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The National Ignition Facility: Alignment from construction to shot operations

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ABSTRACT

The National Ignition Facility in Livermore, California, completed it's commissioning milestone on March 10, 2009 when it fired all 192 beams at a combined energy of 1.1 MJ at 351nm. Subsequently, a target shot series from August through December of 2009 culminated in scale ignition target design experiments up to 1.2 MJ in the National Ignition Campaign. Preparations are underway through the first half of of 2010 leading to DT ignition and gain experiments in the fall of 2010 into 2011. The top level requirement for beam pointing to target of 50μm rms is the culmination of 15 years of engineering design of a stable facility, commissioning of precision alignment, and precise shot operations controls. Key design documents which guided this project were published in the mid 1990's, driving systems designs. Precision Survey methods were used throughout construction, commissioning and operations for precision placement. Rigorous commissioning processes were used to ensure and validate placement and alignment throughout commissioning and in present day operations. Accurate and rapid system alignment during operations is accomplished by an impressive controls system to align and validate alignment readiness, assuring machine safety and productive experiments.

1. INTRODUCTION

1.1 NIF facility overview

The National Ignition Facility (NIF) is the world's largest laser, designed to create the conditions necessary for controlled inertial confinement fusion in a laboratory setting [1]. The laser system and target chamber are housed in a building 150m by 90m, standing 42m from roof to lowest level (Figure 1).

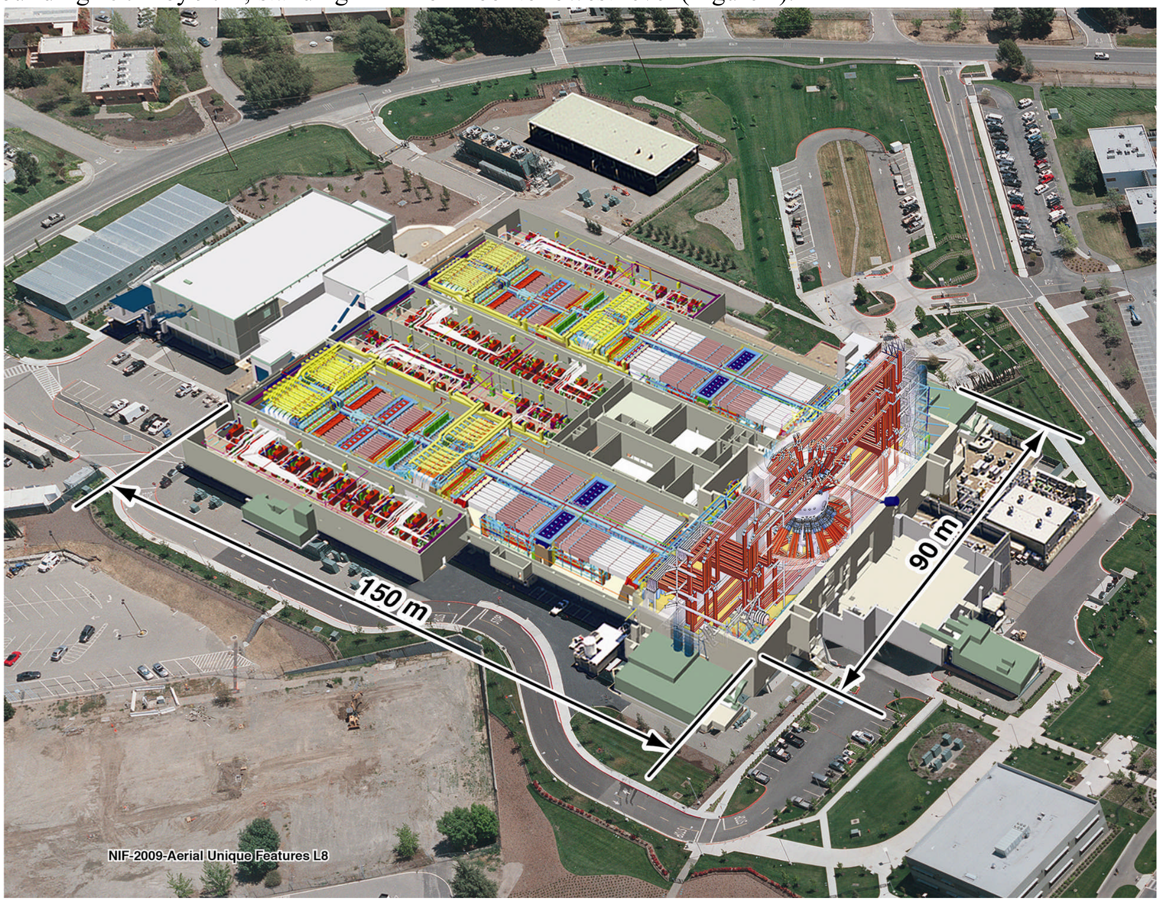

Figure 1 Aerial cut-away view of the NIF Building. The 192 beam lasers are in the center two rectangular bays. Capacitor banks surround each laser bay on the left, and the beams are transported to the target chamber at the center-right of the image. Utility, support, and personnel buildings are arrayed around the central NIF building.

NIF is a national center for fusion and the physics of extreme temperatures and pressures, for the US Department of Energy and the National Nuclear Security Adminstration. It will allow study of these extreme conditions which otherwise only exist in the center of stars or in nuclear weapons.

