new insight, the NIF laser propagation model was used to guide changing the placement of the optics within the IOM to minimize their vulnerability to non-linear intensification created by the type of flaws most likely to be found in the fully operational system. These flaws include digs and coating defects, fused-silica bulk inclusions, mitigation sites and fabrication flaws on the 1ω CPP.

Modulation from three different types of mechanisms were found to lead to downstream intensification in the 3ω section:

- Linear diffraction
- Sum Frequency Generation, $X^{(2)}$
- Optical Kerr Effect, $X^{(3)}$

An outline of this analysis and the placement of optics in the IOM before and after this analysis was completed is given in Fig. 116. Pseudoscopic images located at the colored crosses are typically 3 to 5 times more intense than the average. These relocations and the redesigned capability for individual exchange of optical components within the IOM are also shown in Fig. 117. The stiff high-precision mechanism for holding the optical components that was available in the original IOM design was replaced with individual light-weight, but still stiff, alumina bezel mounts used in the redesigned configuration. With the new configuration, optics that are identified by the Final Optics Damage Inspection (FODI) system as having excessive damage can be individually removed and sent to an off-line mitigation facility. (See “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” also in this issue of *FS&T*) Being able to exchange FOA optics individually is a key feature for successful operation of the Optics Recycle Loop.

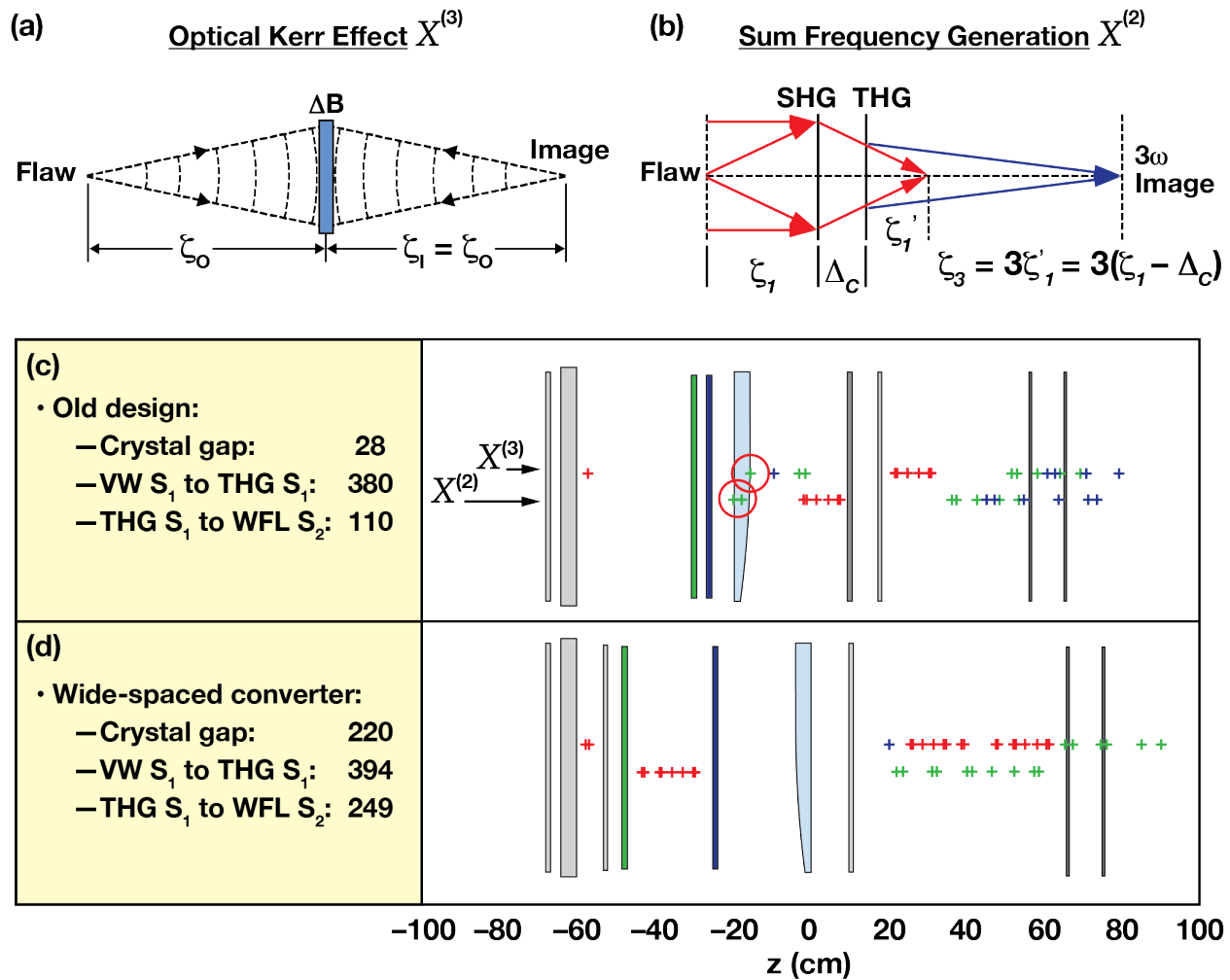


Fig. 116: (a) Basic geometry for the analysis of pseudoscopic imaging. (b) Geometry of the analysis for combined pseudoscopic imaging and sum-frequency generation. (c) Configuration of the optical components in the IOMs before the prototyping experiments in 2003–04. (d) Reconfigured locations of the optics now used in the NIF IOMs.

More discussion of pseudoscopic imaging in the NIF laser is discussed in the “Damage Mechanisms Avoided or Managed for NIF Large Optics”, also in this issue of *FS&T*.

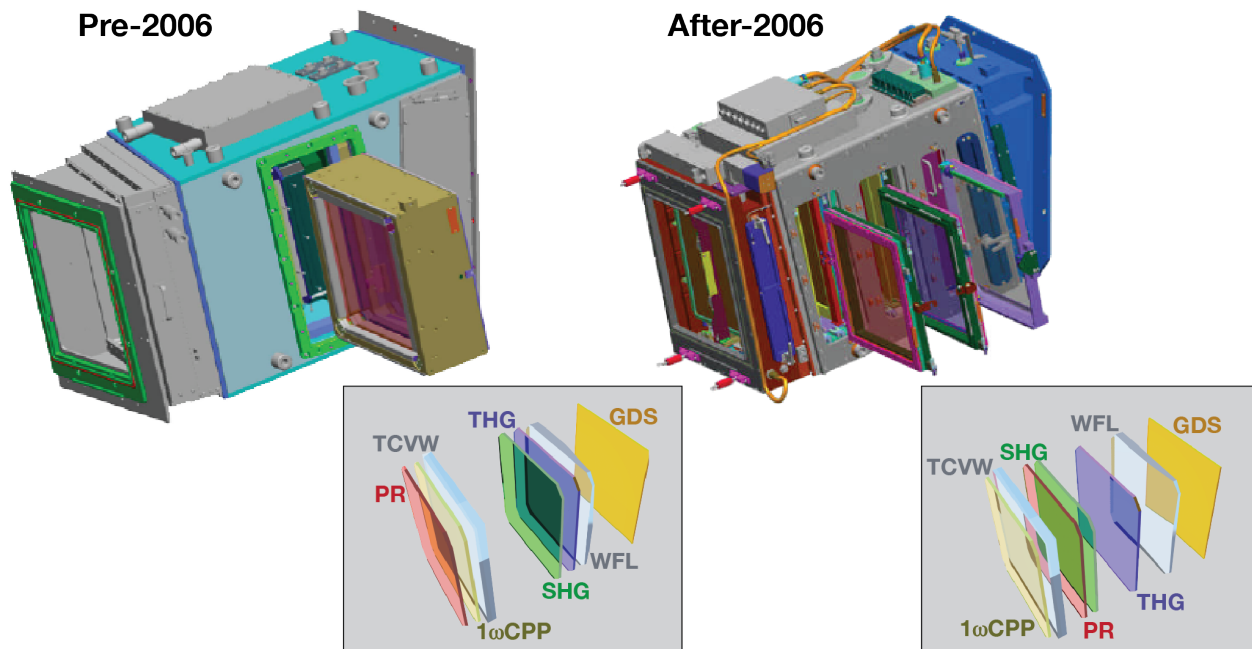


Fig. 117: Comparison of the pre-2006 IOM and the redesigned IOM hardware.

VII.O. Rapid exchange of FOA optic LRUs

“Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold”, one of the other articles in this special issue of *FS&T*, covers the topic of operating the NIF laser well above the threshold for growth of initiated sites on the exit surface of fused-silica optics, a regime where no other laser has ever attempted to operate. Section VII.K discusses two of the features of an FOA important for supporting the Recycle Loop; the third is discussed here.

The ability to rapidly exchange a damaged FOA optic with its near-perfect replacement is a necessary capability for efficient use of NIF facility time. Optical LRUs within the FOA can be exchanged through removable hatches located on the sides of the IOMs. These LRUs slide into and out of position on custom rails designed to minimize the number of particles generated by slides and wheels. Each optic can be replaced individually by opening their appropriate o-ring

sealed cover and retracting it into an attached clean box, called a Loop Case. A reverse sequence is used to install the replacement optic. A Loop Case being attached to an IOM is seen in Fig. 118.



Fig. 118 Close-up view of an FOA optic exchange

A photograph of two optic exchanges underway at the same time is given in Fig. 119, one each for IOMs in Q31T on opposite sides of the same FOA. With the platforms seen in Fig. 119 personnel have safe, convenient access to the IOMs, keeping the time required for LRU exchange to a minimum.

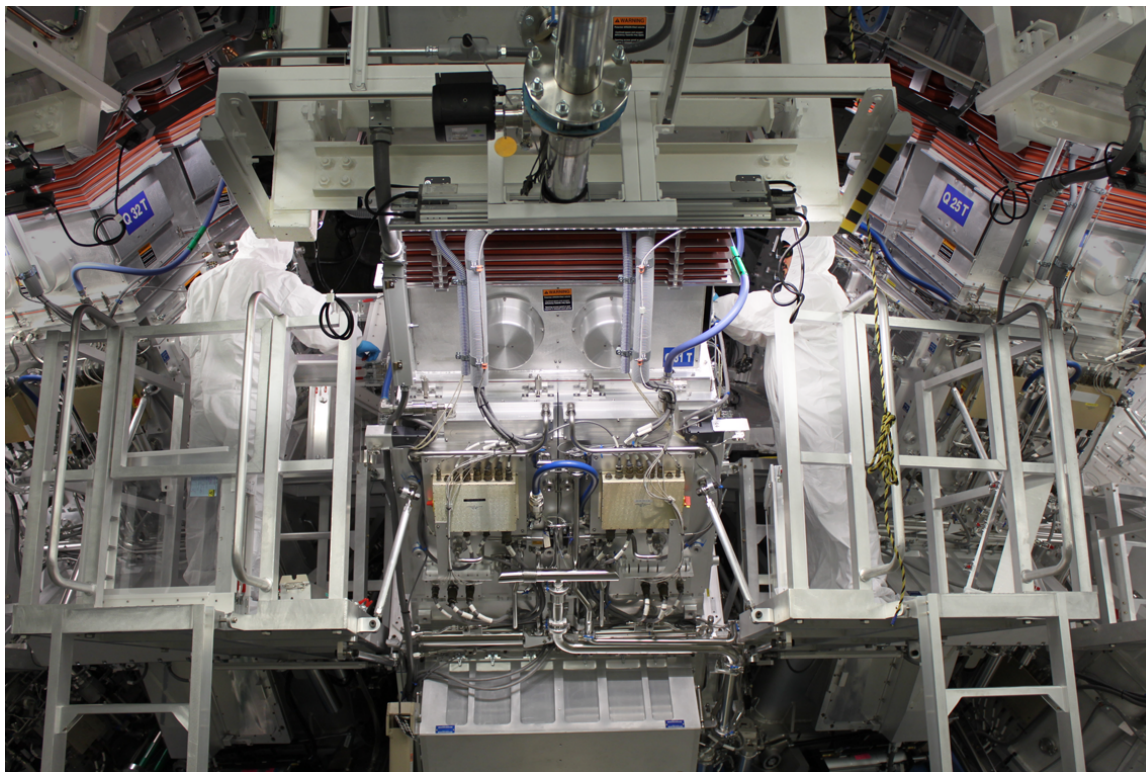


Fig. 119: In this photograph, two NIF operators can be seen as they are exchanging optic LRUs on opposite sides of Q31T. Platforms built next to the FOAs make access to the LRUs safe and time efficient. The mid-plane of the target chamber is below the bottom of this picture. Two “top hat” beam dumps installed to “catch” the focus of unexpected grating order ghosts from two of the GDSs can also be seen just below the red retractable beam tube (bellows) of Q31T.

VII.P. Hardware Modifications After Installation of IOMs

During early operation of the IOMs in NIF, two previously unidentified ghost reflections were found to cause damage to components in the beamline. The first one hit the bezel mounting structure of the WFLs. Mitigation was accomplished by removing a portion of the bezel material and replacing it with a piece of absorbing glass similar to that already used throughout the IOMs for absorption of scattered light and previously identified ghosts.

