Precision Engineering within the National Ignition Campaign

J.S. Taylor, K. Carlisle, J.L. Klingmann, P. Geraghty, T.T. Saito, R.C. Montesanti
Lawrence Livermore National Laboratory, USA
jstaylor@llnl.gov

Abstract

"The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is a stadium-sized facility containing a 192 beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber and room for 100 diagnostics. NIF is the world's largest and most energetic laser experimental system, providing a scientific center to study inertial confinement fusion and matter at extreme energy densities and pressures."[1] It was dedicated on May 29, 2009 and is now engaged in daily science experiments. Precision Engineering concepts and rigor have guided many elements in NIF's construction and are essential in its future experimental programs. We describe several key precision engineering applications within NIF and its experimental program, including, diamond fly-cutting large crystals, mitigating optical damage with precision material removal techniques, alignment of the 192 beams with targets and diagnostics, and the design and fabrication of targets.

1 The Precision Engineering Challenges for Large Scale Optical Manufacturing

Constructing NIF with its 75,000 optical elements, which include 7,500 large optics to handle the 40-cm-square laser beam, and preparing it for ignition experiments presented many precision engineering and manufacturing challenges. NIF set new goals for optical manufacturers to supply damage-free meter-sized optics in high volume at an affordable price. Never before had transmission optics been required to operate at such high laser fluences. The most stringent of these requirements is laser damage resistance, which requires a fabrication process that produces an optical surface essentially free of any subsurface damage. The finished NIF glass and crystal optics are specified by the parameters listed in Table 1 below in four separate spatial bands covering a spatial frequency from 2.5×10^{-3} to 100 mm^{-1}.

1.1 Crystals - Diamond Fly-Cutting

Crystals are grown from potassium dihydrogen phosphate (KDP), which can take up to two years to grow to an economical size suitable for cutting into plates [2] (see figures below). The plates must be cut at a specific angle relative to the crystal growth axis to within ±5 μradians to obtain the desired frequency conversion. Various processes are used to cut the crystals to obtain a (420 × 420 × 10) mm blank before single-point diamond-fly-cutting to obtain the desired crystal angle.

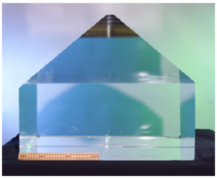
Table 1. NIF Optics Specifications

Measured Band	**Band 1**		**Band 2**		**Band 3**		**Band 4**
Spatial scale length (mm)	400 to 33		33 to 2.5		2.5 to 0.12		0.12 to 0.01
Spatial freq. (mm^{-1})	2.5×10^{-3} to 3.0×10^{-2}		3.0×10^{-2} to 0.4		0.4 to 8.3		8.3 to 100
Parameter	P-to-V (waves)	rms gradient (nm/cm)	Rq (rms) (nm)	A (nm^2 • mm)	Rq (rms) (nm)	A (nm^2 • mm)	Rq (rms) (nm)
Optic type:							
Glass	0.33	7	1.8	1.0	1.6	1.0	0.4
Crystal	—	11	5	15	2.6 pk (1.5 avg)	15	2.5 pk (1.5 avg)

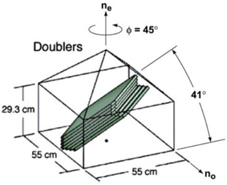
Where Rq is the rms "waviness" or roughness, and A is the amplitude parameter of the power spectral density (PSD) not-to-exceed function used to specify Bands 2 and 3. λ = 633 nm

LLNL designed and built several of the machines like the one shown below, which shows the crystal supported by a 3-axis vertical stage with 3-axis laser feedback to achieve the desired angle and accuracy. The hydrostatic work slide is driven by a linear drive and the fly-cutter uses an air bearing spindle (Professional Instr.) and drive assembly. To achieve a damage free surface the fly-cutter uses a combination of four diamond tools each taking a progressively smaller depth of cut down to 0.5μm. Asynchronous error motion of the fly-cutter must also be kept below 12nm to achieve the required surface roughness. The machine uses a temperature controlled oil shower system to maintain machine geometry and process coolant.

