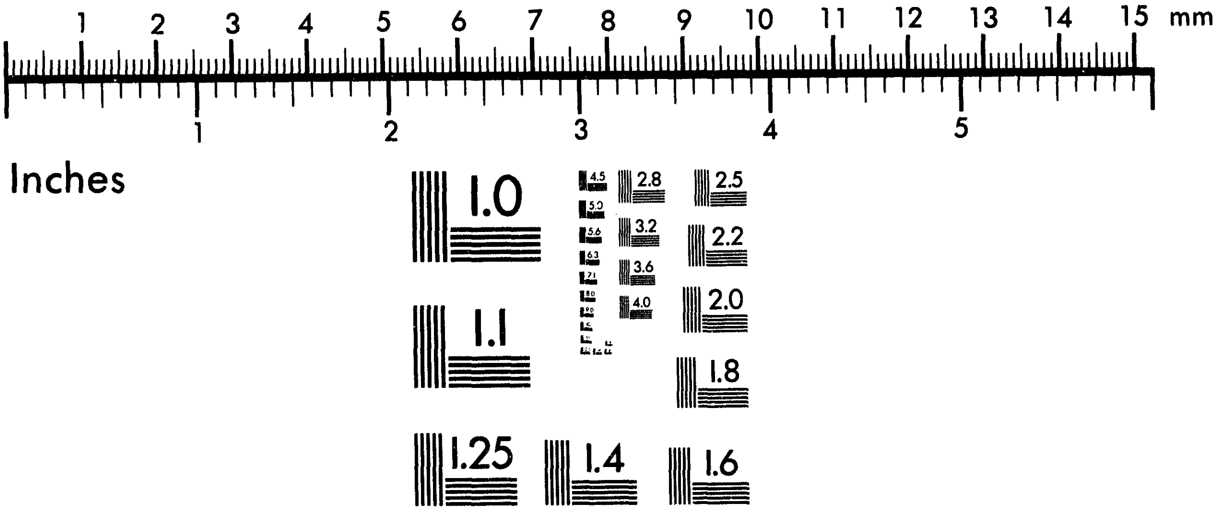
Centimeter

Inches



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National Ignition Facility

Experimental Plan

May 1994

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Contents

Executive Summary

As part of the Conceptual Design Report (CDR) for the National Ignition Facility (NIF), scientists from Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), the University of Rochester's Laboratory for Laser Energetics (UR/LLE), and EG&G formed an NIF Target Diagnostics Working Group.

The purpose of the Target Diagnostics Working Group is to prepare conceptual designs of target diagnostics for inclusion in the facility CDR and to determine how these specifications impact the CDR. To accomplish this, a subgroup has directed its efforts at constructing an approximate experimental plan for the ignition campaign of the NIF CDR. The results of this effort are contained in this document, the Experimental Plan for achieving fusion ignition in the NIF.

This group initially concentrated on the flow-down requirements of the experimental campaign leading to ignition, which will dominate the initial efforts of the NIF. It is envisaged, however, that before ignition, there will be parallel campaigns supporting weapons physics, weapons effects, and other research.

This plan was developed by analyzing the sequence of activities required to finally fire the laser at the level of power and precision necessary to achieve the conditions of an ignition hohlraum target, and to then use our experience in activating and running Nova experiments to estimate the rate of completing these activities. Many of the activities on the NIF have parallels on Nova, including the laser power balance achieved in Precision Nova, hohlraum symmetry tuning on Nova, laser beam synchronization, and plasma diagnostics activation. Not all NIF activities have Nova-equivalent activities; for example, phasing the power in the inner and outer laser beam cones. As in any large facility or project, the facility cannot be turned on and achieve ignition on its first shot. A sequence of fine adjustments or "tuning" is necessary. This situation is analogous to the test flights of a new generation of airplane.

This plan specifies the experimental activities from the point in time when the first laser beams can be fired into the target chamber. A corresponding plan for the laser activation will be compiled by another group, and will be integrated with the activities described in this experimental plan.

The NIF laser will eventually produce an energy of 1.8 MJ. An extremely important part of the experimental plan is that relatively low laser energies will be required for most of the shots in this plan. It is only midway through the activities of this plan that a laser energy of 1 MJ in a shaped pulse will be required. The full 1.8 MJ will be required for very few shots.

This Experimental Plan specifies the shot allocations for the various experimental campaigns required to progress from laser start-up to target ignition. As a result of several years experience in running a large laser system (the Nova laser) and completing experimental campaigns, the shot rate at which experimental campaigns are completed can be reliably estimated. This allows a detailed plan for shot allocation to be constructed. A realistic level of contingency is built into the shot plan with multiplicative laser and diagnostic reliability factors of 0.8. Although it is not expected that the details of the shot allocations will be rigidly followed, the plan provides good strategic guidance from which detailed shot schedules can be developed.

The primary consequence of the Experimental Plan is an estimate of the level of resources required to go from facility start-up to ignition. As part of the resources, the plan defines the sequence of activation of the plasma diagnostics required to achieve ignition. As a consequence, the plasma diagnostics that need to be incorporated in the CDR can be rationally chosen.

This Experimental Plan requires approximately 1600 shots on the NIF, in addition to approximately three months of downtime for installation of the cryogenic target positioner. Emphasis has been placed on starting the experimental program as early as possible in order to minimize time and cost to ignition. Most of the startup experiments prior to beam power balance require low energy on a subset of the beams, and can therefore be started once construction of the first set of beams is complete. In addition, (1) it is estimated that another 400 shots will be required for laser activation and a more accurate number will arise from the laser activation plan; (2) shots will be required for weapons physics and weapons effects experiments not requiring ignition; (3) some shots may be used for inertial fusion energy development.

The annual shot rate on the NIF is estimated to be greater than 600. This, together with the fraction of time devoted to the ignition campaign, will determine the time required to achieve ignition.

1.0 Experimental Plan

1.1 Introduction

The NIF Experimental Plan for achieving fusion ignition is comprised of four stages.

1. Start-up experiments consist of shots to validate the laser performance, including synchronization, smoothing, pointing, spot size, and power balance with temporally shaped pulses, and shots needed to bring diagnostics into operation.
2. Hohlraum tuning experiments, in which beam phasing is adjusted to minimize the time-dependent asymmetry in x-ray drive.
3. Cryogenic pre-ignition experiments, which include low-convergence and high-convergence implosions with dudded fuel. These experiments will allow close-in diagnostics to obtain data for a detailed comparison with design calculations.
4. Ignition experiments.

The Experimental Plan is structured to maximize utility of the facility as its capabilities become available. Experience with Nova has been used to anticipate the experiment steps to achieve ignition and to predict the number of shots required to achieve each step. During the ignition campaign, there will be parallel experiments on weapons physics, weapons effects, and inertial fusion energy.

The NIF and its Experimental Plan are heavily influenced by experience on laser facilities of increasing size and complexity that have been successfully built and operated at LLNL. In its ten years of operation, the Nova laser has evolved from an experimental laser to a high-shot-rate, well-diagnosed, precise target-shooting facility that regularly runs 17 to 20 hours per day. The target shooting program has changed from a locally devised and executed program of experiments on poorly understood hohlraums to a nationally agreed-upon program[1] of experiments scheduled and executed by an inter-laboratory group and monitored by a federal advisory committee, the Inertial Confinement Fusion Advisory Committee.

The annual shot rate on Nova has increased by a factor of 2.5 since 1986, as shown in Figure 1. There are many factors determining the shot rate of a large facility. The increase in the shot rate is a result of many improvements in the operational procedures of the facility and an increase in demand for experiments.