Facility construction began with groundbreaking on May 29, 1997, with building completion in September, 2001. Beampath enclosure installation was completed in April, 2003, although the first 4 beamlines of laser systems were installed in 2002 as sections of the beampath enclosures were completed. The first 4-beam laser tests began in December, 2002, with target experiments in August, 2003. The 4-beam experiments concluded in October, 2004, providing valuable data on laser systems operation along with physics results relevant to target design. In a similar fashion, laser operations results resulted in engineering changes to improve systems, lower costs, and improve operability. Laser system installation and commissioning continued, with the first bundle of 8 beams completed and tested in August, 2005. The following 4 years were spent installing and commissioning the remainder of the laser line-replaceable-units (LRU's) leading to the first 192 beam system shot, and on March 10, 2009 the system demonstrated performance of 1.1 MJ of

351 nm light to target chamber center. Target experiments commenced in May, 2009 with a series of target tuning shots to be followed by ignition and gain experiments planned for the latter half of 2010 into 2011. Figures 2 and 3 show Laser Bay 2 and part of the upper hemisphere of the target chamber respectively at completion.

Figure 2. View of Laser Bay 2 from atop the main amplifiers. The round tubes carry the beams through focus at the cavity spatial filter, to the Plasma Electrode Pockels Cells, and through the Power Amplifier into the Switchyard through the far wall.

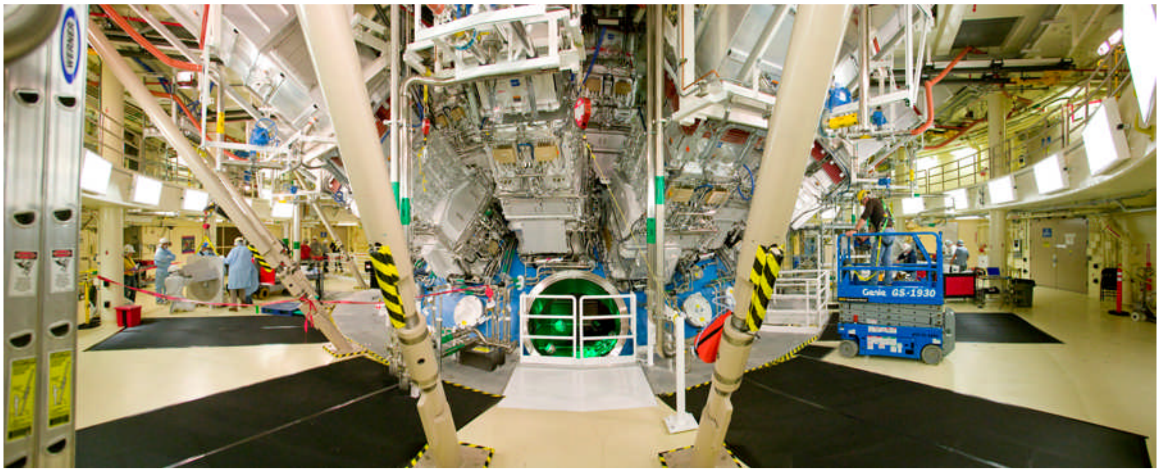

Figure 3. The upper hemisphere of the 10m diameter target chamber is shown here. The large, rectangular assemblies each carry 4 beams, and contain the final optics including optics for frequency conversion, phaseplate beam conditioning, vacuum barrier, focus, diagnostics, and debris protection. The large open port views into chamber center but is covered with a solid port when at vacuum. Note the large turnbuckles which were used for precise positioning of floor structures during construction.

1.2 NIF Architecture

Numerous papers have been written which describe the NIF architecture in their introductory sections, in particular Spaeth *et.al.*[2] and Miller *et.al.*[1]. Here we briefly review the architecture as it's relevant to NIF beam alignment aspects.

NIF consists of 192, 37-cm-square laser beams arranged in 24 bundles of two-by-eight beams which are focused into a 10m diameter target chamber. It is a conventional flashlamp-pumped neodymium-doped phosphate-glass laser of unique four-pass design for its size. Each square 1053nm beam is multi-pass amplified through sixteen 40-cm aperture laser slabs, 3072 total (125 metric tons), transported to the target chamber through beamtubes and 5 mirrors, frequency converted to 351 nm, and focused on the target.

A single NIF beamline is shown schematically in Figure 4. The beam starts at the Master Oscillator Room (MOR), where 3 fiber oscillators and associated modulators provide 48 individual pulses precisely formatted temporally and spectrally.