The second ghost caused long lines of damage on the LM8s. Investigation revealed it was a ghost from a DDS, crossing from one beamline to hit the LM8 of an adjacent beamline. This ghost had an intensity much higher than expected due to highly warped surface figures (missed by the QA process) on the first batch of 1 mm DDSs. After the out-of-spec DDSs were replaced, damage was still found in the same general area of the LM8s but with a different morphology. Identification of the ghost that caused this damage required detective work that had begun with observation of the on-axis plasma (argon) spark during experiments completed in FY03 and FY04. That spark was caused by focus of a primary ghost (actually a family of ghosts) described in one of the bulleted paragraphs in Section VII.N. The family found in FY03/FY04 was mitigated with introduction of the wedged focus lens as part of the IOM redesign of FY06. With the wedged lens, the foci of this family were then directed into a region of the argon in between the two side-by-side beamlines of a quad, where they were expected to be harmless. The first indication that they were not harmless was observed when a second type of damage morphology was found on LM8 mirrors. The explanation became that the primary cause of the argon spark was 1ω reflections that had passed through the lens, reflected either by the backside of the lens or by the GDS; and that the primary cause of the damage was light from 3ω members of this family that was focused near but not at, the 1ω spark and subsequently refracted by the negative lens of the electron-density perturbation surrounding the spark by just enough to move the 3ω focus to near the surface of the LM8. Damage to the LM8s ended with installation of ‘cereal-box’-shaped beam dumps between the two beamlines. These beam dumps are made of titanium because it has higher resistance to optical ablation than aluminum. With titanium the amount of atomized metal produced by the spark is reduced and cleanliness levels within the beam tube are improved. A photograph of two of these beam dumps is seen in Fig. 120.

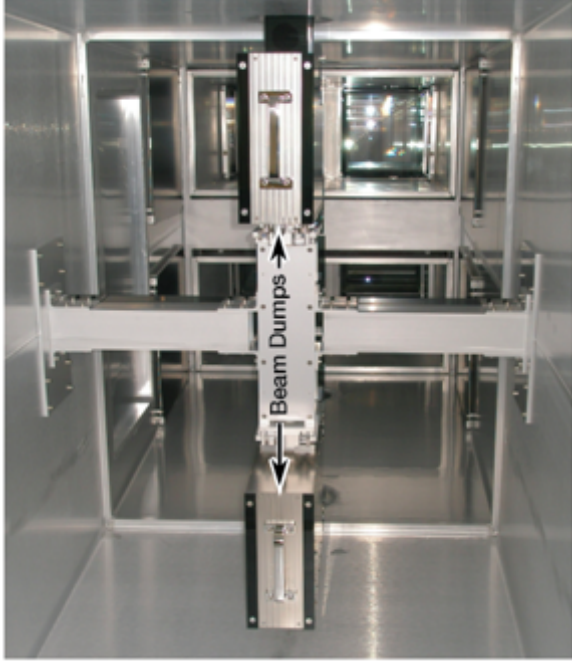


Fig. 120: Photograph of two “cereal-box”-shaped beam dumps and their support structure, looking into the FOA from an argon beam tube. The handles that allow installation of these beam dumps can be seen in this photograph. Entry of light into the beam dump is from the opposite, the FOA, side.

VII.Q. Shot-by-shot Performance of the 3ω Laser

Many of the end-item performance features of the FOAs have to be described in terms of the integrated performance of the entire system and for these the reader is referred to the article “National Ignition Facility Laser System Performance” also in this issue of *FS&T*. In addition to this top-level report of integrated performance, several sets of flowdown-performance measurements were made in PDS during 2006 and 2007 as part of laser testing at that time. (Ref. 48) Several of these are included in Figs. 121 and 122. The first of these figures illustrates the smooth near-field beam profiles obtained at both 2ω and 3ω . The second presents a summary of the integrated performance of a representative beamline measured in 2007. It includes

measurements of the output power as a function of time; a histogram of the probability distribution of fluence across the near-field beam profile, summarized in terms of the spatial beam contrast; a measurement of the spatial beam profile presented at the equivalent of the target focal plane at target chamber center, with a 1ω CPP in the beam; and a simultaneous measurement of the SSD bandwidth together with its calculated expectation.

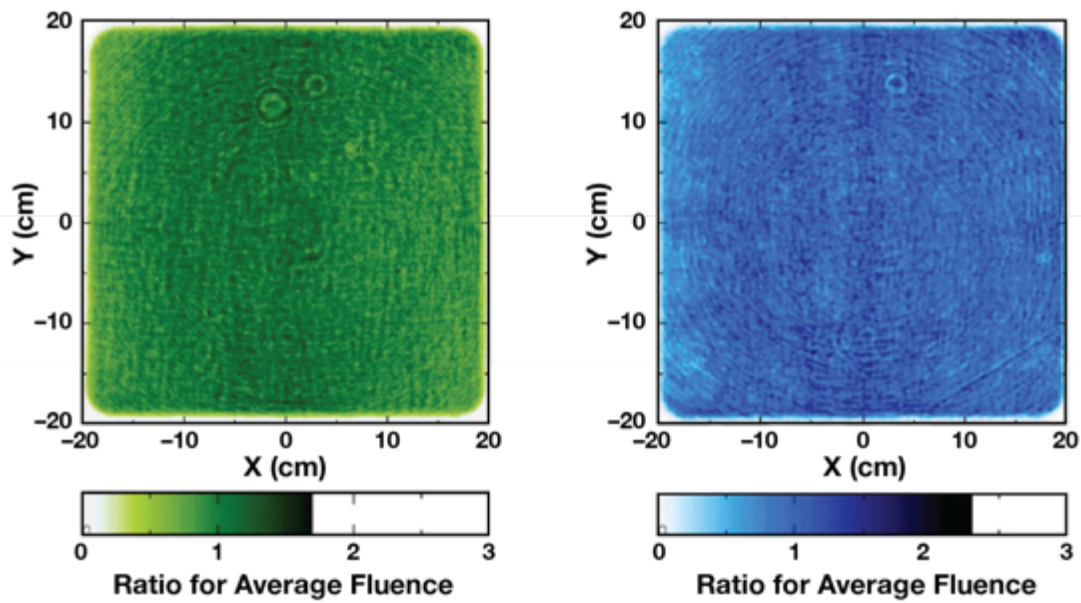


Fig. 121: Near-field profiles of the NIF laser at 11.4 kJ 2ω on the left, and at 10.4 kJ 3ω on the right, as measured in PDS in 2004 illustrating the uniformity and low spatial contrast of the frequency converted beams.¹⁸¹

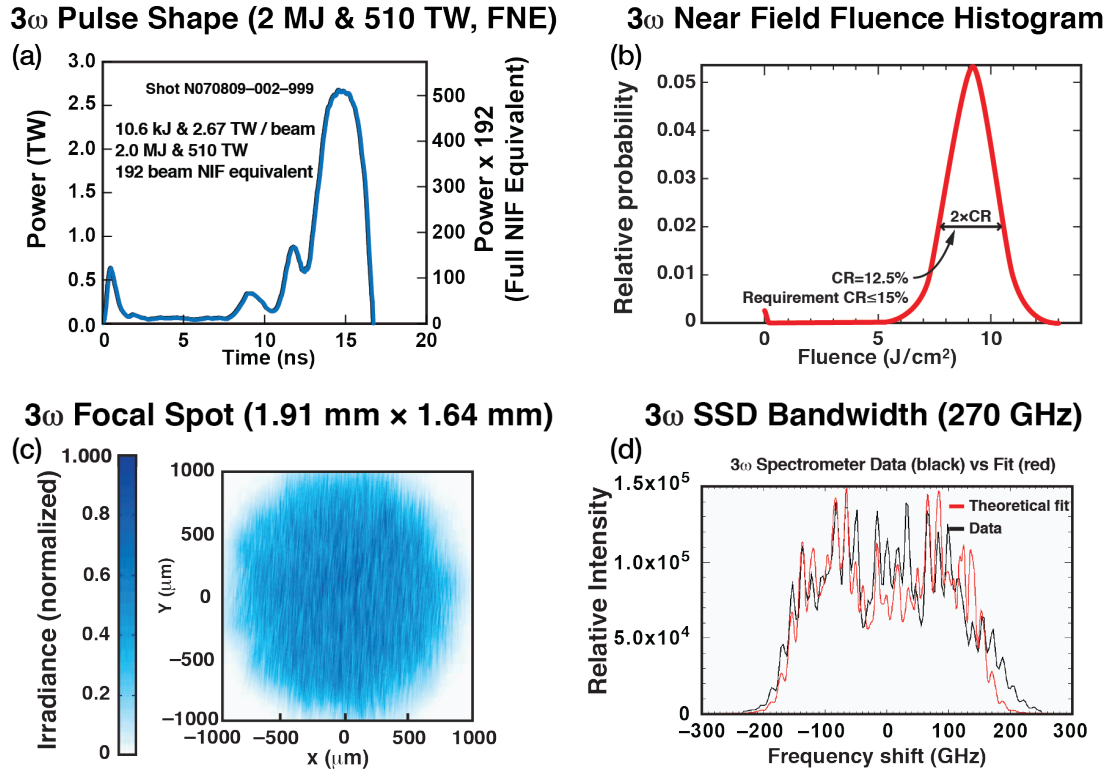


Fig. 122: Simultaneous measurements for the full-NIF-equivalent (FNE) output from a representative beamline sent to the PDS diagnostic station in 2007. (a) Shaped-pulse power vs time (Ref. 48) (b) probability density function of the fluence across the near-field beam profile (c) irradiance of the focused beam at a plane equivalent to the plane of target chamber center with a 1w CPP in the beam (Ref. 48) (d) frequency content of the laser, measured compared to its theoretical prediction.

VII.R. Summary overview of the NIF Final Optics Assemblies

The Final Optic Assemblies, the 3ω delivery subsystems of NIF, have implemented design concepts that were developed over many years of study of ICF lasers. As the concepts for the FOAs were being developed, two uppermost goals were always kept in mind: goals for its performance on a shot-by-shot basis (see Table XI) and goals for staying at this high level of

performance on a routine basis (see Table XII). Improvements in understanding and technology were required for the first of these goals; entirely new ways of thinking were required for meeting the second. The “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” in this issue of *FS&T* provides more detail about additional facilities and procedures required to keep the FOA in routine operation while operating at well over the threshold for damage growth at 3ω .

TABLE XI: Summary of the primary shot-to-shot performance responsibilities of the NIF 3ω Laser.

	Functional Responsibility	FOA Design response
Performance	Efficient conversion efficiency over the full dynamic range of the drive pulse	Type I/Type II converter Stable low loss AR coatings
	Focus the 3ω light, with effective wavelength separation on target	Aspheric 7.7-m focal length off-axis wedged lens
	Less than 5% fluence contrast added at 3ω	High-precision, low-scatter optical surfaces
	Meet user requirements for spot size and smoothness on target	Phase plates, Polarization Smoothing crystals
	Focusing on target, rocking curves for conversion efficiency optimization	Vacuum stepper motors and encoders

TABLE XII: Summary of the routine-operations responsibilities of the NIF 3ω Laser.

	Functional Responsibility	Final optics design response
Routine Operations	Protect final optics from target debris	Deploy automated disposable debris shields between the final optics and the target
	Protect up-stream optics from counter-propagating light originating in the final optics	Maintain AR coating performance by controlling IOM atmosphere
		Manage residual reflections by: * Eliminating on-axis ghost foci * Protecting nearby metal surfaces with absorbing glass armor * Capturing off-axis ghost foci
	Protect the 3ω optics from fratracide and damage growth	* Optimize final optic placement * Pre-screen optics for intensifying flaws
	Manage the impact of optical damage to the final optics	* Fiducialize optics for damage site registration * Edge-lit optics for FODI inspection * Individual optic, fast turn-around LRU exchange

VIII. SHOT SET-UP

Section IV.B presents an overview of the wide range of services provided by the Laser Performance Operations Model (LPOM). Since 2003 when LPOM first began to support shots on NIF the number of features it delivers and the quality of these features have been considerably expanded and improved. During these years, however, the inner core strategy of LPOM for setting up shots has not changed. The same core algorithms written by Wade Williams in 2003 are in use today, operating much faster now with improvements in the speed of the computers and the number of computers assigned the work.

The logical end point of shot set-up by LPOM is definition of the temporal profiles needed from the Master Oscillator Room. These profiles are then delivered to the NIF beamlines for amplification and frequency conversion, providing the 3ω pulse shapes requested by the users. This section gives a minimal description of events as the request for a shot is generated and it then expands upon the logic and events that occur as Expert Groups, LPOM and VBL

complete their work of setting up shots for NIF, including analysis and review of the beamline parameters from the viewpoint of machine safety.

Definition of the target-physics goals for a 3ω shot begins long before the day of the shot. Review and approval of an experiment by the NIF governance participants can start up to 18 months ahead of time. That approval process includes studies of target behavior as a function of pulse shape variations by a code such as Hydra or LASNEX. Successful transit through the governance process also assigns a responsible individual, the RI, for the shot(s).

The RI is responsible for requesting the shot, defining the shot parameters and ensuring the review for machine safety. Two web-accessible software tools are available to support the RI as these tasks are completed. The Pulse Shape Editor (“the editor”) and the Campaign Management Tool (CMT) are used to specify the requested laser pulse shape and timing for each quad, and the energy for each beam. This tool is also used to define details of the requested laser output as part of evaluating the risk of damage to the laser hardware.

The RI specifies three independent wavelengths, one for the inner 23.5-degree beam cones, a second for the 30-degree beam cones and a third for the outer beam cones. Wavelength choices are made for management of coupling of the laser beam to the target plasma and to improve the time-dependent shape of the imploding target capsule. The RI also specifies the bandwidth for Smoothing by Spectral Dispersion (SSD) (set in the MOR) and the continuous phase plates (CPPs) that are to be fielded in each beamline. The bandwidth must be at least 45 GHz in order to protect the optical components of the laser and typically the CPPs chosen are the standard design used for ignition targets. (See Section VII.J, Focal Spot Smoothing by Spectral Dispersion, for a description of available CPPs.)