In parallel with the increase in the number of laser shots, the quality of target experiments has improved. From 1985–1990, target diagnostics on Nova were improved from a very basic set of eight Nova Phase I diagnostics to a set of ~60 state-of-the-art diagnostics[2] listed in Table 1. During the Precision Nova Campaign, the reproducibility, power, energy balance, and pointing capability of Nova was also improved. The goals of a power balance of 5–8% over a shaped laser pulse and pointing accuracy of 30 μm rms have been demonstrated, as shown in Figure 2.

Target shooting campaigns on Nova have evolved to quantitative demonstrations of the target parameters relevant to NIF. A set of target physics milestones was agreed upon by the National Academy of Science Review Committee in 1991. Nine out of the

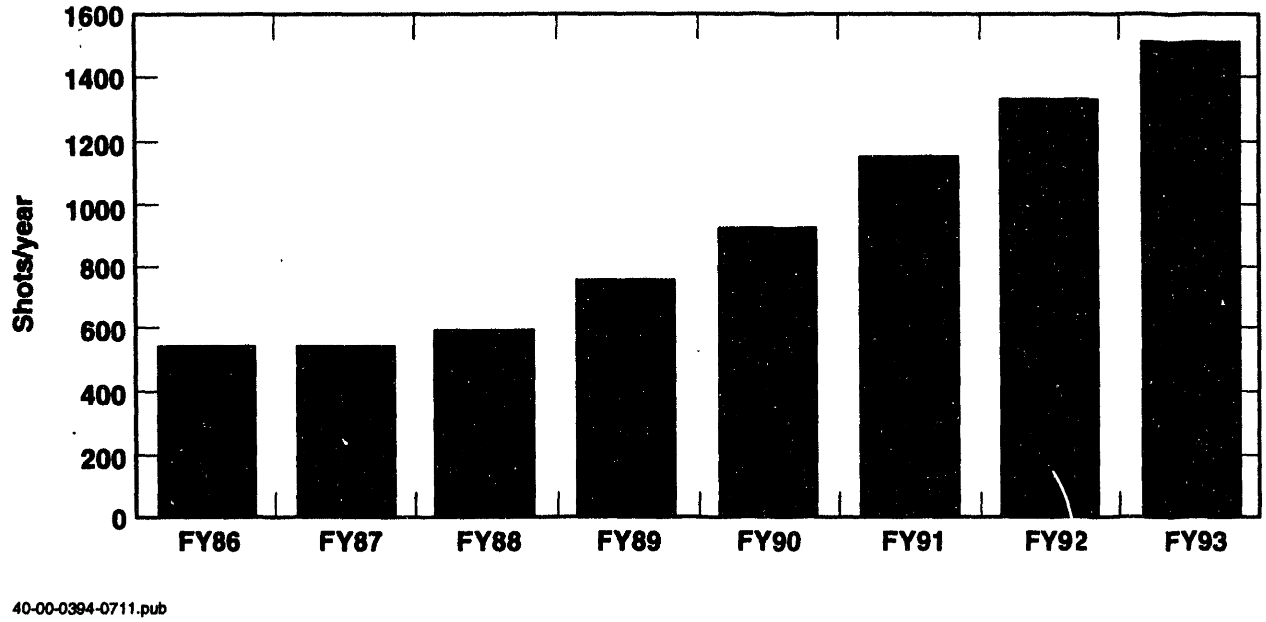


Figure 1. The Nova laser's annual shot rate has increased by 2.5 since 1986.

twelve milestones were completed by a joint LLNL/LANL team of scientists by early 1994.

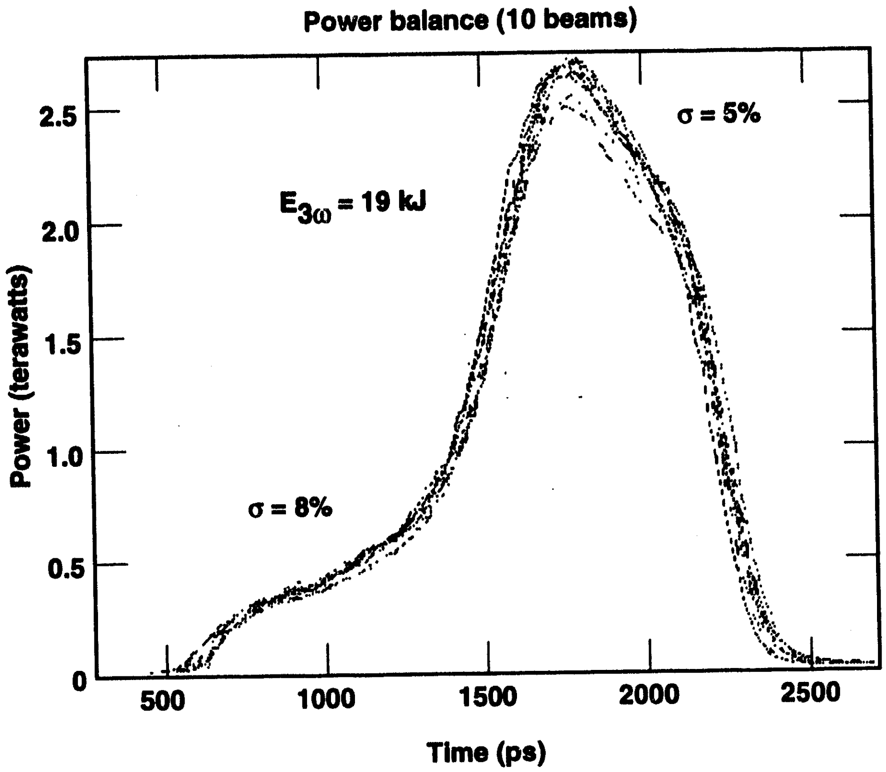
The NIF Experimental Plan resulted from analyzing the sequence of activities required to fire the laser with the power and precision necessary to achieve the conditions of an ignition hohlraum target, as described in the NIF CDR,[3] Sections 3.1.2 and 3.2. The experience in activating and running Nova experiments was then used to estimate the cost and time to complete these activities. Many of the activities on the NIF have parallels on Nova. Some examples of activities similar to Nova activities are hohlraum symmetry tuning and plasma diagnostic activation. However, an example of a NIF-unique activity is phasing the power in the inner and outer beam cones for controlling the time-dependent, hohlraum drive symmetry.

This plan specifies the experimental sequence beginning when the first laser beams can be fired into the target chamber, and continuing until ignition. It has been integrated with the corresponding plan for laser start-up, and is summarized in Table 2.

As a result of several years of experience operating Nova, the number of shots required to complete an experimental campaign can be reliably estimated, allowing a detailed plan to be constructed. The plan specifies the shot allocations for the various experimental series required from laser start-up to target ignition. It also provides an estimate of the plasma diagnostic and laser resources required for each step in the experimental campaign. The plan defines the sequence of activation of plasma diagnostics required to ascertain the achievement of ignition.

Table 1. Sumary of Nova diagnostics.