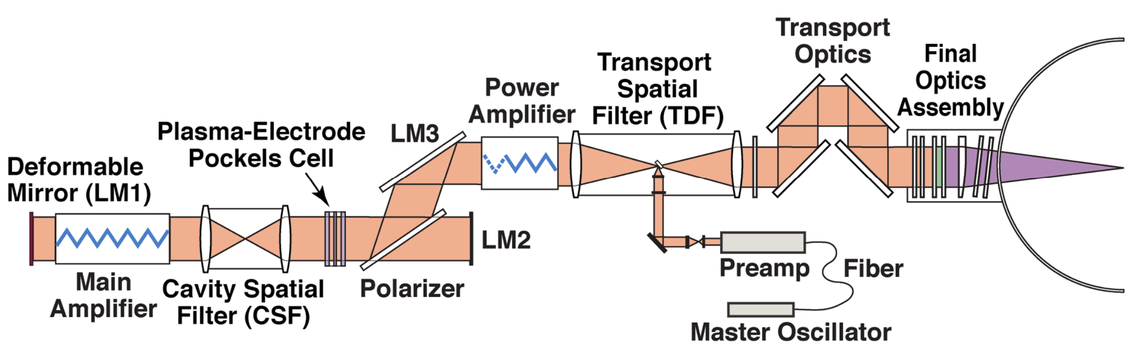

Figure 4. Schematic layout for one of the 192 beamlines, from fiber oscillator to fusion target. The beam is created, amplified and then injected into the Transport spatial filter. It undergoes 4 amplification passes in the cavity, two in the power amplifier, transported to the target chamber, frequency converted and conditioned, and focused onto target.

The nominal 700pJ pulses propagate via single-mode polarizing fiber to the preamplifier [3] for two stages of amplification to ~1J, an experiment-dependent value as subsequent gain is fixed in discrete steps. The preamplifier consists of first, a diode-pumped regenerative amplifier into which the precisely shaped and conditioned MOR pulse is switched and amplified through 57 round trips to approximately 2 mJ. This is followed by a four-pass, flashlamp-pumped Nd:glass rod amplifier cavity (Figure 5) which amplifies the beam to the approximately 1 J, with the beam power, energy, and near-field acquired for analysis by the Injection Sensor Package (ISP).

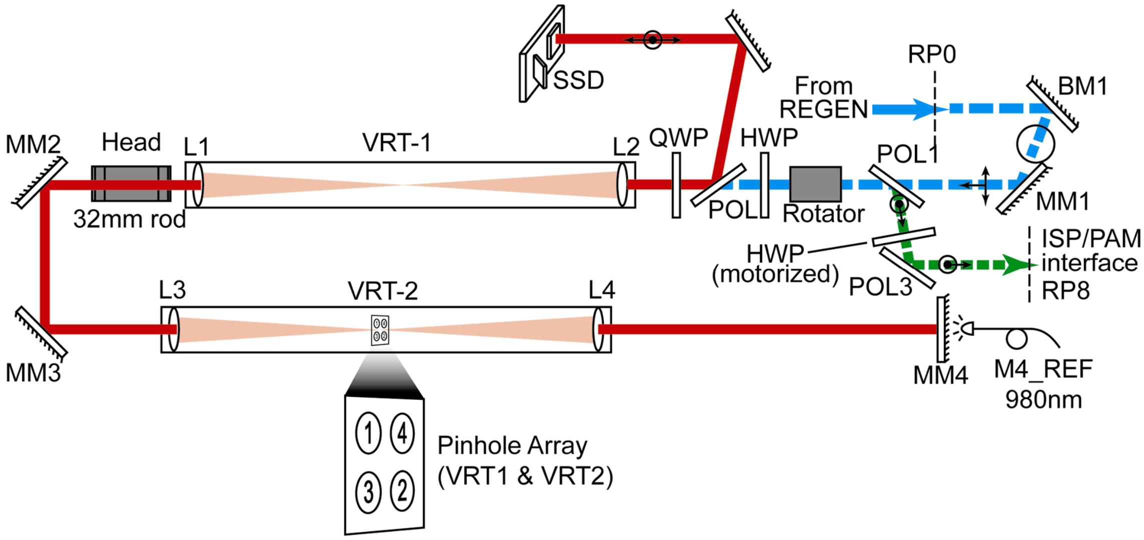

Figure 5. The regenerative amplifier (not shown) injects ~2mJ into this 4-pass flashlamp-pumped rod amplifier. Passive switching is provided by the Faraday rotator and the combination quarter- and half-wave plates. Alignment references for centering and pointing are provided by the M4_REF, and by the same diode illuminating the VRT-2 pinhole array pass-4.

The output from each preamplifier module (PAM) is aligned to the Injection Sensor Package (ISP) centering and pointing references prior to shot. The 48 beams then undergo a 4× split prior to alignment into the each of the 192 Main Laser transport spatial filters. Beam injection into the main laser (Figure 4) is done by matching the f/80 for the 30 m focal length Transport Spatial Filter (TSF) and injecting off a mirror positioned near the TSF focus pass 1. The injection focus is offset from the TSF optical centerline, to position the output beam 35 mm laterally from the injection beam in the TSF. Expanded to 372 mm, the beam is collimated then amplified through the five pumped slabs of the power amplifier, reflects off LM3 and the Polarizer, passes through the 11.8m focal length cavity spatial filter (CSF) pass-1, and through eleven pumped slabs to mirror LM1. LM1 re-points the beam back through pass 2 and LM2 points the beam to pass 3 then out pass 4 to the Transport Filter section. An excellent review of this 4-pass architecture is presented by Zacharias *et. al.*[4].

The beam passes into the NIF Switchyard where a series of 4 to 5 mirrors (beamline dependent) re-maps the rectangular array of main laser beams into the target chamber. The final mirror is LM8, after which the beams go into the final optics assembly for beam conditioning, frequency conversion, and focusing.

