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The National Ignition Facility: The Path to a Carbon-Free Energy Future

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ABSTRACT

The National Ignition Facility (NIF), the world's largest and most energetic laser system, is now operational at Lawrence Livermore National Laboratory (LLNL). The NIF will enable exploration of scientific problems in national strategic security, basic science and fusion energy. One of the early NIF goals centers on achieving laboratory-scale thermonuclear ignition and energy gain, demonstrating the feasibility of laser fusion as a viable source of clean, carbon-free energy. This talk will discuss the precision technology and engineering challenges of building the NIF and those we must overcome to make fusion energy a commercial reality.

Key Words: Laser fusion, precision optics, micro-machining, NIF, LIFE

1. INTRODUCTION

The National Ignition Facility shown in figure 1 is a 70,000 meter facility housing a 192-beam precision optical instrument designed to deliver 1.8 MJ of 3ω (351 nm) temporally and spatially formatted laser energy.[1-2] The laser beams propagate 1.5 kilometers and are aligned and pointed to 50 µm RMS, timed to arrive at the target within 10 ps, and power balanced within 2%. Through off-axis aspheric wedged focus lenses, the 3ω lasers are focused into a millimeter-sized volume called a hohlraum. The 192 lasers strike the hohlraum interior creating X-rays that bathe a mm sized fusion capsule. The target is cryogenically cooled to 18 degrees Kelvin and held at constant temperature within ±0.001 degree Kelvin. During the laser pulse, X-rays ablate the target and compress the target to one fortieth of its original radius. Under these conditions, targets will achieve temperatures of 100 million degrees and pressures over 100 billion atmospheres. Within the target, hydrogen isotopes (tritium and deuterium) will fuse to form helium, neutrons, and X-rays. Because of the mass change per Einstein's famous equation $E=mc^2$, there is a net production of energy.

Within three days of Theodore Maiman's demonstration of the laser at Hughes Research Lab, John Nuckels at LLNL predicted that the laser could be used to generate the necessary conditions to achieve fusion ignition and the concept of Inertial Confinement Fusion (ICF) was born.[3] In 1972 the ICF program was started at LLNL with construction of a series of fusion lasers of increasing power culminating in the completion of the NIF in 2008. Fusion lasers are actively being built and operated internationally in multiple laser programs including Omega EP at the Laboratory for Laser Energetics (USA), Laser Megajoule (France), SG-III & SG-IV (China), HELEN & Orion (UK), and LFEX & GEKKO (Japan).

Fig. 1 CAD representation of the National Ignition Facility, a 70,000 m^2 laser facility constructed to demonstrate Laser Inertial Confinement Fusion.

One of the central goals of NIF is to provide the scientific validation of the inertial confinement fusion process creating a technical pathway for economically viable clean, carbon-free energy production.[4] The NIF laser was based on 1980's laser architecture that could be scaled to a 40 cm × 40 cm aperture. 500 Terawatts of electricity is used to generate the pump light for the laser glass slabs. The use of flashlamps on NIF limits the electrical to laser energy efficiency to less than 1%. Additionally the heat that is generated and the current cooling technology limits the shot rate on NIF to only a few shots daily.

Today, the technologies exist to construct lasers with an electrical to laser energy efficiency that is closer to 20% using a laser diode and phosphate based Neodymium-doped laser glass architecture.[5] Higher efficiency is achieved by the narrow spectral emission of the pump source that is spectrally centered within absorption bands of the laser glass. The reduced losses are manifested as lower heat losses which combined with high velocity helium cooling enables multi-hertz laser shot operations.

The NIF facility is currently engaged in the National Ignition Campaign, a period development of a robust, relieable ignition platform with routine operation of the NIF as a user facility by fiscal year 2013.[6] By applying what has been learned about NIF construction and operations of a megajoule class laser with target optimization as part of the National Ignition Campaign, the technology is in place to design and construct a prototype fusion power plant based on Laser Inertial Fusion Energy or LIFE.[7]

2. NIF OPTICS

For a better understanding of the precision engineering challenges of LIFE, an overview of the technical accomplishments of the NIF laser will provide a good basis for comparison. The number and aperture size of the NIF beams is dictated by the total laser power requirement, size limitations of laser glass melting and crystal growth, and finally the laser resistance of the optical materials and surfaces used on NIF. The focusability of the laser beams and the total energy into the target are directly proportional to the quality of the optical components and wavefront correction of deformable mirrors that are used to overcome thermal, optical, and pump-induced distortions within the laser beams. The current spot size requirement on NIF is 600 μm with a pointing requirement of 50 μm RMS for all 192 beamlines.