		No.
X-ray imagers		
Wolther x-ray microscope	22X	1
• Gated x-ray pinhole camera	GXI, WAX, GACS	4
• Gated soft x-ray framing camera	SXRFC	1
Streaked soft x-ray imager	NSDSS	1
• Ring aperture microscope	RAM	1
Streaked slit/array imager	SSC/SMP	2
Kirkpatrick Baez microscopes	8X	2
Axial pinhole cameras	APH	2
• Large area backlighting		
Point projection spectroscopy	PPS	2
• Soft x-ray microscope		1
XRL beam divergence camera	Cube	1
XRL spatial coherence diagnostic		1
X-ray spectrometers		
• Streaked crystal spectrometers	NSCS, Keanetech	2
High-resolution streaked specrometer	HICKS	1
Static crystal spectrometers	Henway, POS	6
High-resolution cyrstal spectrometer	HOPS	1
Gated crystal spectrometers	TOPS	1
Gated imaging XUV spectrometer	IXUVS	
Laue spectrometer	HETS	1
• Low-resolution x-ray diode array	Dante	2
Low-resolution, high-energy fluorescers	FFLEX	2
Spatial coherence diagnostic		1
Grazing incidence spectrometer	COFFIN	1
• High-resolution spectrometer	HIRES	1
Time-resolved soft x-ray spectrometer	SFFD	1
Gated grazing incidence spectrometer	McPIGS	1
Neutron diagnostics		
Yield	Cu, In scin	3
Bandtime	NETMCP, Ga	3
Burnwidth	NTD & GaAs	2
• High-resolution, high-sensitivity spectrometer	LaNSA	1
Medium-resolution neutron spectrometer	NTOF	3
• Ultra-high-resolution spectrometer	fNTOF	1
High-resolution, high-sensitivity spectroscopy	LANL Ti	1
Neutron imager	MPAM	
Optical spectrometers and imagers		
Streaked/gated imager	SOP	2
Streaked optical spectrometers	SOS, BSS	4
Multiple streaked spectroscopy	MATRES	1
Spatially discr. streaked optical spectroscopy	SDOSS	1
Calorimeter array	EBM	1
Full beam backscatter	SOS5	1



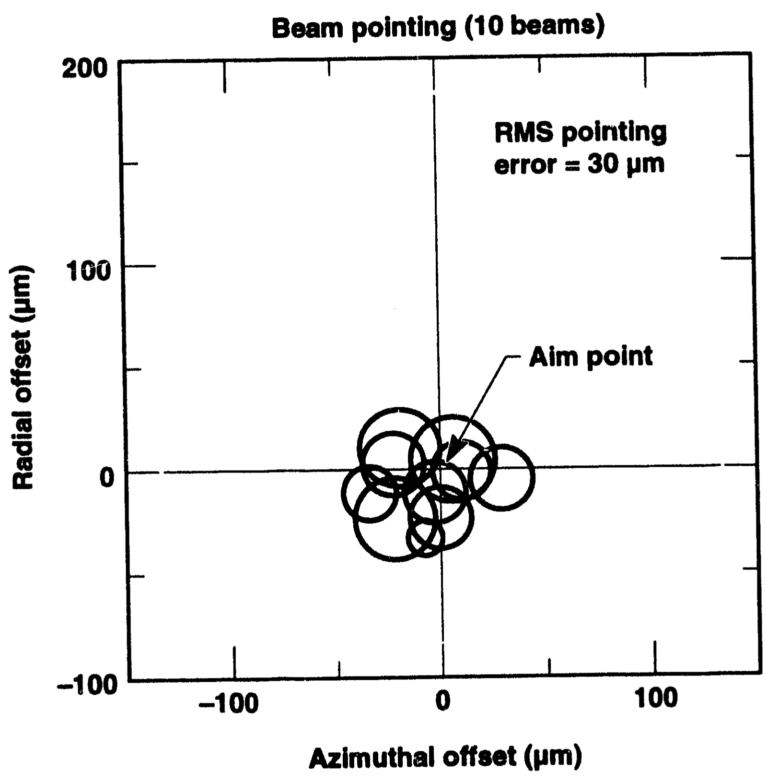


Figure 2. Nova laser power balance and beam pointing.

Table 2. Summary of the experimental plan for NIF.

No.	Experimental Campaign	E, τ	Shots†
1.2.1	Startup Experiments	(per beamlet)	
	.1 Disk shots, core diagnostics	1 kJ, 0.1 to 1 ns	50
	.2 Beam synchronization at target	100 J, 0.1 ns	90
	.3 Beam smoothing implementation	2 kJ, 5 ns	80
	.4 Beam pointing, spot size	100 J, 0.1 ns	280
	.5 Power balance	1-1.5 MJ, shaped	70
1.2.2	Hohlraum symmetry experiments	(total energy)	
	.1 Square pulse hohlraums	0.5 MJ, 4 ns	70
	.2 Square pulse implosions	0.5 MJ, 4 ns	60
	.3 Tuning: filling	0.5 MJ, 4 ns	40
	.4 Tuning: instabilities	0.5 MJ, 4 ns	50
	.5 Tuning: T_r vs time	1.0 MJ, shaped	20
	.6 Tuning: shock timing	1.0 MJ, shaped	50
	.7 Tuning: time-average symmetry	1.0 MJ, shaped	70
	.8 Tuning: time-dependent symmetry	1.0 MJ, shaped	210
1.2.3	Cryogenic and pre-ignition experiments	(total energy)	
	Install cryogenic positioner		3 months
	.1 Low convergence and dudded cryogenic implosions	1 MJ, 5 ns	120 *
	.2 High convergence, sub-ignition	1 MJ, shaped	110
	.3 High yield, activation check	1 MJ, 5 ns	20
1.2.4	Ignition shots	(total energy)	
	.1 Ignition experiments	<1.8 MJ, shaped	30
	.2 Parameterization of ignition	<1.8 MJ, shaped	170

* Effective number of shots.
† The uncertainty in the estimated number of shots is perhaps a factor of two.

This plan requires approximately 1600 shots on the NIF, in addition to approximately three months of downtime for installation of the cryogenic target positioner. Emphasis has been placed on starting the experimental program as early as possible to minimize the time and cost to achieve ignition. Most of the startup experiments prior to beam power balance require low energy on a subset of the beams, and can therefore begin when start-up of the first set of beams is complete. Accordingly, the plan calls for interleaving experimental measurements with the final stages of laser construction as shown in Figures 3 and 4. Beam power balance experiments and many of the hohlraum

