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Short Pulse High Brightness X-ray Production with the PLEIADES Thomson Scattering Source

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Abstract We describe PLEIADES, a compact, tunable, high-brightness, ultra-short pulse, Thomson x-ray source. The peak brightness of the source is expected to exceed 10^{20} photons/s/0.1% bandwidth/mm^2/mrad^2. Initial results are reported and compared to theoretical calculations.

1 Introduction

The use of short laser pulses and high brightness, relativistic electron sources to generate high peak intensity, ultra-short x-ray pulses enables exciting new experimental capabilities. These include femtosecond pump-probe experiments used to temporally resolve material structural dynamics on atomic time scales [1], advanced biomedical imaging [2], and x-ray protein crystallography [3].

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). This source generates x-rays by scattering a high intensity, sub-ps, 800 nm laser pulse off a high-brightness photo-injector generated electron beam at the LLNL 100 MeV linac.

The scattered laser photons are relativistically up shifted in frequency into the hard x-ray range and are emitted in a narrow cone about the electron beam direction. The x-ray energy, E_x is given by

$$E_x = E_L 2\gamma^2 \left(1 - \cos\phi\right), \tag{1}$$

where E_L is the laser photon energy, $\gamma = E/m_e c^2$ is the normalized electron energy, and ϕ is the angle of incidence between the laser and electron beams. The x-ray energy is therefore tunable through electron beam energy, giving for PLEIADES (20-100 MeV electrons) a range of 10-200 keV x-ray pulses.

Thomson scattering 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 [4,5]. The LLNL source is expected to achieve fluxes between 10^7 and 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 Experimental 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 is designed to produce up to 1 nC of charge at 5 MeV [6]. The traveling-wave accelerator sections are then used to boost the electron beam to energies ranging from 20-100 MeV. The electron bunch is generated at the copper photo-cathode by a picosecond, 300 mJ, UV laser that is synchronized to the interaction drive laser. In addition, the 2.8 GHz power that drives both the gun and the accelerator is derived by frequency multiplying the 81 MHz pulse train output signal of the mode-locked oscillator which seeds both the IR interaction laser and the UV photo-cathode drive laser. In this way the laser and electron beams are synchronized to the picosecond level required in this experiment.

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

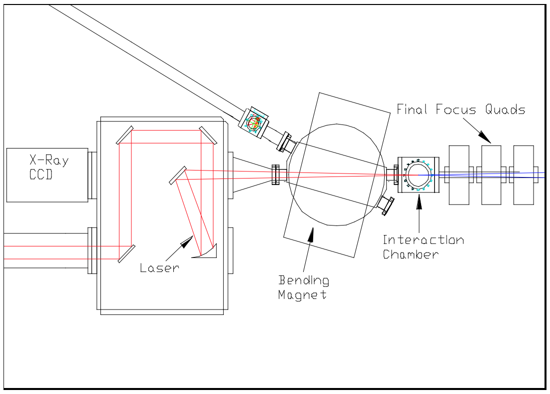

Fig. 1 The PLEIADES Interaction Beamline

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. An x-ray photodiode and a Germanium-Lithium detector are also available for x-ray detection.

3 Predicted Performance

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

$$\frac{dN_x}{dt}(t) = \sigma_T c \left[1 - \boldsymbol{v} \cdot \boldsymbol{k}\right] \iiint\limits_V n_\gamma(\boldsymbol{x}, t)\, n_e(\boldsymbol{x}, t)\, \mathrm{d}V, \tag{2}$$

where N_x is the total number of x-rays produced, $n_\gamma(\boldsymbol{x}, t)$ is the laser photon density, $n_e(\boldsymbol{x}, t)$ is the electron density, σ_T is total Thomson cross section, $\boldsymbol{v}$ is the velocity of the electron beam, and $\boldsymbol{k}$ is the wave number of the laser pulse. For 180° scattering, as depicted in Fig 1, the integrated x-ray dose is found to be

$$N_x \propto \frac{N_e N_\gamma}{r_e^2 + r_L^2}, \tag{3}$$

where r_e and r_L are, respectively, the electron and laser beam spot sizes at the interaction point and N_e and N_γ are the total number of electrons and photons in the two beams.