The NIF laser contains approximately 7,500 large optics.[8-18] These optics are sized depending on their incident angle for the 37 cm × 37 cm square aperture beams. For example, the largest optics such as the laser glass and polarizers at nearly a meter on diagonal are used at Brewster's angle. In the preamplifier section and diagnostic systems there are an additional 30,000 small (<15 cm diameter) optics on NIF.

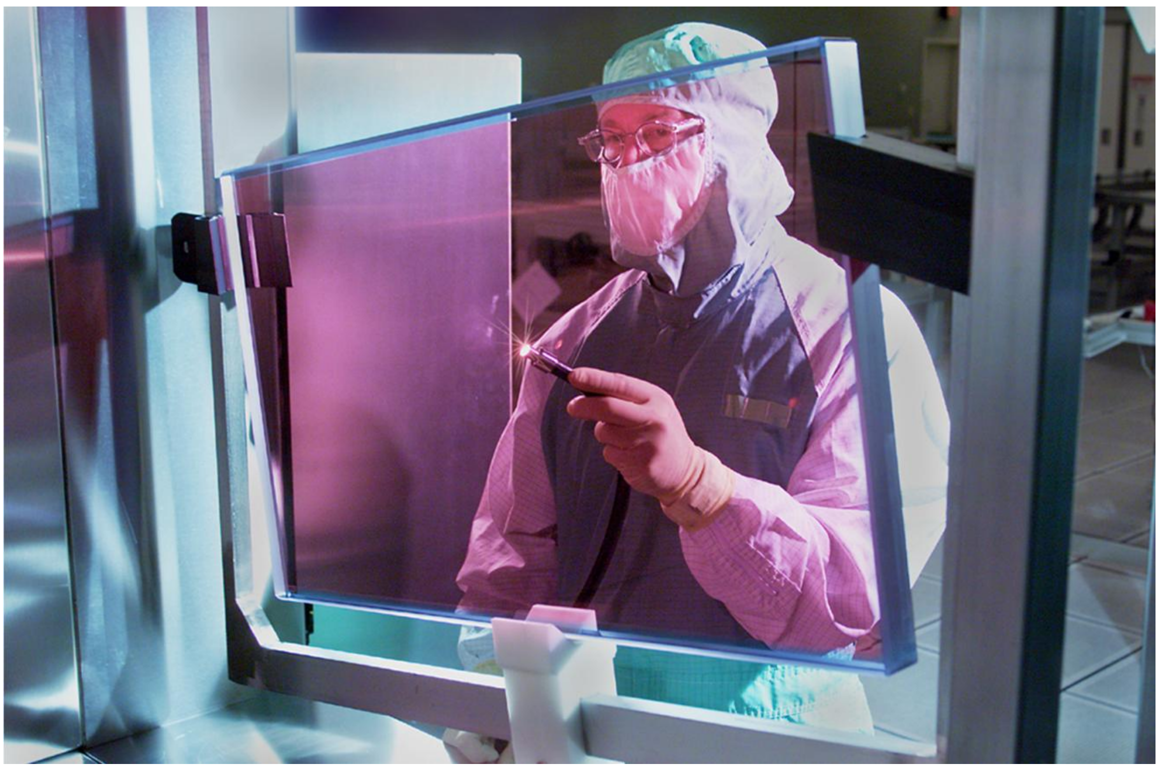

Fig. 2 One of 3,072 Neodymium-doped laser glass slabs used to amplify the NIF laser from a picojoule to 4 megajoules at 1053 nm.

2.1 OPTICS MANUFACTURING

The manufacturing rate needed for the NIF large optics was an order of magnitude faster than what was achieved for the 10 beam 100 kilojoule class NOVA laser, the NIF predecessor constructed at LLNL in the early 1980's. Additionally, the 3ω (351 nm) fluences for NIF optics are an order of magnitude greater than for NOVA optics. To achieve these manufacturing rates, a three-year development program, started in 1994, was aimed at demonstrating deterministic manufacturing methods that could be scaled to meter class optics during a three-year facilitization phase. A one-year pilot production phase commenced to optimize the full-scale manufacturing processes on the new equipment in 2000 followed by an eight-year production phase culminating in optics completion at the end of 2008.

