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Development of a Metrology Instrument for Mapping the Crystallographic Axis in Large Optics*

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Abstract

A metrology instrument has been developed to scan crystals and map the peak tuning angles for frequency conversion from the infrared to the ultra violet over large apertures. The need for such a device emerged from the National Ignition Facility (NIF) program where frequency conversion crystals have been found to have significant crystallographic axis wander at the large NIF aperture size of 41 cm square. With only limited access to a large aperture laser system capable of testing these crystals, scientists have been unable to determine which crystal life-cycle components most affect these angular anomalies. A system that can scan crystals with a small diameter probe laser beam and deliver microradian accuracy and repeatability from probe point to probe point is needed. The Crystal Alignment Verification Equipment (CAVE) is the instrument designed to meet these needs and fit into the budget and time constraints of the ongoing NIF development.

In order to measure NIF crystals, the CAVE has a workspace of 50 x 50 cm and an angular measurement accuracy of 10 μradians. Other precision requirements are probe beam energy measurement to 2% of peak, thermal control to 20 ± 0.1°C around the crystal, crystal mounting surface flatness of 1 μm over 40 cm square, and clean operations to Class 100 standards. Crystals are measured in a vertical position in a kinematic mount capable of tuning the crystal to 1 μradian. The mirrors steering the probe beam can be aligned to the same precision.

Making tip/tilt mounts with microradian level adjustment is relatively commonplace. The real precision engineering challenge of the CAVE system is maintaining the angular alignment accuracy of the probe laser relative to the crystal for each spatial position to be measured. The design team determined that a precision XY stage with the required workspace and angular accuracy would be prohibitive to develop under the given tight time constraints. Instead the CAVE uses commercially available slides and makes up for their inaccuracies with metrology. The key to the CAVE device is referencing all angular measurements relative to a master reference surface. The angles of the probe laser and the crystal mount are measured relative to a 61 cm optical flat for every spatial location. Autocollimation and imaging are used to achieve the microradian angular precision. Slide errors are removed by alignment of the crystal and the beam for each new probe point through active feedback from the autocollimation system.

The first prototype CAVE system is being constructed and tested at Lawrence Livermore National Laboratory. The mechanical and optical errors are being measured and analyzed to verify the critical performance specification of 10 μ radians. Others facing the same challenge of designing point-to-point probe system for measuring optical axes can use the knowledge gained from this design.

Keywords: crystallographic axis, autocollimation, metrology frame, optical mounting, optical testing, and National Ignition Facility

1. Introduction

In order to meet current NIF specifications, third harmonic conversion efficiencies of greater than 80% of the input pulse peak irradiance are required. The NIF converter design sends an input irradiance of 3.3 GW/cm^2 through a pair of 410 mm square crystals, a type I 11 mm thick KDP second harmonic generator (SHG) and a type II 9.2 mm thick KD*P third harmonic generator (THG)[i]. The ideal conversion efficiency for this system including crystal absorption is 90.8%[ii]. This sets a total conversion error budget of 9.35% of which angular sensitivity is a large contributor, Table 1. Figure 1, shows the microradian level tuning that must be maintained. The solid curve represents

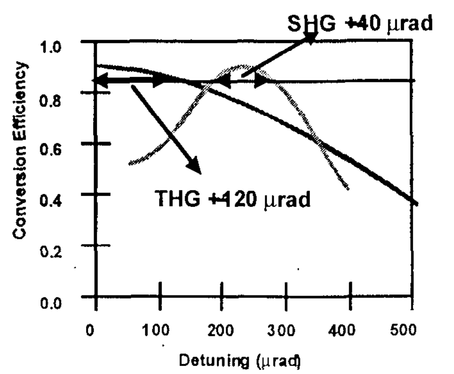

Figure 1. Rocking curve data for NIF doubling (SHG) and mixing (THG) crystals.

the detuning of the SHG to find the optimal mixture of 1ω and 2ω light for maximum 3ω conversion through the THG which gives a 40 μradian error band for 85% conversion. The dotted line shows the detuning of the THG given the optimum mixture from the SHG (120 mradian error band for 85% conversion). Evidence from current experiments at Lawrence Livermore National Laboratory indicate that these curves, known as rocking curves, can shift for different spatial locations on a crystal. Significant spatial non-uniformity in frequency conversion has been observed with the 37 cm aperture Beamlet experiment.[iii] A device is needed to measure these conversion variations directly by measuring multiple rocking curves over an entire crystal.

Table 1. NIF frequency converter error budget.[1]

SourceofEfficiency Reduction	Magnitude
1w Beam Losses	2.2 %
Coating loss	4.26
Loss terms	0.76 %
Angular Sensitivity Terms	1.44%
CAVEoffsets	0.69 %

The CAVE device has been designed and is being constructed to fill the role of measuring harmonic conversion over entire crystal apertures. The final version of CAVE will be used for crystal alignment verification of the NIF Final Optics Assemblies before they are installed to the laser system[iv].