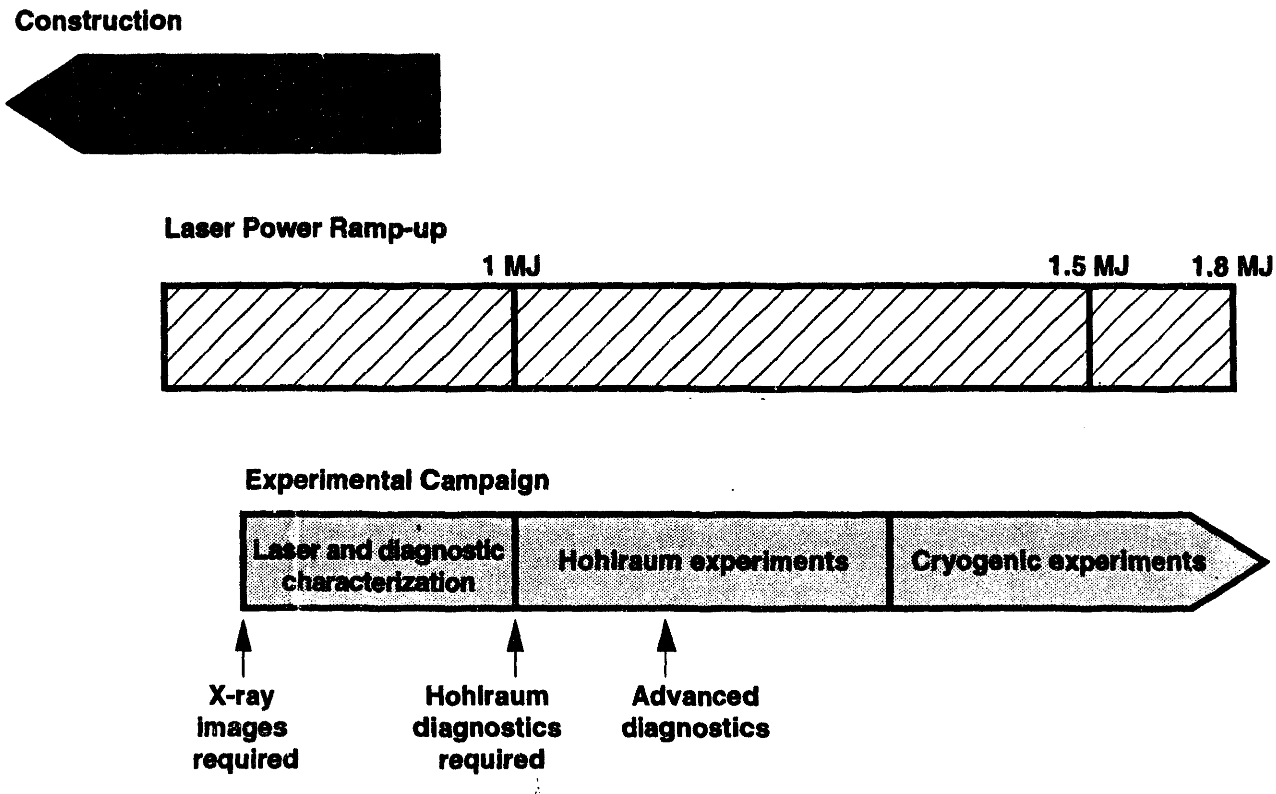


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Figure 3. National Ignition Facility construction, activation, and operation strategy.

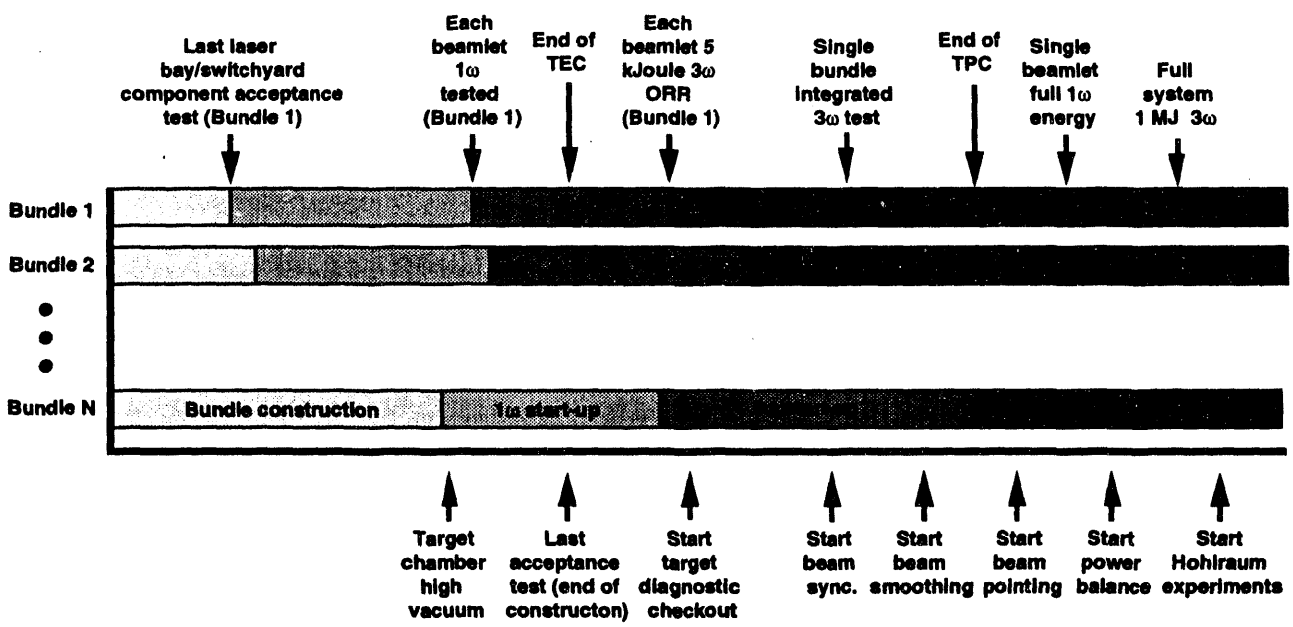

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Figure 4. National Ignition Facility laser activation and target experiments.

tuning experiments require beam energies of 1 MJ or less. The later hohlraum tuning and the pre-ignition experiments require 1–1.5 MJ. A timeline for the laser, experiments, and diagnostic activities is shown in Figure 5.

1.2 Experimental Campaigns for Fusion Ignition

The shot estimates in this section are shown in Table 3. In this table, a reproducibility factor from one to three, based on Nova experience, is assumed for reproducibility checks. Assumed reliability factors of 0.8 for the laser and 0.8 for the diagnostics are multiplicative. There is uncertainty in these estimates, and an estimate of the uncertainty in the total is ±30%.

1.2.1 Startup Experiments. These experiments require about 500 shots, detailed in Sections 1.2.1.1 through 1.2.1.5, at relatively low energies of few hundred Joules to a few kJ per beamlet. These experiments include disk shots for the measurement and adjust-