Throughout the optics manufacturing process, the material removal rate decreases from grinding through polishing. The key to reducing the optical fabrication manufacturing time is in quickly converging to the final desired flatness or shape at each manufacturing step thus minimizing the amount of material removal needed during the slower subsequent fabrication steps. Traditionally, optics were manufactured using fairly labor intensive processes such as loose-abrasive grinding and highly skilled opticians with few controls over continuous polisher flatness. This necessitated a high number of iterations between interferometry and polishing before finally meeting specification. These processes have been replaced by deterministic processes such as fixed abrasive grinding, high speed synthetic lap polish out, and computer controls on continuous polishers to maintain lap flatness for improved predictability of when an optic meets specifications. As an example of the improved convergence, the number of wavefront testing iterations for amplifier slabs dropped by an order of magnitude when manufacturing NIF slabs. Double-sided polishing has also been used on NIF windows to reduce their manufacturing time.

Small-tool figuring processes such as Magnetorheological Finishing (MRF) illustrated in figure 3, Computer Controlled Optical Surfacing (CCOS), and Ion Figuring (IF) are all highly deterministic figuring processes that have been employed on NIF to achieve the NIF wavefront specifications of 211 nm P-V and 7 nm/cm RMS gradient. Early experience with these processes illustrated that small periodic spatial frequencies polished into the optical surface, which may meet the P-V and RMS gradient specification, could still lead to phase modulations and hence downstream amplitude beam modulations. PSD specifications resolved this problem by controlling the amplitude of periodic wavefront phase.[19] Polishing tools had to be optimized to meet these new specifications.

2.2 PRECISION FABRICATION FOR HIGH FLUENCE OPERATIONS

The combined surface area of the NIF large optics is 40 times larger than the Keck primary mirror while NIF optics must survive a photon flux that is 19 orders of magnitude greater than the Keck mirror. The highest stressed optics in fusion lasers are those located in the 3ω section of the laser. Improved laser resistance has remained an active area of research since the beginning of the laser fusion program and will continue to be an active area for future improved NIF performance (potential 3ω operations above 1.8 MJ) or reduced operations costs on NIF by increasing optic lifetime. Initiated laser damage is typically about 30 μm in diameter with a melt zone of about 1 μm caused by highly absorbing precursors that are less than 100 nm in diameter. Today, NIF large optics are being consistently manufactured with less than 10^{-13} of the optical surface area covered with 3ω absorbing defects that could initiate laser damage at the peak NIF operating fluence. What might appear at first to be conflicting requirements, the quality of the surfaces needed to improve to reduce the number of nano-absorbing defects that initiate laser damage while the manufacturing time needed to be reduced to lower costs, but in reality, better process control and increased determinism for faster fabrication reduces the surface flaws leading to high laser resistant optics.

For 3ω laser fusion optics, a link between surface flaws such as scratches, fractures, and digs and degraded laser resistance has been clearly established.[20-22] To minimize these flaws, polishing research has focused on the following: minimization of grinding-induced damage, determination of adequate material removal between manufacturing steps to remove sub-surface damage, shear polishing, elimination of rogue particles during polishing, post surface treatment to eliminate absorption centers, and mitigation strategies to arrest damage growth. Through this research, the number of surface initiation sites on NIF 3ω optics has dropped by four orders of magnitude since 1997.

MRF has been demonstrated to significantly increase the 3ω laser resistance of fused silica surfaces by removing polishing-induced subsurface damage.[23] Unlike conventional lap polishing where the mechanical forces of the polishing particles are perpendicular to the workpiece, MRF polishing is using shear forces leading to significantly less fracturing and cracking of the surface. The carbonyl iron within the magnetic field also creates an effective filter that restricts particles larger than the polishing compound from reaching the workpiece. The disadvantage of MRF is that some of the iron becomes imbedded in the hydrated surface layer known as the beilby layer. Iron strongly absorbs at 3ω leading to micro-pitting of the surface when laser irradiated. This micro-pitting leads to a haziness of the optical surface known as grey haze. Chemically etching the surface removes the 100 nm thick beilby layer and embedded iron leaving a 3ω laser resistant surface with no micro-pitting.

Since MRF polishing does not create subsurface damage, it is an ideal tool to determine the subsurface damage depth of the various manufacturing steps used to shape, grind, polish, and figure an optic.[24] Combined with acid etching, a wedge polished into the surface with MRF makes it fairly easy to determine the typical subsurface damage depth that occurred during the preceding fabrication step. Through this work, it has been determined that the conventional wisdom of removing three times the particle diameter of the previous processing step is typically inadequate. It has also been shown that the amount of material needed to be removed on each processing step is extremely process and equipment dependent mandating characterization before being able to come up with processes that yield minimal subsurface damage.

