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Abstract. We report on the performance of an S-band RF photocathode electron gun and accelerator for operation with the PLEIADES Thomson x-ray source at LLNL. Simulations of beam production, transport, and focus are presented. It is shown that a 1 ps, 500 pC electron bunch with a normalized emittance of less than 5 π mm-mrad can be delivered to the interaction point. Initial electron measurements are presented. Calculations of expected x-ray flux are also performed, demonstrating an expected peak spectral brightness of 10^{20} photons/s/mm^2/mrad^2/0.1% bandwidth. Effects of RF phase jitter are also presented, and planned phase measurements and control methods are discussed.

INTRODUCTION

PLEIADES (Picosecond Laser Electron InterAction for 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) will be 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).

To achieve such a high x-ray flux, a very high brightness electron beam, capable of being focused to a roughly 20 μm spot size at the interaction point, will be required. The PLEIADES beamline has been designed to meet these demands by producing a 1-2 ps, 500 pC bunch with a normalized emittance of less than 5 π mm-mrad.

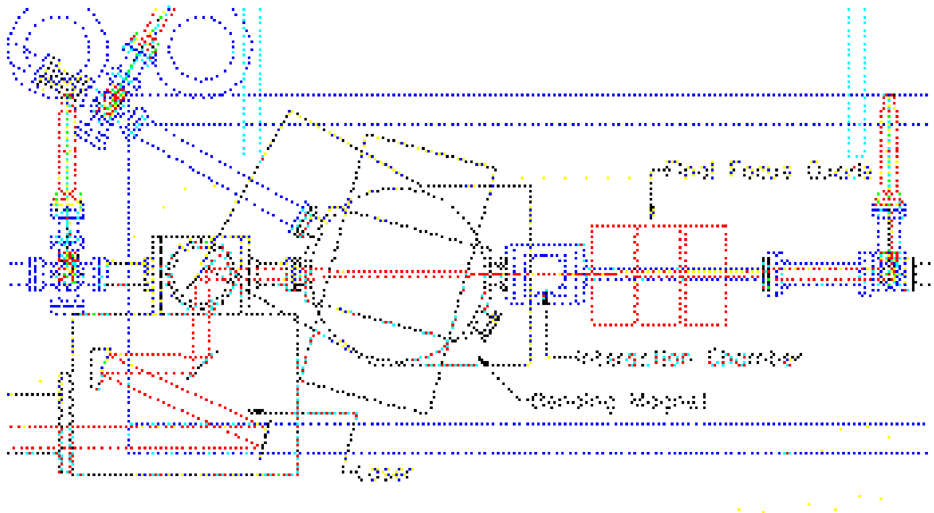

FIGURE 1. Interaction geometry.

EXPERIMENTAL LAYOUT

The PLEIADES facility consists of a Ti-Sapphire OPCPA laser system capable of producing bandwidth limited laser pulses of 50 fs with up to 1 joule of energy at 800 nm, an S-band photo-cathode RF gun [2], and a 100 MeV linac consisting of 4, 2.5-meter-long accelerator sections. The RF gun is driven by a picosecond, 1 mJ, UV laser that is synchronized to the interaction drive laser.

A schematic of the interaction region is shown in Figure 1. To maximize x-ray flux while minimizing effects of timing jitter, the laser incidence angle will initially be 180 degrees with respect to the electron beam direction, though a 90 degree interaction geometry will also be possible. 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 bend dipole magnet will be 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 will be used to focus the laser to a diffraction-limited 15 μm FWHM spot size at the interaction point. A beryllium flat mirror placed in the x-ray beam path will serve as the final steering optic for the laser, while being transparent to the x-ray beam.

ELECTRON BEAM PRODUCTION

Initial experiments will focus on the generation of 30 keV x-rays produced in a head on collision using a 35 MeV electron beam. The 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 electro-static 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 subsequent acceleration and optimization of beam energy spread and emittance during transport through the subsequent accelerator sections.

The two primary factors that determine the minimum electron bunch spot size at the interaction point are beam emittance and energy spread. In addition, the x-ray flux will also depend on electron bunch charge. However, optimizing emittance and energy spread places a practical limit on the amount of charge in the bunch. After finding optimized cases for several different bunch charges, 0.5 nC was found to be a good compromise between high bunch charge and low emittance.