With the crystal machined to the correct conversion angle, it is then transferred to another diamond fly-cutting machine for finishing to the correct thickness, flatness, parallelism and surface roughness. The Finishing Machine represents the 'state-of-the-art' in precision diamond machining. Many of the LLNL team members that designed the Large Optics Diamond Turning Machine (LODTM) were engaged in the design of this machine working closely with Moore Tool. The major difference in this machine was the work piece orientation that required the crystal to be held vertically in order to reduce surface damage from the cutting process. The hydrostatic work slide was originally (~1998) driven by a capstan drive, which now utilizes a linear drive. Another critical parameter is a constant 3 mm/min work slide velocity to achieve the surface quality required. The fly-cutter uses an air bearing (Professional Instruments) driven through a flexible drive assembly to reduce thermal influences to the spindle that would affect the critical depth of cut and flatness of the crystal. An additional temperature control system was integrated into the bearing design. The 1m diameter fly-cutter disc demanded rigorous analysis to achieve the required dynamic performance. The load carrying capacity of the air bearing was limited, requiring a light weight, high stiffness and well damped fly-cutter assembly. To achieve the 1 nm rms roughness specified for the finished optic, the asynchronous error motion measured at the tool radial position of 550mm had to be < 12nm at the working speed of 1000 rpm. Keeping the relative motion (nm) between tool and work piece together with the asynchronous error was the most demanding requirement for the machine requiring many months of careful machine measurements.



KDP crystal



Plates cut from boule

Diamond Fly-cutting

2 Laser Damage Mitigation

Optics that are subjected to NIF's extremely high fluences typically develop laser-induced surface damage. In particular, the final optics, comprising the KDP frequency conversion crystals and the fused silica focusing lenses can show damage, often in the form of micro-fractures.[3,4] As part of our user facility shot plan, laser damage is repaired at the Optics Mitigation Facility (OMF). Once initiated, some sites will grow with subsequent high power laser shots, and if left untreated, will grow to a size that will make the optic unusable. The operational strategy we are following to mitigate damage growth and extend optic life is known as the Loop Strategy.[5] Optics with growing damage sites are removed, treated, reinstalled, and exposed to additional high power laser shots. This is repeated until further processing is no longer practical and the optic is replaced with a new one. The process, mitigation, consists of removing the surface damage fractures in a way that arrests the damage growth and leaves behind a surface feature that is benign to the laser system, typically occupying a negligible percentage of surface area.

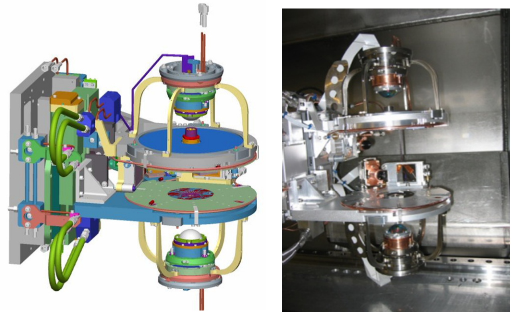
The Final Optics have two material types: KDP crystals that convert the laser frequency (from 1ω to 3ω, ie. 1053 nm to 351 nm) and the focusing optics which are made of fused silica. The mitigation process is similar for both types of material in that the surface damage is removed by a series of spiral cuts that leave behind a conical feature and material that can withstand future high fluence illumination. KDP optics are processed with a 100 μm ball nose radius on a high speed spindle so that ductile mode machining of KDP/DKDP results. The metric for ductile/brittle transmission is the undeformed chip thickness. The rotating axis is carefully aligned and material removal parameters are carefully controlled so that the remaining crystal has minimum sub-surface damage and thus the optimum laser damage resistance. A machine vision system is used for tool set-up and to monitor the machining process. The machined shapes have been as large as 1.5 mm in diameter and 0.25 mm deep, and as small as 250 microns in diameter and 25 microns deep. The damage sites in fused silica optics are mitigated using CO_2 laser ablation. [6,7]

Precision engineering principals have been applied to the design of these machines with great success. Both machine types require absolute positioning of the optic to within 5 microns of the cutting “tool”. The fused silica machines have subassemblies that are removed and inserted into the process laser that require submicron repeatability. The KDP machines use a unique flexure assembly and controls that can achieve relative position and repeatability tolerances, within the mitigation profile, to less than 50nm. These machines have successfully mitigated surface damage on optics that have been reinstalled on NIF and undergone additional high power laser shots.

3 Precision Alignment

The metrology foundation for all alignment on the NIF is based on a survey tracker network that has been used to locate all of the final turning optics of the laser system. This network thus has the best information of the location of the ‘center of the chamber’, the best-fit center of the location of the focusing laser beams. Two orthogonal telescopes on the Target Chamber equator are registered to this network on a periodic basis and form the transfer datum for all alignments relative to Target

Chamber Center (TCC). These telescopes, called the Chamber Center Reference System (CCRS), measure five degrees of freedom at the center of the Target Chamber, insensitive to only azimuthal angle. The targets for these telescopes are prisms with accurately placed fiducials on the hypotenuse face. Each telescope has a camera on a targeting axis that evaluates these fiducials on the prism at TCC relative to a grid on the CCRS table, giving x-y centering information. Additionally, there is an autocollimation axis that registers the angle of the prism about the horizontal axis. The stability of these telescopes is important in that they are relied upon for positioning experimental packages (targets) at the center of a 10-meter sphere within 100-micrometers accuracy and 10-micrometers repeatability and angle accuracy of 1-milli-radian. In terms of dynamic range, this implies a long term stability of 1:10^5 and repeatability of 1:10^6.