VIII.A. Expert Group Review of Shots

The characteristics of the 3ω laser beams and experimental configurations requested by the RI are reviewed by the Expert Groups described in Table XIII. Their review considers the ability of the laser to reach the requested shot output and avoidance of conditions that could threaten the safety of the laser or the target diagnostics. In general the Expert Groups rely on a combination of code results and their experience with prior shots having similar laser-target configurations. Codes are used to model target or laser performance and to interpret the results of various measurements. The in-situ measurements of damage sites by FODI are particularly important for monitoring damage initiation and growth on the 3ω optics. (More information on FODI can be found in “Optics Recycle Loop Strategy for NIF Operations above UV Laser Induced Damage Threshold” also in this issue of *FS&T*).

TABLE XIII: Expert Groups that support analysis and approval of requested shot configurations.

Working Groups & Responsibilities	Basis for reviews
• Backscatter Risk Assessment – Evaluate likelihood and amount of backscatter expected from requested target/laser configuration	• Simulations of laser/plasma conditions and predicted backscatter gain coefficients • Empirical database of prior shots
• TaLIS (Target & Laser Interaction Sphere) – Evaluate the planned shot configuration and alignment sequence for interferences, scattered light, debris and shrapnel – Evaluate risks for diagnostics and disposable debris shields	• Visualization with CAD models of target, beams, and diagnostics • Experience • Detailed hydrodynamic modeling and comparison with empirical database of prior shots and observations
• BLIP (Beamline Integrated Performance) – Ensure that risk to optics remains within acceptable limits	• Laser propagation codes • Experience and measurements from prior shots
• NOL (NIF Optics Lifetime) – Maintain running list of beamline power restrictions – Manage planning for optics inspections and replacements	• Post-shot optics inspection measurements and image analysis • Detailed predictions of damage based on optics damage initiation and growth models

For new target/laser configurations, it may be necessary to first field a target shot at lower energy and to measure the levels of backscatter experienced before authorizing higher energies for a similar target. In these situations the ability of the DrD to measure the stimulated Brillouin backscatter for a large number beamlines, as described by Fig. 112 is extremely helpful. The risk associated with high levels of backscatter is that the light reflected back into the FOA can damage the LM8 final turning mirrors. These mirrors are designed for use at 1ω , and are at risk at 3ω if the back-reflected fluence from the target is above $\sim 1 \text{ J/cm}^2$ at the mirror surface.

Similarly, for new target, laser, or diagnostic filter configurations, it may be necessary to perform debris tests for diagnostics, or schedule FODI inspections to evaluate the debris impact to the disposable debris shields. Depending on the target configuration and energy, there may be risk to a diagnostic detector that requires only minimal filtering (and thus is vulnerable to damage by target debris) to achieve the physics goals of the measurement. In such cases, it may be necessary to field the instrument in a safe configuration on a similar shot as a debris test prior to fielding it in an exposed configuration.¹⁸² The debris wind and x-ray loading impinging on a diagnostic snout can also result in deformation of the diagnostic components such as pinhole and collimator plates.¹⁸³

VIII.B. Configuring the beamline for a shot

Setting the configuration of a quad for a specific shot (or purpose of a quad for a shot, such as a backlighter) includes choosing the number of slabs to be energized in both the MA (usually 7, 9 or 11) and the PA (usually 3 or 5). Figure 65 provides an illustration of the slabs that are (circa 2014) installed in NIF. It gives a plan view looking down through the stack of four laser slabs of each slab LRU. Even though a stack of slabs is always present in the laser, those slabs contribute gain only when their flashlamps are fired. The flashlamps in NIF are typically

fired at either 20% or 21% of their explosion fraction. Thus with the currently installed-slab configuration it is still possible to operate the laser in a number of different amplifier configurations. The nomenclature for the amplifier configuration first gives the number of MA slabs energized, then the number of PA slabs energized, followed by the flashlamp explosion fraction. During the year between July 2013 and July 2014, it has been about equally probable that for full system shots most of the bundles will be set up in either a 9-5 (21%) or a 11-5 (20%) configuration. A 9-5 (21%) configuration has less stored energy in the amplifier chain than an 11-5 (20%) configuration. Several considerations contribute to making the choice of configuration, including the degree of saturation in the ILS and in the main laser (higher saturation means more stable performance and less contrast), the stored energy that remains in the slabs once the pulse is over (with leftover stored energy, the threat of a backward propagating 1ω pulse is higher due to the higher residual gain), the choice of backlighter-target locations, and the total energy and peak power requested for the shot. Some backlighter targets may require quads that deliver a comparatively small amount of energy, calling for beamlines in a 7-5 (21%) configuration.

Because flashlamps are dedicated to bundles and there are two quads (an upper quad and a lower quad) in each bundle, some limitations are placed on the flexibility of the configuration for individual quads. Iterations on the machine configuration requested by the RI may be necessary before final “Shot Setup” for the shot can begin.

Typically, only two components are considered changeable within the FOA. These two are the CPPs and the DDSs. The CPPs of only a few beams are reconfigured between shots to support smaller beam spots and higher intensities on target for laser-plasma interaction studies or for driving x-ray backlighters.

Disposable Debris Shield (DDS) locations and cassettes (included in the FOA for protection of the Final Optics from target debris) are discussed in Section VII.M. Each DDS cassette holds five DDSs that can be individually inserted and withdrawn from the beamline. Figure 123 provides a close-up photograph of a DDS cassette showing the partial insertion of DDS #2. The Working Groups can select a pristine or an already used DDS for any given shot. DDS transmission is known based on an initial measurement and calculated degradation due to laser solarization and coating by debris that has been collected since it was installed. The accuracy of the predicted transmission of the DDS has been validated with several hundred target shots and direct transmission measurements of many DDSs over the past 3 years. (see Fig. 114) More on disposable debris shields is included in Section VII.M, in particular in Fig. 114.

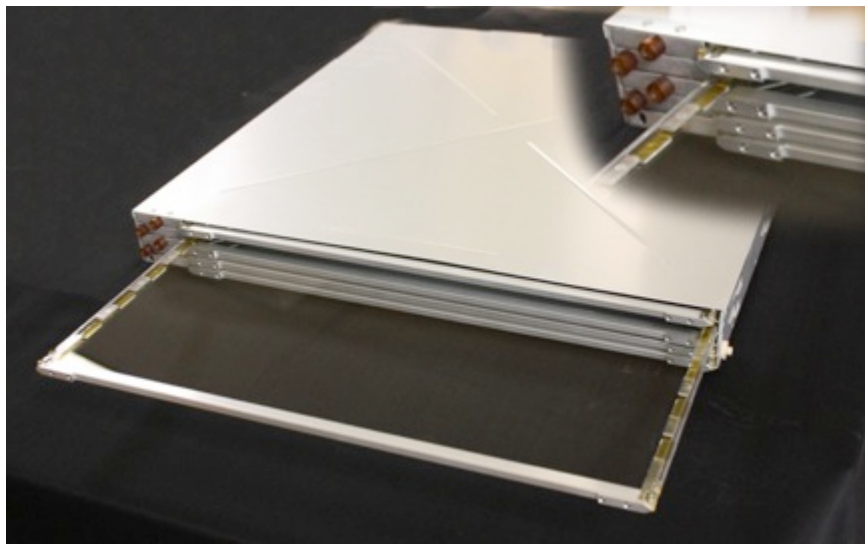


Fig. 123: Here, a disposable debris shield is shown partially extracted from a cassette that holds five optics. Each DDS can be remotely inserted individually into the beamline to protect the grating debris shield and other optical elements in the FOA.

VIII.C. Shot set up for the ILS and the pulse shapes from the AMCs

For each quad, the detailed setup of the ILS is based on LPOM/VBL calculations of the laser starting with a request for the 3ω quad-sum pulse shape and the energy on target for each beam, taking into account the defined main laser amplifier and final optics configurations. This process is defined below, starting with the user-defined shot goals.

Typically, all of the beams in a quad are specified to have the same energy, but in some cases individual beams may have different energies or be turned off altogether. The Pulse Shape Editor, a companion to the Campaign Management Tool (CMT) is available to support the RI in specifying the nominal quad-sum power profile (expressed as the output from a single beam, i.e., one fourth of the power profile requested for the quad). Two options are available in the Pulse Shape Editor for making the power profile request. It will accept requests based on a cubic spline fit using the so-called Munro parameters with as few as ~ 11 time-amplitude pairs (for an ICF-like pulse) or it will linearly interpolate between as many as 300 time-amplitude pairs (which do not need to be uniformly spaced in time). The Pulse Shape Editor interpolates the amplitude values of the requested pulse shape for up to 600 amplitude values separated by 50 ps for a pulselength of up to 30 ns duration and provides graphical feedback of the interpolated pulse shape to the user. In CMT, the RI selects the nominal pulse shape for the shot from those defined in the Pulse Shape Editor and specifies the energy for individual beams. If necessary, in CMT the RI can override the nominal values entered into the Pulse Shape Editor. CMT then transmits the shot request in XML format to LPOM.

A scheduling function of LPOM manages the priorities for these shot requests, and as time on the LPOM computers becomes available, LPOM performs the setup calculations for the newly proposed shot.

Shot-set-up logic is based on setting up the performance of the four beamlines of a quad, taking into account that there are two quads in each bundle. The four beams of a quad share the output from a single PAM, and all beams in a bundle are energized by the flashlamps that are shared by the two quads (eight beamlines) within a bundle.

A schematic for the laser architecture of a quad from the viewpoint of LPOM is included in Fig. 124. For each quad, there is one AMC in the MOR that generates the pulse shape for each preamplifier. A preamplifier consists of a regen preamplifier in sequence with a four-pass preamplifier. Waveplate variable attenuators are located at the input and output of each four-pass preamplifier. Each regen/four-pass preamplifier provides input to one PABTS. Within the PABTS, polarization rotators followed by polarizers are used to split the energy from its preamplifier into four beams, one each to be injected into one main laser beamline. The four pulse shapes that leave the PABTS differ from each other only in their relative amplitudes, no other pulse shape differences are introduced by the PABTS. The output beams from the PABTS are the input beams to the 1ω main laser amplifiers.

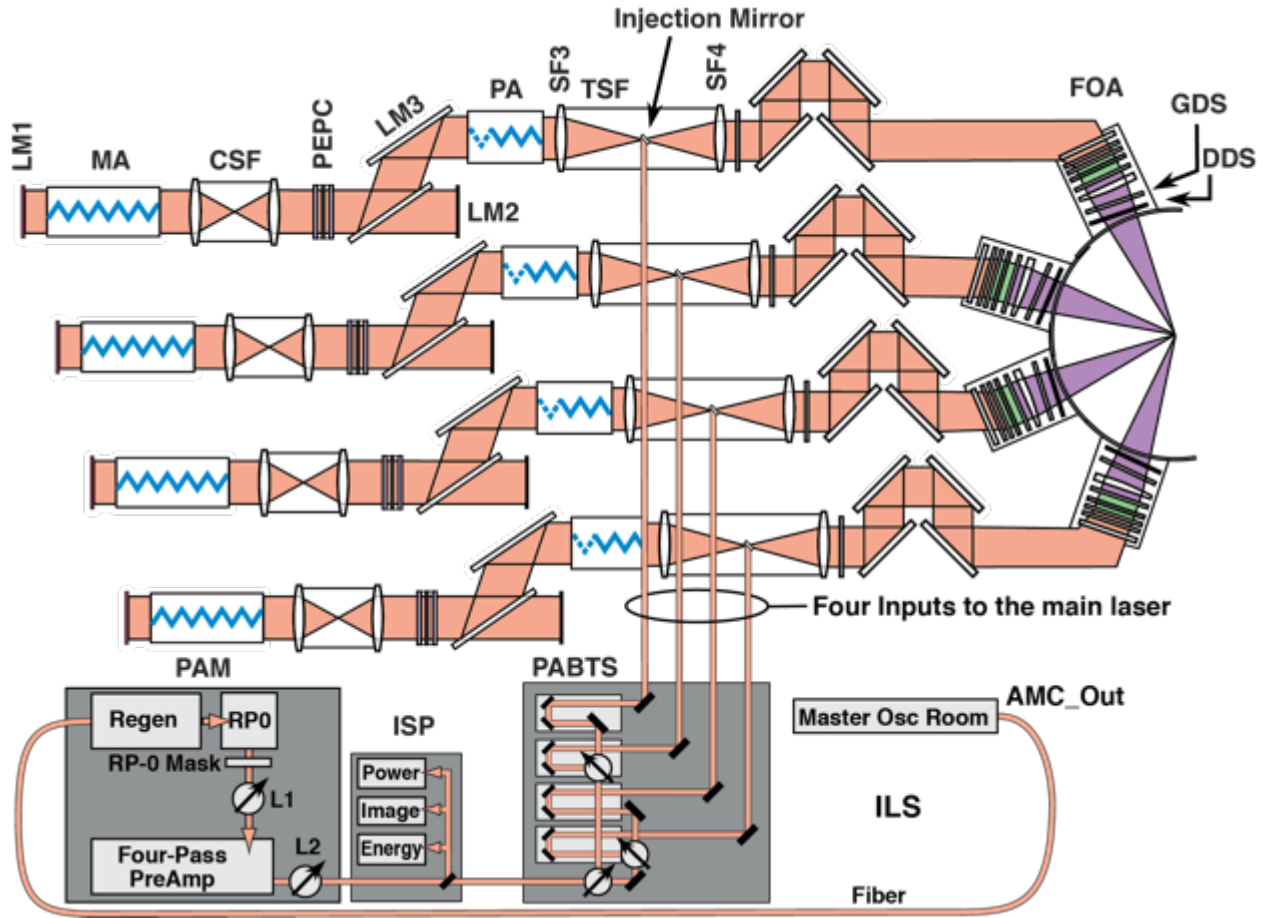


Fig. 124: Quad-centric view of the laser by LPOM, including schematic of the ILS, 1ω main laser and FOA features important for shot set-up.