The KDP and DKDP frequency conversion crystals used on NIF are diamond turned due to the high solubility and softness of the crystal making conventional polishing very difficult. Subsurface characterization was used to determine the optimum material removal values for each cut to yield high fluence surfaces. Initial MRF studies of KDP material demonstrate promising results for not only increasing the surface laser resistance, but also reducing the surface roughness caused by the diamond turning lines.[25]

Fig. 3 Magnetorheological Finishing Machine capable of polishing meter class optics to meet the stringent wavefront and laser resistance requirements.

2.3 OPTICS PROCESSING

Although flaw and defect reductions have proven remarkably successful by reducing laser damage precursors by over two orders of magnitude, their complete removal is unrealistic due to the time and cost necessary to manufacture completely flaw-free optics. Therefore, three processing strategies have been developed to make flaws that initiate within the NIF fluence operating range benign. These processes have been termed mitigation because not only are unstable laser initiated growth sites arrested, any features that remain on the optic have minimal forward propagating intensification so that downstream optics are not put at risk of laser damage.

For the NIF laser, a number of mitigation strategies have been developed for specific purposes. One approach is to pre-irradiate the optic with a low fluence and ramp to the operating fluence (or slightly above the operating fluence). This process is also known as laser conditioning and has been applied to laser glass, KDP and DKDP crystals, and optical coatings. A gentle fluence ramp tends to initiate laser damage on a significantly smaller scale or possibly in the case of crystals creates a photo-induced absorption reduction of bulk defects, leaving micron-sized initiated sites within the bulk or on the surface that are stable to the NIF operating fluence. As long as the bulk scatter is less than 0.1%, the crystal is usable on NIF. In the case of crystals it has been found that the optimum pulse length for laser conditioning is a pulse shorter than 1 ns compared to the NIF operating pulse which can exceed 20 ns with a very complex temporal pulse shape.[26-27]

In the case of multilayer high reflector optical coatings, one micron size inclusions imbedded within the film cause a geometrically-induced electric field intensification which leads to the formation of a plasma during laser irradiation.[28] The nodular defect is ejected leaving a micro-pit in the surface. By using a gentle fluence ramp, this ejection can leave non-fractured micro-pitting that is laser resistant above the NIF 1ω operating fluence of 20 J/cm^2 at a 3 ns pulse length.

Laser glass was also pretreated with an off-line laser scanning system.[29] Solid micron-sized inclusions of highly absorbing Platinum are damaged during this pretreatment process. The laser glass slabs have been sorted and binned by Platinum damage sizes. Slabs with no Platinum are placed into the highest fluence sections of the laser. Slabs with larger Platinum size damage are placed into the lowest fluence sections of the laser.

An alternate mitigation approach has been to chemically treat fused silica optics to reduce the atomic flaws within surface fractures and cracks. These fractures are residual subsurface damage from grinding, polishing, or optics handling that are exposed once the beilby layer is etched away. Fractures caused before the polishing process is completed can lead to absorbing polishing compound imbedded into the surface. Suratwala and his team have determined a HF-based Buffered Oxide Etch (BOE) process that removes the absorbing sites within fused silica optics without introducing absorbing etchant byproducts through the use of proper etchant chemistry, agitation, and rinsing.[30] Although the scratches and fractures increase in size and cause increased scatter, the elimination of the absorbing defects within the fractures makes these surfaces flaws benign to the 3ω laser thus reducing surface initiation by 2 orders of magnitude.

A third mitigation strategy that has been developed is the micromachining of initiated flaws to remove the absorbing damaged material. Through the use of CO_2 lasers, fused silica surfaces can be machined to remove absorbing material while leaving a carefully sculpted pit that minimizes the laser amplitude modulation at downstream optic locations. Thermal flow can be used to melt the absorbing material and through surface passivation, a low absorbing pit can be created.[31] A second technique using evaporative machining can also create benign conical pits yielding a high laser resistance.[32]

The mitigation strategy used for KDP and DKDP crystal surfaces is a high speed single crystal diamond drill to also create non-absorbing conical pits.[33] This mechanical approach to micromachining overcomes thermal cracking issues caused by laser machining while creating very reproducible pit geometries that minimizes laser amplitude modulation at downstream optic locations.[34]

Micro-machining mitigation technologies are also being developed for high reflector coatings. Optical interference coatings are composed of multiple materials with different thermal expansion coefficients and absorption spectra leading to significant thermal cracking when attempting the CO_2 laser machining processes used for fused silica. Electric-field intensification due to large conical pit angles created by the KDP crystal high speed diamond drill leads to pits with low laser resistance at the nanosecond pulse length used for the NIF laser.[35] Femtosecond laser machining combines the advantages of a non-thermal ablative process which can create pits with steep sidewalls for minimal electric-field intensification for laser resistant mitigation pits.[36] A mitigation strategy that was developed for sol gel coatings consisted of a syringe with decane to dissolve the coating leaving a circular uncoated region around an optic flaw with little downstream modulation.[37]

One final advantage of the micromachining mitigation technologies is that once all of the initiating flaws are exposed during normal NIF laser operations or off-line laser conditioning scans, the growing sites can be removed leaving a robust laser-hardened optic ready for reinstallation.

