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HIGH ENERGY, HIGH BRIGHTNESS X-RAYS PRODUCED BY COMPTON BACKSCATTERING AT THE LIVERMORE PLEIADES FACILITY

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Abstract

PLEIADES (Picosecond Laser Electron Interaction for the Dynamic Evaluation of Structures) produces tunable 30-140 keV x-rays with 0.3-5 ps pulse lengths and up to 10^7 photons/pulse by colliding a high brightness electron beam with a high power laser. The electron beam is created by an rf photo-injector system, accelerated by a 120 MeV linac, and focused to 20 µm with novel permanent magnet quadrupoles. To produce Compton back scattered x-rays, the electron bunch is overlapped with a Ti:Sapphire laser that delivers 500 mJ, 100 fs, pulses to the interaction point. K-edge radiography at 115 keV on Uranium has verified the angle correlated energy spectrum inherent in Compton scattering and high-energy tunability of the Livermore source. Current upgrades to the facility will allow laser pumping of targets synchronized to the x-ray source enabling dynamic diffraction and time-resolved studies of high Z materials. Near future plans include extending the radiation energies to >400 keV, allowing for nuclear fluorescence studies of materials.

INTRODUCTION

Dynamic studies of materials have been an active area of research that include x-ray sources and pump probing of materials [1-3]. Furthermore, short timescale events such as melting and refreezing demand very short pulse, hard x-ray sources. Third generation synchrotron light sources have probed structures on the atomic length scales, but their resolution is limited to roughly 100 ps and is not well matched the for elemental process in materials where the time scale for atomic motion, for example, is <50 fs.

Livermore has undertaken the development of PLIEADES [4], an ultra-short, bright, hard x-ray source based on Compton backscattering, where a high brightness electron beam is overlapped with a high power laser. Previous results have demonstrated the utility of such sources [5]. The major thrust of PLIEADES is to use the hard x-rays in laser-x-ray pump probe experiments of high Z materials, the schematic shown in Fig. 1.

EXPERIMENTAL SETUP

Overlapping a high brightness electron beam and a high power laser generates the ultra fast x-rays. The electron beam source is a 1.6 cell S-band photo-injector gun with emittance compensating solenoids. The electron beam exits the gun with an energy of 3.5 MeV and is then

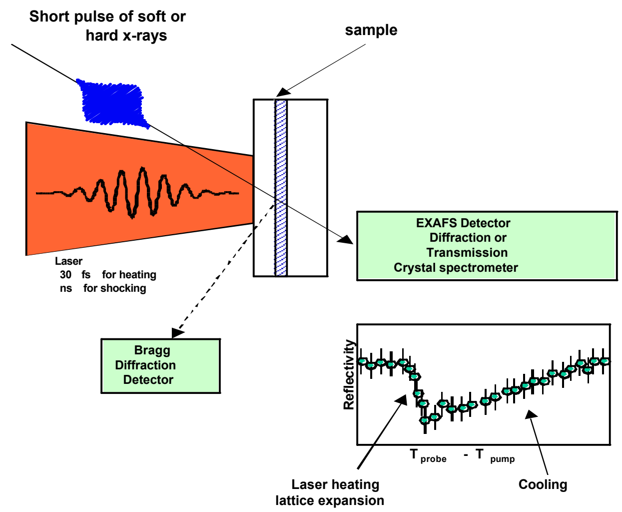

Fig. 1. Schematic of laser-x-ray pump probe

matched into the 4 x 2.5 m section accelerator, boosting the energy to over 120 MeV. The electron beam enters the interaction region where measurements of the energy, energy spread, emittance and spot size are made. A quadrupole triplet matches the beam into the final focusing permanent magnetic quadrupole (PMQ) triplet [6]. The PMQs, with gradients over 500 T/m, focus the 200 pC electron bunch to 30 µm at the interaction point (IP) where it is overlapped with the interaction laser.

The interaction FALCON laser [7] is based on a Ti:S (800 nm/1.5eV) chirped pulse amplification system. After leaving the oscillator, the pulse is stretched with a grating and then amplified by a rengenerative amplifier and two 4-pass amplifiers, all Ti:S based. The pulse is then propagated to a compressor that shortens the pulse to 100 fs from nearly 700 ps. After the compressor, the beam is propagated and focused to 30 µm at the IP with nearly 500 mJ energy.