Figure 125 is a more compact view of a quad, intended to be identical in function with Fig. 124 but better aligned with the mathematical concepts important for shot set up. The notation f_i indicates the fraction of the input energy for the i th beam compared to the total input energy going to the 1ω main laser. The notations “L1” and “L2” are used to indicate loss terms or attenuation corresponding to the waveplates at the input and output of the four-pass preamplifier. The notation FC indicates the location of a frequency converter. Fluence is indicated by the symbol ϕ . Mathematically, the transmission of the grating debris shield (see

Section VII.M) is designated by $t3\omega$. In practice, the value of $t3\omega$ is used to characterize the overall performance of each individual beamline. A compensation factor, $t3\omega_adjust$, is also available at the mathematical location of the grating debris shield for handling situations where the model projections for all 192 beams and measurements are known to disagree. Values for $t3\omega_adjust$ make 2 to 5% corrections, depending upon the pulse shape and system configuration. The model of the DDS transmission incorporated into LPOM is a function of target mass, debris load, solarization experienced during prior shots and the 1ω and 3ω intensity of the current shot.

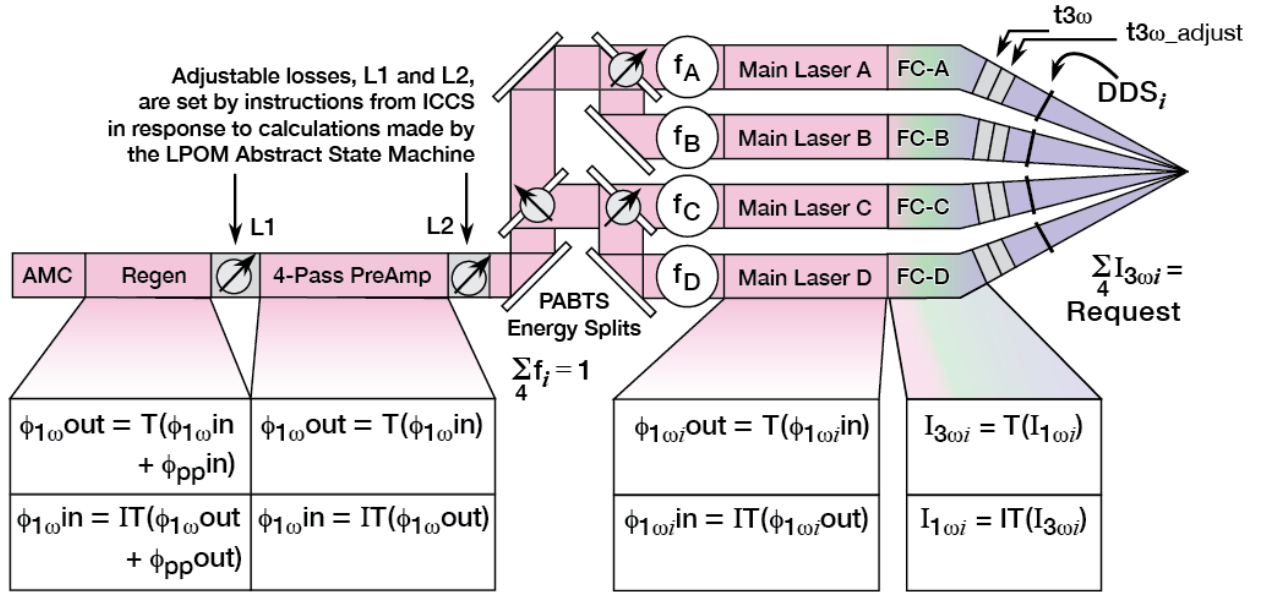


Fig. 125: Schematic for the architecture of a quad from the viewpoint of the mathematics of LPOM/VBL. The notations of $T(\text{argument})$ for transfer function and $IT(\text{argument})$ for an inverse transfer function are further discussed in the text that follows.

The overall performance of the NIF beamlines may be described by a series of transfer functions and inverse-transfer functions that relate the pulse input and output at each section of the laser. Each of these functions yields a single-valued answer that depends on only one

variable. The next paragraphs will cover the *concepts* for simple transfer functions and inverse-transfer functions. This discussion is followed by a description of how the combination of LPOM and VBL complete the detailed calculations using similar concepts but with higher accuracy.

A simple model for the output fluence of a laser amplifier in terms of the input fluence (the integrated intensity up to time t in the pulse) is given by the Franz-Nodvik equation:

$$\varphi_{Out} = \varphi_s \ln \left\{ G_0 \left[\exp \left(\frac{\varphi_{In}}{\varphi_s} \right) - 1 \right] + 1 \right\} \quad (\text{VIII-1})$$

where φ_{Out} is the output fluence from the main amplifier, φ_{In} is the fluence input to the main amplifier, φ_s is the saturation fluence of the laser medium, defined as $h\nu/\sigma$, with σ equal to the laser transition cross-section. G_0 is the small-signal gain given by $\exp(\alpha_0 L)$ with α_0 , the small signal gain coefficient = $N\sigma$ where N is the number of inverted atoms/cm³. A plot of φ_{Out} vs. φ_{In} that is characteristic for a single pass of a NIF main amplifier is included in Fig. 126 (a).

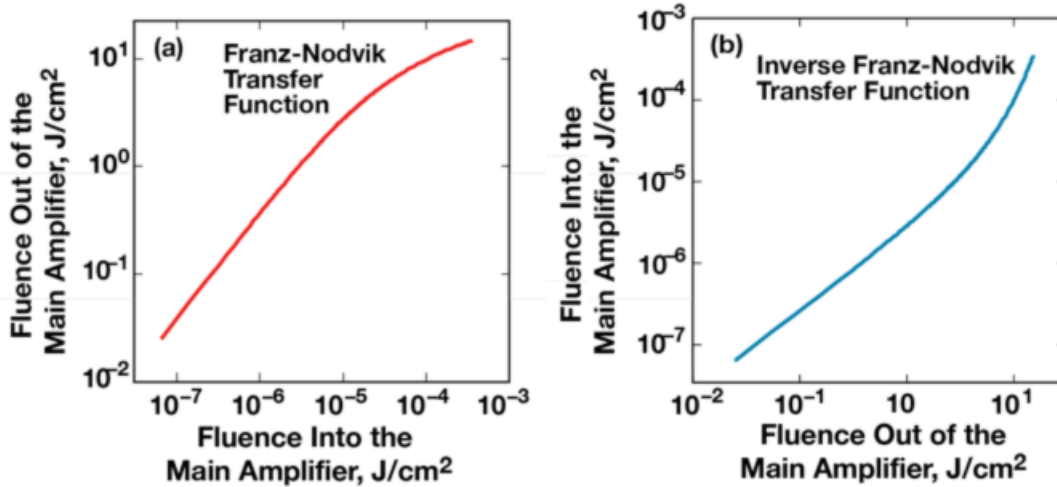


Fig. 126: Transfer functions for the integrated intensity (fluence) into and out of a main amplifier. (a) The transfer function for integrated intensity (fluence) for one pass out of a main amplifier as a function of only one variable, the integrated intensity (fluence) up to any time t

into that amplifier (b) The inverse transfer function for integrated intensity that needs to be injected into the main amplifier as a function of the fluence desired out of the main amplifier.

Equation VIII-1 can also be called the Franz-Nodvik transfer function for one pass of the main amplifier. The terminology for transfer function is designated by T(argument) in the rows of Fig. 125. Note that the Franz-Nodvik equation exhibits saturation behavior, that is, the available output fluence saturates when no more energy can be extracted from the laser media than was originally stored by firing of the flashlamps.

A remarkable feature of the Franz-Nodvik equation is that it can be inverted to give an analytic equation with a form very similar to that of the original as given by Equation (VIII-1), but now with the input fluence given in terms of the output fluence:

$$\varphi_{in} = \varphi_s \ln \left\{ \frac{1}{G_0} \left[\exp \left(\frac{\varphi_{out}}{\varphi_s} \right) - 1 \right] + 1 \right\} \quad (\text{VIII-2})$$

Equation (VIII-2) is the inverse Franz-Nodvik (FN) transfer function, plotted in Fig. 126 (b) once again for one pass through the main amplifier. An inverse transfer function is designated in the rows of Fig. 125 by IT(argument).

Similar FN-transfer and inverse-FN-transfer functions can be written for both of the four-pass and regenerative preamplifiers. The situation for the regen is a little different in that, for stability, it needs to operate in a well-saturated regime. Reaching the necessary level of saturation requires output energy from the AMC of >350 pJ, while at the same time being limited to an output power of 200 mW to avoid issues with SRS generation in the fiber. If the first LPOM/VBL calculation does not require a requested AMC pulse with this much energy, an AMC post-pulse is added to make up the difference. The post-pulse is clipped off by a Pockels

cell before the continuing pulse reaches the four-pass preamplifier. Transfer and inverse transfer functions for the regenerative preamplifier have to take the post-pulse into account.

The transfer and inverse-transfer functions for a NIF-like frequency converter (for the simplest case) are those for a plane-wave converter. Figure 127 (a) and (b) plot these functions. Note that here again, the transfer and inverse-transfer functions give a single-valued result for a single variable; this time the variable is the intensity at any time t during the pulse.

The transfer-function approach relies on operating the NIF laser within its specified power/energy ranges. Off-normal events such as pinhole clipping or operating with very high powers where beam information is lost due to spatial filtering will also invalidate this method.

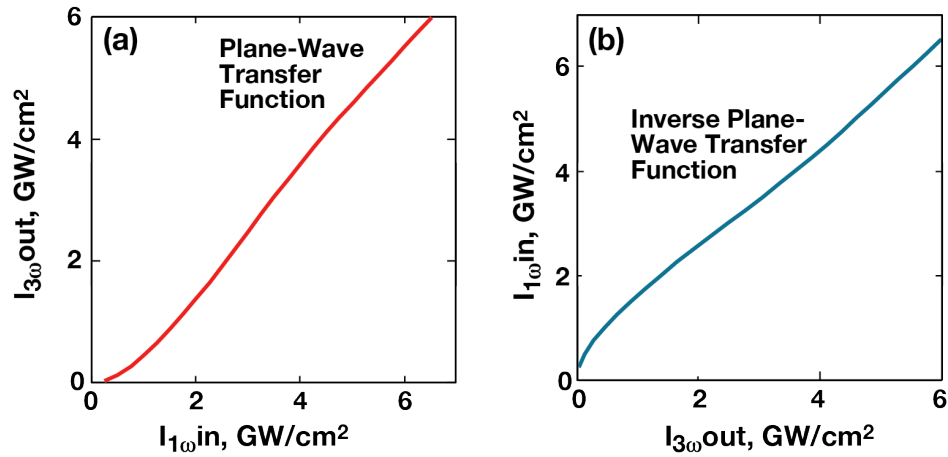


Fig. 127: Transfer and inverse transfer functions for plane-wave conversion of 1ω intensity to 3ω intensity for a NIF-like converter with an 11 mm doubler and a 9 mm tripler.

The detailed setup of the ILS is based on automated LPOM calculations. LPOM uses these same concepts of transfer functions and inverse-transfer functions, but these transfer

functions are generated individually for each beam on the basis of beam propagation calculations using VBL for specific shot goals. VBL uses configuration files and spatially dependent models for gain and frequency-converter performance that are appropriate for each beamline configuration as it exists at the time of the VBL calculation. These parameters can change as the characteristics of the disposable debris shield and programmable-spatial-shapers change or when one of the final optics is exchanged as part of operation of the Optics Recycle Loop. A forward run by VBL is logically similar to using a transfer function. An input-pulse-solve by VBL is logically similar to using an inverse-transfer function.