Target alignment sensor (TAS) solid model and hardware deployed at NIF

Target and beam positioning are accomplished with the Target Alignment Sensor (TAS). This instrument has four CCD cameras and acts as the intermediate platform for beam and target alignment – beams are aligned to the TAS, targets are aligned to the TAS and the final relative beam-to-target error is dependent on instrument accuracy and stability. The TAS is registered to the CCRS datums with two attached prisms. The cameras are arranged two each on two vertically moving platens, with one camera viewing vertically to align beams and targets in the horizontal plane and a second side-view camera to set target height only. During the alignment process with TAS, the laser beams from the NIF chamber are intercepted and reflected from their path to the target with 200 mm diameter mirrors on each platen, and focus (same path length) onto the TAS upper and lower cameras. This arrangement allows the same camera to capture images of the target, specifically at the aim-point on the target for the laser spots, and an accurate reflection of the incident laser beam.

The requirements on the TAS internal accuracy, the target-to-TAS and beam-to-TAS processes are:

Process or System	**Requirement (µm)**
TAS internal accuracy	5.0
Target-to-TAS	3.6
Beams-to-TAS (assumed uncorrelated error, with 96 beams each top and bottom)	6.5

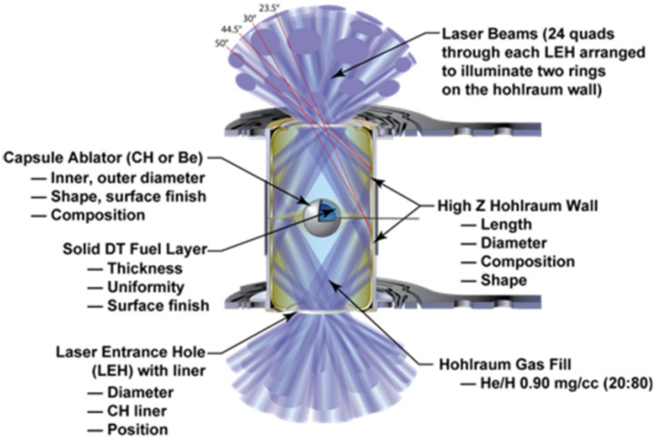
For each shot, a suite of diagnostics is fielded to gather data as the primary purpose of the experiment. A subset of these diagnostics are located on positioners called Diagnostic Insertion Manipulators (DIMs) and must be aligned for each shot. The usual alignment objective is to a feature on the target and tolerances range from 25-micrometers to 1-millimeter. The current approach uses telescopes located directly across the chamber from the instrument. Critical requirements of these systems are stable axes relative to the chamber center reference (CCRS) and an accurately characterized image plane to allow accurate positioning off the optical axis.

Future developments may involve moving away from image-based systems to distance measurement alignment systems, which require "repeatable-absolute accuracy" distance measurement. These systems do not need to measure accurately relative to an external standard but do need to make interrupted measurements between objects in the chamber with repeatable accuracy between 10 and 50 micrometers depending on the diagnostic application. The attraction to this approach is that it eliminates the approximately 6-meter Abbe offset of an imaging system external to the chamber. This concept and others are being considered to improve alignment accuracy, system robustness and operational speed.

4 Target Design and Fabrication

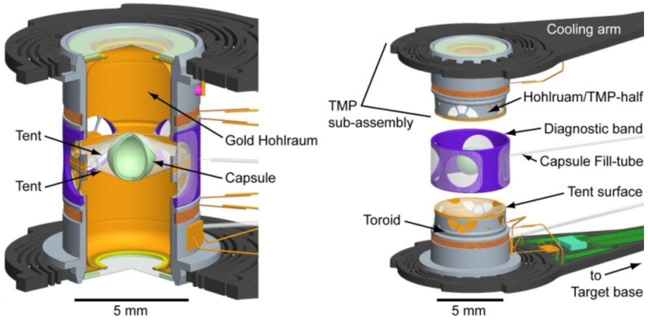
Targets are an essential element of experiments within the National Ignition Campaign [8,9]. The essential physics requirements and engineering embodiment of an ignition target are shown below.[10] Ignition targets are based on indirect-drive, where laser energy is first converted to x-rays, which in turn drive the ablation process at the capsule. 96 laser beams enter each of two laser entrance holes of a cylindrical cavity called a hohlraum, and are incident upon the inner Au or Au-U surface. The ensuing plasma generates the x-rays that uniformly heat the capsule and ablate its surface (either plastic or Be). This ablation process drives capsule compression. Precise pulse characteristics from the lasers generate shocks that are focused to the inner surface. A layer of DT ice on the inner wall of the capsule is compressed along with the ablator wall, and temperature and pressure rise to conditions needed for fusion.

