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We have developed and implemented a broadband X-ray spectrometer with a variable energy range for use at the Atomic Weapons Establishment’s Orion Laser. The spectrometer covers an energy bandwidth of ∼1–2 keV using two independently mounted, movable Bragg diffraction crystals. Using combinations of cesium hydrogen phthalate, ammonium dihydrogen phosphate, and pentaerythritol crystals, spectra covering the 1.4–2.5, 1.85–3.15, or 3.55–5.1 keV energy bands have been measured. Image plate is used for detection owing to its high dynamic range. Background signals caused by high energy X-rays and particles commonly produced in high energy laser experiments are reduced by a series of tantalum baffles and filters installed between the source and crystal and also between the crystals and detector.

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I. INTRODUCTION

Bragg’s law has been used with crystals to generate x-ray spectra for over a century. Bragg’s law states that light incident on a crystal will be diffracted at an angle based on its angle of incidence, the lattice spacing of the crystal used, and the wavelength of the light. This is a well-tested technique for investigating laser-produced plasmas. Here, we use multiple crystals arranged side by side and offset in angle to cover a wide range of x-rays in order to characterize the plasma from which the light is emitted. The instrument was built specifically for use on buried layer experiments on the Orion laser at the Atomic Weapons Establishment (AWE), where broadband spectra give information on plasma density, temperature, and Ionization Potential Depression (IPD).

II. EXPERIMENTAL SETUP

The Lawrence Livermore X-ray Spectrometer (LLXS) was fielded on the Orion laser at the AWE (Fig. 1). Orion consists of ten long pulse beams capable of delivering 500 J of 351 nm light with a pulse duration of 100 ps to 5 ns, and two short pulse beams delivering 500 J of 1064 nm light of durations between 0.5 and 20 ps. Diagnostics are mounted on Ten Inch Manipulators (TIMs) and then driven into the target chamber center to gather data. LLXS was fielded in TIM 46, which sits below target chamber center (TCC). TIM 46’s axis looks up to form an angle of 45° with the equatorial plane. The target was rotated such that TIM 46 was looking at the front, at an angle of 25° from the target surface.

A. Basic design

This diagnostic has the challenging task of surviving the high particle and x-ray flux and high electro-magnetic pulse (EMP) environment that is present in the Orion target chamber. LLXS itself is made of thick aluminum (a minimum of 9 mm on each side, 13 mm on the top, and 1.5 mm on the bottom). In addition to this, each side of the spectrometer is covered with 1 mm of tantalum cladding in an effort to prevent hard x-rays and hot electrons from entering. The entrance to LLXS is a removable nose cone made out of 1 mm of aluminum and has a 240 μm tantalum collimator at its end. This is the first of several baffles that act to further reduce the background counts present on the image plate. The nose cone can be replaced with an aluminum pointer for alignment. Once aligned, the image plate lies 290 mm from target chamber center, and the collimator on the front of the nose cone lies 42 mm away. Image plate was chosen as the detector because of its high dynamic range. Therefore, it is less likely to saturate from the large signal that is still present despite the filtration used.

B. Baffling and filtration

Along the top and sides on the inside of LLXS are 45 2.1 mm wide gaps spaced every 4 mm. These are used for removable filters and/or baffles that can be arranged for each specific crystal setup. On Orion, the first slot (closest to TCC) was filled with a filter holder that contained an 800 nm thick aluminum filter. This filter’s primary function was to act as a blast shield should any debris make it past the collimator at the front of the nose cone.

In slot number two was a pair of 1 mm thick tantalum “goal post” baffles. These baffles earned this moniker by having a U shape 15.25 mm wide and 25.25 mm tall. This shape acts as coarse baffling to filter out light that would otherwise be incident on the crystals further in. In slot three was another...
pair of 1 mm thick tantalum baffles. This set of baffles was laser cut for the specific crystal arrangement being used at the time and would only pass light though onto each crystal individually. The final set of baffles was also of the same design as those in slot three, but sat behind the crystals in approximately slot thirty. These baffles blocked all but the light that had diffracted off of each crystal, and, furthermore, prevented hard x-rays and hot electrons from impinging on the image plate. The total thickness of 6 mm of tantalum baffles transmits less than 10% of the photons below 7 keV, and less than 55% at 20 keV.

The image plate itself sat in a caddy placed at the rear of the spectrometer behind a 25 μm beryllium filter. This final filter was instrumental in sifting out the low-energy rays both generated inside the spectrometer from hot electrons interacting with the aluminum body and any light that managed to pass through the baffles.

C. Crystal settings

LLXS currently has baffles and crystal mounts for three different energy bands. The first setting comprises two cesium hydrogen phthalate (CsAP(001)) crystals, each 5 cm long and approximately 1.5 cm wide. The crystal mounts are made of aluminum and hold the crystals side by side, one lower than the other. Each crystal is rotated 3.5° from the TIM axis and sits at 3.8 and 2.5 cm below the axis. This setting covers Bragg angles from ∼11° to ∼20°. This covers an energy range of ∼1400 eV to ∼2500 eV, with a small gap of about 30 eV where the diffraction off of the two crystals does not quite overlap.