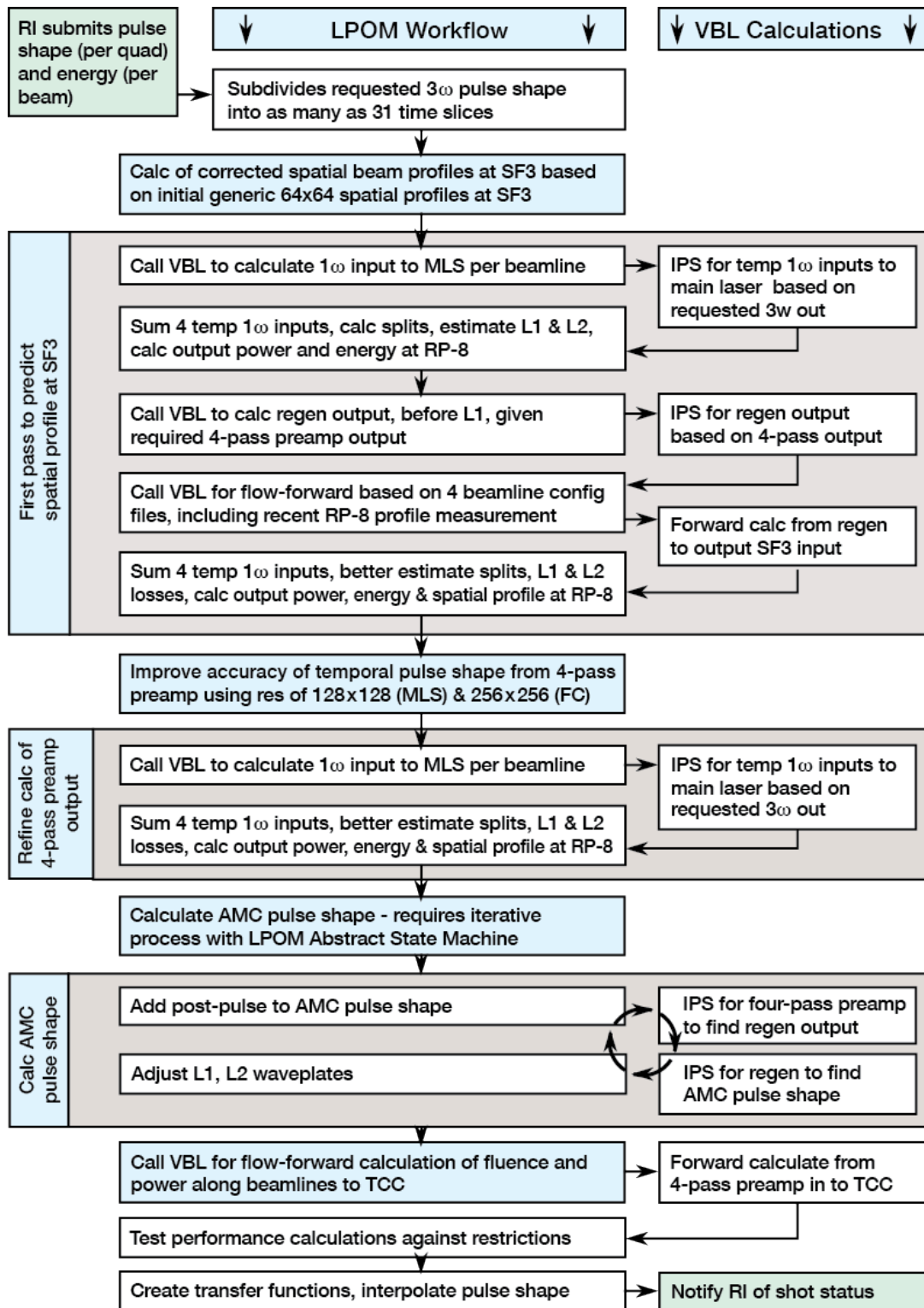


Fig. 128: Logic flow diagram for shot set up used by LPOM/VBL.

The logic flow diagram for shot set up is given in Fig. 128. It is based on multiple specific calculations to establish the expected spatial beam profiles injected into the main laser, and then a series of iterative calculations based on a detailed rule-set managed in LPOM.

Two repeating features of events in the flow diagram are discussed before going into the details of the logic flow. First of all, every time LPOM makes a call to VBL for either a forward run or an input-pulse-solve, it also passes along several instructions for the calculation. These additional items include:

- Configuration files for each beamline, such as phase profiles for optics, distances between optics that are specific for each individual beamline and spatial profiles that are to be used at specific locations
- The spatial resolution desired for the calculation
- The in and out locations along the beamline for that run

Secondly, each time the VBL input pulse solver is called, it completes a similar set of steps. It first creates an estimate of the input power profile $P_{in}(t)$, at the first component at the “in” beamline location for the run. Starting at that point, it then does a full-chain simulation up to the last component at the “out” location for the defined run to derive the resulting power profile, $P_{out}(t)$. VBL then compares that calculated output to the requested result and uses the comparison to refine the estimated input; it resets the beam line to its initial state and iterates until the comparison of the calculation is within a predetermined error, now typically 0.5%. Because this “guess-and-correct” strategy must be done in a compute-time-sensitive environment, and because the chain simulation dominates the execution time, a lot of effort has gone into minimizing both the time per iteration to achieve the limited goal of correct energetics and the

number of iterations required to converge to an accurate solution. Minimizing the time per iteration involves a number of simple steps:

- Temporarily disable all graphic and binary output.
- Use low-resolution runs (both temporally and spatially) to establish the starting point for the higher resolution iterative procedure.
- As an alternative, allow LPOM to enter a starting point and skip this start-up procedure.
- Ignore diffraction during early iterations until the solution is very close; then turn on diffraction for the final solution.
- While diffraction is inactive, ignore all imposed aberrations and spatial filters—except for the beam inversion effect of the telescopes.

To begin the shot set up calculation, LPOM first subdivides the pulse into as many as 31 equal time slices and adjusts the power for each time step to conserve energy relative to the more finely resolved 50 ps requested pulse shape. An example of such a temporal re-gridding is given in Fig. 129 for a high-foot shot taken in 2013. Experience over the years has shown that 31 time slices are enough for the energetics of requested ICF-like pulses to converge with sufficient accuracy when analyzed by one of the LLNL physical-optics codes. Other shaped pulses use time slices appropriate for their shape.

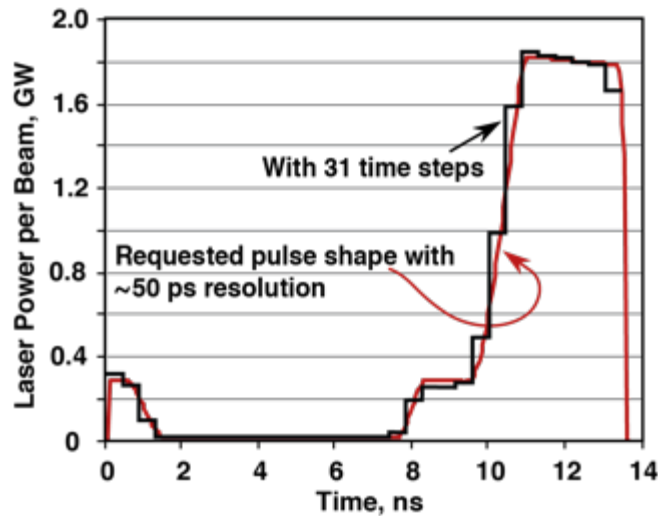


Fig. 129: Comparison of an example high-foot requested pulse shape with 50 ps intervals re-gridded for 31 timesteps.

There are four major logical steps in the sequence of smaller steps taken by LPOM/VBL in the shot set-up calculation. The goal of the first major step for a quad is to find the 1ω spatial profiles at the four SF3 locations, the four inputs to the main laser. These spatial profiles are necessary as inputs for the next major step; they are necessary to achieve the accuracy desired for that step. These spatial profiles are pulse shape dependent due to gain saturation effects in the multi-pass architecture of NIF. LPOM starts this calculation by sending the 31 time-slice pulse shapes to VBL with a call for an input-pulse-solve of the pulse shape required at the location of RP-8 (the input to the PABTS, then followed by the 1ω main amplifiers) given the user-specified 3ω output pulse at TCC. The VBL pulse-solve uses a single generic RP-8 beam profile based on profiles of the apodizer and beam-shaping masks located at RP-0. VBL uses its “guess and correct” strategy to find the individual inputs to the main lasers that can create the requested 3ω energies and pulse shapes at TCC. The first input-pulse-solve calculations are done at low-resolution with 64×64 pixels across each of the four calculated beam profiles. Because there are

differences in the gain and frequency conversion of each beam in a quad, these VBL calculations produce requested outputs from the individual PABTS beams that are not just replications of each other differing only in amplitude. As a result they are only an approximation of the temporal profiles that will finally be required from the PABTS. These four different calculated pulse shapes at the input to the main laser are next summed and on the basis of the relative energies for each different input, a first estimate of the splits needed in the PABTS is generated. With an appropriate estimate of L2 (see Fig. 125, obtained by experience from other similar shots), LPOM calculates the desired output from the four-pass preamplifier and calls VBL for an input-pulse-solve to find the input needed to the four-pass preamplifier. Then with its initial estimate of L1, LPOM can solve for the regen preamplifier output. LPOM then sends the calculated regen preamplifier output pulse to VBL with a call for a forward calculation from the output of the regen to SF3, the input to the 1ω main laser beamlines. This calculation includes the spatial profile effects of the apodizer and beam shaping mask at RP-0, the programmable spatial shapers at RP-0 and a beam-shape multiplier derived from a recent ISP measurement of the beam profile at RP-8. This calculation provides the spatial profile at SF3 for the four inputs to the main laser, thus accomplishing the first goal.

The goal of the second major step of the shot set-up is to more precisely calculate the output temporal pulse shape needed from the 4-pass preamplifier at RP-8. This starts by repeating the first sequence of steps described above, but this time based on the higher resolution spatial beam profiles calculated at SF3, and by using “full” resolution for the VBL set-up simulations, 128×128 , re-gridded to 256×256 for the frequency conversion portion of the calculation. LPOM sends the requested 3ω pulse shape at TCC to VBL with a call for an input-pulse-solve of the 1ω input energy per beamline at the output of the PABTS, but this time with a

spatial profile consistent with the SF3 profile found above. VBL continues this iteration process until convergence of the calculation at TCC compared to the request is $< 0.5\%$. Once again four inputs with different energies and temporal pulse shapes are found at SF3. LPOM again sums these four different 1ω input pulse shapes, but with the improved accuracy made possible by the more accurate spatial profiles at SF3, it can calculate better estimates of the splits needed in the PABTS and refine the values of L1 and L2.

At this point, the third major step of the set-up calculation begins. It is a sequence of calculations as an Abstract State Machine with the goal of finding the pulse shape required from the AMC. The Abstract State Machine provides a flexible approach for management of a set of “if-then” states. It starts with the calculations for RP-8 found as described above, and as it moves from state-to-state, LPOM makes calls to VBL for specific calculations as required by each state. Its first critical decision is whether or not an AMC post-pulse is needed. Logic for moving through the State Machine relies on understanding that the regen must deliver an output energy of ~ 10 mJ in order for it to be in the saturated regime and that the output power from the AMC must stay below 200 mW to avoid Stimulated Raman Scattering in the fiber that delivers the AMC pulse to the regen. The Abstract State Machine operates within a complex rule-set to converge to a solution that can request a pulse shape from the AMC of the sort given in Fig. 28. As it moves through the set of the “if-then” states, it completes, as necessary, calls to VBL for input-pulse-solves for the four-pass preamplifier to find the regen out and for the regen to find the AMC pulse shape out. In addition to defining an AMC post-pulse (if necessary) it also defines final settings for the L1 and L2 waveplates.

With the final AMC pulse shape determined, the fourth major logical step of the set-up calculation calls VBL for one final full-forward run that begins at the input to the four-pass

preamplifier and runs to 3ω out at TCC, at full resolution with diffraction on and with the lower-laser-level drain calculation running. The intensity and fluence are calculated at locations of key optical components along the beamlines and compared to documented restrictions that have been placed on these optics. Any intrusion into a restricted condition is graded to produce either a yellow- or a red-alert flag for expert review. There are five categories of restrictions:

- Restrictions established for avoiding damage to optics that are documented as not-to-exceed peak values built into the VBL input file for each optic location (in particular in the four-pass preamplifier)
- Restrictions for avoiding surface damage initiation to the LM4 mirrors. Gaussian equivalent FWHM pulselengths are first calculated using Equivinit¹⁸⁴ (an LLNL internally developed application) for the 1ω temporal pulse at LM4, as found by VBL. Measured values of $\rho(\phi)$ for the mirrors are combined with the effective values of the fluence at LM4 to predict the number of new sites expected for a candidate shot. A yellow alert is placed on the shot if the expected number of new sites is greater than 10^{-3} . More information on this type of calculation is given in the paper, “Damage Mechanisms Avoided or Managed for NIF Large Optics”, also in this issue of *FS&T*.
- Restrictions on the maximum calculated values of ΔB (the phase pushback resulting from the non-linear index of refraction) that can be tolerated along the 1ω amplifier. (maximum $\Delta B < 1.8$ radians)
- Restrictions on the peak intensity in space and time at a location just before the frequency doubling crystal, the second harmonic generator. This restriction is established to avoid filamentation in the frequency converter and downstream optics

- Beamline specific restrictions on peak output power (also related to filamentation) in the optics, as defined by the NIF Optics Lifetime (NOL) working group

All yellow-alert conditions are referred to the Beamline Integrated Performance (BLIP) working group for acceptance or rejection. After BLIP evaluation, if the condition is not allowed, the RI for the shot is notified and changes to the shot setup are recommended. No shots are allowed to proceed under a red-alert condition.

When this last full-forward run is completed, transfer functions can then be written for the paths from the AMC to the ISP, the ISP to the OSP and the OSP to TCC. These transfer functions are then used to calculate the predicted power as a function of time in 50 ps intervals by interpolating the calculations for the 31 time slices along these transfer function curves. The 50 ps interval AMC pulse shape values are sent to ICCS for interpretation in the MOR for set up of the AMC. The waveplate rotations for the two loss terms L1 and L2 and the PABTS splits are sent to ICCS for machine setup.

VIII.D. Performance-based corrections

The LPOM model is a state-of-the-art model for the NIF laser performance, but there are still inconsistencies between the predicted and actual performance. Experience developed over hundreds of laser shots indicates that the performance is very repeatable, but that time-dependent corrections need to be applied in order to accurately realize the requested pulse shapes. These corrections are referred to as Loop 1 and Loop 3 corrections.

The Loop 1 correction is a time-dependent correction of the AMC pulse shape based on the actual vs calculated pulse shape at the ISP. This correction is established by setting up the laser for rod shots to the ISP using the LPOM/VBL calculated AMC pulse shape for the

requested shot. A sequence of rod shots is performed, and the actual pulse shape is measured at the ISP. The average deviation over the sequence of rod shots of the achieved pulse shape relative to required is used to define a time-dependent correction for the AMC pulse shape. This correction is then applied in the MOR when setting up for the shot to TCC.

