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Author(s):

J. A. Oertel, T. Archuleta, L. Clark, S. Evans,
A. Hauer, F. E. Marshall, C. G. Peterson, T. Sedillo,
C. Thorn, R. G. Watt

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Gated monochromatic x-ray imager

John A. Oertel, Tom Archuleta, Larry Clark, Scott Evans, Allan Hauer, C. Glen Peterson, Tom Sedillo, Corky Thorn, Robert G. Watt

Los Alamos National Laboratory (LANL), Plasma Physics Group P-24, P.O. Box 1663, MS-E554 Los Alamos, New Mexico 87545

Frederic J. Marshall.

University of Rochester, Laboratory for Laser Energetics (LLE), 250 East River Road Rochester, New York 14623-1212

ABSTRACT

We have recently developed a gated monochromatic x-ray imaging diagnostic for the national Inertial-Confinement Fusion (ICF) program. This new imaging system will be one of the primary diagnostics to be utilized on University of Rochester's Omega laser fusion facility. The new diagnostic is based upon a Kirkpatrick-Baez (KB) microscope dispersed by diffraction crystals, as first described by Marshall and Su.¹ The dispersed images are gated by four individual proximity focused microchannel plates and recorded on film. Spectral coverage is tunable up to 8 keV, spectral resolution has been measured at 20 eV, temporal resolution is 80 ps, and spatial resolution is better than 10 μm .

Keywords: Monochromatic, MCP, Gated X-ray Imager, ICF, and Kirkpatrick-Baez microscope.

1. INTRODUCTION

Some of the most important diagnostics used in the ICF program are gated x-ray imagers.^{2,3} These diagnostics can resolve relatively broadband x-rays (1 - 5 keV), both temporally and spatially. This new technique can isolate line emission from a single atomic species and reduce the contribution from other sources. Observation of gated monochromatic images has important applications which include the measurement of target core size, symmetry, and areal density. Monochromatic imaging may be especially useful for x-ray backlighting.⁴

Figure 1. Schematic of the gated monochromatic imaging system.

Figure 1 is a schematic of the technique used to obtain gated monochromatic x-ray images of laser-fusion target implosions. A KB microscope is arranged so that four images of the target emission are formed. Without an intervening crystal the images would consist of emission from the whole sensitive energy band of the microscope (typically ~ 1 to ~ 7 keV). Monochromatic images are obtained by placing a diffracting crystal before the image plane. The crystals are mounted on two turrets which can rotate through $>45^\circ$ (θ). The diffracted images fall upon gated microchannel plate (MCP) modules which are rotated by an angle 2θ relative to the undiffracted image axis. The KB mirrors are located behind a Be blast shield and there is an additional Be vacuum window between the mirrors and the image plane. The crystals, rotary stages, and MCP modules are located in a 12" diameter vacuum enclosure located at the end of a flight tube. The tank was designed to be easily removed, leaving just the base plate, for instrument calibration and maintenance. For normal operations the tank remains in place and has two 10" vacuum doors (top and rear) for removal of film and minor adjustments. Descriptions of the KB microscope, dispersive elements, rotary stages and the gating system are described below.

2. Imaging Optics

The KB microscope optics used in this diagnostic operates at grazing angles of $\sim 0.7^\circ$. The details of the reflective optics design are given in Marshall and Su.¹ Typical parameters are: mirror radius of curvature = 28 m, magnification = 12, and solid angle per image = 4×10^{-7} sr. Tests performed at the University of Rochester with a DC x-ray source have shown that the best resolution is $\sim 5 \mu\text{m}$ over a $\sim 200 \mu\text{m}$ diameter region degrading to $\sim 25 \mu\text{m}$ over a 1 mm diameter field of view. The KB mirrors are either Ni-, Au-, or Ir-coated. See Figure 2. We are planning to use Ir-coated mirrors in the monochromatic imager as Ir has the best reflectivity at high energies.

Figure 2. Reflectivity vs. photon energy for Ni-, Au-, and Ir-coated KB mirrors as calculated in Marshall and Su.¹

3. Dispersive Elements and Rotary Stages

Images produced by the KB microscope are made monochromatic by placing a diffracting crystal just before the focal plane of the KB. Typical crystals for this application are LiF ($2d = 4.027 \text{ \AA}$) and Highly Oriented Pyrolytic Graphite (HPOG) ($2d = 6.708 \text{ \AA}$). The crystal is placed at an angle θ relative to the incident x-rays and the gating module is placed at an angle of 2θ . The wavelength (λ) of the diffracted x-rays is given by the Bragg equation, $2d\sin\theta = n\lambda$, where d is the crystal plane spacing and n is the diffraction order. Since the crystal has a finite angular response to wavelength λ , this yields a finite field of view Δx given by $\Delta x = d\Delta\theta$, where $\Delta\theta$ is the width of the crystal rocking curve and d is the distance from source to mirror. Typical values for Δx are $700 \text{ \mu m}$ with crystal rocking curves of $\Delta\theta = 0.2^\circ$ (LiF). For an x-ray source emitting broadband radiation, the effective energy band ΔE is given by $\Delta E = E\cos\theta\Delta\theta$. Peak crystal reflectivities (R_p) have been measured at $R_p = 0.15$ for LiF and $R_p = 0.27$ for HPOG.