PLEIADES collides the laser and electron beam at a 180^0 orientation, producing Compton x-rays with energies of $4\gamma^2$*(1.5 eV), where γ is the energy of the electron beam. The Compton radiation is emitted in a forward $1/\gamma$ cone to the electron beam, typically 10-20 mrad for PLIEADES. The x-ray pulse length is similar to the e-beam pulse length, 7ps. However, the x-ray pulse can be shortened considerably by a scheme termed velocity compression [8] whereby the electron beam is chirped by running off peak phase in the 1st linac section, and the energy spread in the beam removed by running off phase in the following linac section [9].

X-RAY PARAMETERS AND INTERACTION WITH MATERIALS

Figure 2 shows the measured flux for a given x-ray energy range, 40–140 keV. Using a calibrated x-ray CCD camera, the peak flux measured is just over 10^7 photons/pulse for the higher energy x-rays. Recently, 10 keV x-rays have been generated with a 20 MeV electron beam, but no flux calculated. Also, the spot size at the x-ray CCD confirms the Compton x-ray angle of emission, $1/\gamma$, over the range of x-rays energies given in Fig. 2.

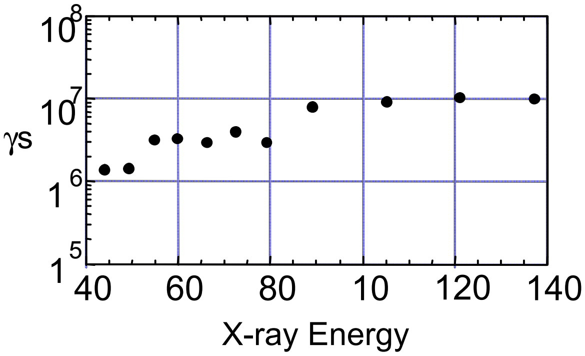

Fig. 2. Measured x-ray flux (photons) vs. x-ray energy

In order to produce ultra-short x-rays, the electron bunch was compressed in the 1st linac section. Measurements from a CTR interferometer [8] done on the electron bunch length, and a compressed length of 300 fs was achieved compared to 5 ps uncompressed. The beam was then overlapped with the FALCON laser, and fs, hard x-rays generated. Fig. 3 shows the x-ray pulses generated from the compressed (a) and uncompressed (b) electron beam. While compression does

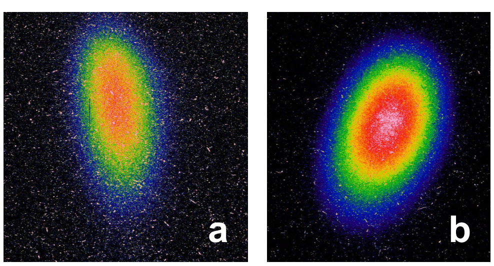

Fig. 3a. X-rays generated from the velocity compressed, 300fs, electron beam vs. (b) uncompressed 5 ps beam.

increase the emittance of the electron beam, the overall x-ray brightness as defined by

$$B = \frac{N_x}{(2\pi)^{5/2}\,\sigma_x^2\sigma_{x'}^2\sigma_\tau\,(0.1\%\mathrm{BW})}, \qquad (1)$$

increased by 70% [9].

K-edge radiography on Uranium demonstrated the high energy tunability of the source and the energy-angle dependence of the Compton backscattering process. A 500 μm thick Uranium foil was placed in the x-ray path, and PLEIADES was tuned to the Uranium k-edge of 115 keV. Fig. 4 shows the resulting x-ray pattern at the CCD integrated over 1000 shots and the expected theoretically calculated pattern given by BLOWER (e-Beam Laser Overlap With Emitted Radiation) [10].

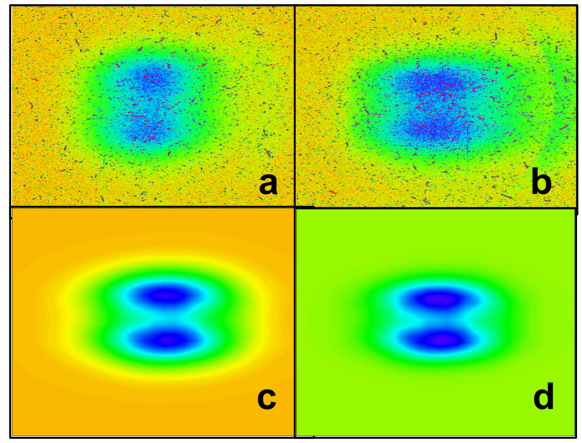

Fig. 4. K-edge radiography through U. 4a. PLEIADES tuned to 115 keV k-edge, for on axis x-rays, which are abosorbed by k-edge. 4b. PLEIADES tuned away from k-edge, on axis x-rays begin being transmitted through foil. 4 c and d are BLOWER simulations.