The Loop 3 correction is a time-dependent correction of the 3ω pulse shape requested at TCC. This correction is established by comparing the actual (measured) 3ω performance relative to the calculated performance given the measured 1ω ISP and OSP performance. One way of establishing the temporally dependent multiplier corrections to the output request at 3ω requires a full system shot but this is only done infrequently. Normally the time dependent multiplier is obtained from pre-existing data for shots with similar energy and set-up parameters. It is applied very early, just after the pulse shape is requested and before any of the detailed calculations begin.

VIII.E. Laser setup management

With the procedures outlined here the quad calculation typically meets the user's request for quad energy and power precisely and the requests for individual beamline energy meets requests within $\sim 2\%$. Once the shot set up calculation has been completed for all of the quads and beamlines and all other criteria for the shot have been met, the shot is passed into the "ready" state and the RI is informed of the proposed shot's new status. If this step fails to complete successfully, the RI is informed that the shot has not been approved and therefore the request must be revised.

While the proposed shot is in the "ready" state, where it typically stays for some number of days, if for any reason the physical configuration of a beamline is changed by the operations

staff, such as for example a DDS is replaced, LPOM demotes the set-up for the quad of that beamline to a “not_approved” status. LPOM automatically reruns the set-up calculations for this quad using VBL and then if other necessary criteria have been met, it refreshes the database with the new results. It is also possible for the RI to make changes to a shot while it is in the ready state, meaning that shot set-up will be rerun for any changes requested as if they were for a newly proposed shot.

On the day of a shot, the shot is loaded into the NIFPROD database of ICCS (Integrated Computer Control System). After it is loaded by ICCS the setup is considered to be in the “open” state and LPOM “freezes” that setup. Once “frozen”, the RI can no longer make any changes and the setup will not be automatically unapproved and recalculated even if beamline conditions change. If a change occurs that may impact the setup, LPOM sends a signal to the “Check Pending Experiments” web page. As part of the shot-cycle, the Shot Director can request an update from LPOM, even multiple updates, at anytime as allowed by ICCS. Recalculation will occur, however, only if the Shot Director requests it manually. This update will be a full LPOM recalculation for the affected quads, starting from scratch. When finished, LPOM again freezes that experiment until the shot completes.

IX. ALIGNMENT OF THE NIF LASER

The task of laser alignment is to both point and center the beams to within specified tolerances as they move through the various apertures in the beamlines on their way to the target while simultaneously achieving the user-requested pointing to the target within a tolerance that was established by the original Functional Requirements and Primary Criteria outlined in Table 1. In addition to pointing and centering of the beams, the angles of the frequency-conversion crystals must be set to match the incident beam axis within tolerances that result in efficient

conversion to 3ω . Several figures have been included in previous discussions that may be helpful here. These are Fig. 6, Schematic view of the laser system, Fig. 42 Diagnostic side of the ISP, Fig. 73 Photo of the CSF pinholes on their pinhole wheel, and Fig. 74, Output Sensor Package.

Flow-down from the requirement for the maximum allowable time between shots also sets the time allowed for completing the alignment task during each shot-setup cycle. Less than 1 hour is allocated for aligning 192 beamlines, 192 doubler and tripler crystals, and 192 beams on target. This section will discuss the logic that is followed by the automatic alignment systems to complete the alignment process within this small time allocation.

Precise automatic alignment of the laser is possible because of earlier preparation of the facility. During construction and installation of the Beampath Infrastructure System, support structures and kinematic mount hardware were surveyed into positions. During commissioning, temporary alignment LRUs and other alignment aids were used for an initial, coarse, alignment.¹⁸⁵ Since that time, the mechanical systems of NIF have been stable and automatic alignment proceeds as planned.

Alignment of the NIF laser beams can be thought of as the internal alignment of three independent “boxes,” which are then aligned with each other using a “handoff” process. The first is the preamplifier, the second is the 1ω main-laser up to centering of the 1ω beam on the FOA, and the third is alignment of the 3ω beam to the target. Each of the alignment steps within these internal ‘boxes’ has common features; they use one or more reference light sources, they incorporate gimbals for angular adjustment of mirrors, and they use feedback for the alignment status.

IX.A. Preamplifier Alignment

Preamplifier alignment consists of relaying the regen output at RP-0 to RP-8' in the ISP. RP-8' is optically equivalent to RP-8 in the pulsed-laser beamline. There is no active alignment within the regenerative preamplifier. Similarly, the vacuum relay telescopes in the four-pass preamplifier were aligned with each other during commissioning, and there has been no further active alignment of these components since that time. Thus alignment of the preamp consists of centering and pointing of the regen beam transmitted through the four-pass preamplifier. This can be done within the alignment tolerances without firing the four-pass preamplifier.

Pre-alignment steps completed during commissioning in 2003 and alignment steps that were taken for the previous shot ensure that alignment of each preamplifier begins for the next shot with the required light sources/pinholes/masks already within the field of view of the near- and far-field images seen by the ISP camera.

Figure 40 identifies MPAI, a centering reference and pointing backlighter source located behind the end mirror of the four-pass preamplifier. Adjustment of the two mirrors between the regen (operating at 1 Hz) and the four-pass preamp is used to center the pulsed regen beam on this light-source reference, as seen by the ISP near-field camera, and to point it to the VRT-2 pass-4 pinhole, which is backlit by the same light source (See Fig. 130).



Fig. 130: Near- and far-field ISP images used for centering and pointing of the 1 Hz regen beam and for co-alignment of the ISP cw alignment beam with the pulsed regen beam (Ref. 185).

With the regen off and the MPAI light source on, the near-field ISP image provides a centering reference at the 4-pass end mirror. With the MPAI off and the regen on, the ISP image shows the corresponding regen beam profile and associated alignment fiducials. The alignment system centers the regen near-field on the MPAI near-field and points the regen far field to the center of the MPAI VRT-2 backlit pinhole.

All of the adjustments and feedback needed are entirely within each preamplifier section. As a result, each preamplifier can be aligned in parallel with the other 47 preamplifiers and in parallel with internal alignment of each beamline of the 1 ω Main Laser System. The total time for preamplifier alignment is five minutes.

Handoff of the alignment role from the regen to the 1 ω cw alignment source in the ISP is key for alignment of the rest of the laser. Angular adjustment of the two reflecting polarizers between the four-pass preamplifier and the ISP (at the green (on-line) beam of Fig. 40) centers and points the regen output to references in the ISP. The (on-line) red dots in the far-right image of Fig. 130 represent the locations of the alignment fiducials on the beam seen in the near-field regen image. Alignment of these fiducials with the black squares, which are the ISP centering reference, assures accurate handoff to the ISP alignment beam, whose ‘T’ pattern (the dark circles) is centered on the same reference. Finally, with the ISP camera in the far-field position, the regen far-field spot is pointed to match the ISP alignment beam far-field (at separate times, but with the same coordinates).

IX.B. Main Laser Alignment

Main-Laser Alignment includes internal alignment of LM1, LM2, LM3 and the polarizer as well as centering of the 1 ω main laser output on the FOA using LM5 and LM8. This

alignment is coupled to the pointing of the beam to the target since that is performed using the same LM5 and LM8 mirrors. Essential components of the alignment system include permanent 1 ω centering references behind LM1 and LM3 as well as several insertable light sources and optical components. Activation of these components occurs in response to instructions from ICCS. A summary of when they are used is given in Table XIV. This table should be consulted for the configuration details as each alignment step for the main-laser system is described. It should be noted, with reference to Fig. 73, that the pinhole wheels for the CSF and TSF spatial filters can be rotated to place various combinations of “pinholes” or alignment components at the focus of the spatial filter lenses. These wheels are turned and stopped by commands from the NIF control system.

TABLE XIV: Summary of alignment-related components and their roles during alignment of the NIF beamlines. Devices inserted at TSF and CSF pinhole planes are placed there temporarily in place of the pinholes, which are rotated out of the beam path.

Alignment Step	Centering references				Insertable alignment components					CSF pinholes		
	LM1		LM3		TSF align beam-fiber position	CSF wave-plates pass 2 & 3	TSF pass 1 corner cube	TSF align beam-splitter cube	FOA corner-cube pair	pass 1 & 2	pass 3	pass 4
	pass 4	pass 2	pass 4	pass 1								
Pol & LM3	on	off	on	off	pass 4	out	out	pass 4	out	out	out	in
LM1	off	on	off	off	"	in	out	"	out		in	out
LM2	off	off	off	on	"	out	in	"	out		out	out
ISP to ML	off	off	on	off	"	out	out	"	out		out	out
Aim to FOA	off	off	off	on	out	out	out	pass 1	in		out	out
KDP angle tuning	off				passes K & 4	NA	out	pass K	out	NA		

Each of the two centering references shown in Fig. 131 has two pairs of light sources, including one pair pointed toward the associated pass-four pinholes. In addition, the LM1 light source has a second pair pointing toward the pass-two pinhole of CSF, and the LM3 light source has a second pair pointing toward the pass-one pinhole of TSF. As part of commissioning, these references were surveyed into their permanent positions (within tolerance of $\pm 100 \mu\text{m}$) while at the same time pointing to within pre-established tolerances. The separation between the LM3 light sources is larger than the separation between the LM1 sources as seen in Fig. 132 (a). Although the coatings on the LM1 and LM3 mirrors transmit less than 1% of the light from the sources, this is enough for their light to be visible to the OSP camera as viewed through the pinholes.

Main-laser alignment occurs when the main-laser amplifiers are cool enough for there to be no need to apply any compensation for pump-induced wavefront distortion, as discussed earlier in Section VI.C.9. The alignment starts with angular adjustment of the polarizer and LM3. It uses the centering references transmitted through LM1 and LM3, the 1ω fiber source positioned at the TSF pass-4 focus, and the CCD camera in the OSP. The 1ω fiber source at the pass-4 focus is aimed toward the TSF output, and the two pass-4 centering references are turned on.

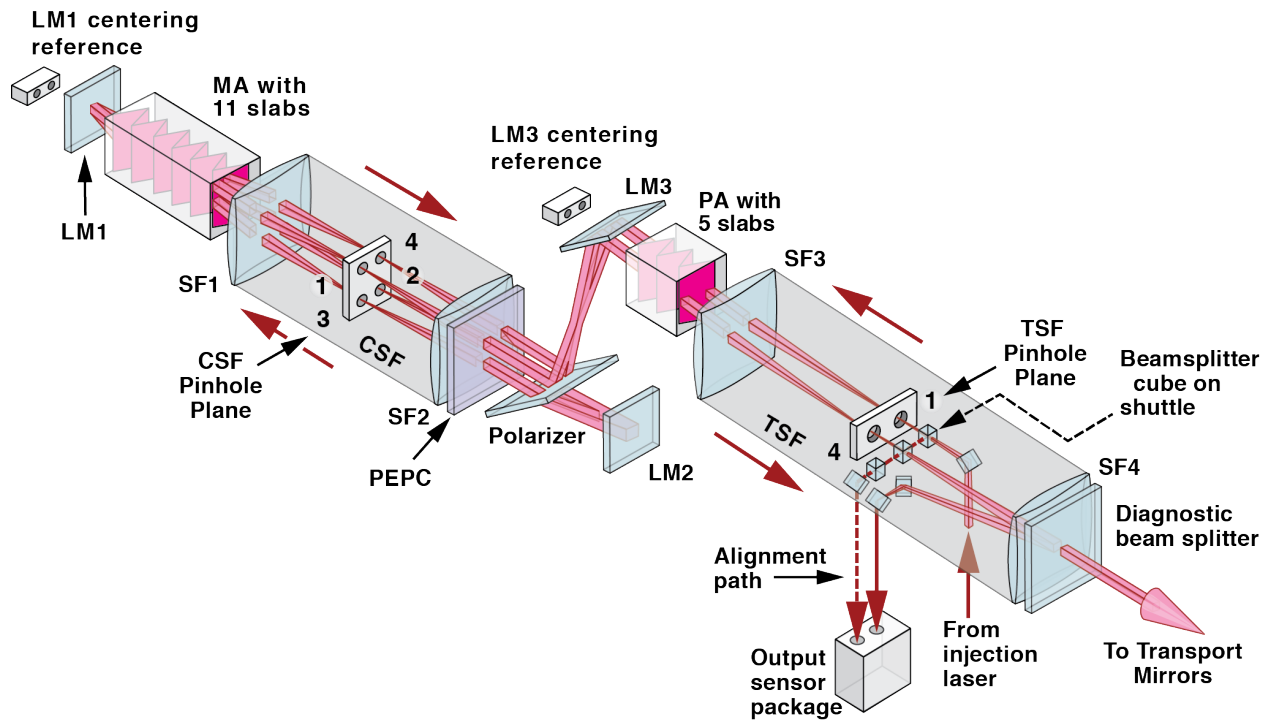


Fig. 131: Each pass in the main amplifiers has a separate pinhole. Centering references are located behind mirrors LM1 and LM3. Spatial filter pinholes serve as pointing references. A beamsplitter cube used only during alignment is available to be placed in the TSF Pass-1 path, the TSF Pass-4 path or at the pass K position where it is used for frequency converter crystal alignment (see Table XIV).

When the OSP camera is focused on LM1, a near-field plane of the main laser, the plane of LM3 is also in focus (LM3 is very nearly in relay with LM1). Thus when focused on the near field, the camera can see both sets of centering references. Centering is accomplished when the LM1 sources are aligned horizontally and vertically with the LM3 sources as in Fig. 132 (a). If the camera is refocused on a far-field plane (at a focus) of the main laser, the back-lit pass-4 pinhole of the CSF and the fiber at the TSF pass-four location can both be seen in the OSP, as shown in Fig. 132 (b). This view provides feedback for pointing. With use of the cross-coupling

relationships between the polarizer and LM3, independent pointing and centering corrections can be made with tip-tilt adjustments of the polarizer and LM3 to bring both the near-field and the far-field images into alignment.