The crystal turrets sit upon two separate computer controlled commercial rotary stages with better than 0.01° resolution.⁵ The rotary stages drive a pair of vertical shafts one of which rotates at twice the angle of the other. This enables the crystal to be at an angle of θ , relative to the incident radiation, while the MCP module is at an angle of 2θ . The usable range of crystal angle is between $\theta = 0^\circ$ to $>45^\circ$. Table 1 shows a list of crystal angles vs. photon energy for LiF and HPOG. Time integrated monochromatic images of backlit wire meshes have been obtained at the LANL Trident laser facility. Figure 3 shows a pair of such backlit grid images recorded on DEF film. Both targets were Cu meshes consisting of $25.4 \text{ \mu m}$ diameter wires spaced by $50.8 \text{ \mu m}$. The meshes were backlit by Ti disks which were irradiated by $\sim 150 \text{ J}$ of 532 nm light in a 1.2 ns (FWHM) pulse. The KB microscope had Au-coated mirrors and an effective energy band of (~ 2 to $\sim 7 \text{ keV}$). The left image was taken without a diffracting crystal while the right image was taken with a LiF crystal set to diffract the Ti($\text{He}\alpha$) line at 4.75 keV . The resolution obtained in the monochromatic image is $\sim 10 \text{ \mu m}$ with some degradation due to the crystal as discussed in Marshall and Su¹ and some due to a less than optimum focus. These images nevertheless demonstrate the ability to obtain time-integrated monochromatic images of laser plasma x-ray emission as a prelude to time-resolving the same.

LiF		HPOG	
Angle (θ)	Energy (KeV)	Angle (θ)	Energy (KeV)
23.25	8	13.72	8
25	7.47	15	7.33
30	6.31	20	5.55
35	5.5	25	4.49
40	4.9	30	3.79
45	4.45	35	3.3
50	4.1	40	2.94
55	3.83	45	2.67

Table 1. Usable crystal angles vs. photon energy for LiF and HPOG.

Figure 3. Time-integrated backlit images of wire meshes taken with a KB microscope on the Trident laser facility. The left image is a polychromatic image (~ 2 to ~ 7 keV) while the right is monochromatic at 4.75 keV.

4. Gating and Image Recording System

The four monochromatic images formed by the microscope and crystals are arranged in a square pattern with 53 mm sides at the image plane. Each image falls on its own 25 mm diameter MCP, which is proximity focused to a fiberoptic faceplate coated with P-11 phosphor. Light from the phosphor is recorded by Kodak 2484 film loaded into a film cassette that is compressed against the fiberoptic faceplate. As shown in Figure 4, each module contains a pair of 25 mm MCPs, with centers separated by 53 mm. Each MCP has an 8 ohm microstrip which acts as the electrical conduit for the gating pulse and the photocathode. The microstrip is constructed of 5000Å Cu overlaid by 1000Å of Au. The MCPs are fed by microstrip ohmic tapers which efficiently transfer the voltage pulse from 50 ohms to 8 ohms and back out again for a pulse monitor and DC biasing. To gate or shutter the x-rays, a short duration, high voltage pulse travels across the MCP stripline with a propagation velocity of $\sim 0.5c$. Photo-electrons from the Au photocathode are amplified only during the pulse duration at a given point along the microstrip. The LANL built gating pulsers have an amplitude of 4 kV and an electrical width of 150 ps FWHM. See Figure 5. These avalanche transistor based pulsers give us an ~ 80 ps optical gate with MCPs having micropore length to diameter ratio of 40 ($L/D = 40$). There may be a noticeable gain reduction due to ohmic losses between the two MCPs because they are fed by the same continuous strip. For our first run of experiments this is acceptable, though subsequent designs will allow the MCPs to be gated and DC biased separately for increased flexibility.

Figure 4. MCP module with a pair of 25 mm L/D = 40 MCPs.

Figure 5. LANL gating pulser with amplitude of 4 kV and FWHM = 150 ps.

5. CONCLUSIONS

This new gated monochromatic x-ray imaging system is a product of a successful collaboration between University of Rochester's Laboratory for Laser Energetics and Los Alamos National Laboratory. We collectively have designed, developed, and tested the imaging system at both LANL's Trident laser system and LLE. This new imaging system will be an important diagnostic for LLE's Omega laser system yielding critical information concerning target symmetry, size and density of ICF implosions.

6. ACKNOWLEDGMENTS

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- ⁵ Rotary stage model ART50N were manufactured by Areotech Inc. 101 Zeta Drive, Pittsburg, PA, 15238.