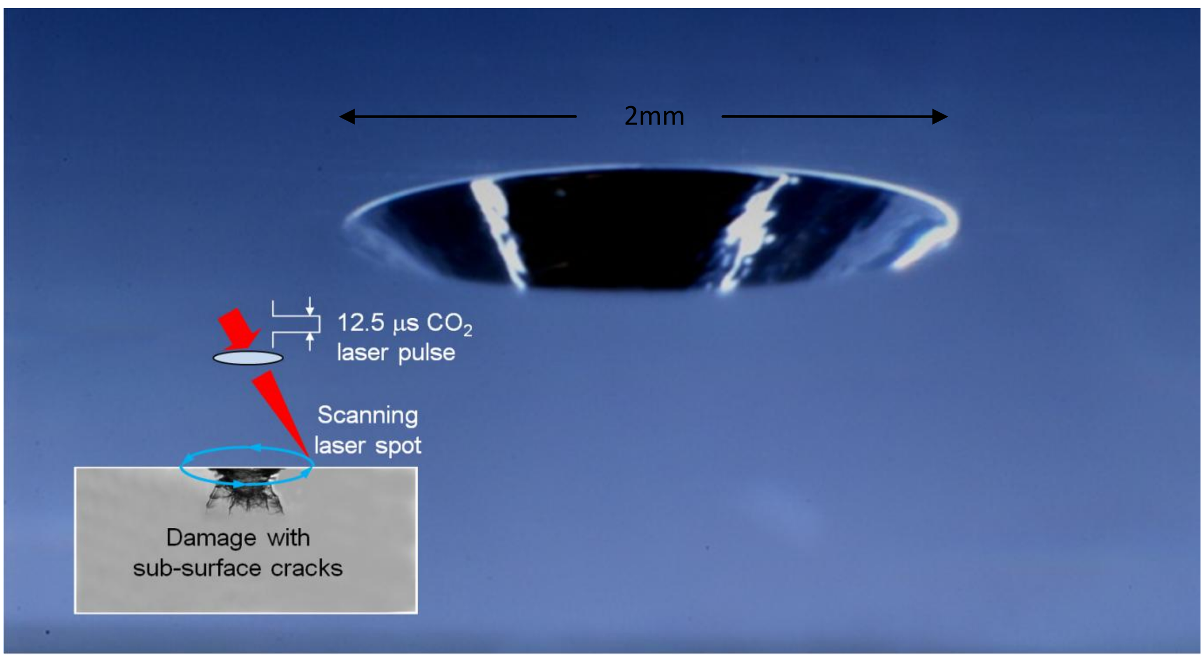

Fig. 4 Fused silica laser damage material is removed by CO_2 laser micro-machining leaving a smooth laser resistant pit and laser hardened optical surface.

2.4 HIGH FLUENCE LASER OPERATIONS

The ability to detect and track growing flaws on NIF optics has a significant positive impact on NIF laser operations. Optics can be laser hardened through a process of flaw initiation, optical removal, and mitigation for reinstallation at a future date. Within NIF there are two inspection systems. LOIS or Large Optic Inspection System is located in the multipass cavity within the 1ω section of the laser to capture all of the laser bay optics from the deformable mirror (LM1) to the diagnostic beamsplitter after the final spatial filter lens. FODI or Final Optics Damage Inspection shown in figure 5, can be inserted at the center of the target chamber between shots to look up each individual beam line to characterize the final optics in the target bay and transport mirrors in the switchyard.[38]

