GENERATION OF HIGH BRIGHTNESS X-RAYS WITH THE PLEIADES THOMSON X-RAY SOURCE

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Abstract

The use of short laser pulses to generate high peak intensity, ultra-short x-ray pulses enables exciting new experimental capabilities, such as femtosecond pump-probe experiments used to temporally resolve material structural dynamics on atomic time scales. PLEIADES (Picosecond Laser Electron InterAction for the Dynamic Evaluation of Structures) is a next generation Thomson scattering x-ray source being developed at Lawrence Livermore National Laboratory (LLNL). Ultra-fast picosecond x-rays (10-200 keV) are generated by colliding an energetic electron beam (20-100 MeV) with a high intensity, sub-ps, 800 nm laser pulse. The peak brightness of the source is expected to exceed 10^{20} photons/s/0.1% bandwidth/mm^2/mrad^2. Simulations of the electron beam production, transport, and final focus are presented. Electron beam measurements, including emittance and final focus spot size are also presented and compared to simulation results. Measurements of x-ray production are also reported and compared to theoretical calculations.

1 INTRODUCTION

PLEIADES (Picosecond Laser Electron InterAction for the Dynamic Evaluation of Structures) is a next generation Thomson scattering x-ray source being developed at Lawrence Livermore National Laboratory (LLNL). Ultra-fast ps x-rays (10-200 keV) are generated by colliding an energetic electron beam (20-100 MeV) with a high intensity, sub-ps, 800 nm laser pulse. Generation of sub-ps pulses of hard x-rays (30 keV) has previously been demonstrated at the LBNL Advanced Light Source injector linac, with x-ray beam fluxes of 10^5 photons per pulse [1]. The LLNL source is expected to achieve fluxes between 10^7 – 10^8 photons for pulse durations of 100 fs to 5 ps using interaction geometries ranging from 90° (side-on collision) to 180° (head-on collision). In this paper, we describe the first production of x-rays using Thomson scattering at the LLNL facility.

2 EXPERIMENT LAYOUT

The PLEIADES facility consists of a Ti-Sapphire laser system capable of producing bandwidth limited laser pulses of 50 fs with up to 500 mJ of energy at 800 nm, an S-band photo-cathode RF gun, and a 100 MeV linac consisting of 4, 2.5-meter-long accelerator sections. The RF gun, which is driven by a picosecond, 300 μJ, UV laser that is synchronized to the interaction drive laser, is designed to produce up to 1 nC of charge at 5 MeV [2]. The accelerator is then used to accelerate the electron beam to energies ranging from 20-100 MeV.

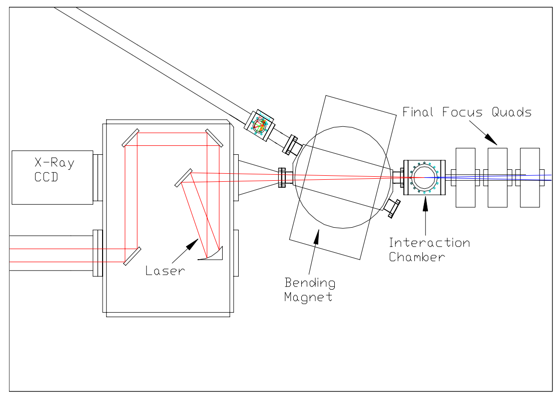

Figure 1: Interaction Geometry

A schematic of the interaction region is shown in Fig. 1. To maximize x-ray flux while minimizing effects of timing jitter, the laser incidence angle is 180 degrees with respect to electron beam direction, though a 90 degree interaction geometry will also be possible in future experiments. The focal length between the final focus quadrupole triplet and the interaction region is 10 cm to allow for maximum focus strength and minimum electron bunch spot size. A 30-degree dipole magnet is used to bend the electron bunch out of the x-ray beam path following the interaction. An off-axis, 1.5 m focal length parabolic mirror is used to focus the laser, which, assuming a diffraction limited spot, should reach a minimum spot size of about 15 μm FWHM at the interaction point. Currently, a fused-silica flat mirror is placed in the x-ray beam path to serve as the final steering optic for the laser, though there are plans to replace this with a beryllium flat, which will be more transparent to the x-ray beam. The interaction chamber also serves as a diagnostic chamber used for imaging and streak camera analysis of the laser and electron bunches. The x-rays have been measured with a 16 bit CCD array fiber coupled to a cesium iodide scintillator.

3 ELECTRON BEAM SIMULATIONS

The electron beamline has been fully modeled, from the S-band photo-cathode RF gun to the interaction point using the Los Alamos particle dynamics code, PARMELA, and the electrostatic and electromagnetic field solvers: POISSON and SUPERFISH. These include simulations of emittance compensation between the RF gun and the first linac section, velocity compression of the bunch through the first linac section, and the acceleration and optimization of the beam energy spread and emittance during transport through the subsequent accelerator sections.