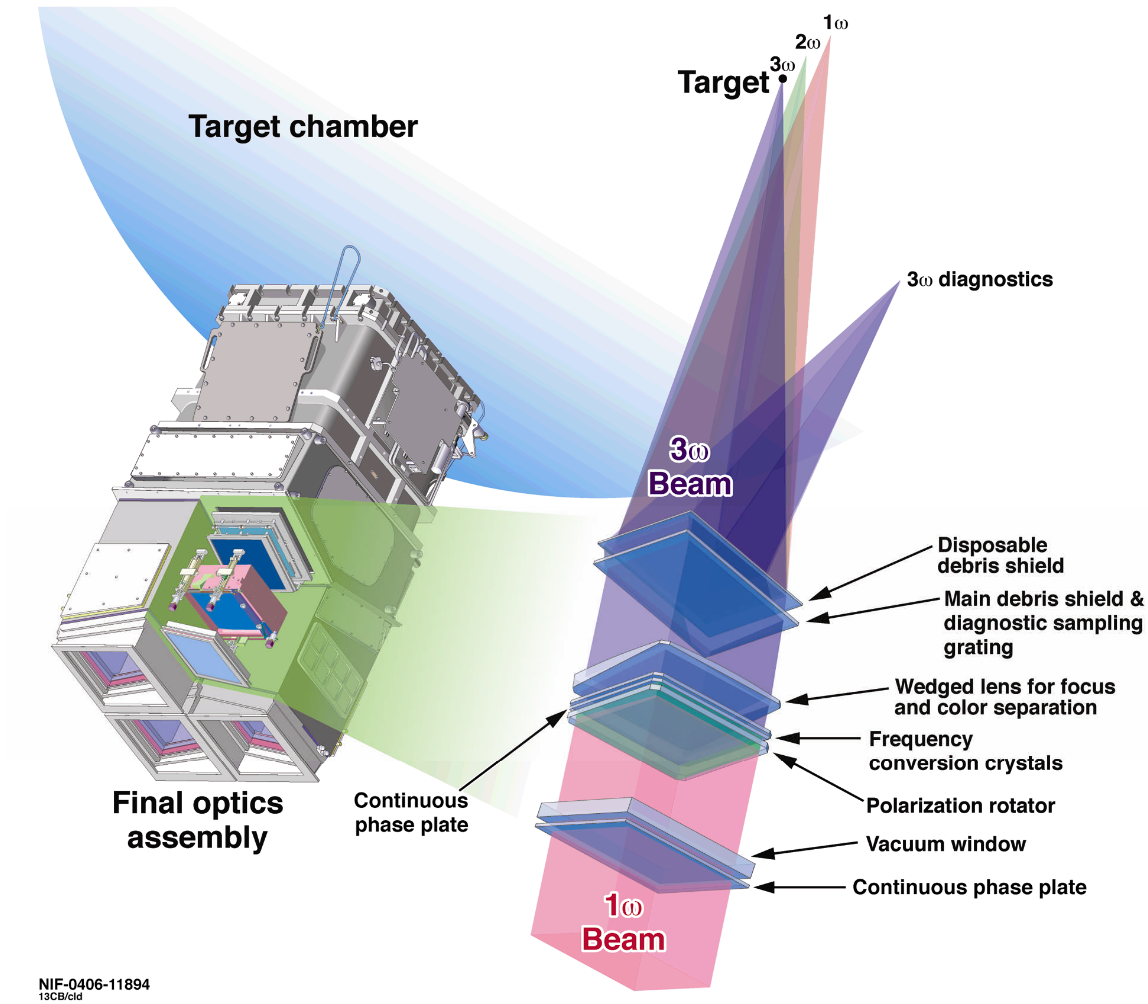

Figure 6. A series of fused-silica and KDP optics comprise NIF final optics as detailed here. The continuous phase plate is in one location or the other, never both, and the polarization rotator is present for only half the beams.

The FOA, several of which can be seen in Figure 3, consists of 6-8 full-aperture optics beamline dependent due to designed-in differences. The various optics provide functions as follows:

1. Vacuum window- transitions from the argon environment for the incoming beam to the near-vacuum FOA environment
2. Phase plate – conditions the beam phase so as to focus to ~750um top-hat profile
3. Polarization rotator – NIF uses polarization smoothing, such that half the beams are in each polarization at focus
4. Frequency conversion crystals – convert the 1053nm beam to 351nm
5. Wedged focus lens – focus the beam to target, while spatially separating residual 1053nm and 531nm light at focus.
6. Main debris shield and diagnostic sampling grating – provides large-object protection for upstream (more expensive) optics, and a low-efficiency grating on the output surface for diagnostic sampling (calorimeter and power sensor)
7. Disposable debris shield – thin, inexpensive optic for primary debris protection

Haynam *et.al.*[5] presents results for beamline performance, where NIF laser requirements for a single beam of the 192 beams was achieved in 2006.

1.3 NIF Alignment

NIF alignment requirements were set at project outset, driven primarily by ignition target performance from which a specification of ±50μm RMS pointing at target chamber center (TCC) for the ensemble of beams was promulgated. Additional requirements were set for pointing through spatial filter pinholes and centering within acceptable beampath apertures to meet machine safety considerations (beam clipping by non-optical components). Pointing to TCC translated into requirements for mirror and other steering optics as to their vibration stability and drift. The laser alignment requirements in turn drove positioning specifications for all system components, including mirrors (±3mm), lenses (±1mm), pinholes (±1mm),, and references (±1mm). These requirements have been met.