The RF gun is designed to accelerate an electron bunch to an initial energy of 5 MeV. The beam will then be transported to the first linac section, during which emittance compensation is performed by focusing the beam to a waist with a solenoid placed directly after the RF gun. In the first linac section, the beam is injected near the zero crossing of the accelerating field in order to provide an energy chirp to the beam. This results in velocity compression of the accelerated bunch. The second accelerator section is then used to accelerate the beam from about 10 MeV to the final beam energy, about 35 MeV. The third section can then be used to remove a large portion of the energy spread induced by the velocity compression process. Throughout the acceleration process, the linac solenoids are carefully optimized to minimize emittance growth.

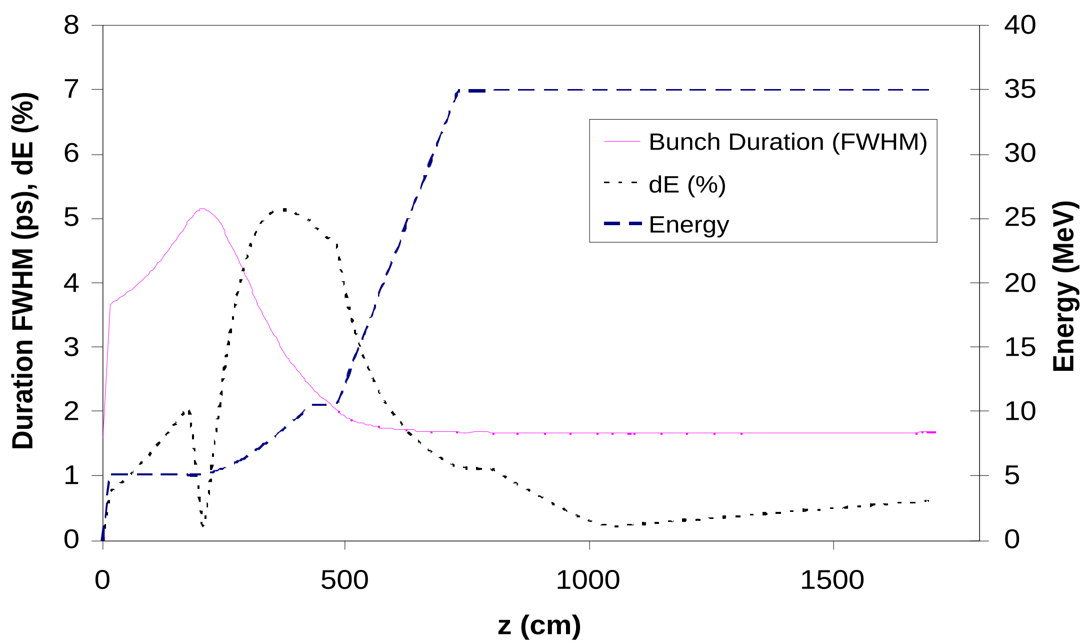

FIGURE 2A. PARMELA simulation showing electron bunch parameters (energy, energy spread, and bunch length) versus longitudinal position in the beam line. The gun cathode position corresponds to z = 0 cm, while the interaction region is located at z = 1700 cm.