2. Design

The CAVE device is designed to measure sample crystals up to the 41 cm square NIF size. A cell is made to hold both a doubling and tripling crystal or a single crystal, Figure 2a. In order to minimize distortion of the crystal from mounting, both mounting surfaces are diamond flycut to 1 micron flat. The cell flanges give an even pre-load of 2 N/cm to hold the crystal edges against the mounting surface. Crystals are held in a vertical position to eliminate gravity sag as they are scanned. Three actuators kinematically attach to the cell tip, and tilt the crystal and are capable of tuning the angles to less than 0.5 μradians.

All angle measurements are referenced to a 610 mm optical flat that is mounted in line with the crystals, Figure 2b. This reference flat is 2.5 waves, at 632 nm, and has angular variations calibrated to 0.8 μradians with a look up table. The flat serves as the null and the angles of the laser and the crystal mount are measured relative to its normal.

The laser autocollimator, Figure 2e and Figure 3b, contains a CCD camera that can detect the relative angle between the probe laser beam and the reference flat's surface normal. The autocollimator camera records the focal spot's position from the probe laser beam and the reference laser beam's reflection off the reference flat.

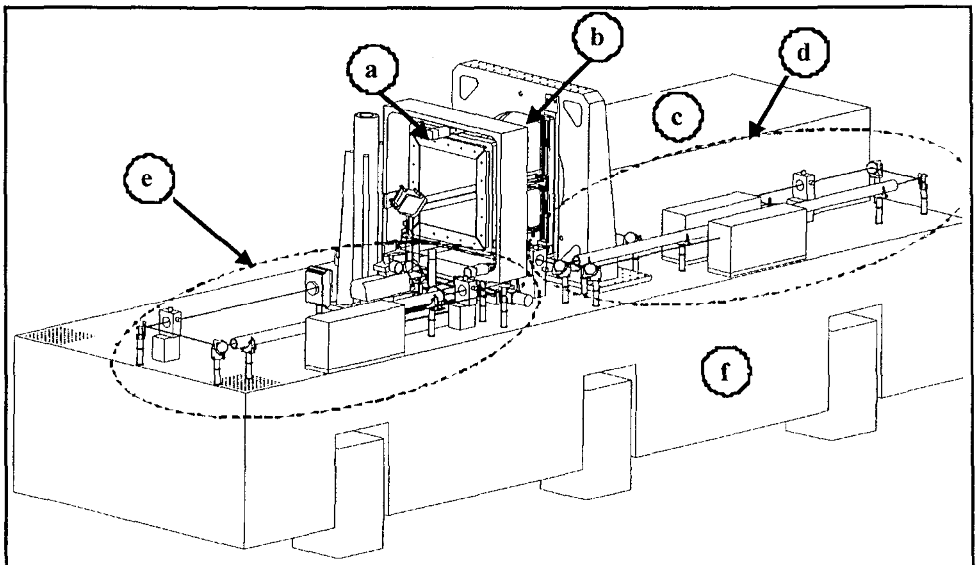

Figure 2. The CAVE device layout, including, a) crystal cell, b) reference flat, c) Nd:YLF probe laser d) input beamtrain, e) output beamtrain, and f) optics table.

The diamond turned surface the crystals are mounted against extends below the crystal to provide a reference surface for measuring the angle of the crystal mount. The crystal autocollimators, Figure 3a, measure the angle of the diamond turned surface relative to the 610 mm reference flat. The autocollimators remove the stage errors as the crystal cell moves horizontally.

The Nd:YLF probe laser, Figure 2c, delivers a fluence of up to 4 GW/cm^2 at the crystal at 1053 nm wavelength. The laser has a pulse length of 100 picoseconds, a beam diameter of 5 mm at the crystal test surface, and a maximum repetition rate of 10 Hz. With this short pulse length, the crystal can be probed with many high fluence pulses without significant thermal changes ($\pm 0.1^{\circ}C$). The input optics, Figure 2d, relay image the laser beam from the last amplifier rod to the crystal surface. A portion of the beam is split off to the reference crystals and reference energy meters. These reference crystals converted energy measurements is used to normalize the output energy from the sample crystal due to variations in the pulse shape, energy or beam profile.

To scan the crystal in the vertical axis, periscopes translate the beam vertically on the input and output sides of the crystal. Two optical trombones maintain the relay path length for each vertical movement. The laser autocollimator monitors the alignment of the output laser beam, Figure 2e. Tip and tilt adjustment of the bottom periscope mirror on the input side controls the pointing of the laser. On the output side another tip and tilt adjustment of the bottom mirror of the output periscope aligns the autocollimator with the reference flat. Further down the output beam the output energy meter measures the pulse conversion. Additional crystal diagnostics have been added to the output side to image the beam at the crystal surface to observe local variations in conversion efficiency.