Four major alignment phases stand out, and are presented in additional detail. They are 1) Beam pointing vibration and drift mitigation through design, 2) construction alignment and positioning, 3) commissioning alignment, and 4) alignment operations. Each of these is dealt with in the following sections.

1) **Beam pointing vibration and drift mitigation through design**: The beam pointing requirement (±50μm RMS) is met by primarily controlling mirror vibration and drift for the 44 mirror reflections each beam undergoes from the first image relay plane (pupil plane) to the target. Spatial filter lens lateral vibration also requires control, albeit to a lesser extent. The beam is also deviated by thermal inhomogeneities, primarily due to flashlamp heating within the laser amplifiers, but also due to temperature and gas mixing effects within the switchyard to target area argon-filled beam tubes. Additonal drift terms arise from thermal transients in the mirror and lens support structures. Tietbohl and Sommer[6] and Sommer and Bliss[7] address these topics.

The design approach for vibration mitigation considered the perturbing source, the coupling to the mirror support structure, and the response of the mirror and support structure. Where control was possible, sources (primarily rotating equipment) were remotely located or isolated from mirror support structures. A trip into NIF's utility systems room presents the visitor with pumps and fans floating on spring and rubber isolators. To minimize response to controlled and uncontrolled sources, the mirror support structures were designed with a stiffness quantified by a fundamental vibration mode of greater than 10 to 20 Hz, to minimize the perturbation amplitude. In addition we designed many of the structures in a steel/concrete hybrid to take the slight damping term advantage provided by such structures.

These results were tabulated and tracked in a table similar to table 11-1 in [7], with many of the terms validated through calculation and measurement. This provided us confidence that the design could meet NIF alignment requirements, as has been now demonstrated through the NIF system performance.

2) **Construction alignment and positioning**: From the outset of NIF construction, it was necessary to control placement and positioning of the building and all internal components, to varying levels of precision. This was done such that all structures conformed to the Optical Configuration Drawings (OCD's), in the sense that when all supporting structures were completed, they would precisely hold the optics at their design location. These OCD's define the position in space for a datum, typically optic mechanical center, for each of the optical elements for NIF including optics, pinholes, alignment references, and other elements directly affecting the optical performance. The OCD's most relevant to building and beampath construction were those for the main laser large optics, switchyard, and final optics. To a lesser extent, OCD's for the relay optics and PABTS also affected the building and particularly the beampath. Each OCD was tied to the next at specific hand-off locations.

With the OCD's precisely defined, supporting structures were designed, from the optic mounts outward to the supporting structures, and ultimately the building itself. Lens, pinhole and alignment reference positioning to ±1mm and everything else to ±3mm were used for the large (from here on, large refers to the 400+mm optics) optical components. Optics were sized to accommodate this while maintaining the nominal 372nm beam size. As all NIF large optics are line replaceable units (LRU's) [8] with one exception (the IOM vacuum window), the precision interface to the beampath is a kinematic mount. Thus the NIF design and construction challenge was to a) position the beampath kinematic mounts precisely and b) position the mating LRU kinematic mount precisely relative to the optic. This challenge comprises both design and implementation, with design models tied to upper level models throughout the facility, and custom automated tools created to extract and verify kinematic mount coordinates into tables used by precision surveyors during installation.

Precision Survey, defined as survey methodology utilizing redundant shots to quantify positioning error, was used extensively to position NIF beampath components. Capable of positioning uncertainties of 25µm or better, precision survey made alignment of the NIF architecture possible. The large optics had to be positioned correctly prior to beam alignment, one example being the large, 48 beam, spatial filter lens vessels which were installed and aligned by precision survey in 2001 with some beamlines not commissioned until 7 years later.

For precision survey to be useful, we established a coordinate system with the origin being midway between the laser bays in the corridor separating laser bays from the optics assembly building. The NIF coordinate system is oriented with **y** ‘up’ and **z** the direction of beam propagation towards the target chamber. A network of survey monuments was developed in 3 stages of precision, starting with the preliminary network which was ‘fit’ to the building wall structural steel, set in place using standard construction survey methodologies. The ‘fit’ involved surveying the building structural steel, then performing a least squares fit of the idealized NIF coordinate system to the structural steel design locations. Once completed, this basic survey network was captured by assigning coordinate values (in NIF coordinates) to survey monuments embedded in the wall footing concrete. This ‘Basic’ network, with an uncertainty of approximately 3mm 3σ was sufficient for placement of the laser bay floor and concrete pedestals upon which the laser equipment would later be mounted. With the internal building concrete completed, a much larger constellation of network monuments were placed, and valued relative to the Basic network, just prior to the Basic network monuments being closed up by wall covering, preventing their further use. This second network was called the ‘Intermediate’ network, and we achieved 1mm-3σ uncertainty. Additional network monuments continued to be added, and once building temperature control was implemented, the final network achieved 155µm-3σ in laser bay 1, 185µm-3σ in SY2. This network was then available throughout the laser bay for positioning kinematic mounts (where visible) and precision survey features precisely located relative to kinematic mounts (for mounts not visible). A similar network, tightly connected to the two laser bay networks, was generated within the switchyards and target bay for use in placement of mirror kinematic mounts and final optics interfaces to the target chamber. A critical aspect of this connection is related to the NIF architecture, in that laser bay beams propagate into the switchyard with their elevation and pointing determined by the fixed laser bay centering and pointing references, and the fixed positions of the transport spatial filter lenses. We discovered early on that the switchyard and target area concrete slabs (the optical ‘bench’) were subsiding relative to the laser bay concrete slab, and made a 10.4mm correction to the relationship between the two separate networks. Later when commissioning the first beams we found we had overcorrected between 3-7mm in SY2, rectified by modifying the vertical placement for the LM4 kinematic mounts in SY1 (LM4 is the first mirror after the beam passes into the switchyard). The vertical position error in SY1 was reduced to a nominal 2mm.