As expected the x-rays at the k-edge are absorbed by the U foil, and those x-rays with energies above or below the k-edge transmitted. The low angle x-rays (those on axis) have the highest energy, were tuned to the k-edge and absorbed. The off axis x-rays are lower energy, off the k-edge and transmitted. The asymmetry in the k-edge transmission is due to the fact that the e-beam was asymmetric at the IP leading to an asymmetric x-ray pulse.

Figure 5 shows 30 keV x-rays diffracted from an Indium Antimonide, (InSb) crystal. The main x-ray beam is passed through a small aperture to eliminate the off-axis, low energy x-rays. While this reduces the flux to the

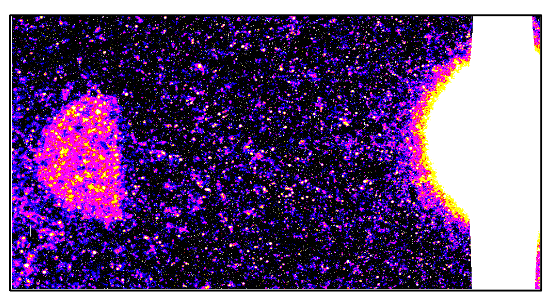

Fig. 5. Diffracted signal from InSb crystal. The beam on the left is the Bragg diffracted signal from the crystal. The beam on the right is the main x-ray pulse, saturated CCD.

crystal, it does narrow the angular and energy spectrum arriving at the InSb sample. As expected, the diffracted signal arrives at the CCD satisfying the Bragg condition.

K-edge radiography can be used to filter the x-rays during diffraction experiments. Tin (Sn) was used as a low pass filter for diffraction from InSb. Figure 6 shows the diffracted signal after Sn is used in the x-ray path. The Sn foils was placed to block only half of the main x-ray pulse, thus a comparison can be made of the k-edge or filtered x-rays and the non-filtered x-rays. As expected the bottom half, filtered by the Sn k-edge, absorbed the high energy x-rays and allowed a lower energy x-ray bunch to diffract from the InSb. The sharp cut off on the bottom, is set by the Bragg condition of Sn k-edge.

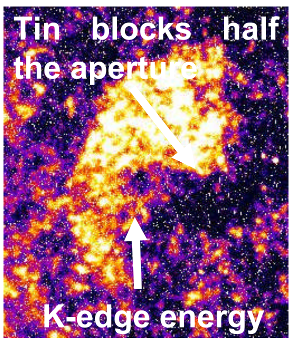

Fig. 6. Diffracted x-rays from InSB. Sn is used to filter the bottom half of the x-ray pulse. The x-rays were tuned so that the high energy x-rays would be absorbed by the Sn, leaving the diffracted signal with a sharp high energy edge.

A pumpline [7] has been constructed and provides up to 20 mJ of IR power for dynamic diffraction experiments. The pump beam is leaked through an aperture in a FALCON mirror and is able to deliver enough power to melt samples. This melting will change the lattice structure, and hence the diffraction pattern shown in Fig. 6. Since the pumpline is derived from the interaction laser, it is synched to the x-ray pulse probling the sample. A delay line [7] for the pump beam is necessary to overlap in time the x-ray and pump pulses.

CONCLUSION

PLEIADES has demonstrated the tunability of a high energy Compton back-scattered x-ray source. Furthermore, k-edge studies have provided a method that reduces the Compton spectrum and allows the study of small changes in the lattice spacing of crystals by observing the change in diffracted Bragg angle. In addition, the laser pump line is set up, and in the future, we hope to pump samples and study the lattice change during melting and refreezing in crystals. Furthermore, plans to increase the Compton backscattered energy to over 600 keV will allow for nuclear fluorescence studies in high Z materials.

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