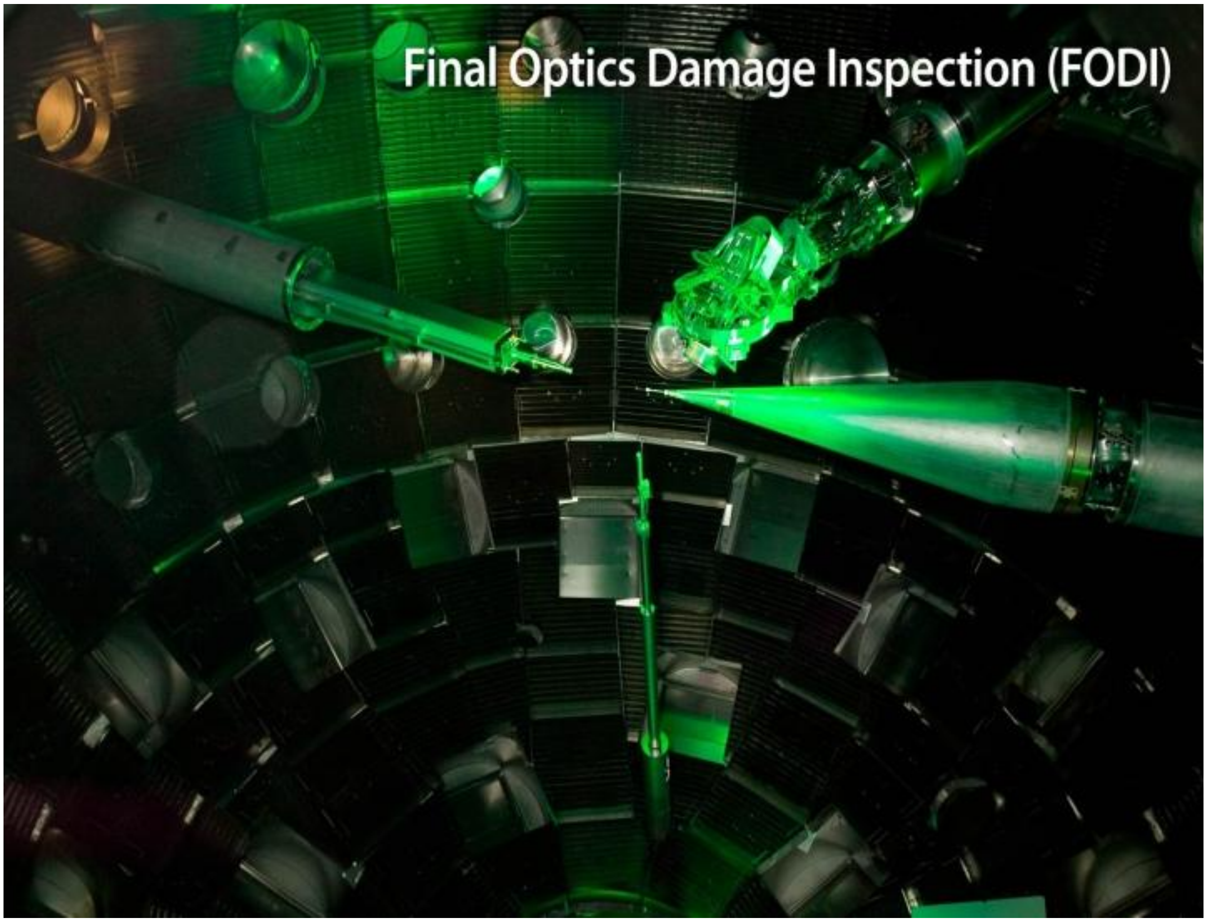

Fig. 5 Final Optics Damage Inspection System is used to track surface flaws on optics for NIF operations.

FODI has to detect and locate 30 μm damage sites with 99% confidence and determine their size to within 15%. A history of the growth of the damage sites is created to help predict, based on the upcoming planned laser shots, the optic lifetime so that the optic can be removed before sites reach 300 μm. FODI must also provide accurate x and y coordinate locations of each flaw for future mitigation and repair. For the range of optic locations in NIF, FODI must operate over a working distance of 5 to 80 meters. This is equivalent to finding a contact lens floating in a 0.5 mile diameter pond from an elevation of 1,500 feet. Finally, FODI must capture images of all of the most critical 960 optics in 192 beams within only two hours while under vacuum at less than 10^{-4} Torr.

To accomplish these stringent goals, a 16 megapixel high resolution camera is located on a six-axis gymbal mounted to a 9,000 Kg five meter long extractable boom. Both dark and bright field images can be collected using an alignment laser. For higher resolution, incoherent side lighting has been installed surrounding the most critical optics. Additionally fiducials have been added to the optics as a reference for the x and y coordinate system used to map each of the flaws. Finally radiometry is used to determine the flaw size as compared to known damage sites on test optics as well as the fiducials.

