Petawatt laser synchrotron source

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Abstract

Electron acceleration in underdense plasmas is studied in the Petawatt laser regime. With increasing laser intensity and interaction length, a collimated beam of x-rays extending to 50 keV is observed in forward direction. The measured x-rays are well described in the synchrotron asymptotic limit of electrons oscillating in a plasma channel. The critical energy of the synchrotron spectrum is found to scale as the maxwellian temperature of simultaneously measured electron spectra. At low laser intensity and short interaction length, the synchrotron model overestimates the radiated energy. Transverse oscillations become negligible and electrons are predominantly accelerated axially in the wakefield regime.

Introduction

Continuous progress in laser wakefield acceleration (LWFA) has brought stable mono-energetic electron beams of high energy within reach[1]. At high enough laser intensities, the electric field of the laser can accelerate electrons directly to relativistic energies[2]. The realization of several novel light sources based on these advanced accelerator concepts are anticipated. Laser accelerated electrons could be injected directly into a magnetic undulator, realizing a compact tunable x-ray source. The laser-based x-ray source could be downsized even further, using the self-generated electric and magnetic fields of the plasma channel as a miniature undulator[3]. In this work we show that it is crucial to the understanding of the acceleration dynamics of electrons to study the x-ray radiation from relativistic accelerating particles in Petawatt laser plasma interactions.

Theoretical Background

The ponderomotive force of a sufficiently intense laser can expel plasma electrons very efficiently, leaving a virtually electron free channel. Electrons inside the channel will feel a net focusing force due to the uncompensated space charge and undergo oscillation at the betatron frequency

$$\omega_\beta = \omega_p / \sqrt{2\gamma_{z0}}\,.$$

Here ω_p is the plasma frequency and λ_{z0} is the Lorentz factor associated with the initial motion of the electrons along the plasma channel. Accelerating charges will radiate. For large betatron strength parameters $a_\beta = \lambda_{z0} r_\beta \omega_\beta / c >> 1$, the radiated energy per electron is well described by the synchrotron asymptotic limit[4]

$$\frac{dI}{dE} \cong \sqrt{3}\frac{e^2}{\pi\varepsilon_0} N_\beta \gamma_{z0} \frac{E}{E_{crit}{}^2} \int_{2E/E_{crit}}^{\infty} K_{5/3}(E/E_{crit})dE \quad (1)$$

Here N_β and r_β is the number and amplitude of oscillations, and $E_{\mathrm{crit}} = 3\hbar a_\beta \lambda_{z0}{}^2 \omega_\beta$ is the energy above and below which half of the total power is radiated. $K_{5/3}$ is a modified Bessel function of the second kind. For $E > E_{\mathrm{crit}}$, the radiated energy decays exponentially. The total number of photons radiated by N_e electrons with a mean energy of E_{crit} scales as

$$N_{ph} \propto N_e N_\beta \gamma_{z0}^{1/2} n^{1/2} r_\beta$$

Experimental Setup

The experiments were performed using the Vulcan Petawatt laser with central wavelength 1.055 µm. The focusing geometry could be changed from f/3 to f/5 by apodizing the beam, yielding a pulse length of (630 ± 120) fs for the f/3 and (760 ± 120) fs for the f/5 with a near diffraction limited spot size. The laser was focused on the front edge of a gas jet, using supersonic plastic nozzles with diameter 1,2,3 and 5mm. The laser strength could be changed by varying the laser energy from $a_0=5$ to $a_0=30$.

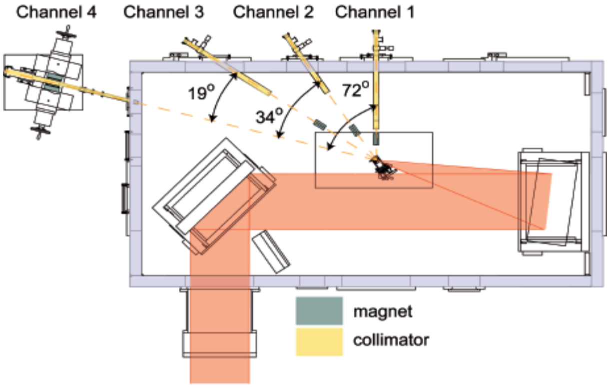

Figure 1. Schematic of experimental setup.

