Asymmetrically cut crystal pair as x-ray magnifier for imaging at high intensity laser facilities[a)]

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(Presented 19 May 2010; received 17 May 2010; accepted 18 August 2010; published online 20 October 2010)

The potential of an x-ray magnifier prepared from a pair of asymmetrically cut crystals is studied to explore high energy x-ray imaging capabilities at high intensity laser facilities. OMEGA-EP and NIF when irradiating mid and high Z targets can be a source of high-energy x-rays whose production mechanisms and use as backlighters are a subject of active research. This paper studies the properties and potential of existing asymmetric cut crystal pairs from the National Institute of Standards and Technology (NIST) built in a new enclosure for imaging x-ray sources. The technique of the x-ray magnifier has been described previously. This new approach is aimed to find a design that could be used at laser facilities by magnifying the x-ray source into a screen far away from the target chamber center, with fixed magnification defined by the crystals' lattice spacing and the asymmetry angles. The magnified image is monochromatic and the imaging wavelength is set by crystal asymmetry and incidence angles. First laboratory results are presented and discussed.
 [doi:10.1063/1.3492382]

I. INTRODUCTION

High energy x-ray imaging is much needed at High Energy Density (HED) experiments at large laser facilities. One answer to this need can be point projection radiography that has been developed for various laser experiments.[1,2] Ideally, to study properties of submillimeter x-ray sources created by (≤ 100 μm) laser focal spot, an imager possessing the following properties may be required:

(i) an ability to produce very high spatial resolution ($\Delta x \leq 10\mu$);
(ii) produce highly monochromatic images;
(iii) produce images at any predetermined energy in the 8–80 keV range;
(iv) ability to block undesired radiation from reaching the detector;
(v) has a linear configuration for ease of alignment and operation, i.e., the imaging and detector parts need to be on the same side of the target;
(vi) small in size such that several units could be packed in a relatively small volume, thus enabling the generation of a time resolved sequence;
(vii) reasonably efficient to provide analyzable information about the target.

The instruments commonly used to image plasmas produced by powerful lasers are mostly pinhole cameras,[3] Kirkpatrick–Baez microscopes,[4] and spherical imagers based on a mirror composed of a crystal with a specific 2d spacing.[5] None of these imagers fulfills the above requirements completely. The pinhole camera images, although very compact and relatively simple to produce multiple images, are not monochromatic and are most probably contaminated by the very energetic radiation emitted by the target. Recent efforts using a pinhole array and a Bragg reflection crystal are providing a better solution for this type of imaging.[6] A Kirkpatrick–Baez microscope can be designed to block undesired radiation from reaching the detector; however, the image it produces is not monochromatic and is limited to fairly low energies. Spherical imagers are monochromatic and have high efficiencies but are limited to very few wavelengths where the 2d spacing of the selected crystal is nearly the same as that of a bright x-ray line. In this case there are only a few possibilities to create an efficient "crystal-wavelength" match and the ones that are available are for imaging lines in the lower energy band.

II. THE TWO-DIMENSIONAL ASYMMETRIC CUT CRYSTAL MAGNIFIER

A two-dimensional x-ray magnifier that is based on two asymmetric cut crystals, originally developed to study the structure of materials, was developed.[7] In the years that followed, this type of magnifier was extensively studied for the use in conjunction with bright synchrotron sources.[8] When an x-ray beam is diffracted from the surface of the crystal obeying the Bragg law, $n\lambda = 2d \sin \theta_B$ (where n is the order, λ is the wavelength, d is the lattice spacing, and θ_B is the Bragg angle), and the planes of the crystal are parallel to the surface, the image has the same size as the source [Fig. 1(a)];

[a)]Contributed paper, published as part of the Proceedings of the 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, May 2010.
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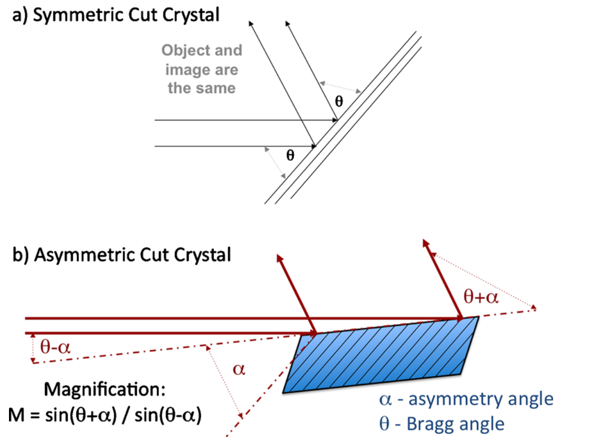

FIG. 1. (Color online) (a) Symmetric and (b) asymmetric Bragg reflection case.