Two modes of linac operation have been investigated through simulation. The first is when the electron beam is accelerated on crest through the accelerator. In this case, the minimum electron bunch length is about 6 ps FWHM (2.5 ps rms). The second mode of operation employs velocity compression, in which the beam is injected into the first linac section near the zero crossing of the accelerating field in order to provide an energy chirp to the beam. This results in longitudinal compression of the accelerated bunch. The second accelerator section is then used to accelerate the beam from about 10 MeV to about 35 MeV. The third and fourth sections can then be used to either remove a large portion of the energy spread induced by the velocity compression process, or to simply accelerate the beam further, depending on the final beam energy desired. Fig. 2 shows the evolution of several of the beam characteristics determined from PARMELA simulations for the case of a 0.5 nC bunch where velocity compression is implemented. At the exit of the accelerator, the electron beam normalized rms emittance is about 3.5 πmm-mrad, the rms bunch length is 0.7 ps, and the rms energy spread is 0.5 %. While it is possible to compress further, this bunch length was chosen to minimize emittance growth resulting from the compression process, while maximizing x-ray yield from the Thomson scattering interaction. In this particular case, the final beam energy is 35 MeV, though larger energies are possible with similar results.

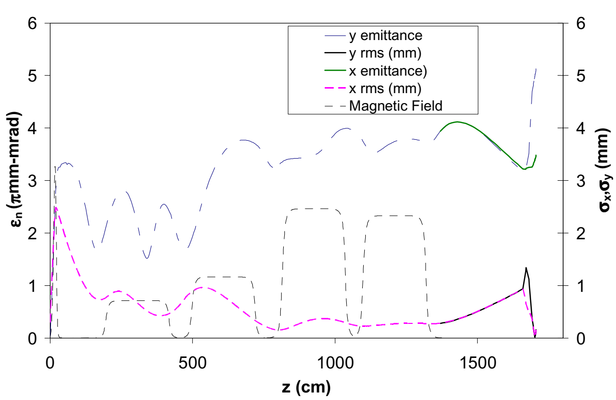

Figure 2: PARMELA simulation of electron beam production from the RF gun to the final focus. Emittance and spot size are plotted vs *z* position from the RF gun cathode.

The electrons are transported 3 meters from the accelerator exit and focused with a high gradient quadrupole triplet. The triplet is about 50 cm long, and the focal length is about 10 cm. The maximum field gradient in the quadrupole magnets is 15 T/m. Final focus simulations were performed using PARMELA and Trace-3D, and have indicated that a spot size of abut 30 μm FWHM (12 μm rms) should be obtainable at the focus.

4 EXPECTED X-RAY PRODUCTION

The expected x-ray production was calculated by integrating the emission probability per unit time, dN_x/dt, given by

$$\frac{dN_x}{dt}(t) = \sigma c\left[1-\mathbf{v}\cdot\mathbf{k}\right] \iiint n_\gamma(\mathbf{x},t)\, n_e(\mathbf{x},t)\, d^3x, \qquad (1)$$

where N_x is the total number of x-rays produced, $n_\gamma(\mathbf{x},t)$ is the laser photon density, $n_e(\mathbf{x},t)$ is the electron density, σ is total Thomson cross section, **v** is the velocity of the electron beam, and **k** is the wave number of the laser pulse. The calculations were performed for a 300 mJ, 300 fs laser pulse in conjunction with the PARMELA output in place of $n_e(\mathbf{x},t)$. $n_\gamma(\mathbf{x},t)$ was assumed to have a Gaussian profile in the transverse and longitudinal dimensions, and the Rayleigh range of the laser focus was determined assuming a 2 X diffraction limited focus. For the electron beam parameters determined from the simulation shown in Fig. 2, the peak x-ray energy is 30 keV, and the peak x-ray flux was found to be about 6 x 10^{19} photons/s with an integrated photon yield of about 10^8. In addition, a 3-D frequency domain code [3] was used to calculate the expected spectral bandwidth to be about 10% on axis, with a peak spectral brightness of about 10^{20} photons/s/0.1% bandwidth/mm^2/mrad^2.

5 BEAM MEASUREMENTS

To date, electron bunches with up to 700 pC of charge have been produced with up to 200 μJ of UV laser energy incident on the gun photo-cathode. The beam has been transported through the linac and accelerated up to 60 MeV without velocity compression. Quad scan emittance measurements have been performed for 300 pC, 60 MeV bunches, yielding a normalized rms emittance of 9 mm-mrad. The rms energy spread has been measured to be 0.2%. Improvements in emittance are expected after planned improvements in the UV drive laser uniformity and optimization of the electron beam transport.