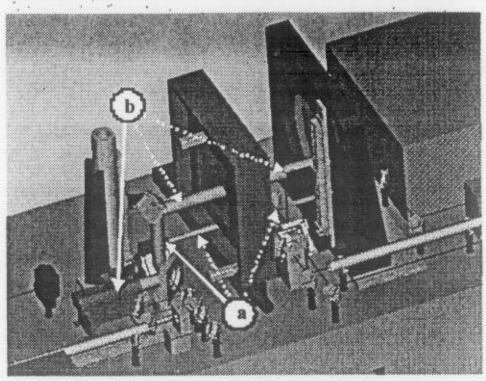

Figure 3. The CAVE measurement core with; a) the crystal autocollimators and measurement paths, and b) the laser autocollimator and measurement path. Dotted lines point to highlighted paths.

Several environmental controls need to be maintained for the CAVE device to operate effectively. The optics table, Figure 2f, is on air isolators to attenuate vibrations above 2 Hz. The table is housed in a Class 100 clean room enclosure that maintains temperature of $20 \pm 0.1^{\circ}C$.

The operating modes of the CAVE device are energy meter calibration, crystal scanning and rocking curve measurement. An absolute energy meter is inserted at several places in the beamtrain to calibrate the input, output and reference energy meters to take out system losses. Once crystals are loaded in the cell, the main stage moves to the first horizontal scanning position and the cell is angularly aligned. For vertical scanning the beam is moved with the periscopes and aligned relative to the reference flat at the new position. When a position is set, the cell is tipped or tilted to the desired angle, a laser pulse is released and all data is recorded. This is repeated for all of the points on the rocking curve. The final output of each experiment is an array of horizontal location, vertical location and probe angle with the corresponding normalized conversion energy output.

3. Instrument Error Budget

The final machine must measure rocking curves at multiple locations on a KDP crystal with a high level of repeatability. The error bars for a single shot (single point on a rocking curve) have been designed to be less than 10 μradians in angle and 2% of total energy. Many of the large angular errors inherent in machine motion are taken out with the metrology control, most notably with the autocollimators which monitor the angles of the crystal and the laser relative to the reference flat. Table 2, shows the angular errors and the root mean square total.

Table 2. CAVE Angle Measurement Error Budget .

Error Component	**Net Error μrad**	**RSS tot**
Reference Flat	1.0	
Clipping and field effects	1.1	
Laser Autocollimator centroid	5	
Resolution and Stability	1.7	
Net Beam relative to Ref. flat		5.48
Mount flatness	1.0	
Crystal Autocol. centroid	5	
Resolution and stability	2.3	
Mount relative to Ref. flat		5.59
Laser beam pointing		5
Scanning errors		1.6
Tot. RSS system errors		**9.42**

4. Instrument Component and System Verifications

Table 2 gives a summary of the angular error budget for CAVE. Each of these error components needs to be validated to ensure the system error budget is met. This process is under way now and is a time consuming process to verify component performance at micro-radian accuracies.

The reference flat and FOC mount surface figures have been measured with interferometry. The reference flat's figure was measured to allow correction for errors caused by using different portions of its surface as reference surfaces. The laser autocollimator looks at different heights on the reference flat as the laser beam is moved to different heights in the crystal. The flat mounting surface for the crystal was measured to determine its deviation from a flat surface. This allows calculation of the errors introduced by clamping crystals. It also allows correction to errors the crystal angle measurement caused by the autocollimators viewing different portions of the mounting flat's area below the crystal, Figure 3a. This data combined with look up tables results in errors for these components under 1 μradian.

As an example of the measurement capability of the system now, Figure 4 shows a single point rocking curve. This shows the primary and secondary peaks in the rocking curve and it is normalized to the 2w reference input power, and each point was averaged from three points. The rocking curve does show the expected hyperbolic sine squared function shape that is typical of rocking curves at medium to low power, under 1 GW/cm^2. Work is continuing on the verification of the system error budget.

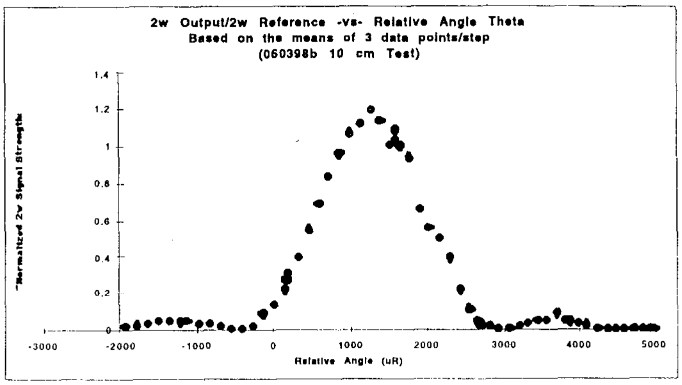

Figure 4 shows a typical single point rocking curve shape.

5. Summary

The first CAVE prototype is currently being constructed and tested at Lawrence Livermore National Laboratory. The device scans KDP crystals and measures conversion efficiency vs. rocking angle for any spatial location. The CAVE is designed for accuracy of 10 μradians in phase matching angle measurement and 2% in conversion energy measurement. The machine errors will be tested and analyzed, leading to a final design that will be used for qualification of the NIF frequency converters. The immediate use for the CAVE prototype will be to help advance crystal development to reach the NIF conversion goals.

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