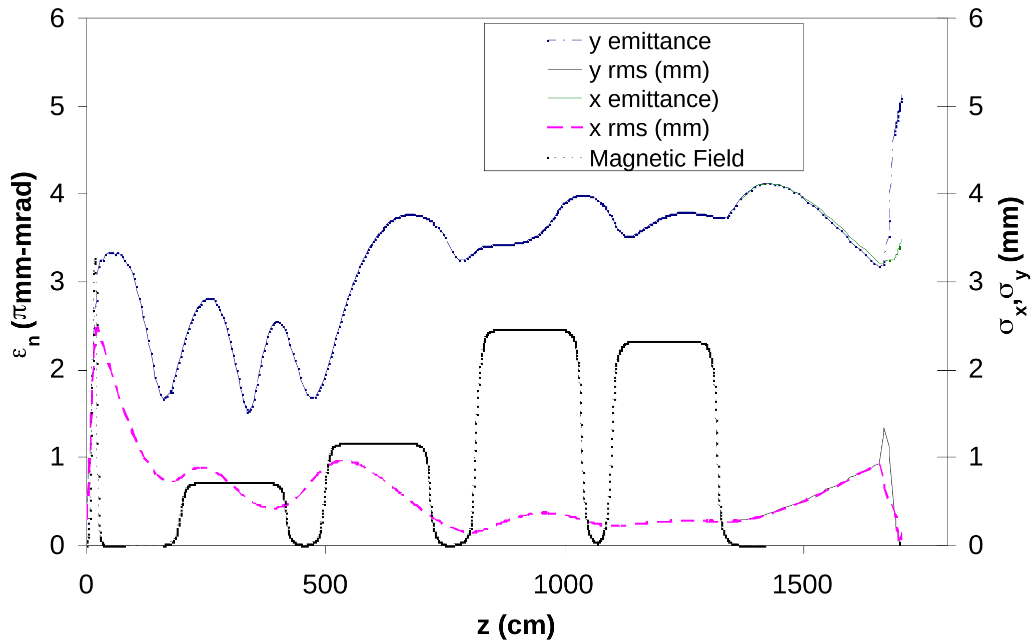

FIGURE 2B. PARMELA simulation showing electron bunch parameters (emittance, and spot size. versus longitudinal position in the beam line. The dotted line shows the solenoid magnetic field strength (in kG) for the gun solenoid and the four linac solenoids.

Figure 2a and 2b show the evolution of several of the beam characteristics during the acceleration process determined from PARMELA simulations, including emittance, energy spread, and bunch length. Velocity compression is used to reduce the bunch length from about 6 ps at the entrance of the accelerator to about 1.7 ps at its exit. 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. By not compressing fully, it is also possible to remove more of the energy spread in the bunch by accelerating off crest in subsequent accelerator sections. This is performed by accelerating the bunch at the opposite zero crossing (180 degree shift) of the zero crossing used in first accelerator section to compress the beam. At the exit of the linac, the bunch energy spread has been reduced to 0.5 % rms, while the rms normalized emittance is 3.5 πmm-mrad.

Final focus simulations were performed using PARMELA and Trace-3D. The electrons are transported 3 meters from the accelerator exit and focused with a 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. The rms convergence angle of the focus is about 3 mrad. In the simulation, the beam is initially defocused in *y*, leading to a larger size in this dimension going into the second quadrupole. This results in more significant chromatic aberrations in the *y* dimension than in *x*, and is manifested by a slightly larger emittance and spot size in *y* at the interaction point, as can be seen in PARMELA simulations of the final focus. Figure 3 shows the transverse profile of the electron bunch at the focus as determined by PARMELA. The electron beam focus parameters are summarized in Table 1.

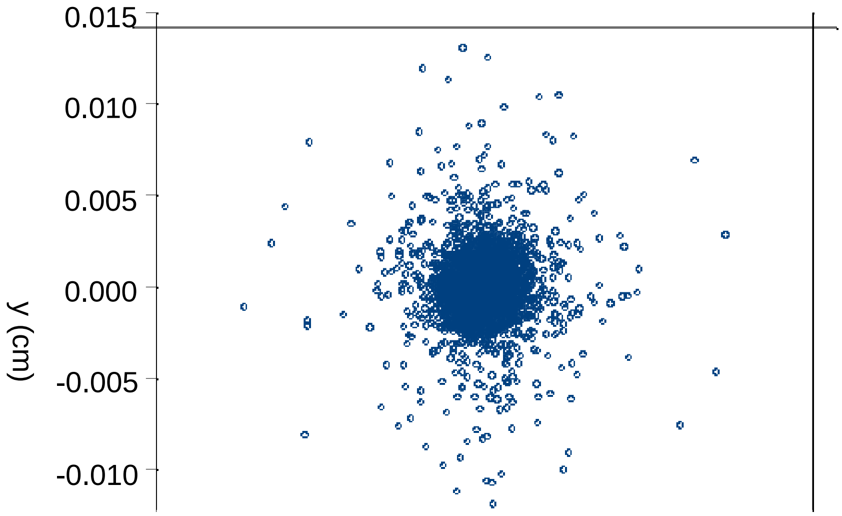

FIGURE 3. Profile of the electron beam at focus.

TABLE 1. Electron Beam Parameters at Focus.