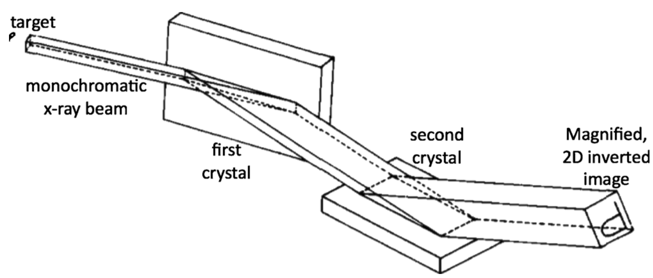

FIG. 2. Basic concept of the two-dimensional x-ray magnifier with a pair of asymmetrically cut crystals (Ref. 1).

however, when the planes of the crystal and the surface of the crystal are not parallel, the magnification will differ [Fig. 1(b)]. In particular, when the surface of the crystal is cut at an angle α approaching the Brag angle θ, the ratio of the image size to the source size is given by the equation

$$M=\sin(\theta+\alpha)/\sin(\theta-\alpha), \quad (1)$$

where θ is the Bragg angle and α is the asymmetry angle of the crystal. When the Bragg angle is in the order of $\theta=10°$ and the asymmetry angle approaches the Bragg angle to within 1° $\Delta=\theta-\alpha=1°$ the magnification approaches values of M=20. When a second crystal with the same asymmetric cut is added in a plane perpendicular to the plane in which the first crystal is mounted, an identical magnification in the perpendicular direction occurs. The result is an x-ray two-dimensional magnified image shown in Fig. 2.

Table I is a partial list of crystals that may be used to produce magnifiers for Kα lines emitted by a selected group of elements. The asymmetric cuts listed in the table are designed to produce ~x20 magnification. Being fairly small in size, a system can be designed such that it includes a number of closely packed magnifiers generating several images on an array of time resolving detectors. A schematic of a possible design is shown in Fig. 3

III. EXPERIMENT TO DEMONSTRATE PERFORMANCE

Recently, we have constructed two magnifiers, the first for the Mo Kα line at 17 keV and the second for the Ag Kα line at 22 keV. Figures 4 and 5 show examples of images taken with the magnifiers.

TABLE I. A list of crystals and x-ray lines that could be used at magnification of about 20 in a two-dimensional x-ray magnifier.

Crystal	2D (A)	α	X-ray line used	Ka1 (keV)	θBr	θIn	θOut	Magnification	Crystal size for 1 mm
Si 111	6.261	12.888	Cu Kα1	8.048	14.245	1.357	27.133	19.263	42.246
Si 220	3.840	21.401	Cu Kα1	8.048	23.654	2.253	45.054	18.008	25.434
Si 400	2.716	31.267	Cu Kα1	8.048	34.558	3.291	65.825	15.894	17.398
Si 111	6.261	5.886	Mo Kα1	17.479	6.506	0.620	12.391	19.845	92.519
Si 220	3.840	9.632	Mo Kα1	17.479	10.645	1.014	20.277	19.587	56.536
Si 400	2.716	13.698	Mo Kα1	17.479	15.140	1.442	28.838	19.169	39.748
Ge 220	4.000	5.750	Mo Kα1	17.479	10.215	4.465	15.965	3.533	12.813
Si 220	3.840	7.579	Ag Kα1	22.163	8.377	0.798	15.957	19.743	71.847
Si 220	3.840	7.133	Ag Kα1	22.163	8.380	1.247	15.513	12.290	45.963
LiF200	4.027	7.225	Ag Kα1	22.163	7.986	0.761	15.211	19.767	75.370
LiF220	2.848	10.250	Ag Kα1	22.163	11.329	1.079	21.578	19.532	53.126
LiF422	1.652	17.909	Ag Kα1	22.163	19.795	1.885	37.704	18.592	30.397
Ge 400	2.830	7.500	Ag Kα1	22.163	11.402	3.902	18.902	4.761	14.670
Ge 220	4.000	5.750	Ag Kα1	22.163	8.040	2.290	13.790	5.966	25.021
Si 220	3.840	4.652	Pr Kα1	36.026	5.142	0.490	9.795	19.903	117.051
LiF200	4.027	4.436	Pr Kα1	36.026	4.903	0.467	9.339	19.912	122.767
LiF220	2.848	6.280	Pr Kα1	36.026	6.941	0.661	13.221	19.824	86.716
LiF422	1.652	10.880	Pr Kα1	36.026	12.025	1.145	22.904	19.473	50.049
Si 220	3.840	3.897	Gd Kα1	42.996	4.307	0.410	8.204	19.932	139.754
LiF200	4.027	3.715	Gd Kα1	42.996	4.106	0.391	7.822	19.938	146.573
LiF220	2.848	5.258	Gd Kα1	42.996	5.811	0.553	11.069	19.876	103.570
LiF422	1.652	9.096	Gd Kα1	42.996	10.053	0.957	19.149	19.631	59.867
LiF422	1.652	6.577	W Kα1	59.318	7.269	0.692	13.846	19.807	82.800
Si 444	1.580	6.878	W Kα1	59.318	7.602	0.724	14.480	19.789	79.171
LiF422	1.652	5.666	Au Kα1	68.804	6.263	0.596	11.929	19.856	96.109
Si 444	1.580	5.821	Au Kα1	68.804	6.549	0.728	14.500	19.715	78.773