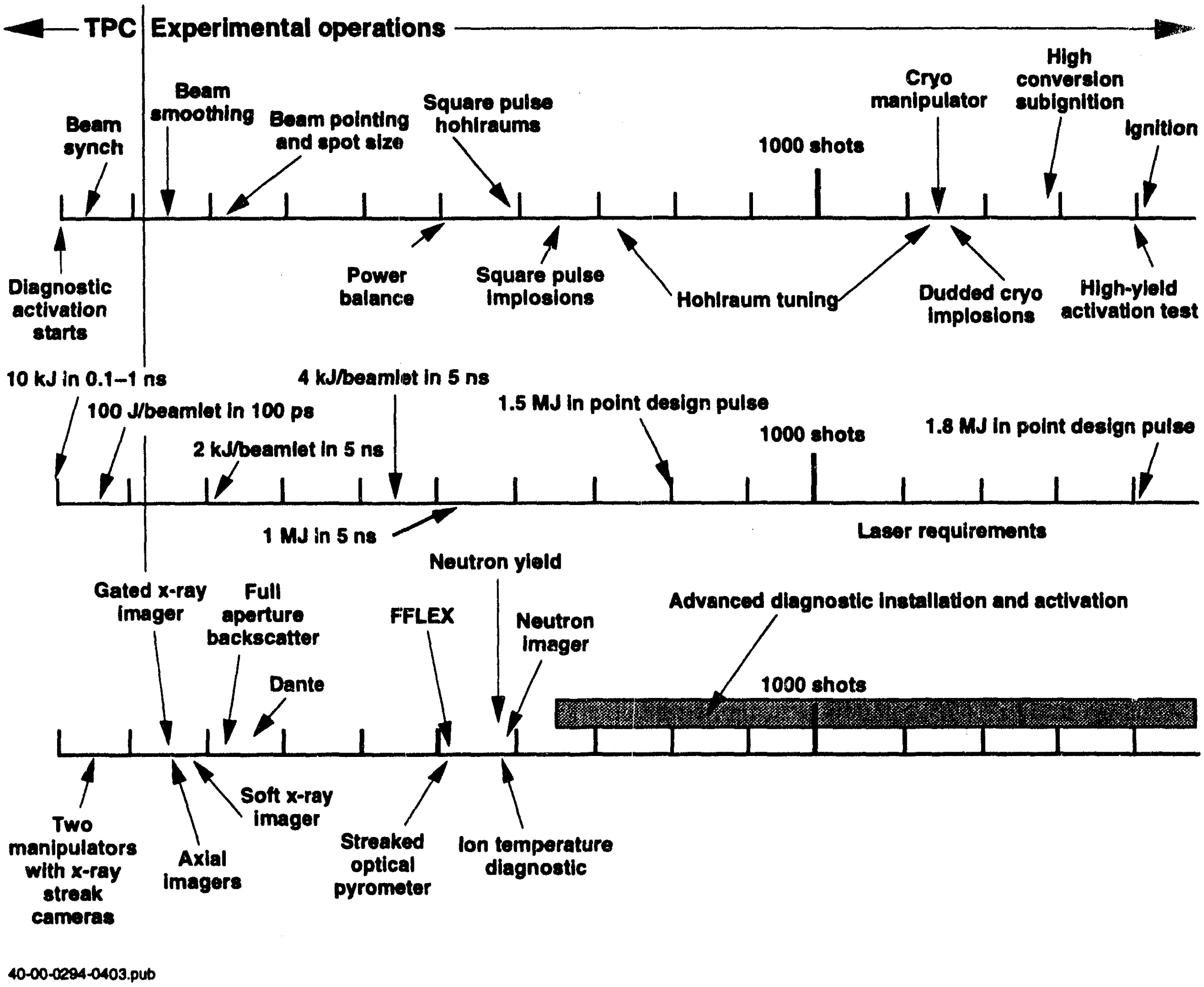

Figure 5. Shotline for inertial confinement fusion experiments.

Table 3. Detailed summary of shot estimate for each experimental campaign.

Assumed reliability			
Laser			0.8
Diagnostics & targets			0.8
1.2.1.1 Disk shots for core diagnostics			
Dante			
	calibration	4	
	repeatability	2	
	reliability	0.64	13
FAB			
	calibration, testing	4	
	repeatability	2	
	reliability	0.64	13
FFLEX			
	x-ray screening	4	
	repeatability	2	
	reliability	0.64	13
SOP			
	timing,background		5
	testing	4	
	repeatability	2	
	reliability	0.64	13
axial viewer			
	pointing, resolution	4	
	repeatability	2	
	reliability	0.64	13
GXI			
	timing, resolution	4	
	repeatability	2	
	reliability	0.64	13
x-ray streak			
	timing, noise control	4	
	repeatability	2	
	reliability	0.64	13
soft x-ray imager			
	instrument damage	4	
	repeatability	2	
	reliability	0.64	13
Parallel tasking			
saves 50%			Total = 53

1.2.1.2 Beam synchronization at target			
	set up		20
	15 beams /shot	16	
	reproducibility	1.5	
	iteration	2	
	reliability	0.64	75
		Total =	95
1.2.1.3 Beam smoothing implementation			
	set-up		10
	groups of 50	5	
	spot sizes	3	
	reproducibility	2	
	reliablity	0.64	47
	problem correction		20
		Total =	77
1.2.1.4 Beam pointing and spot size			
pointing			
	set-up	20	20
	groups of 30	8	
	reproducibility	3	
	iterations	3	
	reliability	0.64	112
focusing			
	groups of 30	8	
	reproducibility	3	
	z position	4	
	reliability	0.64	150
thin wall hohlraums			
	reproducibility	3	
	iterations	2	
	reliablity	0.64	9
		Total =	283
1.2.1.5 Power balance			
	calib. IBD, grps. 30	8	
	power levels	4	
	reliablity	0.64	50
	power balance	1	
	reproducibility	3	
	iterate	5	
	reliablity	0.64	23
		Total =	73

Table 3. (Cont.)

1.2.2.1 Square pulse hohlraums

set-up		10
power levels	2	
reproduciblity	3	
shield geometries	3	
SOP & Dante	2	
reliablity	0.64	56
	Total =	66

1.2.2.2 Square pulse implosions

neutron diag. check		5
convergences	4	
pointings	3	
reproduciblity	3	
reliablity	0.64	56
	Total =	61

1.2.2.3 Hohlraum tuning 1: Bulk filling characterization

set-up		10
power levels	3	
pulse length	3	
iterations	2	
reliablity	0.64	28
	Total =	38

1.2.2.4 Hohlraum tuning 2: Plasma instabilities

set-up		10
power levels	3	
reproducibility	3	
beam smoothing	3	
reliablity	0.64	42
	Total =	52

1.2.2.5 Hohlraum tuning 3: Temperature vs. time

set-up		5
hohlraum sizes	3	
reproducibility	3	
reliablity	0.64	14
	Total =	19

1.2.2.6 Hohlraum tuning 4: Shock timing

set-up		5
hohlraum sizes	3	
reproducibility	3	
pulse shapes	3	
reliablity	0.64	42
	Total =	47

1.2.2.7 Time-averaged symmetry

set-up		5
lengths	5	
pointings	3	
reproducibility	3	
reliablity	0.64	70
	Total =	75

1.2.2.8 Hohlraum tuning 6: Time-dependent asymmetry

pulse length	10	
reproducibility	3	
pulse shape	5	
pointing	3	
hohlraum lengths	3	
reliablity	0.64	
partial mapping of parameter space	10%	211
	Total =	211

Install cryogenic target positioner
3 months

1.2.3.1 Dudded cryogenic implosions

Low rate, 40 shots		
probably equiv. to		120
	Total =	120

1.2.3.2 Higher convergence, sub-ignition experiments

convergences	4	
pulse shapes	3	
reproducibility	2	
target types	3	
reliablity	0.64	112
	Total =	112

Table 3. (Cont.)

1.2.3.3 High yield DT shots		
yield levels	3	
reproducibility	2	
iterate	2	
reliablity	0.64	19
	Total =	19

1.2.4.1 Ignition experiments		
configurations	2	
reproducibility	3	
iterate	3	
reliablity	0.64	28
	Total =	28

1.2.4.2 Parameterization of ignition targets		
laser energy	5	
peak temperature	3	
capsule dimensions	3	
gas fill	3	
peak power duration	2	
surface finish	4	
asymmetry	5	
reproducibility	2	
reliablity	0.64	
partial mapping of parameter space	1%	169
	Total =	169

Total number of shots	
	1599

ment of laser beam synchronization, validation of beam smoothing techniques, and characterization of beam pointing and spot size. In parallel, start-up and checkout of the optical and x-ray, spectral and imaging diagnostics will occur. The large number of shots is mainly due to the large number of laser beams, but the laser shot rate for this activity should greatly exceed the three per day specified in the NIF Functional Requirements[4] because banks of amplifiers can be fired in rotation and several beamlets will be fired on each shot.

An additional 70 shots at 1–1.5 MJ are planned for characterizing the beam power balance with square and temporally shaped pulses.

The shot allocations, descriptions, and requirements for each of these experiments is as follows.

1.2.1.1 Disk shots for core diagnostics

Laser energy required: 1 kJ in 0.1–1 ns

Number of shots required: 50

Special requirements: Core diagnostic set, excluding neutron and shock break-out diagnostics, installed (WBS 1.4.4.2, .9, .10, .15, .17; 1.11.6.3.1, .2, .3, .7).

The twelve-inch manipulators, x-ray streak cameras, time-resolved x-ray imager, static x-ray imagers, soft x-ray imagers, full-aperture backscatter system (FABS), soft x-ray power diagnostic, and filter fluorescer will be activated by disk shots. These are listed in Table 4 along with the CDR sections containing the conceptual design descriptions of the diagnostics. Some shots will be at 100 ps for instrument timing. Streak cameras necessary for beam synchronization will be activated first; remaining diagnostics will be activated as needed in parallel with subsequent tasks.

Deliverables: Core diagnostic set, exclusive of neutron and shock break-out diagnostics, operational and ready for use in experiments.