Programmable beam blockers have also been constructed and installed on NIF.[39] These devices can create low fluence smooth apodized shadows in the NIF laser beam. When combined with the FODI data, these shadows can be co-aligned to growing damage sites on final optics. With low fluence irradiation these damage sites become stable thus extending the operational lifetime of the optic enabling removable during scheduled preventative maintenance periods on NIF.

3. LASER FUSION POWER PLANT

The primary difference between the LIFE (figure 6) and NIF lasers is the shot rate (15 Hz versus 1×10^{-4} Hz) and the electrical to laser conversion efficiency (<1% versus ~20%). These requirements drive a new laser architecture based on laser diodes instead of flash lamps to pump the amplifier slabs. The disadvantage of flash lamp pumping is that much of the broadband spectral emission does not pump the electrons to a higher state allowing for amplified emission, but instead creates phonons or heat. The more efficient diode pumping results in significantly less heat accumulation enabling multi-hertz laser shot operations.

The 7,680 NIF flash lamps are nearly 180 centimeter long cylindrical xenon lamps installed in close proximity to the laser glass slabs. Each flash lamp is driven by 50,000 joules of electricity. Metallic shaped reflectors are located behind the flashlamps to reflect the broadband emitted light into the amplifier slabs. In contrast, diode pumping will require optical components to format and steer the diode light into the amplifier assembly. To accomplish this about 40% of the total optic surface area and 50% of the total optic volume in the LIFE facility is dedicated to pump optics compared to no large optics needed for NIF flash lamp pump delivery.

A significant operational constraint for a power plant is high availability. High reliability and modular serviceability are fundamental attributes needed to achieve an availability of about 99% expected for LIFE plants.[7] The modularity concept has been a primary design philosophy used in most large laser facilities. For example, the Atomic Vapor Laser Isotope Separation (AVLIS) program at LLNL had redundant Copper Vapor Lasers (CVL) that were self-contained beam boxes that ran continuously.[40] During maintenance cycles, a CVL could be removed and swapped with a functional unit. The ability to increase the power of adjacent lasers enabled continuous operations at the desired power levels even during this maintenance period. A similar strategy is envisioned for the LIFE plant.