Setting two is composed of one CsAP and one ammonium dihydrogen phosphate (ADP(101)) crystal. The CsAP has a rotation of 3.35° from the TIM axis and sits 2.5 cm below it. This allows a limited range of ∼1850 eV to ∼2175 eV. The ADP crystal is rotated 10° from the TIM axis and sits 4.75 cm below it. Good data were produced despite the inherent low reflectivity of the ADP crystal. It produced spectra in the range of ∼2750 eV to ∼3180 eV. Therefore, this setting has a rather significant gap between the crystals of ∼600 eV.

The third setting uses two pentaerythritol (PET(002)) crystals, each the same size as the previous CsAP and ADP crystals. PET’s small 2d spacing relative to CsAP allows the crystals to cover much higher energies with a higher spectral resolution. The crystals are rotated at angles of 6° and 4.5° from the TIM axis and sit 4.9 and 4 cm below it, respectively. This gives an energy coverage of ∼3550 eV to ∼5250 eV while producing an overlap between the two spectra substantial enough to combine the image plate lineouts into one spectra.

III. RESULTS

Results from measurements on Orion are shown in Figures 2–7. These were obtained using settings two and three. For each set of data shown, the filter response has been removed and the dispersion of each crystal calculated based on an observation of K-shell transitions from hydrogen-like and helium-like ions with known energies. In order to calculate the dispersion for the second setting, two different targets were needed, one for each crystal. The ADP crystal’s coverage was measured using a 50 μm thick polyethersulphone...
Parylene-N was shot with two 800 ps long pulse beams. Spectra from both targets of 790 nm KCl sandwiched between two layers 310 nm of (PES, OC₆H₄OC₆H₄SO₂C₆H₄) were used to show the overlap between them.

The CsAP crystal dispersion on setting two was calculated using a 200 nm thick Al foil buried under 5 μm of CH₄. This target was shot using a 500 fs short pulse beam; therefore the densities were much higher (and the line widths much broader) than on the other spectra. Figure 2 shows that LLXS was able to spectrally resolve the self-absorption of the Al Ly-β line peak.

The third setting’s dispersion was fit using two types of tamped targets, KCl and NaCl. These targets were each shot with two 800 ps pulses, timed such that when the first was ending the second began. This allowed the targets to expand into the vacuum and blow down to lower densities. The low densities prevented continuum lowering, allowing high n-shell energy states to be present.

NaCl was used to help distinguish what lines originated from the K and what lines were formed from the Cl. Figure 4 shows an example from 790 nm of NaCl buried under 310 nm of Parylene-N. Both the Cl He- and Ly-series limits are visible down to the zeta (n = 7 to n = 1 transition) lines.

Once the Cl lines were identified, they were used to sort through the KCl spectra. The K lines were significantly brighter than the Cl lines, as shown in Figures 5–7. Each crystal on setting three was fit on its own, and then combined for the final spectra. In Figures 6 and 7 the lower energy crystal is shown in blue, the higher energy crystal in purple. Three line features overlap, and their intensities agree very well with no normalization needed. More detail can be seen in Figure 7, all four (Cl He-α, Cl Ly-α, K He-, and K Ly-) series limits are clearly visible.

Both tested settings were shown to produce quality spectra for long pulse beam shots. Short pulse data were also collected; however, the data were not as clean with the exception of the Al data shown. This could be resolved with more filtration to better sort out the hard x-rays produced during high intensity laser shots.

The data that were gathered by LLXS during this experimental campaign can be used to determine the temperature and density of the plasma by measuring spectral line ratios and line widths, respectively. The data produced from setting three may also have a wide enough spectral range to determine the plasma temperature from the free-bound continuum as well. This gives a self-consistent means of checking the initial measurement without having to compare the result with a second diagnostic.

Each type of crystal used (CsAP, ADP, and PET) produced fine spectra. The data from the ADP crystal are of particular note, as ADP has approximately 5 times lower reflectivity than the other crystals tested for their respective energy ranges. The LLXS design can accommodate with a CCD detector sitting ~30 cm from TCC, therefore it is attached to an airbox with an onboard computer and cooling system. However, after a few days of shots the thermoelectric cooler on the CCD malfunctioned. It is currently hypothesized that the EMP generated from the high flux environment of Orion was too great for the current shielding on the CCD. Additional shielding will be implemented on further campaigns.

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FIG. 5. Image plate from KCl target. The two PET crystals have been moved to show the overlap between them.

FIG. 6. A target of 790 nm KCl sandwiched between two layers 310 nm of Parylene-N was shot with two 800 ps long pulse beams. Spectra from both PET crystals were combined to form one continuous spectrum.

FIG. 7. Zoomed in KCl spectra. The Cl He-series, Cl Ly-series, K He-series, and K Ly-series limits are all clearly visible down to the zeta lines.

IV. DISCUSSION

D. J. Hoarty et al., High Energy Density Phys. 9, 661 (2013).