1.2.1.2 Beam synchronization at target

Laser energy required: 100 J/beamlet in 100 ps

Number of shots required: 90

Special requirements: Basic target and laser alignment systems and two x-ray streak cameras (WBS 1.4.4.15,17) activated. Two twelve-inch manipulators are required for the x-ray streak cameras.

At the end of laser start-up, the beams will be approximately synchronized at the target chamber center. Verification that all beams arrive at the target position within 30-ps relative precision will require target shots with short (100 ps) laser pulses. Disk targets will be imaged using an x-ray streak camera such that individual beams and their arrival times can be identified by spatial position on the x-ray streaks. Beams will be timed in small numbers (15) so that they can be identified. Cross-timing between measurement sets will also be necessary. Beam pointing must be adjustable over at least 1 cm at chamber center for these tests. Fifteen beams per shot requires 16 shots to do a

Table 4. List of Phase I (core) diagnostics.

WBS No.	Name of diagnostic	CDR Section
1.11.6.3.1	Soft x-raypower diagostic	5.4.3.2.6
1.11.6.3.2	Shock breakout measurement (SOP)	5.4.3.2.7
1.11.6.3.3	Filter-fluorescer (FFLEX)	5.4.3.2.8
1.11.6.3.4	Total neutron yield (neutron activation)	5.4.3.2.9
1.11.6.3.5	Neutron time-of-flight detector (nTOF)	5.4.3.2.10
1.11.6.3.6	Neutron Imager	5.4.3.2.11
1.11.6.3.7	Full aperture backscatter system (FABS)	5.3.13.3.2.5
1.4.4.2	Time-resolved x-ray imager (GXI)	5.4.3.2.1
1.4.4.9	Soft x-ray imager (SXRI)	5.4.3.2.2
1.4.4.10	Static x-ray imager (SXI)	5.4.3.2.3
1.4.4.15	Twelve-inch diagnostic manipulators (TIM)	5.4.3.2.4
1.4.4.17	Streak slit camera (SSC)	5.4.3.2.5

full system check-out of 240 beams. A 192-beam system will require fewer shots. A factor of 1.5 is estimated for reproducibility checks and a factor of two is required for changing the timing of beams and checking that the change has been correctly implemented.

Deliverables: All beams coincident within 30 ps at target chamber center.

1.2.1.3 Beam smoothing implementation

Laser energy required: 2 kJ/beamlet in 5-ns pulse

Number of shots required: 80

Special requirements: X-ray imagers (WBS 1.4.4.10) available.

Verification of the efficacy of the smoothing technique will be established by target shots. Disk targets will be illuminated with subsets of the beams (up to 50 at a time) distributed over 1-cm targets to isolate problem beams. The uniformity of the x-ray emission from each of the laser beams will be measured using optical and x-ray imagers to determine the smoothness of the laser beam. The correlation between x-ray emission and laser intensity and the corresponding smoothness of x-ray emission and smoothness of laser beam will need to be quantitatively established beforehand. Spot sizes will be varied to cover the range of focusing used in hohlraums. Beams will overlap in a manner similar to that in a hohlraums.

Deliverables: Beam smoothing meeting the specifications in Article 3.2.1.11 of the NIF Functional Requirements.

1.2.1.4. Beam pointing and spot size

Laser energy required: 100 J/beamlet in 100-ps pulse, 2–4 kJ/beamlet in 5-ns pulse

Number of shots required: 280

Special requirements: High energy must be available for final tests. X-ray imagers (WBS 1.4.4.2,1.4.4.9,1.4.4.10) must also be available.

The laser beam pointing accuracy must be quantified to 50-μm accuracy. The first experiments will be disk shots imaged with an x-ray pinhole camera. Beams will be tested in groups of approximately 30 so that they can be identified by coarse spatial position with respect to a fiducial. Beam spots will be imaged to determine focal spot size. Initial work will be done at low laser energies, but limited final tests must be done at ~50% of full energy to verify that there are no power-dependent effects. This work will include thin-walled hohlraum imaging using subsets of the beams to quantify positioning of the beam spots on the walls of the hohlraum. Rapid turnaround of data analysis is required. Thirty beams per shot will require 8 shots for a full system check-out of 240 beams. These shots will have a quick turn-around time, and a 192-beam system will require fewer shots.

Deliverables: All beams pointed to within 50 μm rms and 98% of beam energy within a 600-μm circle.

1.2.1.5 Power balance

Laser energy required: 1–1.5 MJ in 5-ns pulse initially, 1 MJ in point-design pulse ultimately.

Number of shots required: 70

Special requirements: None

Calorimeter shots at various energies will be required to determine the laser gain curve for the highly saturated pulse shapes used to drive the fusion targets. The time resolved incident beam diagnostic will be used for these shots. This activity will begin with flat-top pulses and continue with shaped pulses for use in hohlraum tuning.

Deliverables: All beams balanced to 8% per Section 3.2 of the Functional Requirements for point-design target pulse shape.

1.2.2 Hohlraum Tuning Experiments

The symmetry of hohlraum drive will need to be fine-tuned empirically because of the high degree of precision required. Calculations will provide a guide for beam placement and phasing of the inner and outer ring, but fine-tuning by experiment is required because of imprecision in the knowledge of hohlraum albedo and hohlraum albedo effects. The hohlraum tuning experiments require approximately 570 shots, detailed in Sections 1.2.2.1 through 1.2.2.8, with beam energy up to 1 MJ in a point-design pulse shape and a few shots at 1.5 MJ in a shaped pulse.

Shots to characterize ignition hohlraums will be required, including measurements of plasma filling, plasma instabilities, radiation-drive temperature, and both time-averaged and time-resolved radiation flux symmetry. The shot allocations, descriptions, and requirements for each of these experiments is as follows:

1.2.2.1 Square pulse hohlraums

Laser energy required: 0.5 MJ in 4-ns pulse

Number of shots required: 70

Special requirements: FABS (WBS 1.11.6.3.7), Soft x-ray power diagnostic (WBS 1.11.6.3.1), FFLEX (WBS 1.11.6.3.3), Shock breakout system (WBS 1.11.6.3.2), Soft x-ray imager (1.4.4.9).

These experiments allow diagnostic techniques for characterizing hohlraums (shock breakout, time-resolved x-ray diodes) to be checked against simple models of hohlraum drive for the first time on NIF. Operational procedures, such as alignment of instruments and use of viewing holes and patches, will be established. The hohlraum data obtained will be compared to the extensive database existing from Nova experiments. 1ω and 2ω shielding techniques will be verified and shields required for the diagnostics will be developed.

Deliverables: Verification of simple hohlraum models extended to NIF sub-scale hohlraums.

1.2.2.2 Square pulse implosions

Laser energy required: 0.5 MJ in 4-ns pulse.

Number of shots required: 60

Special requirements: Neutron yield (WBS 1.11.6.3.4), neutron imager (WBS 1.11.6.3.6), and ion temperature via neutron time of flight (WBS 1.11.6.3.5) diagnostic available.

Simple square-pulse implosions will be used to verify neutron diagnostic techniques and to check fundamental implosion parameters such as yield and timing. Comparison to simple models and the Nova database will be made at different convergence levels and with different pointing schemes. These experiments will provide the first opportunity to test neutron diagnostics.

Deliverables: Simple implosion models extended to NIF levels.

1.2.2.3 Hohlraum tuning 1: Bulk filling characterization

Laser energy required: 0.5 MJ in 4-ns pulse.

Number of shots required: 40

Special requirements: X-ray, optical spectrometers available.

Characterization of plasma produced during the foot portion of the drive pulse. Power levels and pulse lengths will be varied to study development of plasma filling.