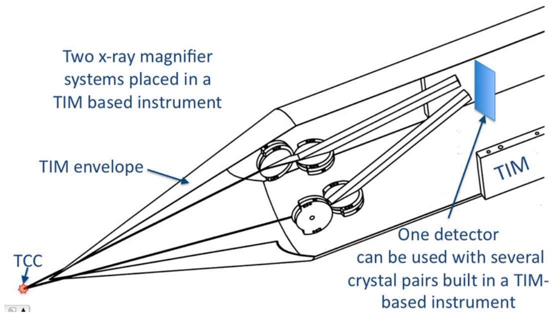

FIG. 3. (Color online) Sketch of a TIM based instrument.

Since the magnifier is not a focusing device and it produces highly monochromatic images that are significantly magnified, its efficiency is fairly low. Nevertheless, it is believed that it is sufficiently efficient to produce images with reasonable signal to noise ratio from tens to hundreds keV x-ray energies at large laser systems.

The alignment of one or two crystal pairs of a TIM based instrument for the imaging of laser irradiated targets could be performed under controlled conditions in an x-ray laboratory. A pointer would be precisely aligned to point to the source with preset registration to the magnifier. The alignment of the instrument at the laser facility will be performed with great precision based on the pointer tip. An alignment precision of about 100 μm for a reasonable ~254 mm crystal-to-target standoff distance will be required.

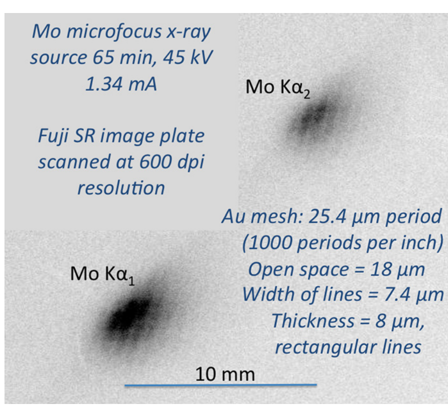

FIG. 4. (Color online) Magnified x-ray images of a gold mesh with 25.4 μm period. Image is magnified ~20 times. The 10 mm marker measures on the image plate.

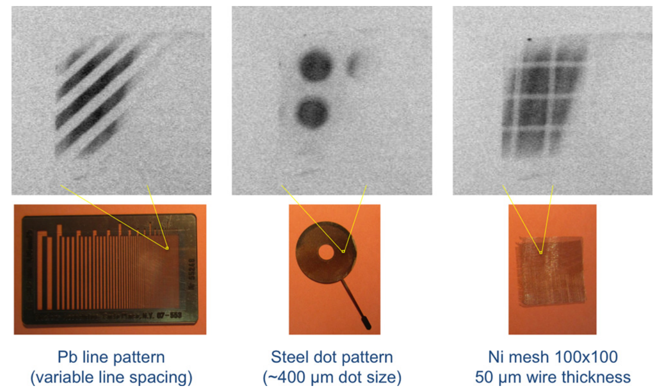

FIG. 5. (Color online) Magnified images of various targets at a silver x-ray source at NIST. Magnification: 12.3.

IV. CONCLUSION

Based on the first tests of the x-ray magnifier crystal pair system, it is clear that this technique could be adopted for laser produced plasma experiments. It could be used in a similar manner as a back illuminated radiography imaging system with the advantage of using a large backlighter x-ray source and the resolution only be determined by the crystal. It could also be used as a direct x-ray imager of the laser irradiated target. As shown in Fig. 3, several magnifier systems could be fitted into a TIM at the OMEGA-EP laser facility for a first test of the imaging technique.

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