Parameter	Value
ε_{xn} (mm-mrad)	3.4
ε_{yn} (mm-mrad)	5.0
σ_x (µm)	12
σ_y (µm)	20
σ_t (ps)	0.74
Bunch Charge (nC)	0.5

CALCULATION OF X-RAY PRODUCTION

The expected x-ray production was calculated and the effects of RF phase and timing jitter were determined by integrating the emission probability per unit time, dN_x/dt, given by

(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, and σ is total Thomson cross section. The calculations were performed for a 300 mJ, 300 fs laser pulse in conjunction with the PARMELA output in place of $n_e(\mathbf{x},t)$. In this case, $n_\gamma(\mathbf{x},t)$ was assumed to have a Gaussian profile, given by

(2)

where z_0 is the laser Rayleigh length, Δt is the pulse duration, η_γ is the peak photon density, and w_0 is the minimum laser spot size. $n_e(\mathbf{x},t)$ is replaced with a delta-function representing the position and charge of each PARMELA macro-particle as a function of time. Figure 4 shows the calculated x-ray pulse profile in time. The average photon energy is 30 kV, and the peak x-ray flux is about 6 x 10^{19} photons/s with an integrated photon yield of about 10^8. A 3-D frequency domain calculation [3] of the x-ray output has also been performed, showing the spectral bandwidth to be about 10%. The peak spectral brightness is calculated to be 10^{20} photons/s/0.1% bandwidth/mm^2/mrad^2.

Effects of phase jitter were simulated by varying the relative phase of the linac sections with respect to the RF gun in the PARMELA simulations, and using the resulting electron beam parameters in the calculation of the x-ray production. Figure 5 shows the expected x-ray yield versus phase jitter for the cases where the electron beam is compressed in the first section (accelerated near the zero crossing), and not compressed (accelerated on crest).

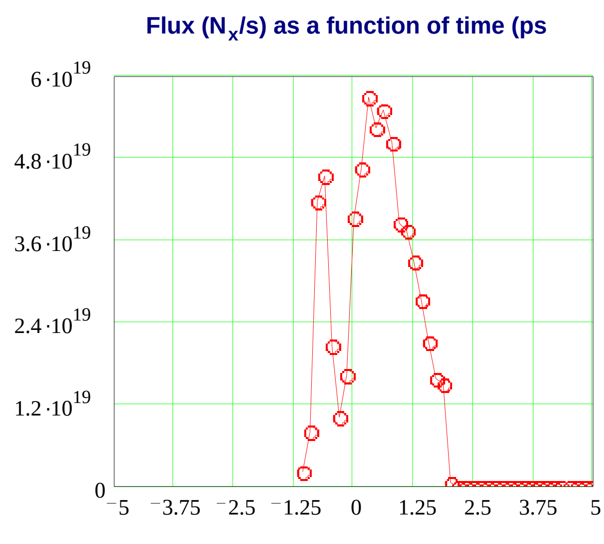

FIGURE 4. X-ray flux (photon/s) vs. time (ps). The total number of photons in the pulse is about 10^8, and the average photon energy is 30kV.

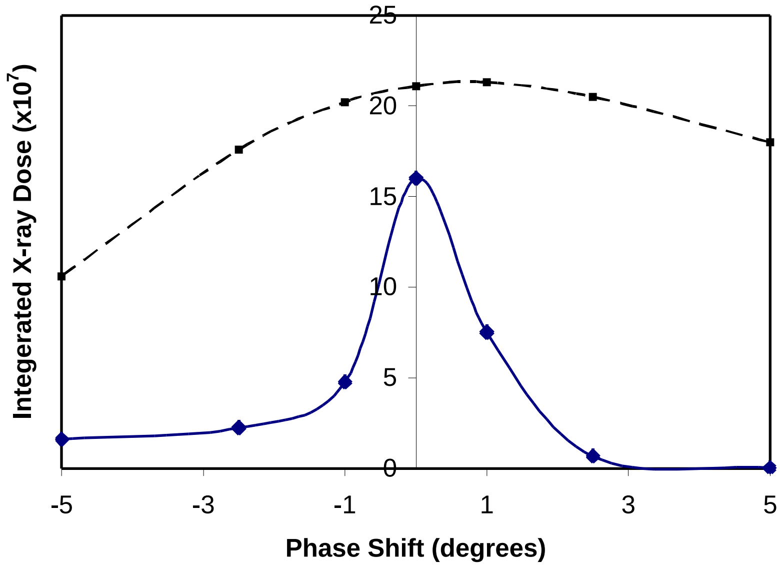

FIGURE 5. Simulated x-ray yield versus phase shift (Solid: compressed beam. Dotted: uncompressed).