Deliverables: Description of plasma evolution during the foot portion of NIF point-design pulse shape.

1.2.2.4 Hohlraum tuning 2: Plasma instabilities

Laser energy required: 0.5 MJ in 4-ns pulse with limited 1-MJ shaped pulses.

Number of shots required: 50

Special requirements: Optical spectrometers

Measurement of the plasma instabilities SBS, SRS, and filamentation will be made at varying power levels and with different beam-smoothing configurations. A limited number of shots will be fired into a scaled point-design hohlraum at 1 MJ with a shaped pulse.

Deliverables: Characterization of plasma instabilities present during foot portion of NIF point-design pulse shape.

1.2.2.5 Hohlraum tuning 3: Temperature vs. time

Laser energy required: 1.0 MJ in point-design pulse shape.

Number of shots required: 20

Hohlraum size will be varied to determine the level of spot and wall motion.

Deliverables: Hohlraum with temperature profile required for NIF point design.

1.2.2.6 Hohlraum tuning 4: Shock timing

Laser energy required: 1.0 MJ in point-design pulse shape.

Number of shots required: 50

Shock time history will be measured by break-out in planar foils. Tuning of the pulse shape and hohlraum size to produce properly timed shocks for implosions will be implemented by varying the laser's temporal profile.

Deliverables: Hohlraum with characteristics required to produce properly timed shocks in ignition target.

1.2.2.7 Hohlraum tuning 5: Time-averaged symmetry

Laser energy required: 1.0 MJ in point-design pulse shape.

Number of shots required: 70

Tuning of hohlraum size and beam pointing to control the time-averaged symmetry. Diagnostics used will include x-ray and neutron imaging of symmetry capsules.

Deliverables: Hohlraum with minimal drive asymmetry.

1.2.2.8 Hohlraum tuning 6: Time-dependent asymmetry tuning

Laser energy required: 1.0 MJ in point-design pulse shape.

Number of shots required: 211

Time-dependent asymmetry will be measured using x-ray and neutron-imaged symmetry capsules and varying length pulses and/or other techniques currently being developed on Nova, such as x-ray backlit low-density spheres. Dependence upon pulse shape, beam phasing, and pointing will be studied with nearly all of the shots restricted to scaled 1-MJ point-design hohlraums. A few shots will be at a higher energy up to 1.5 MJ.

Deliverables: Hohlraum with swings in time-dependent asymmetry less than required for ignition point design.

1.2.3 Cryogenic and Pre-ignition Experiments. During the three-month installation of the cryogenic target positioner, no target shooting will occur. To obtain data for a detailed comparison to modeling, about 230 shots at 1-MJ energy will be devoted to both low-convergence and high-convergence implosions. Targets with dudded fuel will allow close-in diagnostics to be used. A small number of high-yield DT targets will also be shot to guarantee that all ES&H operational procedures are properly in place for later ignition experiments. The shot allocations, descriptions, and requirements for each of these experiments is as follows:

1.2.3.1 Low convergence and dudded cryogenic implosions

Laser energy required: 1 MJ in 5-ns pulse.

Number of shots required: 40

Special requirements: Cryogenic target positioner, neutron spectrometer.

Low convergence, dudded-fuel target experiments with no possibility of ignition will be performed to gain cryogenic operational experience under hohlraum conditions that can be accurately diagnosed using close-in diagnostics. Achieving suitable cryogenic conditions will result in a shot rate much lower than normal. This phase will require about 40 shots, which are, however, expected to take the time required for 120 shots under noncryogenic conditions.

Deliverables: Demonstration of experimental capability to use cryogenic targets.

1.2.3.2 Higher convergence, sub-ignition experiments

Total laser energy required: 1 MJ in shaped pulse.

Number of shots required: 110

These targets will allow the measurement of pre-ignition, high-convergence conditions, and a detailed comparison to modeling. Close-in diagnostics will allow precision measurements to be made of implosion dynamics. Convergence and pulse shape will be varied; different target designs will be required to accommodate various types of diagnostic techniques.

Deliverables: Verification of modeling.

1.2.3.3 High yield shots

Total laser energy required: 1 MJ in 5-ns pulse.

Number of shots required: 20

High yield, non-igniting targets filled with warm, equimolar deuterium tritium will be shot to ascertain the activation levels associated with high yields and to make sure that the facility meets all appropriate ES&H regulations before proceeding. Different yield levels will be used and appropriate shielding/instrument modifications will be made in an iterative fashion.

Deliverables: Target area capable of meeting ES&H requirements for an ignition target.

1.2.4 Ignition Experiments

It is expected that approximately 200 shots will be required to obtain fusion ignition and to explore the relevant parameter space for igniting targets. The shot allocations, descriptions, and requirements for each of these experiments is as follows:

1.2.4.1 Ignition experiments

Total laser energy required: up to 1.8 MJ in point-design pulse shape.

Number of shots required: 30

Special requirements: High neutron yield procedures are in place. Close-in diagnostics are removed.

Ignition, defined as a doubling of the temperature by alpha particle deposition, will be slowly approached by ramping up the laser energy. Few of the shots will be at the full energy of 1.8 MJ in a point-design pulse shape. Observed problems will be addressed in an iterative fashion. In this phase of operation, the shot rate will be determined by radioactivity considerations.

Deliverables: Ignition experiment data.

1.2.4.2 Parameterization of ignition targets

Total laser energy required: 1.8 MJ in pulses approximating point-design pulse.

Number of shots required: 170

Studies and optimization of select portions of the parameter space for igniting targets will be done by varying target and beam conditions. Anticipated variations in target design include ablator material, convergence ratio, and peak-to-foot drive temperature. Many of these targets will use diluted fuel and thus will not be high-yield shots. Parameters studied will include total laser energy, peak temperature, capsule dimensions and gas fill, duration of peak power, surface finish, and asymmetry.

Deliverables: Understanding of dependence of capsule performance upon key parameters.

The sequence of events for the four target experiments campaigns described above is shown in Figure 5.

1.3 Target Diagnostics

There are two sets of Phase I target diagnostics included in the total project cost (TPC). The division of diagnostics between these two sets is based on the descriptions in the NIF Functional Requirements. Section 2.2.8 of the Functional Requirements document describes the measurement capabilities that the facility shall have in order to verify laser performance. The set of target diagnostics required to make these measurements is included in the total estimated cost (TEC) under WBS element 1.4.4. Several other Phase I target diagnostics are needed to perform the initial ICF target experiments shortly after KD4. The cost of these additional diagnostics is included in the OPC under WBS element 1.11.6.3. The conceptual design description of both sets of target diagnostics is included in Section 5.4.3 of the NIF CDR, except for the backscatter system, which is described in Section 5.3.13 of the NIF CDR. These Phase I diagnostics are listed in Table 4. Addition diagnostics required for experiments on NIF will be added in Phase II. Many of the diagnostics are NIF versions of existing Nova diagnostics. Three broad areas of measurements are addressed here: (1) x-ray imaging and spectroscopy, (2) optical imaging and spectroscopy, and (3) neutron measurements. Some of the Phase II diagnostics have also been identified and are referred to in the following sections.

The sequence of events during NIF start-up and initial ignition campaign are shown in Figure 5.

1.3.1 Phase I X-ray Imaging and Spectroscopy Diagnostics. A large number of x-ray imaging and spectroscopic diagnostics are in routine use on Nova. The plan is to adapt and develop several of these for NIF, as follows:

1.3.1.1 Twelve-inch (diagnostic) manipulators (TIMS) (WBS 1.4.4.15). Many of the NIF x-ray diagnostics will be designed so they can be inserted, aligned, and withdrawn from the target chamber using twelve-inch bore manipulators (TIMs) without breaking chamber vacuum. A similar technique is successfully used on Nova with the six-inch manipulators (SIMs), and the Nova diagnostics (and some from the Omega Upgrade) will be compatible with the TIMs on the NIF chamber.