A sketch of the experimental setup is given in figure 1. A magnetic electron spectrometer was used to acquire electron spectra in forward direction with a detector range from 20-200MeV. The x-ray radiation was characterized at four different angles using various metal foils with 1/e cutoff energy ranging from keV to tens of keV. The foils were coupled to Fuji BAS-MS image plate. Some foils were chosen with identical transmission characteristics except for a narrow energy range around their K-edges. Such a combination is known as Ross filter pair and subtraction of respective signal levels allows the total number of photons per steradian per energy bin to be measured. The response of the image plate was absolutely calibrated[5].

Measurements

By placing a 270 μm Cu wire mesh in forward direction, it was determined that the x-rays measured at 0° (channel 4) originate from the gas plume. Penumbral images of a knife edge yielded vertical x-ray source sizes of 90-350 μm. There was no measurable x-ray emission originating from the source at all other angles (channel 1, 2 and 3). This highly directional forward emission is characteristic of radiation emission due to the acceleration of relativistic electrons.

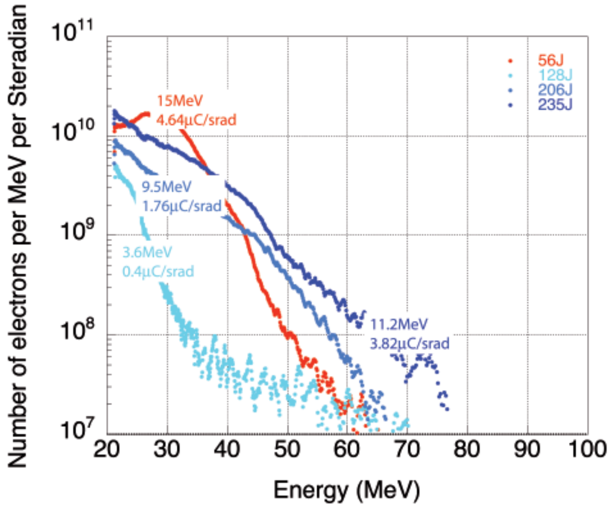

Figure 2. Electron spectra for different laser energies.

An f/3 laser energy scan was carried out at 1.6×10^{19} Wcm^{-2} on a 2 mm nozzle. As shown in figure 2, two distinctly different types of electron spectra exist. At low a_0, the spectrum is clearly non-maxwellian. Such spectra are regularly observed in LWFA, if trapping of electrons in a small volume of phase space is achieved. At higher a_0, the spectra become maxwellian. Direct laser acceleration (DLA)[2] can lead to thermalization of initially wakefield accelerated electrons[6]. If this hot tail of electrons is produced by DLA, the electron energy in betatron resonance with the laser should scale linearly with the laser energy $\lambda_{z0} \propto (1 + a_0^2/4) \propto E_L$. The maxwellian spectra in figure 2 follow this scaling remarkably well, indicating that DLA is present. The non-maxwellian spectrum does not agree with this scaling at all, which means a different acceleration mechanism must have been prevalent.

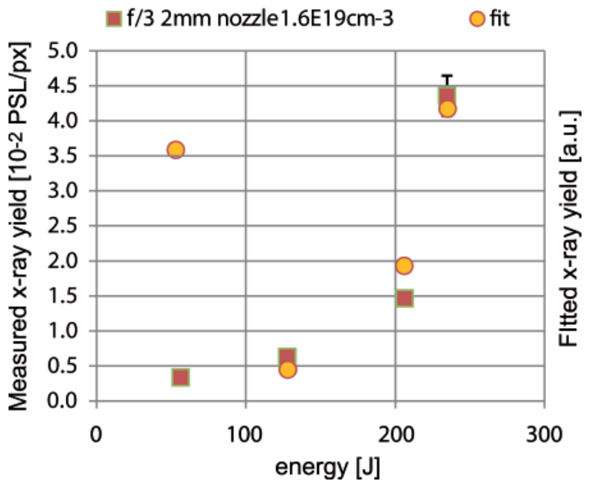

Figure 3. X-ray energy deposition for different laser energies.

The simultaneously measured x-ray energy deposition through a 20 μm Nickel filter is found to increase with laser energy as shown in figure 3. For large a_0, the measured x-ray yield is fitted well by $N_{ph} \propto N_e N_\beta \lambda_{z0}^{1/2} n^{1/2} r_\beta$. Here $N_\beta \propto 1/\lambda_\beta \propto n^{1/2}/\lambda_{z0}^{1/2}$ and the measured electron charge for N_e was used. The density n is set constant and r_β is assumed to be constant. For small a_0, the simple model overestimates the measured radiation. Transverse oscillations are significant for large a_0 indicative of resonant coupling of laser energy to the betatron motion. For low a_0, the acceleration in the wakefield is mostly axial and radiation due to transverse oscillations in the channel is negligible.