We employed this network to position over 40,000 kinematic mounts and other precision survey features, which were typically a ¼” hole either precisely machined into a structure or else precisely valued using offline measurements including survey or coordinate measuring machines. Other precision survey features included glued-on survey retroreflector nests, edges, corners or practically any definable feature to which survey metrology instruments could be positioned. The process was straight-forward, with survey instruments (laser trackers) displaying the position in NIF coordinates, with the installers adjusting its position until it was within tolerance. A more complicated process was necessary for large structures such as the 16 large spatial filter vacuum vessels (Figure 7). Kinematic mounts for each vessel’s 12 spatial filter LRU’s (4 lenses per LRU), were installed and aligned prior to vessel installation in the laser bays. Ensuring the transfer of NIF coordinates into the kinematic mount offline positioning was performed as follows:

Figure 7. The vacuum vessels each containing a cluster of 48 Spatial Filter Lenses were installed and precision aligned to their final position in 2001, to ±1mm for lens center placement. Main laser beam alignment completed in 2008 with no further vessel or lens kinematic mount adjustment.

1. The apertures for each set of 4 beams (visible in Figure 7) were measured by precision survey while the spatial filter vessel was supported level in a temperature controlled environment.
2. The apertures were valued in the NIF coordinate system, so as to best-fit (least squares error) to their design positions into that coordinate system
3. Using that temporary network, all the kinematic mounts were installed and precision positioned
4. Precision survey features (in this case, survey network retroreflector magnetic nests) were mounted on the lower part of the vessel where they could be later observed by survey instruments once installed in the NIF building.
5. A final survey was performed of the kinematic mounts, with the results best-fit again into their design positions in the NIF coordinate system. Note that we no longer needed to refer to the aperture positions. The precision survey features were valued in this coordinate system
6. When the spatial filter vessels were hoisted into position as seen in Figure 7, they were shimmed and translated until the precision survey features were within their design tolerances of ±200µm.

Other large NIF structures and vessels were similarly positioned. Small optics also used precision survey techniques to position their mounts or mount stops prior to going clean, at which time survey no longer could be used effectively due to enclosures and covers.

1.4 Commissioning Alignment

With the vessels, enclosures and kinematic mounts installed and aligned, we began installing the optics LRU's [8], which were pre-aligned [9] in the optics assembly building which is adjacent and connected to the laser bays. We followed a rigorous process of Installation Qualification (IQ) and Operational Qualification (OQ), and tracked IQ/OQ precedence, completion and documentation using an active flowchart network tool and LRU 'seating chart'. Typically the IQ is a functional test involving only the LRU in question, whereas an OQ is a higher-level of functionality involving multiple LRU's working together. Beam alignment is an OQ activity.

The initial beam alignment was a daunting task at the outset, as the beampath is enclosed and not accessible, precluding conventional alignment methodology. Basically, the beam is injected into TSF pass 1, performs 4 passes in the cavity, and reappears within ±400 µR in the TSF pass-4 after 2 polarizer passes, 6 spatial filter pinhole passes, 8 mirror reflections, 10 spatial filter lens passes, 12 PEPC window/crystal passes and 54 amplifier slab passes, with a total propagation distance of 280m and no intervening alignment sensors. For NIF operation, the only permanent main laser alignment sensor is a near/far-field camera in the Output Sensor Package (OSP), sampling the beam through an alignment beampath from an insertable 50% pickoff cube positioned behind either the TSF pass 1 or 4 pinhole. For commissioning we installed temporary sensors in both the Cavity spatial filter and the Transport spatial filter, to prealign mirrors LM1, LM2, LM3 and the polarizer, to ensure that beams injected into TSF pass-1 would return to pass-4 for advanced alignment commissioning