Precision Engineering enters into the target design and fabrication process along many avenues. There are specifications for the key parameters including hohlraum and capsule dimensions, centering, all spanning numerous component fabrication steps and assembly operations. Detailed error budgets for assemblies indicate that component tolerances and the precision of assembly equipment are consistent with the physics requirements of the target package. The concept of containing the essential physics components within an engineering Thermal-Mechanical Package (TMP) provides a useful construct for applying precision engineering definitions of datum surfaces, design for manufacturability/measurability, non-binding toroidal joints, and design for thermal insensitvity. The targets are shot at DT ice conditions (~18K) and must be gas tight, and thus be able to retain precision and robustness during extreme temperature shifts.



Physics Requirements for an Ignition Target

Learning that has been obtained during extensive prototyping of targets, has led to the construction of new assembly tools that greatly enhance the determinism of the assembly process. These tools address the requirement for the near simultaneous movement and bonding of up to six sub-assemblies with detailed control (or constraint) of all degrees-of-freedom. [11,12] These tools also invoke force and torque sensors in assembly so that the operator can respond to small deviations in component alignment with sufficient fidelity to avoid buckling of thin-walled components. New agile versions of our assembly tools provide the ability to reconfigure motion axes in response to a variety of target geometries.



Engineering Embodiment of an Ignition Target

References:

This work was performed under the auspices of the U.S. Department of Energy by Lawrenece Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-CONF-423982

[1] Miller, G., “The National ignition Facility” and E. Moses, “Multi-Megajoule NIF: Ushering In A New Era in High Energy Density Science” Proc. SPIE Vol. 5341 (2004).
[2] Zaitseva, A-N., and L. Carman, “Rapid growth of KDP-type crystals,” Prog. Cryst. Growth Charact. Mater. **43**, 1-118, (2001) and J. J. DeYoreo et. Al. “Developing KH2PO4 and KD2PO4 Crystals For The World’s Most Power Laser”, Inter. Mat’l. Rev. **47** (2002) p. 113.
[3] Norton, M. A., et. al, “Growth of Laser Initiated Damage in Fused Silica at 351 nm”, *Laser Science and Technology Program Annual Report – 2000*, LLNL Report UCRL-ID-142744-00 and UCRL-JC-13964 (2001).
[4] Demos, S. G., et.al., “Mechanisms to explain damage growth in optical materials”, *Laser-Induced Damage in Optical Materials*, 2000, SPIE Vol. **4347**, 277-284 (2001).
[5] Burnham, A. K., et. al., “Improving 351 nm damage performance of large-aperture fused silica and DKDP optics”, *Laser-Induced Damage in Optical Materials*, 2001, SPIE Vol. **4679**, 173-185 (2002).
[6] Hrubesh, L., et. al, “Surface Damage Growth Mitigation on KDP/DKDP Optics Using Single-Crystal Diamond Micro-Machining”, *Laser-Induced Damage in Optical Materials*, 2002, SPIE Vol. **5273**, 273-279 (2004)
[7] Geraghty, P., et. al “Surface damage growth mitigation on KDP/DKDP optics using single-crystal diamond micro-machining ball end mill contouring”, *Laser-Induced Damage in Optical Materials*, 2006, SPIE Vol. **6403**, (2007).
[8] Atherton, L. J., et. al., “The ignition target for the National Ignition Facility” Proc. 7th EUSPEN Int. Conf., Bremen, May 2007.
[9] Klingmann, J. L., et. al., “Design and Fabrication of a Novel Cryogenic Laser-Driven Ignition Target,” Proc. Of 7th EUSPEN Int. Conf., Bremen, May 2007.
[10] Haan, S. W., et. al., “REV3 Update of requirements for NIF ignition targets”, Fusion Sci. & Tech., 55, Apr. 2009, 227-232.
[11] Montesanti, R. C., et. al., “Robotic system for precision assembly of NIF targets”, 2008 ASPE Annual Meeting, Portland, OR, Oct 2008.
[12] Castro, C., Montesanti, R. C., Taylor, J. S., Hamza, A. V., Dzenitis, E. G., “Reconfigurable Assembly Station for Precision Manufacture of Nuclear Fusion Ignition Targets”, 2009 ASPE Annual Meeting, Monterey, CA Oct 2009.