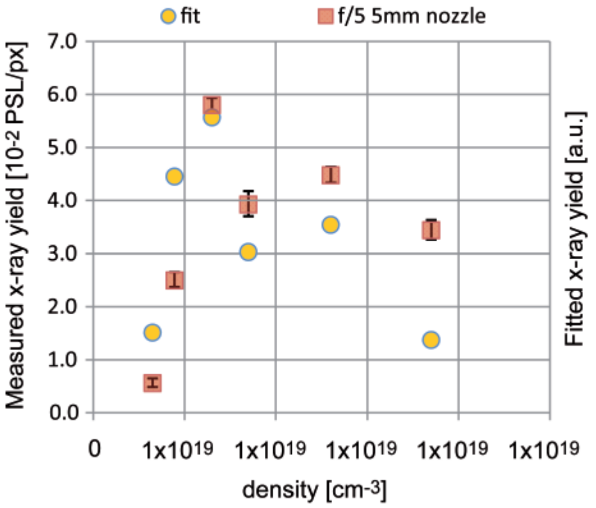

Figure 4. X-ray energy deposition for different plasma densities.

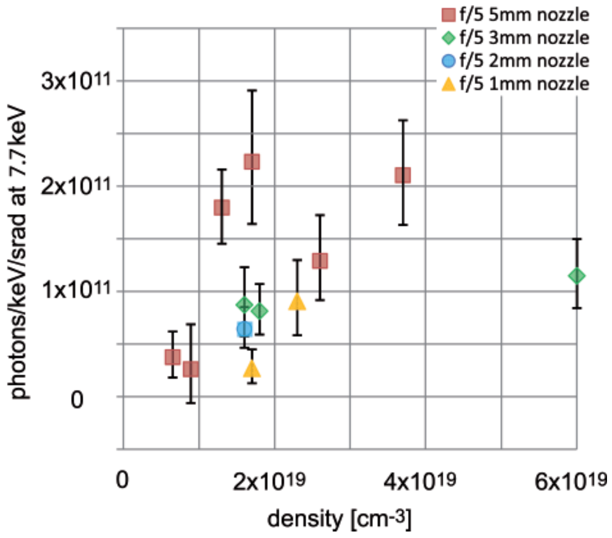

Figure 5. X-ray signal for different plasma densities and interaction lengths.

A plasma density scan is conducted at low power (f/5, $a_0=9$) with a 5 mm nozzle. As shown in figure 4, the x-ray energy deposition through a 20 μm Nickel filter is reasonably fitted with the formula for the synchrotron asymptotic limit.

Figure 5 shows the x-ray energy deposition through a 20 μm nickel filter for an f/5 interaction length scan with $a_0=9$. As depicted in figure 5, the total number of photons per keV and steradian increases almost linearly with interaction length at densities (1.8±0.4)cm^{-3}. Applying the simple scaling laws for synchrotron radiation fails to reproduce the measured yields accurately. Evidently N_β cannot be assumed to scale linearly with nozzle length as this would predict much higher x-ray yields for the 5 mm nozzle than measured. Benchmarking the x-ray yield with the measured electron charges overestimates the x-ray yields for the 1 and 2 mm nozzle. This could mean electrons experience little transverse acceleration for short nozzles compatible with predominantly axial acceleration in the wakefield regime. In fact, simultaneously measured electron spectra reveal remarkably different shapes for short and long interaction length. As shown in figure 6, the electron distribution is clearly non-maxwellian for short nozzles. With increasing interaction length, the lasers ability to thermalize the spectra rises. A DLA mechanism is believed to be responsible for this transition, consistent with the increased level of synchrotron radiation.

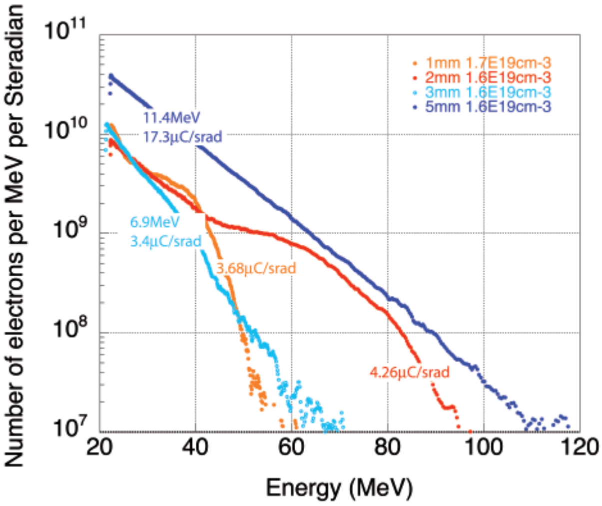

Figure 6. Electron spectra for different interaction length.