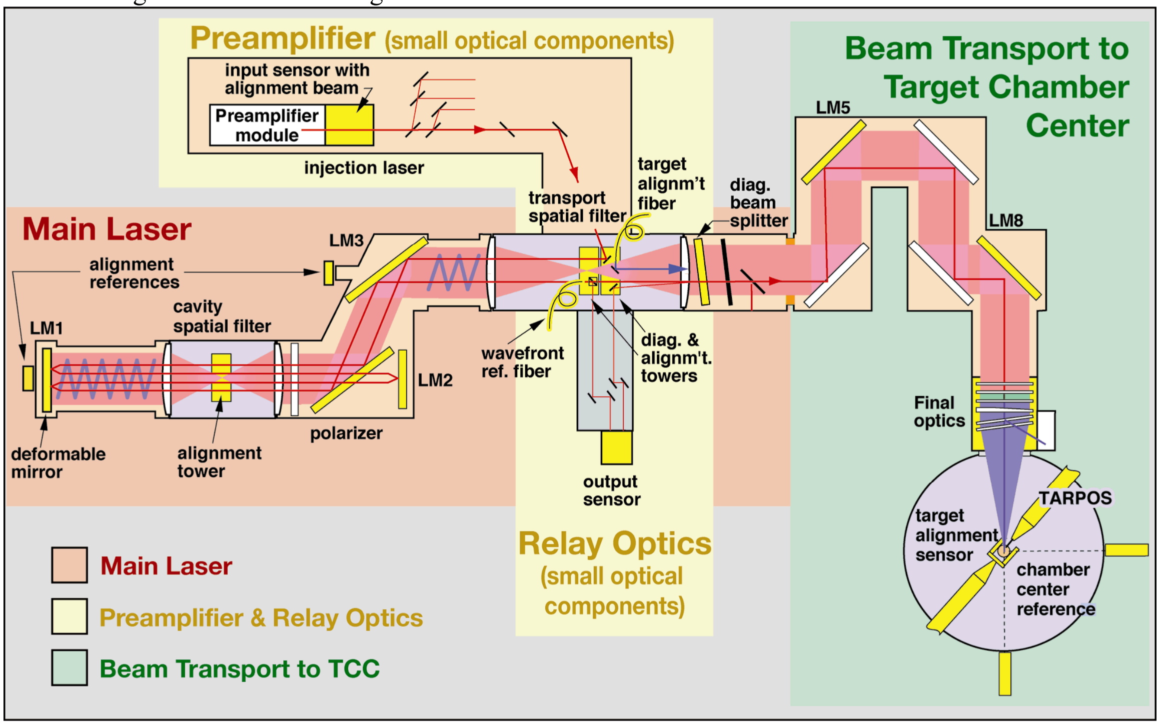

Figure 8. The NIF project performed alignment commissioning in the four regions of the Relay Optics, Preamplifier, Main Laser, and Beam Transport to TCC

The other areas designated in Figure 8 were the preamplifier, relay optics, and beam transport to TCC. Their commissioning alignment was as follows;

a) **Preamplifier** – The preamplifier and beam transport to injection was generally aligned using conventional methods. The preamplifier module was aligned and commissioned offline, then installed to kinematic references. The transport section optic mounts had mechanical stops installed by precision survey as previously discussed to provide the best initial positioning, mounts later fine positioned using the ISP alignment beam, crosshairs, and a temporary sensor just prior to beam injection into the TSF. Injection alignment utilized a pilot beam from the temporary Spatial Filter Tower propagating backwards towards the preamplifier.
b) **Relay Optics** – The relay optics on NIF transport a beam sample to the OSP during alignment, and another beam sample for wavefront and shot-time beam diagnostics. The alignment path has 9 installed optics per beam, the diagnostic path 19 optics. They were aligned using a combination of precision survey at the OSP kinematic mounts and a special survey instrument called an optical Plummet mounted at the OSP location prior to OSP installation. The relay optic mounts were positioned laterally along a line-of-sight between the Plummet and an illuminated crosshair/target in the temporary Spatial Filter Towers.
c) **Beam transport to TCC** – Mirrors LM4 through LM8 were adjusted using retroreflectors mounted to the mechanical center of each mirror in turn. For example, LM4 was adjusted with retroreflectors mounted on LM5 and viewed back in the OSP, pass-1. The retroreflector images were aligned to pass-1 of the LM3 lightsource by manually adjusting the LM4 tip/tilt actuators, identically to the method used for beam centering to the final optics

With the system pre-aligned sufficiently to propagate the main beams and through the diagnostic and alignment paths, we commissioned automatic alignment throughout. In every case except for encoder-offset alignment used in the final optics, we acquire a reference image then a beam image, and adjust mirrors until the beam centering or pointing is aligned to the reference within the specified tolerance. There are over 20 different image types processed to extract alignment features. For the duration of each alignment loop, the camera 'owns' the reference as a specific pixel as determined from the reference image at the beginning of each loop every time it's executed. Commissioning involved finding beams, setting camera exposure and focus, calibrating mirror actuators for direction and magnitude, and implementing coordinated 'cross-coupled' adjustments. This is described further in the following section.

1.5 Alignment operations

NIF Automatic alignment systems permit autonomous alignment for all 192 beams to the OSP in less than 10 minutes, and alignment to target chamber center in less than 44 minutes. Preamplifier alignment for all 48 PAMs takes 5 minutes. These alignments can proceed in parallel to a large extent. As all but the encoder loops require image processing, we established and maintain an image processing team to create and maintain robust image analysis algorithms [10]. Preamplifier, Main Laser, and TCC alignment operations are similar, here we only describe main laser alignment in detail.