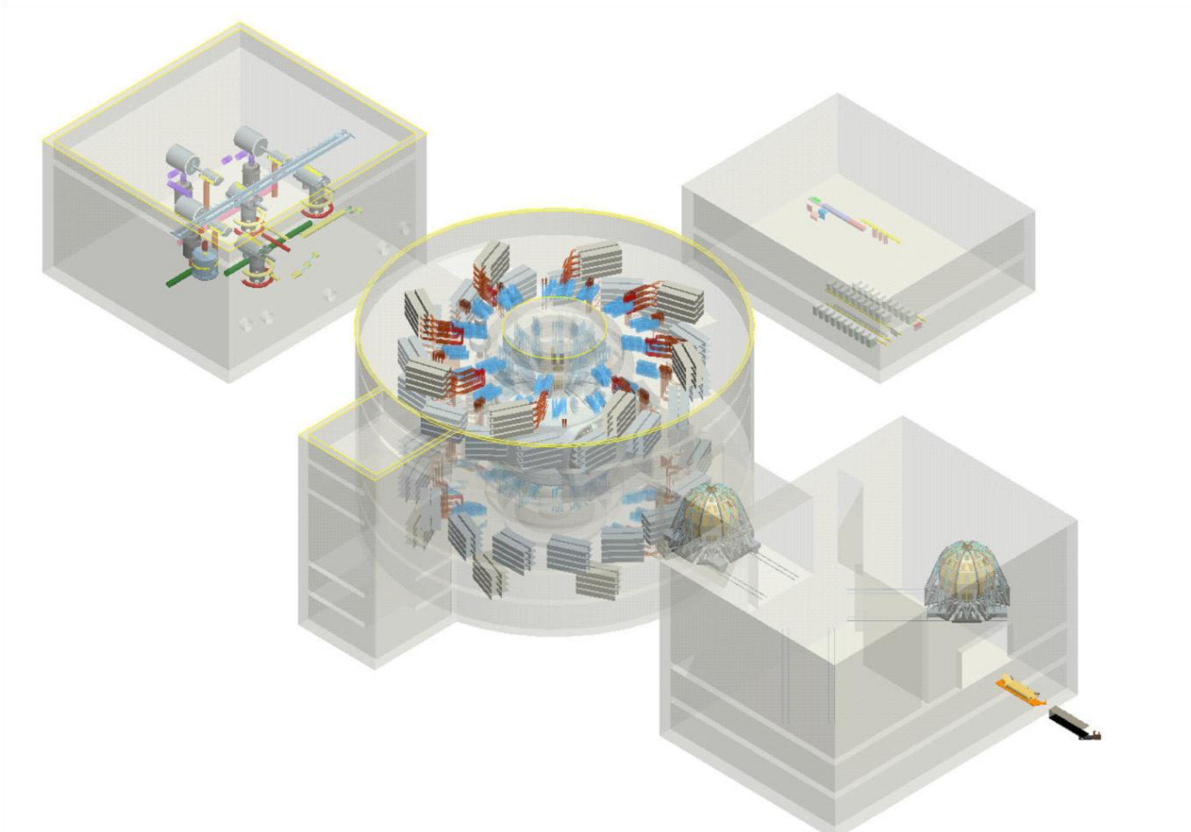

Fig. 6 CAD representation of a future Laser Inertial Fusion Energy (LIFE) power plant.

The 1ω amplifier is envisioned to be a self-contained beam box that would house the amplifiers, spatial filters, diode pumping, diagnostic, and relay optics that would fit into a 30 cubic meter box capable of being transported in a standard tractor trailer truck. Compared to a NIF beamline in the laser bay, this LIFE box is an order of magnitude shorter in length. This is accomplished by an architecture that multipasses optics, folds the beams, uses normal incident laser glass slabs, and a smaller aperture for shorter spatial filters. Both the NIF and LIFE system utilize a Pockels Cell to multipass amplifier slabs and to reduce the size of the building and to minimize the number of optical components. Both systems are based on a four pass configuration, unlike the single pass architecture used for the NOVA laser. Currently the NIF laser bay has two adjacent spatial filters that occupy about 70% of the laser bay path length. The LIFE beam boxes are folded one on top of the other significantly reducing the footprint. The NIF amplifier slabs are used in an open Brewster's angle (56.5 degrees) alternating zigzag pattern to facilitate flashlamp pumping. The NIF configuration also eliminates the need for antireflection coatings on the slabs, however, it consumes a large path length compared to the normal incidence LIFE amplifier assembly. Finally a square aperture of 27 cm (LIFE) versus 37 cm (NIF) significantly shortens the spatial filters and enables the use of lower f-number lenses.

These beam boxes would be manufactured and assembled at commercial vendors and shipped to the LIFE plant ready for installation. Kinematically mounted in the LIFE facility, beam boxes will be easy to swap to remove lasers in need of service and replace with new ones. Built in auto alignment systems would minimize the amount of downtime and the expertise needed by plant operations technicians.

A comparable strategy would be used for the transport mirrors. They would also be housed in a modular box. One of the disadvantages with the NIF beam delivery architecture is a wide range of mirror types and angles are needed to steer the beams into the target chamber. The use of a hohlraum dictates conversion of the linear array of beams in the laser bay into a cylindrical configuration with upper and lower cones of light converging to the center of the target chamber. Because of the short beam box length, a carousel configuration illustrated in figure 6 minimizes the number of different beam transport box configurations and also significantly reduces the overall footprint of the LIFE building.

The number of beam boxes is dictated by the total power requirements for Ignition, laser power handling of the individual optical components, and aperture size. Because of the higher laser resistance at 1ω than 3ω, smaller apertures are used in the amplifier beam boxes compared to the beem steering optics that are the same aperture as NIF final optics.

The additional requirement of high availability for a commercial power plant also factors into the number of beam lines and aperture needed for a LIFE plant. Therefore, improved laser resistance remains an active area of research for future improved NIF performance (potential operations above 1.8 MJ), reduced operations costs on NIF by increasing optic lifetime, and an opportunity to reduce the construction costs of future LIFE power plants through smaller optic sizes.

A LIFE plant would require a comparable production time period to manufacture almost 10× more optics than on the NIF laser. At nearly five times greater surface area and two times more glass volume, optics precision manufacturing will need to transition from a custom optics manufacturing model to true high volume manufacturing.

4. CONCLUSIONS

Precision engineering has been a crucial part of the success of the fabrication of the NIF laser. Throughout the entire facility, extremely high precision is needed to create the pulse formatted beam, amplify it for uniform power balance, point it to the target, and time the arrival of each of the beams to the target. Without this precision, targets would not compress symmetrically to achieve the conditions necessary for fusion. Precision engineering will play a crucial role in the design, development, and construction of future fusion power plants to reduce our dependence on fossil fuels and the potentially damaging impact on the environment.

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