1.3.1.2 Streaked slit camera (SSC) (WBS 1.4.4.17). Two x-ray streak cameras will be fielded in close proximity to a target using the first pair of TIMs. These cameras will provide time-resolved x-ray images and/or spectra with spatial resolution of about 10 μm, similar to ones on Nova. A pair of the cameras will be needed for beam synchronization activities (Section 1.2.1.2).

1.3.1.3 Static x-ray imager (SXI) (WBS 1.4.4.10). The static x-ray imagers are x-ray microscopes providing time-integrated images at 2.5-keV photon energy with 25-μm spatial resolution. They will have a 1-cm field-of-view from close to the poles of the target chamber so that x-ray images of the hohlraum laser entrance holes can be taken routinely. Together with the gated x-ray imagers, these diagnostics will be required for the beam smoothing implementation (Section 1.2.1.3) and beam pointing and spot-size measurements (Section 1.2.1.4).

1.3.1.4 Time-resolved x-ray imagers (GXI) (WBS 1.4.4.2). Time-resolved x-ray imagers will provide time-gated x-ray images at photon energies between about 1 keV and 4 keV with a temporal resolution of 30 ps and a spatial resolution of 5 to 10 μm. These will be used primarily for hohlraum symmetry tuning. Because they will be based on x-ray pinhole technology, they will be fielded in the TIMs. They will also be needed for the beam smoothing implementation (Section 1.2.1.3) and for beam pointing and spot size measurements (Section 1.2.1.4).

1.3.1.5 Soft x-ray power diagnostics (WBS 1.11.6.3.1). The hohlraum radiation temperature will be measured by two techniques that have been successfully used on Nova. The x-ray flux escaping from a small hole in the hohlraum wall will be measured by an absolutely calibrated, broad band, time-resolving x-ray spectrometer. This instrument will either be similar to the Nova Dante system or will use a new technique presently being tested on Saturn at Sandia National Laboratory, Albuquerque. Hohlraum radiation temperature history will be determined from these measurements. Start-up of this diagnostic will require many shots that will be accomplished during the beam pointing activity (Section 1.2.2.4).

1.3.1.6 Soft x-ray imager (SXRI) (WBS 1.4.4.9). The soft x-ray imager will record low energy, gated x-ray images used to measure beam pointing and spot size and hohlraum symmetry.

1.3.1.7 High-energy x-ray spectrometer (FFLEX) (WBS 1.11.6.3.3). The high-energy x-ray spectrometer, similar to the FFLEX diagnostic on Nova, will be an absolutely calibrated filter fluorescer array used to measure the photon spectrum in various energy channels from 5 keV to 100 keV. The energy of fast electrons produced by parametric plasma scattering instabilities can be determined from these measurements. This diagnostic will be required for the first phase of hohlraum experiments (Section 1.2.2.1).

Phase II x-ray spectrometers and imagers will include streaked and gated crystal spectrometers for density and hydrodynamic mix measurements, high-resolution x-ray imagers, and robust x-ray imagers.

1.3.2 Phase I Optical Imaging and Spectroscopy. Several optical imaging and spectroscopic diagnostics in routine use on Nova will be adapted to NIF, as follows:

1.3.2.1 Shock break-out diagnostic (SOP) (WBS 1.11.6.3.2). The shock break-out diagnostic will be similar to the streaked optical pyrometer (SOP) on Nova. It will provide a time-resolved measurement of the optical signal created by the shock breakout from the target. In addition to the passive system used on Nova, an active version of this system is being designed to enable measurements over wider dynamic range in radiation temperature. This system will measure the time-resolved loss in reflectivity of a probe laser beam on a witness plate, thereby determining hohlraum radiation temperature history. It will be needed for the first phase of hohlraum experiments (Section 1.2.2.1), but it will be useful to have in place for the first disk experiments (Section 1.2.1.2) to confirm the direct-drive pressure attained by the shock breakout from disks.

1.3.2.2 Full-aperture backscatter system (FABS) (WBS 1.11.6.3.7). The full-aperture backscatter system, similar to the FABS on Nova, will provide measurements of backscattered light from parametric plasma scattering instabilities (SBS and SRS).

Backscattered light will be collected from several beamlets. This diagnostic requires sufficient space behind the appropriate final turning mirrors to accommodate its optics. The FABS will be used to demonstrate energy delivery to targets during the beam pointing activities (Section 1.2.1.4) and will be required for the first phase of hohlraum tuning (Section 1.2.2.3).

1.3.3 Phase I Neutron Measurements. Because neutrons are produced in both the DD and the DT fusion reactions measurements of neutron yields and energy spectra provide a diagnostic of conditions in the fusion fuel. Several neutron diagnostics exist on Nova, and some of these will be adapted to the NIF. These diagnostics include instruments to measure the neutron activation of various detector materials as a standard measure of thermonuclear yield, and various scintillator-based diagnostics in which neutrons are converted to a light signal in a plastic scintillator and the light signal recorded on phototubes or cameras. The neutron energy spread depends on the temperature of the fuel ions at burn time. Another scintillator-based diagnostic provides measurements of burn duration.

1.3.3.1 Total neutron yield detector (WBS 1.11.6.3.4). The total neutron yield (Y) is determined by measuring the neutron activation of various detector materials. This diagnostic will require a counting room near the target chamber. It will have a lower limit of detectability of about 10^9 neutrons. This detector will be needed for the first implosions (Section 1.2.2.2).

1.3.3.2 Neutron time-of-flight detector (WBS 1.11.6.3.5). A scintillator-based, neutron time-of-flight (nTOF) detector will combine into one detector the functions of Nova's Large Area Neutron Scattering Array (LANSA) and the ion temperature diagnostic. It will require a collimator near the target chamber. The 10-meter-diameter spherical clear space that is required around the spectrometer has been included in the building layout. This diagnostic will be required for the first implosions planned on the NIF (Section 1.2.2.2).

1.3.4 Phase II Diagnostics. Some plans have been made for the Phase II neutron diagnostics. One such scintillator-based diagnostic will be similar to the Nova LANSA. On Nova, this is a 960-channel diagnostic measures the time-of-flight of neutrons of different energies, from which the neutron energy spectrum can be constructed. The ratio of high-energy (12 to 17 MeV) neutrons from the secondary DT reaction to the low-energy (2.5 MeV) neutrons from the primary DD reactions is proportional to the deuterium fuel's areal density at burn time; this is an important measure of capsule performance.

In addition, a time-integrated, neutron-penumbral aperture imaging detector (NPAM) will be fielded on the NIF. Such imaging has been done on Nova for yields as low as 10^{13} neutrons, with 60 μm spatial resolution. Work will be done on Nova to evaluate the feasibility of extending this technique down to 10^{11} neutrons and 15 μm spatial resolution, and to adapt the technique to the NIF.

A summary of other anticipated Phase II diagnostics is listed in Table 5.

Table 5. Phase II diagnostics.

Neutron Diagnostics	X-ray Diagnostics	Other Diagnostics
Neutron spectrometer, LaNSA	Time-resolved x-ray spectrometer (TRXS) (3 req'd)	Energy balance module (EBM) (Many req'd)
Bang-time and burn duration (BTBD)	Monochromatic x-ray imager (MXI)	SRS spectrometer (2 req'd)
		Cassegrain optic (CO)
Neutron coded-aperture microscope (NCAM) (4 req'd)	XRI (4 req'd)	
Gamma ray spectrometer (GRS)		

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