Up to six filters were used simultaneously per shot with 1/e cutoff energy ranging from keV to tens of keV allowing for a reliable reconstruction of E_{crit}. In the synchrotron asymptotic limit, the spectrum in forward direction can be approximated by a generalized form of equation (1)[4]. Convolving the spectrum with the filter transmission T(E) and the image plate response R(E), the x-ray energy deposition in PSL can be calculated for each filter i and proportionality factor α:

$$\int \frac{d^2 I}{dE d\Omega} T_i(E) R(E) dE = \alpha PSL_{calc,i}$$

Minimizing

$$\chi^2 = (\alpha PSL_{calc,i} - PSL_{measured,i})^2$$

yields the best fit parameter E_{crit}. Figure 7 shows an example of a least squares fit giving an E_{crit}=20keV. We find the critical energy of the synchrotron spectrum decreases with increasing plasma density (figure 8) and decreasing nozzle length. These are exactly the same trends that were found for the maximum electron energy and temperature for these shots (figure 6). The measured x-ray signal is therefore a direct fingerprint of the acceleration dynamics of the detected electrons.

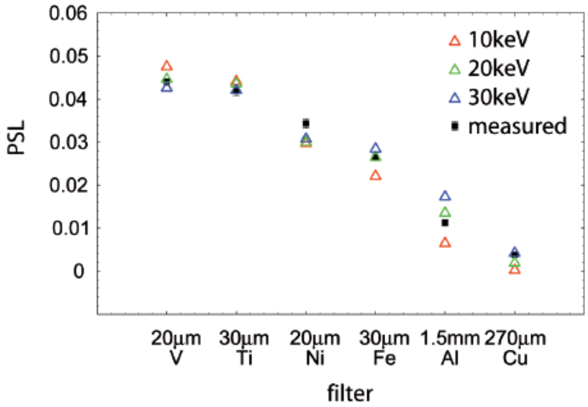

Figure 7. Least squares fit of a synchrotron spectrum to the measured x-ray signals.

Critical energies >30 keV have been measured, requiring betatron oscillation amplitudes on the order of $r_\beta \approx 30$ µm. This corresponds to $a_\beta > 100$, representing the most violent all-laser generated plasma wiggler realized until now. With equation (1) and the measurements of absolute photon numbers, the x-ray conversion efficiency can be calculated. This is found to be on the order of 10^{-7} (~10µJ) of the laser energy with as much as 10% (~1µJ) radiated above 50 keV.

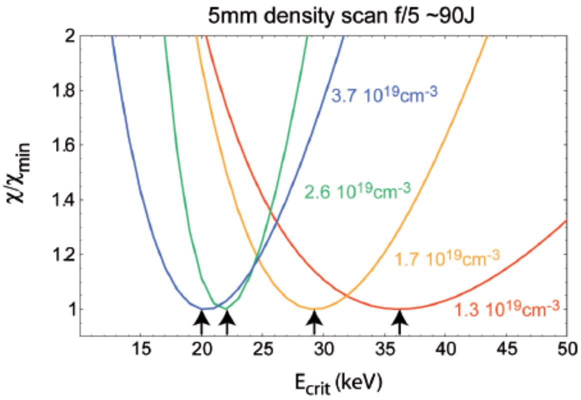

Figure 8. E_{crit} of synchrotron spectrum for 5 mm density scan.

Conclusion

We have shown that it is crucial to the understanding of the acceleration dynamics of electrons to study the x-ray radiation from relativistic accelerating particles in the PW regime. In combination with simultaneously measured electron spectra we were able to identify the transition between two distinctly different acceleration regimes. At low laser a_0, axial acceleration in the wakefield is dominant, yielding non-maxwellian spectra. Transverse oscillations are insignificant and the synchrotron model overestimates the measured x-ray yield. With increasing a_0 and interaction length, electron energy gain is mainly due to a betatron resonance with the laser field, thermalizing the electron spectra. Violent transverse oscillations give rise to an x-ray beam that is well described in the synchrotron asymptotic limit. The critical energy of the spectra is found to scale as the electron temperature.

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