Table 1 Simulated Electron and Laser Bunch Parameters

Parameter	Value	Units
Emittance ε_n	5.0	mm mrad (rms)
E-beam spot size r_e	50	μm (FWHM)
Laser spot size r_L	20	μm (FWHM)
E-beam duration	1.6	psec (FWHM)
Laser duration	300	fsec (FWHM)
E-beam charge	0.5	nC
Laser Energy	300	mJ

The x-ray production process was simulated using 3D codes in both the time and frequency domains [7] to obtain integrated photon yield and spectral information. PARMELA electron beam dynamics simulations from the photo-cathode to the interaction point were used to determine $n_e(\boldsymbol{x}, t)$, while $n_\gamma(\boldsymbol{x}, t)$ was assumed to be Gaussian in the transverse and longitudinal dimensions, and the Rayleigh range of the laser focus was determined assuming a 2 times diffraction limited focus. Using the electron and laser beam parameters in Table 1, these simulations give an integrated photon yield of about 10^8, a spectral bandwidth of 10% on-axis, and a peak spectral brightness of approximately 10^{20} photons/s/0.1% bandwidth/mm^2/mrad^2.

4 Experimental Measurements

To date, electron bunches with up to 700 pC of charge have been produced with up to 200 mJ of UV laser energy incident on the gun photo-cathode. The beam has been transported through the linac and accelerated up to 60 MeV. 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. 2, indicating good tem-

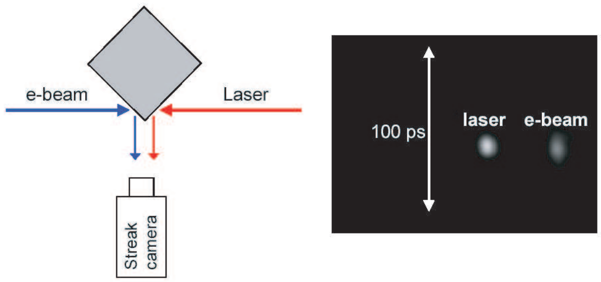

Fig. 2 Laser/electron synchronization measurement.

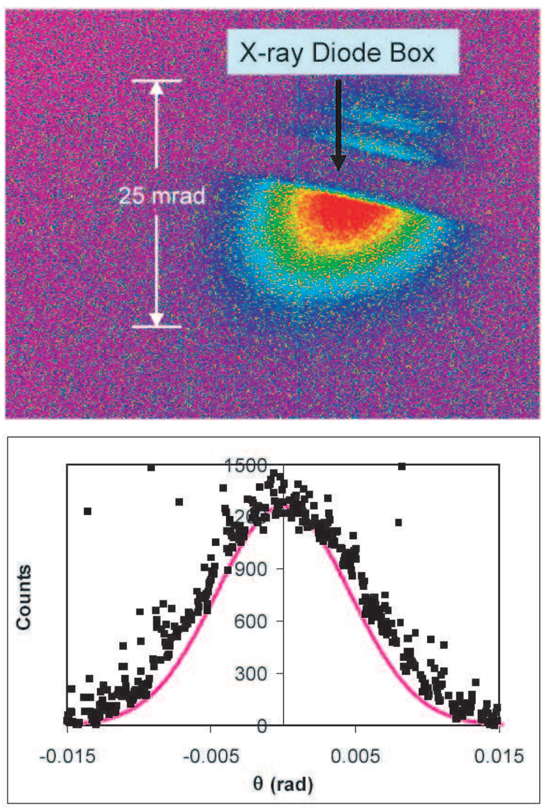

Fig. 3 Measurement of x-ray beam profile. Top: CCD image. Bottom: Line-out intensity profile, measured (dots) and theory (line).

poral 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.

First light of the PLEIADES Thomson x-ray source was achieved in January, 2003. Figure 3 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. 3) 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.

5 Conclusions

The PLEIADES Thomson X-ray source is a unique, high peak brightness x-ray source that will be useful for ultrafast 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.

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