It is seen that the phase jitter requirement for the compressed beam is less than one degree (or about 1 ps). Thus, picosecond phase and timing control will be required to maintain stability of the x-ray source when velocity compression is implemented.

ELECTRON BEAM CHARACTERIZATION

To date, electron bunches with up to 700 pC of charge have been produced with up to 100 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. Emittance measurements have been performed using a quad scan. Figure 6 shows quad scan data for a 300 pC, 60 MeV bunch. The measurements were performed with a 10 cm effective length quadrupole magnet placed after the final linac section. The beam profile was imaged with a YAG scintillator placed 1.42 meters from the quadrupole. The rms normalized emittance is 14.6 πmm-mrad, and the Twiss parameters are given by $\alpha = -1.15$ and $\beta = 7.84$ mm/mrad. Improvements in emittance are expected with improvements in the UV drive laser uniformity and optimization of the electron beam transport.

Phase jitter between the drive laser oscillator and the RF phase in the gun has been measured by mixing a 2.8 GHz signal generated by the laser oscillator with a signal produced by a probe inside the RF gun. This has shown short time scale (< 1 minute) phase stability of ± 1 degree. Longer term phase drifts will be eliminated by a computer controlled feed back loop and voltage controlled phase shifter. Plans are also underway to implement a direct measurement of the UV drive laser arrival phase in the RF gun. The direct phase measurement will employ a 20 GHz bandwidth, 800 nm optical fiber switch modulated by microwaves sampled from the RF gun to provide a nonlinear correlation between the gun fields and the IR laser pulse used to produce the UV photocathode drive laser.

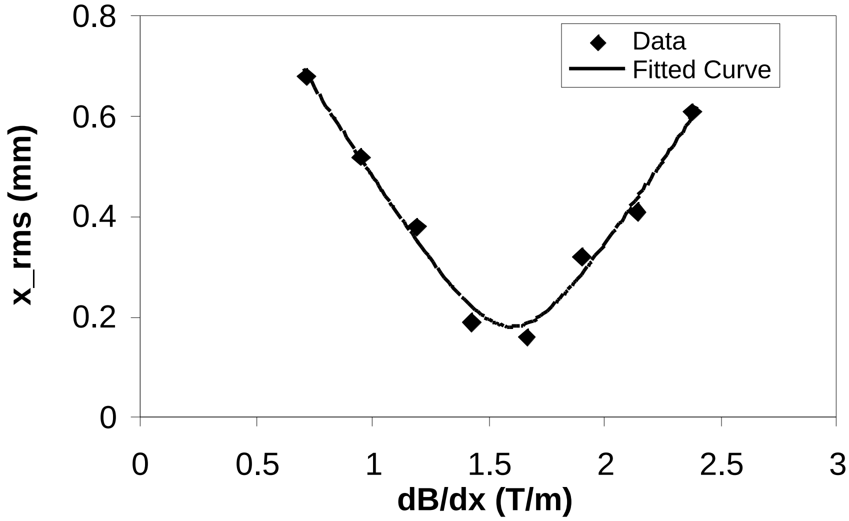

FIGURE 6. Quad scan measurement of 60 MeV electron beam. $\varepsilon_n = 14.6\ \pi$mm-mrad.

CONCLUSIONS

The PLEIADES Thomson x-ray source facility will provide high brightness (> 10^7 x-rays/pulse), picosecond pulses for dynamic measurements in matter, including radiography, dynamic diffraction, and spectroscopy. The PLEIADES electron beamline will be capable of producing the high brightness electron beam needed to drive this source. Simulations have shown that a 1 ps, 500 pC bunch with an rms normalized emittance of less than 5 πmm-mrad should be achievable, and will allow for the attainment of a 20-30 μm spot size at the interaction point. Initial electron beam measurements have been performed, and expected performance parameters and planned jitter measurements and control methods have been presented.

ACKNOWLEDGMENTS

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