When completed, the National Ignition Facility (NIF; Livermore, CA) will be the world’s largest laser system, a 192-beam, flash-lamp-pumped neodymium-doped glass laser capable of generating 1.8 MJ of energy at 351 nm after frequency conversion in a 3-ns pulse. Each beam has a nominal aperture of 40 cm.

Accurate metrology with high throughput is essential for successful production of the more than 7500 large-aperture (0.5 to 1.0 m) optical components for the NIF. These optics comprise a surface area of more than 2000 m², also making NIF the largest precision optical instrument in the world. To accommodate high production volumes, a suite of 19 metrology tools with apertures in excess of 40 cm has been fielded at production vendors by Lawrence Livermore National Laboratory (LLNL; Livermore, CA). These instruments include eight phase-shifting interferometers and three white-light interferometers that will together evaluate 100% of the NIF large optics including laser glass slabs, Pockels cells, wedged focus lenses, and thin flats (phase plates, beam separation gratings, and debris shields).

Production metrology on large-aperture laser optics presents numerous challenges. For high throughput, instruments such as the interferometers must be located near the manufacturing facilities, yet still be isolated from vibration, air turbulence, heat, and humidity sources. In addition, the facilities require appropriate sample-mounting and handling equipment, as some NIF optics exceed 55 kg in weight. To effectively measure optics in a production environment, the instruments must also have minimal downtime. To ensure high system availability, our Large-Optic Metrology Group at NIF is tasked with maintaining the metrology tools and analysis codes, as well as interpreting the data. We work with the optic production and metrology equipment vendors to maintain the high reliability and accuracy of the tools. Our goal is for 95% system availability on 95% of the tools.

The main production metrology tools are commercially produced, 24-in., phase-shifting, Fizeau-type...
interferometers incorporating diode lasers operating near 660 nm with rotatable polarization. A thermoelectrically cooled, megapixel camera with spatial resolution of about 0.5 mm/pixel acquires wavefront data at 30 Hz. The instrument achieves phase shifting by moving the transmission flat with piezoelectric drivers. A low-noise, eight-frame algorithm with phase separation of 90° between frames determines the optical path difference. The interferometers are mounted on air-floated, one-piece optical tables or granite slabs typically located near the shop floor; a special linkage couples the transmission and return flats to lower vibration. A dual-canopy enclosure mitigates air turbulence and temperature fluctuations.

**crystal challenges**

The production of plates of potassium dihydrogen phosphate (KDP) and its deuterated isomorph (DKDP) for use in optical switching and frequency generation is among the most challenging production tasks on the NIF project. There are stringent requirements for plate thickness $t$, phase matching angle $\theta$, birefringence variation, transmitted wavefront (TWF) and reflected wavefront (RWF), surface roughness (in-band power spectral density: PSD1 (33 to 2.5 mm) and PSD2 (2.5 to 0.12 mm)), wedge angle, and scratch/dig (see table). Fabrication of the crystal plates takes place at Cleveland Crystals Inc. (CCI; Cleveland OH). LLNL has fielded a number of metrology tools at CCI that are used throughout the crystal production process to ensure that these specifications are met (see figure 1).

The fabrication process begins when the crystal boule is sawed into plates. In the semi-finishing portion, each of these plates goes through an iterative process of correcting the cut angle relative to the phase-matching angle. The crystal alignment test system (CATS) and orthogonal polarization interferometry (OPI) are used in this step. CATS is a kilohertz neodymium-doped yttrium lithium fluoride (Nd:YLF)-based system that measures the frequency-conversion efficiency of a semifinished doubler or tripler plate as a function of tuning angle. Comparison of the plate’s conversion efficiency versus tuning angle (rocking curve) to that of a well-characterized proof crystal allows the difference between the plate cut angle and phase angle to be determined to within ±4 µrad. CATS measures the rocking curve at 10 discrete points in the crystal. Comparison of CATS data to OPI data prior to the next crystal finishing iteration ensures adequate sampling; this is particularly important for rapid-growth KDP second-harmonic-generation crystals, which
may exhibit substantial birefringence variation.

The OPI measurement, performed on a 24-in., phase-shifted interferometer, consists of sequential horizontal- and vertical-polarization wavefront measurements. The idea behind OPI is that the horizontal polarization determines the optical path length \( n_0 \) due to the ordinary index of refraction \( n_o \); here, we assume \( n_o \) to be invariant in the crystal. The vertical polarization determines the optical path length \( n_e(\phi) \) due to the extraordinary index projection \( n_e(\phi) \) defined by the index ellipsoid equation

\[
\frac{x^2}{n_e^2} + \frac{y^2}{n_o^2} = \left( \frac{\lambda}{2n_o} \right)^2
\]

where \( n_o \) and \( n_e(\phi) \) refer to the refractive indices along the a- and c-axes of the crystal. The optical path difference is manipulated according to the prescription \( \phi_e - \phi_o = [n_e(x, y) - n_o(x, y)] t(x, y)/\lambda \) where we account for perturbations in \( n_e(x, y) \) and sample thickness \( t(x, y) \) by \( n_e(x, y) = n_e + \delta n(x, y) \) and \( t(x, y) = t + \delta t(x, y) \). These relationships allow us to determine the birefringence variation within the crystal.

Because the OPI data is a relative measurement, we compare the data to the CATS results to determine the new crystal cut angle for the subsequent semi-finishing pass (see figure 2). This process continues until the crystal is cut to the proper angle and the plate passes onto the final finishing process.

**finishing up**

Final finishing consists of high-precision diamond turning of the plate. After this is complete, technicians repeat the entire OPI, TWF, RWF, and PSD measurement suite using the large-aperture interferometer. In addition, they measure micro-roughness and PSD2 at nine sites on a 3 × 3 grid on each side of the plate using a commercially available white-light interferometer. Data from these measurements is analyzed using CPHASE, an LLNL-produced program that calculates the PSD function for specific spatial frequency ranges of 33 to 2.5 mm and 2.5 to 0.12 mm. The software subsequently generates RMS wavefront data for these frequency bands.

At the end of this process, a scratch/dig inspection is done on the plate using a variable power (up to 200X) microscope. Images from the microscope are captured digitally and analyzed for number and area. LLNL has developed a slight variation on the ISO 10110 standard for scratch/dig acceptance that places strict limits on scratch length. If the crystal does not pass scratch/dig specifications, the final finishing process is repeated until either the specifications are met or the crystal becomes too thin to be usable.

To help ensure the highest possible performance of the NIF, KDP and DKDP crystals for the laser will meet stringent requirements for thickness, wedge angle, phase-matching angle, homogeneity, TWF, RWF, surface roughness, and scratch/dig. The crystal production process is one of the most challenging for the NIF, but we are supporting it with large-aperture metrology tools that have proven to be reliable and accurate.

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Acknowledgements

This work is supported under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract N. W-7405-ENG-48.

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