The Main Laser is aligned in 6 alignment loops, to the LM3 Light Source Launcher centering reference, and to the TSF pass-4 wavefront and pointing reference (Figure 8). For each loop, the source and reference laser light is transported to the OSP by a the TSF-mounted and actuated 50% splitter cube and associated relay optics. First the reference is acquired and image processed to extract the reference position, then the source (undergoing alignment) is acquired, image processed, adjusted, acquired, etc. until the requisite error is reduced to it's requirement.

Referring to the mirrors and sources shown in Figure 8, a control matrix, was developed from the response matrix below.

$$\begin{pmatrix} \mathbf{LM1cent}_{x,y} \\ \mathbf{CSFp4}_{x,y} \\ \mathbf{CSFp3}_{x,y} \\ \mathbf{TSFp1}_{x,y} \\ \mathbf{ISPcwCent}_{x,y} \\ \mathbf{ISPcwPoint}_{x,y} \end{pmatrix} = \begin{pmatrix} \alpha & 0 & 0 \\ \eta_1 & \beta & 0 \\ \eta_2 & \eta_3 & \gamma \end{pmatrix} \begin{pmatrix} \mathbf{LM3}_{x,y} \\ \mathbf{POL}_{x,y} \\ \mathbf{LM1}_{x,y} \\ \mathbf{LM2}_{x,y} \\ \mathbf{M7}_{x,y} \\ \mathbf{M9}_{x,y} \end{pmatrix}$$

The column elements are 1×2, and the matrix elements are 4×4

***LM1cent* loop –** Image of the LM1 lightsource is aligned to the LM3 lightsource by adjusting LM3 and the polarizer until the error is less than 1mm. Note that the LM3 lightsource is the centering reference for all the main laser and alignment to TCC.
***CSFp4* loop –** Image of the CSF pass-4 pinhole is aligned to less than 1μR to the TSF pass-4 pointing reference by adjusting the LM3 and polarizer. As this loop and the *LM1cent* loop are linearly independent, the 'cross-coupling' matrix (inverse of **α**) allows their independent adjustment. Furthermore, as the centering loop is much less sensitive to mirror actuation (1000× less sensitive mm vs. μR) than the pointing loop, we always perform centering first.
***CSFp3* and *TSFp1* loops** – The respective pinhole images are aligned to the TSF pass-4 pointing reference to less than 1μR using first LM1 then LM2, using the inverse of the **β** matrix.
***ISPcwCent* and *ISPcwPoint* loops –** The ISP-cw beam used for alignment of the main laser and IOM centering is aligned to the LM3 lightsource and the TSF pass-4 reference for centering and pointing respectively, using mirrors M7 and M9 in the injection path and preamplifier beam transport sections. They are aligned to less than 0.5mm and 0.5μR using an inverse of the **γ** matrix.

In theory one could measure all the errors and adjust the 6 mirrors simultaneously. This is impractical however, as mirror adjustment time is much shorter than the time required to reconfigure the beamline, sources, attenuation, focus and CCD camera for each of the 6 measurements. Furthermore, this would require reacquisition of references every iteration whereas completing one of the 6 alignments at a time, we only need reacquire the beam image for each iteration. Performing alignment this way, there is no need to determine the off axis **η** elements as they are eliminated (like Gaussian elimination) during alignment.

Centering alignment to the target chamber center utilizes the ISP-cw beam reflecting off final optics corner cubes as was described in the commissioning alignment section for LM4 – LM8 alignment. Only LM5 and LM8 are actuated, the rest of the transport mirrors remain fixed following their manual adjustment during commissioning. For pointing to target chamber center, an intermediate wavelength (375nm) is launched from the transport spatial filter region, to focus where a frequency converted 1053nm beam (converted to 351nm) would focus at TCC. English *et. al.*[11] describe this approach, although NIF changed to 375nm since that paper was written. The 375nm beam lateral offset is co-aligned to the 351nm beam through a series of low-energy shots to the Target Alignment Sensor [12]. Finally, the frequency converting crystals

(Figure 6) surface reflections are optically aligned to a reference back in the Transport Spatial Filter then offset to their shot positions using encoders.

1.6 Alignment performance

The critical performance measures for alignment include time to align and pointing accuracy to target. Alignment time affects shot cycle time, while pointing and centering accuracy within the main laser must be sufficient for machine-safe and repeatable laser performance. Pointing to TCC critically affects target performance. Statistics on 192 beam shots show PAM alignment time averages 4.2 min, Main Laser 9.7 min, and Alignment to TCC averaging 44 minutes which is acceptable but improvements such as interleaving image acquisition are ongoing with a goal of 25 minutes.

Pointing performance to target is measured on a dedicated shot utilizing a flat Si target overcoated with gold, with a number of indexing holes for top and bottom registration. An x-ray imaging camera[13] records the results. We have achieved better than 70µm RMS pointing performing such shots.

Now completed, the NIF is fulfilling its mission as the Inertial Confinement Fusion Facility, and experiments are proceeding. A summary of results obtained between August and December, 2009 is presented in reference [14].

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The authors would like to thank the efforts and dedication of countless professionals including LLNL employees, supporting contractor individuals, and vendors. Projects such as NIF require engineering support in all the disciplines, physics expertise, conventional facility specialists, electrical and mechanical crafts, and administrative support in all the areas of management, financial, procurement etc. The support and great effort by all combine to make NIF the success it is, and at the point where Inertial Confinement Fusion experiments leading to target ignition can commence.

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