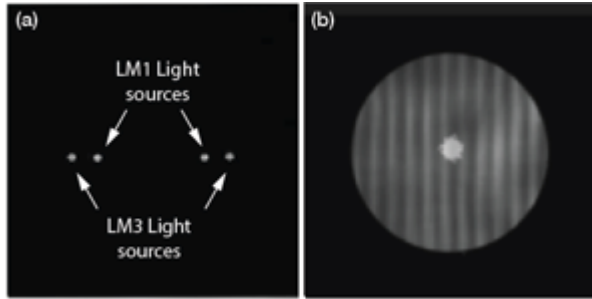


Fig. 132: (a) Near-field pattern of the LM1 light sources centered between the two LM3 light sources as seen by the OSP camera when focused on LM1 (near field) (b) Superimposed back-lit pass-4 pinhole of the CSF and the 1ω fiber in the TSF pass-4 location as seen by the OSP camera when focused on the pass-4 pinhole (far-field).

LM1 is adjusted next. Prior to continuing the alignment sequence, the deformable mirror (LM1) wavefront correction loop is operated to minimize aberrations in the main laser (See Section VI.C.9). A quick summary follows here. Completion of the wavefront correction loop optimizes the quality of main laser far-field images used for subsequent pointing adjustments. A $1.053\ \mu\text{m}$ reference beam from a single-mode fiber, pointed toward the target chamber, is inserted into the TSF pass #4 pinhole plane. A sample of the nearly perfect diffraction-limited wavefront from this source is reflected by the diagnostics beam splitter (DBS) located just after the TSF output lens (SF4) and directed to a Hartmann sensor in the Output Sensor Package (OSP) (see Sections 6.3.8 and 6.3.9, and Fig. 73). The resulting Hartmann image is recorded as the “reference” phase-front of an ideal point source at the TSF pinhole (in effect, this ignores any aberration contributed by SF4). The fiber is

next withdrawn to allow the 1ω alignment beam from the ISP to be recorded by the same Hartmann sensor. The cw (continuous wave) alignment beam from the ISP carries with it wavefront aberrations that were imposed by the optics along its multiple passes through the beamline (now including SF4). During this process, a small half-wave rotator is inserted into the CSF pinhole plane to mimic the role played by firing the PEPC. The adaptive optic control software then adjusts the actuators of the deformable mirror until the Hartman image matches the “reference” Hartman image. It is in this step that residual errors in figure, homogeneity errors, and off-axis beam aberrations are corrected.

Angular alignment of LM1 continues with removal of the pass-1, pass-2 and pass-4 pinholes of the CSF. With the CSF pass-2 centering reference behind LM1 turned on, light from this source is reflected by LM2 and backlights the CSF pass-3 pinhole. LM1 then points the image of this pinhole into CSF pass-4. Because all pinhole planes are in relay with each other, the image of the CSF pass-3 pinhole is successively relayed to the CSF pass-4 and TSF pass-4 pinhole planes. Adjustment of LM1 centers the CSF pass-3 pinhole image on the TSF pass-4 fiber pointing reference as observed with the OSP, which produces an image similar to Fig. 132 (b). Adjustment of LM2 begins with removing all of the CSF pinholes and turning on the pass-1 centering reference behind LM3. A corner cube behind a $50\mu\text{rad}$ aperture is temporarily placed in the TSF pass 1 pinhole position. It retro-reflects light back toward the CSF (which corresponds to the ‘forward’ direction of the pulsed-beam). This light follows the entire four-pass path in the main amplifier (MA), including reflection by LM2. Adjustment of LM2 points the image of the corner cube to match the TSF pass 4 pointing-reference image in the OSP far-

field. See Fig. 133 (a) and (b).

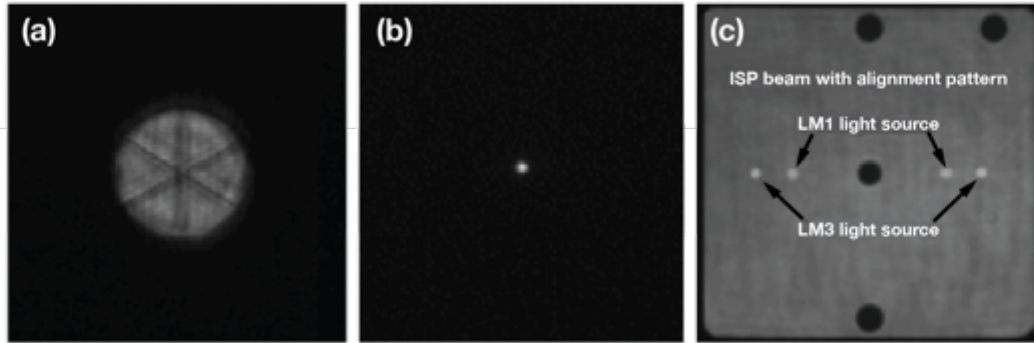


Fig. 133: (a) and (b) are far-field OPS images of the TSF pass-1 corner cube and the TSF pass-4 pointing reference. In (c) a near-field OSP image shows the cw ISP gamma pattern (four dark dots) centered between the LM1 and LM3 light source patterns. The images are not viewed simultaneously. In general, the pixel address of the reference is recorded, and the beam position is adjusted to match.

At this point LM1, LM2, LM3, and the main laser polarizer are self consistently aligned to propagate a beam from the ILS to the output of the main laser. A pair of mirrors in the PABTS is next used to co-align the cw alignment beam from the ISP with the just-completed main-laser alignment. The ISP cw alignment beam is centered in the main laser by “centering” the beam’s ‘T’ fiducial pattern (see Fig. 42 and subsequent text) on the LM1 and LM3 centering references while the OSP camera is focused on the near field, as seen in Fig. 133 (c). When properly pointed, the focus of the cw alignment beam overlaps the location of the 1ω TSF pass-4 fiber reference. The resulting OSP far-field image is virtually identical with the image in Fig. 133(b). With alignment complete, the pump-induced correction (see Section VI.C.9) is added to the closed-loop correction acquired in the step described above; the mirror figure is then

”frozen” and remains unchanged through the rest of the shot cycle. The subsequent rod shot and system shot have this total correction applied.

IX.C. Final Optics and Target Chamber Alignment

Centering the 1ω output beam on the final optics, setting the crystal angles, and pointing the pulsed 3ω beam to the target are then performed in a defined sequence. This starts by setting the tip/tilt of the LM5 and LM8 mirrors and the angles of the frequency conversion crystals to previously established motor reference stepcount values, referred to as the 3ω TCC setpoint.

Centering of the 1ω output on the final optics by angular adjustment of the transport mirrors, LM5 and LM8, requires feedback that is provided, in part, by a pair of insertable corner cubes placed immediately ahead of the final optics assembly (FOA). The two corner cubes are offset by equal amounts on opposite sides of the desired center-line.

Moving the beamsplitter cube shown in Fig. 131 and listed in Table XIV into pass 1 of the TSF allows 50% of the injected ISP alignment beam to continue into the main laser. When it arrives at the pair of corner cubes, the parts of the beam that illuminate the corner cubes are reflected back on themselves and reverse their path back through the entire beamline. If the beam is centered on the pair of corner cubes, the midpoint of the returning spots will be in the center of the beam. When these two samples of the beam reach the TSF alignment beam splitter cube the second time, 50% of the remaining light is directed to the OSP via the alignment path where it is viewed by the OSP camera focused in the near-field. Light from the Pass-1 LM3 light sources is also reflected by the TSF beamsplitter cube and also directed into the alignment path to the OSP. Correct alignment is achieved when the midpoint of the returning spots coincides with the

midpoint of the LM3 light source spots producing an image similar to the one in Fig. 132(a). The corner cube reflections appear instead of the LM1 light source, which is turned off.

Setting the angles of the frequency conversion crystals in the FOA requires looking at back-reflections from both the doubler and the tripler crystals, which are independently adjustable. Beams are pointed into the target chamber at different angles depending on the target design, the presence of backlighting targets, and other details. Therefore, to remain correctly oriented relative to the incoming beams for each shot, the frequency conversion crystals must be angle tuned after beam alignment to the target by looking at reflections from the crystals.

In the TSF, the alignment beamsplitter cube is translated to its pass-K position and rotation of the filter wheel moves the pass-K reference fiber into position behind the cube as illustrated in Fig. 134(a). Light from the reference fiber is reflected to the output sensor (OSP) to establish a reference-pointing image. Then, as seen in Fig. 134(b), the filter wheel rotates to bring the pass-4 fiber and pass-K mirror into position. The expanding beam is collimated by the TSF output lens, continues to the crystals being aligned and is reflected back to the TSF. The first crystal aligned is the tripler. The doubler is tilted off so that the only reflection back to the TSF is from the tripler. When the tripler is in its nominal orientation, this reflection passes through the beamsplitter, reflects off the pinhole wheel mirror, and is also reflected to the OSP where its position is compared with the pass-K reference pointing image. Once this reflection is captured, the control system aligns it to match the fiber reference. The values reported from encoders attached to the tip/tilt mechanism of the crystal stages are recorded as a reference, and the tripler is offset so that the reflection falls outside the OSP field of view. The doubler is then aligned using the second surface reflection. Once the reflection is on-screen, the control loop

offsets the crystal to verify the first surface reflection, and then returns to the second surface and performs the alignment. The tip/tilt encoder values are also recorded for the doubler.

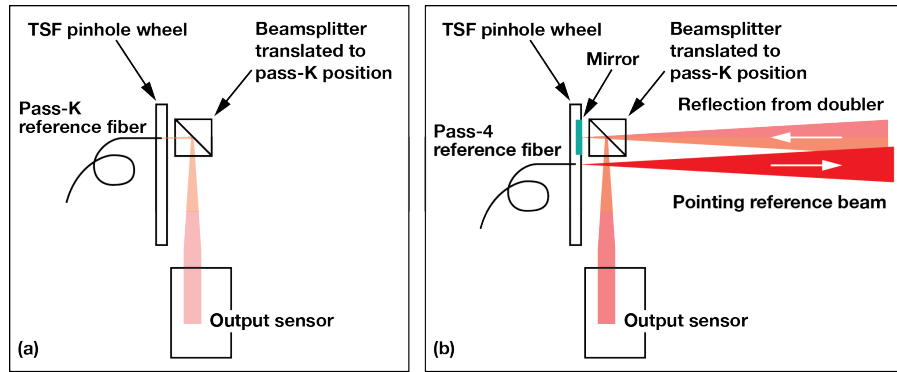


Fig. 134: Reflections from the frequency conversion crystals are used to establish the correct crystal alignment for each shot. (a) Configuration for establishing the pointing reference for reflections from the frequency conversion crystals. (b) Configuration for detecting the reflections from the crystal optics.

Pointing of each beam to the target is accomplished with optical handoff from the 1ω ISP cw alignment beam to an insertable fiber light source in the pass-4 focus of the TSF that has a wavelength close to but not exactly the same as the $0.351\mu\text{m}$ 3ω beam. Light from this fiber point source at $0.375\mu\text{m}$, directed toward the target chamber, expands to fill the output lens of the TSF. The $0.375\mu\text{m}$ fiber source is positioned with slight transverse and focus off-sets from the center of the TSF pinhole to compensate for dispersion in the optics between its wavelength and the true 3ω wavelength. With this compensation, the light from the fiber becomes the alignment beam for pointing to the target. The choice of $0.375\mu\text{m}$ was made for alignment purposes because it is close to $0.351\mu\text{m}$, yet far enough away to be reflected by the transport mirror coatings, which are designed to reflect at the alignment wavelength while transmitting

back-reflected SBS from the target (close to 3ω) that would be dangerous to the OSP diagnostics.

Two target chamber center reference system (CCRS) modules are mounted orthogonal to each other outside of the target chamber on its equator. They each project a beam into the target chamber, and the intersection of the two beam centerlines defines the designated target chamber center (TCC). During installation, the plane of the crossing CCRS beams was set to be perpendicular to the central axes of the converging laser cones. Another instrument called the Target Alignment Sensor (TAS),¹⁸⁶ seen in Fig. 136 (a) and (b), includes precision prisms that serve as references for establishing its own position and four CCD cameras for target alignment.

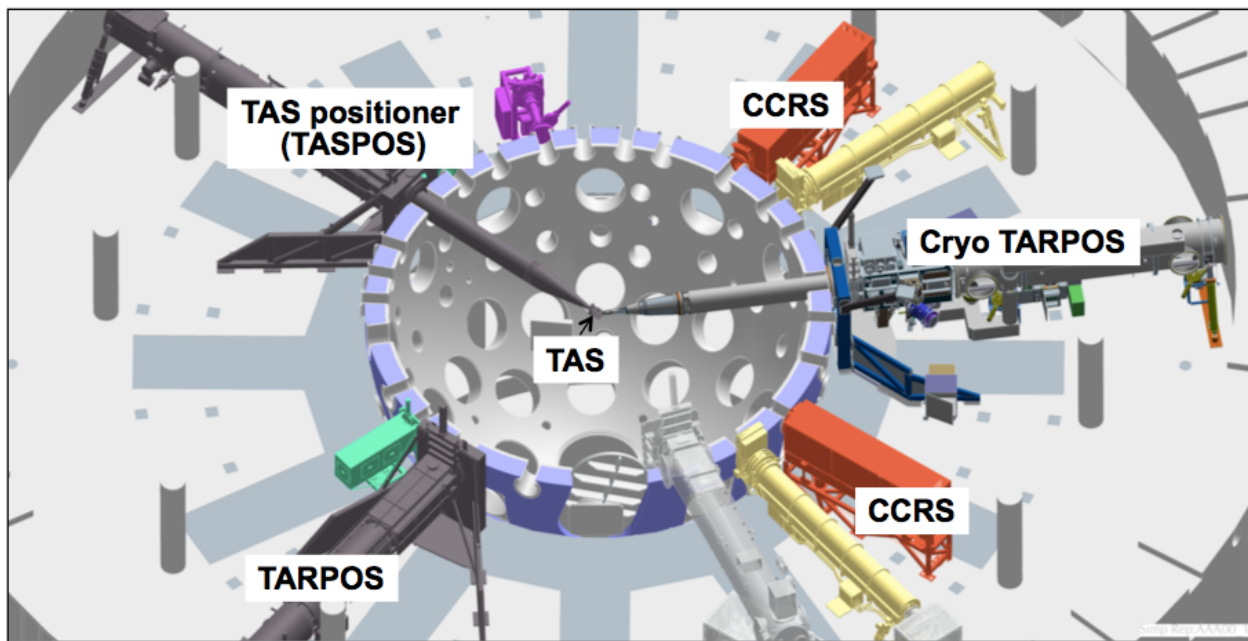


Fig. 135: Target area alignment systems include the target chamber center reference system (CCRS), the target alignment sensor (TAS) and target positioners (TARPOS).