Both the electron beam and the interaction drive laser have been imaged by placing a metal cube in the interaction chamber to send OTR light from the electron beam and laser light into the same camera. Using a CCD camera, the electron beam spot sized has been measured to be about 70 μm rms, while the laser spot size has been measured to be about 30 μm. This is about twice the optimized spot size determined from PARMELA simulations, based on the measured beam emittance. Further optimization of the final focus quads should help reduce the measured spot size.

The synchronization between the laser and electron bunches has been characterized with a streak camera. A schematic of the measurement, as well as the streak camera image is shown in Fig. 3, indicating good temporal overlap of the two bunches. The jitter has been measured to be within the resolution of the streak camera (about 2 ps), which is in agreement with indirect timing jitter measurements performed by mixing wakefields produced by the electron bunch with a frequency multiplied photo-diode signal from the laser oscillator.

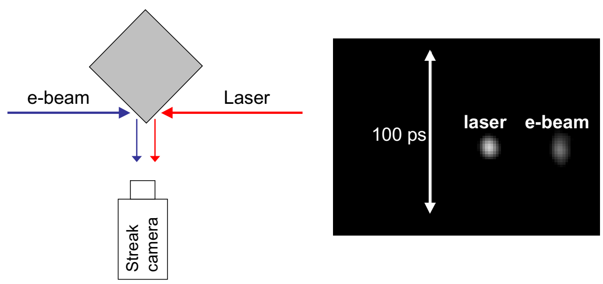

Figure 3: E-beam to laser synchronization measurement.

6 X-RAY PRODUCTION

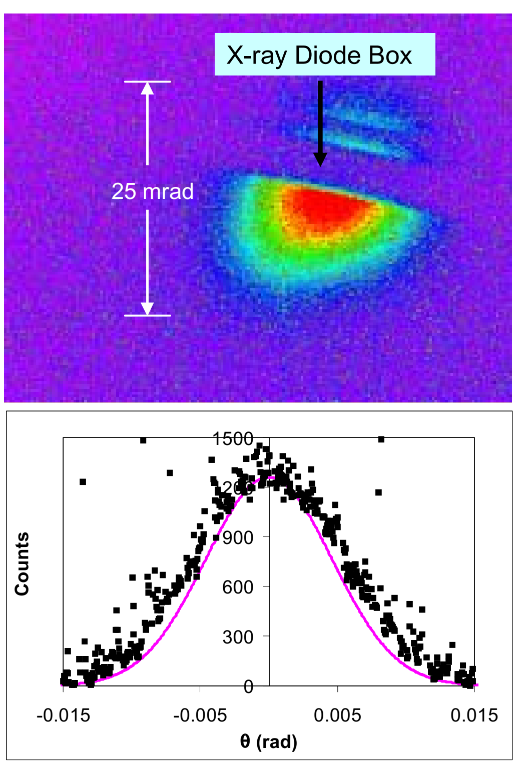

Figure 4: Measurement of X-ray beam profile. Top: CCD image. Bottom: Line-out intensity profile: measurement (dots), theory (line).

First light of the PLEIADES Thomson x-ray source was achieved in January, 2003. Figure 4 shows the measured beam profile taken with the x-ray CCD camera. The electron beam energy in this case was 54 MeV, and the bunch charge was about 250 pC. The laser energy delivered at the interaction was about 40 mJ. The image is integrated over 1200 shots. The estimated average photon count per shot is about 5 x 10^4, and the peak photon energy is about 70 keV. The theoretical intensity profile (shown in the bottom half of Fig. 4) agrees well with the measured profile. The theoretical curve includes the broadening effects from the measured beam emittance and the narrowing effects derived from the spectral dependence of the transmission coefficient of the laser turning mirror.

Dramatic improvements of the per shot x-ray dose are expected after improvements in the electron beam final focus optics, maximization of the IR drive laser energy delivered to the interaction region, and reduction of electron beam emittance through the optimization of both the photocathode drive laser uniformity and the electron beam transport. These improvements will allow for the realization of final focus spot sizes as small as 10 µm rms, and the production of up to 10^8 x-ray photons per collision.

7 CONCLUSIONS

The PLEIADES Thomson X-ray source is a unique, high peak brightness x-ray source that will be useful for ultra-fast imaging applications to temporally resolve material structural dynamics on atomic time scales. Electron beam transport and x-ray production simulations have been performed to completely model the theoretical source performance. To date, 0.3 nC, 54 MeV bunches have been focused to 70 µm rms spot sized and collided with a 40 mJ, 30 µm laser pulse to produce 70 keV x-rays. Optimization of the experiment will include increasing the laser energy delivered to the interaction region to about 300 mJ, and decreasing the electron beam emittance to less the 5 mm-mrad rms. This will enable the achievement of a 10 µm spot size at the interaction and the production of 10^8 x-ray photons per pulse. Once optimization is complete, PLEIADES should achieve a peak x-ray brightness approaching 10^{20} photons/s/0.1% bandwidth/mm^2/mrad^2.

8 ACKNOWLEDGEMENTS

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