The TAS has two important roles that both rely on optical-feedback: one is for positioning the target to a user-selected location and the other is for pointing the 192 beams to

the target. Positioning of a target begins with positioning of the TAS relative to target chamber center. In this step, light originating in each CCRS is reflected back to the CCRS by precision roof-top prisms carried on the TAS. Cross-hair reticles on the front surface of the prisms give the reflected images sufficient information for adjusting the position and orientation of the TAS.¹⁸⁷ With TAS aligned, its jaw spacing is set for the specific size of the target. Each of these jaws consists of two cameras and a reflective mirror mounted in opposition on identical stages that can be translated vertically away from the center to match the vertical separation of the two target fiducials as viewed by the side CCDs. Often these target fiducials are the top and bottom surfaces of an indirectly driven hohlraum (where the laser entrance holes (LEHs) can be seen. The axes of the jaw stages are assembled to be as precisely parallel as possible, and the prism assemblies are mounted accurately orthogonal to the stages to ensure the axis of the target matches the axis of the beam cones. Then, the target, held by the TARPOS, is inserted into the TAS. In each of the jaw assemblies, the upper or lower CCD image is used to measure the target horizontal position and the side CCD provides information on its elevation. The target positioner is adjusted iteratively using its five degrees of freedom (3 for position, 2 for angle) until the two target fiducials appear at the desired locations on all four TAS cameras.

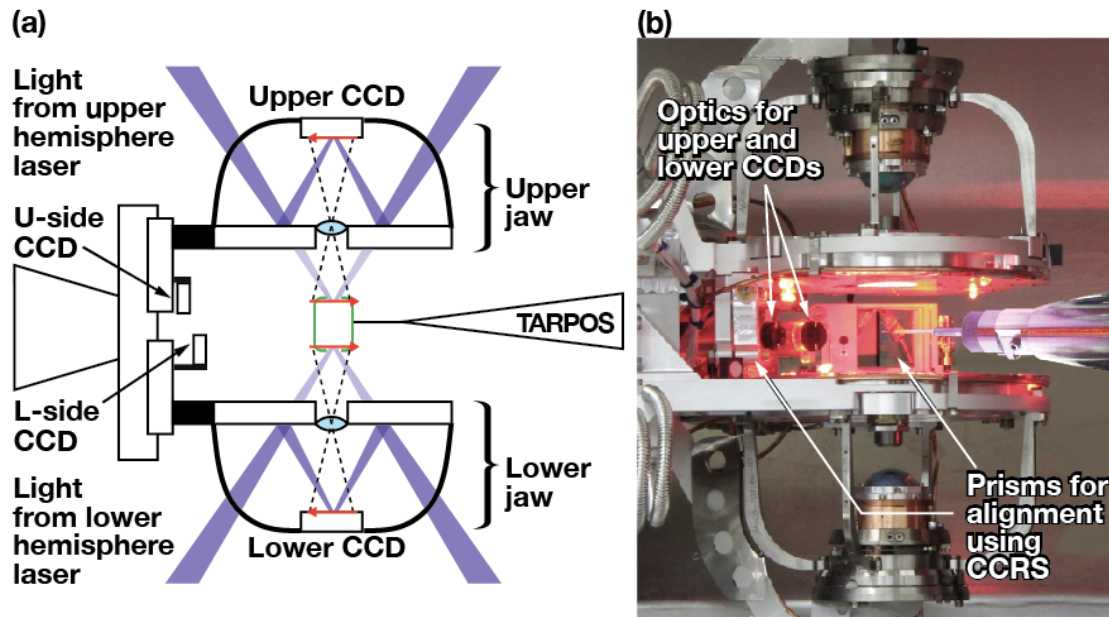


Fig. 136: (a) A schematic illustration of the TAS showing its dual function of defining the target position and guiding beams to their correct position on the target (b) Photograph of the target positioner placing a flat horizontal target between the mirrors of the target alignment sensor (TAS) in position for a shot. This photograph also shows the prisms that are imaged by CCRS to place TAS in the target chamber.

As seen in Fig. 136 (a), focused beams from the laser are reflected from the top and bottom mirrors onto the same upper and lower CCD cameras that are used for viewing the target. This produces images that allow correlation of the beam pointing with the location where each beam will hit the target when the TAS is removed. The spacing from each mirror to the associated target plane is very precisely measured during calibration and then fixed to ensure that the distances from the mirrors to the CCDs and from the mirrors to the target are identical. Because the two stages can independently (but still precisely) adjust the vertical translation of each jaw, the TAS can accommodate varying dimensions of different targets. Typically for ICF targets they are set at equal vertical offsets from TCC to image the top and bottom entrance holes

of the target, respectively. During pointing of the laser beams the control system points each of the beams to a calculated pixel location on each TAS camera based on its desired position relative to the target and the location of the top and bottom CCD chips in the target chamber. The control system calculation for pointing angle corrects for several systematic errors such as those introduced by the detailed shape of the dome and the small wavelength difference between the $0.375\ \mu\text{m}$ alignment beam and the 3ω laser beams.

Adjustments of the LM5 and LM8 mirrors to TAS are accomplished with motor moves that are cross coupled to maintain beam centering at the FOA, In addition, the frequency conversion crystals follow with coupled motor moves to maintain their angle with respect to the incident beam.

Once the alignment loop is complete and the beams are aligned to TAS, the backreflection from the second surface of the doubler is verified and adjusted if necessary. The overall movement of this crystal during beam pointing to TAS is measured using the tip/tilt encoders. The tripler is then adjusted using its tip/tilt encoders to match this offset plus an overall additional offset of $\sim 11.16\ \text{mrad}$ that had been determined earlier by a rocking curve measurement. Rocking curves use a series of low-energy rod shots from one beam at a time to measure the intensity of the 3ω output as function of the tripler tilt angle. The sensors for these intensity measurements are once again, the TAS cameras.

Rocking curves are used to find the optimum tripler angle for frequency conversion. Once the angle for peak conversion is identified the individual crystal offsets from the nominal pass-K pointing angle are established.¹⁸⁷

Prior to the full energy shot, additional small adjustments are made to account for the current crystal temperature and the exact 1ω wavelength specified for the shot.

Additional information and some performance results can be found in references 37 and 185.

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As stated in the abstract for this paper, “the NIF laser is the culmination of more than 40 years of work at Lawrence Livermore National Laboratory dedicated to delivery of laser systems capable of driving experiments for the study of high-energy-density-physics” and in particular for the study of inertial confinement fusion. This quest has involved several generations of scientists, engineers and technologists, at Lawrence Livermore National Laboratory, the supporting Institutions and their Industrial partners. Expertise has been handed down across multiple generations of the participants, accumulating the experience needed for successfully meeting the original requirements for NIF and following the evolution of target-designer concepts as they have matured.

Credit for accomplishing the design, construction and operation of NIF goes to the thousands of people who contributed the technical ideas and the follow-up effort that kept these streams of thoughts going over those 40 years. They all deserve credit for this robust system that can meet the ICF-specified needs for shot-by-shot performance and the routine operation that is planned for its 30-year lifetime. Particular appreciation is extended to the more than 400 contributors who are listed below:

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ACRONYM LIST

1ω , The fundamental frequency of a Nd^{+3} Laser, for NIF the wavelength is 1.053 μm

2ω , The second harmonic of 1ω , for NIF the wavelength is 0.53 μm

3ω , The third harmonic of 1ω , for NIF the wavelength is 0.351 μm

4-pass, Four-pass preamplifier

ADDS, Automated Disposable Debris Shield

AGV, Autonomously-Guided Vehicle

AMC, Amplitude Modulation Chasses

AMP, Advanced Materials Processing

AMPLAB, Amplifier Module Prototype Laboratory

ASE, Amplified Spontaneous Emission

AVLIS, Atomic Vapor Laser isotope Separation

BIS, Beampath Infrastructure, the laser exoskeleton

BK-7, a borosilicate crown glass

BLIP, Beamline Integrated Performance Working Group

CAD, Computer Aided Design

CCI, Cleveland Crystals Industries

CCRS, Target Chamber Center Reference System

CDA, clean dry air

CDR, Conceptual Design Report

CEA, Commissariat à l'Energie Atomique et aux énergies alternatives

CMT, Campaign Management Tool

CPP, Continuous Phase Plate

CSF, Cavity Spatial Filter, A large telescope

DBS, Diagnostic Beamsplitter

DD, Direct Drive

DDS, Disposable Debris Shield

DKDP, Deuterated Potassium Dihydrogen Phosphate

Doghouse, Spool holding disposable debris shields, named after its shape

DrD, Drive Diagnostics, operates at 3ω

FAU, Frame Assembly Units, support laser slabs and flashlamps

FET, Field Effect Transistor

FM-AM, Frequency Modulation to Amplitude Modulation

FN, Franz-Nodvik

FOA, Final Optics Assembly

FODI, Final Optics Damage Inspection system

FR&PC, Functional Requirements and Primary Criteria

FS&T, This Journal, Fusion Science and Technology

GDS, Grating Debris Shield

HMDS, Hexamethyldisiloxane

ICCS, Integrated Computer Control System

ICF, Inertial Confinement Fusion

IL product, Intensity of a laser times the Length of its propagation

ILS, Injection Laser System

IOM, Integrated Optics Module

ISO, International Organization for Standardization

ISP, Input Sensor Package

KDP, Potassium Dihydrogen Phosphate

LIGO, Laser Interferometer Gravitational Wave Observatory

LLNL, Lawrence Livermore National Laboratory

LM1, LM2 and LM3, Main Laser Mirrors

LM1, The deformable mirror, Laser Mirror 1, also a relay plane

LM4 through LM8, Transport Mirrors

LMJ, Laser MegaJoule, the French counterpart of NIF

LoCoS, Location Component State, the name of a major NIF database

LOIS, Large Optic Inspection System

LPOM, Laser Performance and Operation Model

LRU, Line Replaceable Units

MA, Main Amplifier, part of the NIF laser chain

MIRÓ, a physical optics propagation code

MLS, Main Laser System

MOR, Master Oscillator Room

MPAI, a centering reference and pointing backlighter source located behind the end mirror of the four-pass-preamplifier

MRF®, Magneto-Rheological Finishing

NAS, National Academy of Science

NEL, NIF Early Light

NIF, National Ignition Facility

NOL, NIF Optics Lifetime Working Group

OAB Optics Assembly Building

OH, Hydroxyl

OI, Optics Inspection

OPF, Optics Processing Facility

OSP, Output Sensor Package

PA, Power Amplifier, part of the NIF laser chain

PABTS, PreAmplifier Beam Transport System

PAM, Preamplifier Module

PCS, Power Conditioning System

PDD, Polar Direct Drive

PDS, Precision Diagnostic System

PEPC, Plasma Electrode Pockels Cell

PILC, pre-ionization/lamp-check

PMN, lead-magnesium-niobate actuators

Pol, polarizer

PR, Polarization Rotator crystals

Prop92, A physical optics propagation code

PS, polarization scrambler crystal

PSD-1 and PSD-2, Power Spectral Density ranges, See Fig. 66

PSS, Programmable Spatial Shaper

PZT, Lead zirconium titanate

QC, Quality control

QWP, quarter waveplate

Regen, Regenerative Preamplifier

RI, Responsible Individual

RP-0, Relay plane zero

RP-10, The last relay plane before entering the large amplifiers

RP-8, Relay plane eight

RP-8', A relay plane of the laser located within the ISP, optically equivalent to RP-8

RP-9, Relay plane nine

SBS, Stimulated Brillouin Scattering

SD, Shot Director

SF1 through SF4, Lenses of the CSF and TSF

SHG, Second Harmonic Generators

SIDE, Side Illumination Damage Evaluation

SNL, Sub-Nanosecond Laser

sol-gel, a method for producing solid materials from small molecules

SRRS, Stimulated Rotational Raman Scattering

SSD, Smoothing by Spectral Dispersion

TaLIS, Target and Laser Interaction Sphere Working Group

TARPOS, Target positioner

TAS, Target Alignment Sensor

TCC, Target Chamber Center

TCVW, Target Chamber Vacuum Window

TEM, Transverse Electromagnetic

THG, Third Harmonic Generators

TSF, Transport Spatial Filter, A large telescope

VBL, Virtual Beamline, a physical optics propagation code

VRT, Vacuum Relay Telescope

WFL, Wedged Focus Lens

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