

Observations of Synchrotron Radiation from Electrons Accelerated in a Petawatt Laser Generated Plasma Cavity

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The dynamics of plasma electrons in the focus of a petawatt laser beam are studied via measurements of their x-ray synchrotron radiation. With increasing laser intensity, a forward directed beam of x-rays extending to 50 keV is observed. The measured x-rays are well described in the synchrotron asymptotic limit of electrons oscillating in a plasma channel. The critical energy of the measured synchrotron spectrum is found to scale as the maxwellian temperature of the simultaneously measured electron spectra. At low laser intensity transverse oscillations are negligible as the electrons are predominantly accelerated axially by the laser generated wakefield. At high laser intensity, electrons are directly accelerated by the laser and enter a highly radiative regime with up to 5% of their energy turned into x-rays.

PACS numbers: Valid PACS appear here

The advent of high power lasers has led to rapid progress in the field of plasma based particle acceleration [1]. In particular, the measurement of monoenergetic electron beams from wakefields generated by short lasers [2] has stimulated great interest in producing such beams and understanding their dynamics. One potential use for these compact sources of energetic particles is as a driver for novel light sources. Laser-accelerated electrons could be injected into a magnetic undulator realizing a compact tunable-energy femtosecond x-ray source synchronized to the laser. A laser-based x-ray source could be downsized further, using the self-generated magnetic and electrostatic fields of the plasma channel as a miniature undulator [3]. For electron beams of sufficiently high quality, an ion channel laser analogous to conventional free electron lasers may be feasible [4]. X-rays can also be produced in intense laser-plasma interactions by non-linear Thomson scattering [5].

Relativistic electron beams have also been measured from interactions at very high laser intensities, where electrons gain energy directly from the laser [6]. At high intensity, the ponderomotive force of the laser can expel plasma electrons leaving a positively charged ion channel. Electrons inside the channel experience a net focusing force due to the space charge and undergo oscillation at the betatron frequency $\omega_\beta = \omega_p/\sqrt{2\gamma_{z0}}$, where ω_p is the plasma frequency and γ_{z0} is the Lorentz factor associated with the electrons motion along the plasma channel. Electrons resonant with the laser frequency can gain energy from the transverse electric field of the laser, which can be directed into longitudinal momentum through the

$\mathbf{v} \times \mathbf{B}$ force [7].

Accelerating charges radiate electromagnetic radiation. For small betatron strength parameters $a_\beta = \gamma_{z0} r_\beta \omega_\beta / c \ll 1$ (undulator limit), the spectrum of the radiation will be narrowly peaked about the resonant frequency $\omega_1 = M_0 \omega_\beta / (1 + M_0 \alpha^2 / 2)$ where $2r_\beta$ is the oscillation amplitude, $M_0 = 2\gamma_{z0}^2 / (1 + a_\beta^2 / 2)$ is the Doppler factor and α is the angle between the direction of observation and the direction of γ_{z0} [8]. This highlights the interdependency of spectral and angular distributions. As $a_\beta \rightarrow 1$, emitted radiation also appears at harmonics of the resonant frequency. For large betatron strength parameter $a_\beta \gg 1$ (wiggler limit), high harmonic radiation is generated and a synchrotron spectrum with broad emission consisting of closely spaced harmonics is produced. The properties of the radiation spectrum for harmonics $m \gg 1$ is given by the synchrotron asymptotic limit (SAL) [8]:

$$\frac{dI}{d(\hbar\omega)} \cong \sqrt{3} \frac{e^2}{\pi\epsilon_0} N_\beta \gamma_{z0} \frac{E}{E_{crit}} \int_{2\xi}^{\infty} K_{5/3}(\xi') d\xi' \quad (1)$$

N_β is the number of oscillations, $\xi = E/E_{crit}$ and $E_{crit} = 3\hbar a_\beta \gamma_{z0}^2 \omega_\beta$ is the energy above and below which roughly half of the total energy is radiated. $K_{5/3}$ is a modified Bessel function of the second kind. The total number of photons radiated by N_e electrons with a mean energy of E_{crit} scales as

$$N_{ph} \propto N_e N_\beta \gamma_{z0}^{1/2} n_e^{1/2} r_\beta \quad (2)$$

where n_e is the plasma density. The radiated energy

is confined to a cone around $\vec{\beta}$ with opening angle $\theta \approx a_0\beta/\gamma_{z0}$.

In this letter we report the first observation of synchrotron x-ray radiation from relativistic electrons produced from a gaseous target irradiated with a petawatt laser. We show that the x-ray measurements provide information about the dynamics of the laser-plasma acceleration. For mildly relativistic pulses, the x-ray radiation indicates a small oscillation parameter, which correlates with non-Maxwellian electron spectra and modulated transmitted optical spectra, all indicative of wakefield acceleration of the accelerated electrons. For ultra-relativistic pulses, stronger x-ray emission indicates a larger oscillation parameter. Electron energy gain is mainly due to a betatron resonance with the laser field, which serves to thermalise the electron spectra. Violent transverse oscillations give rise to an x-ray beam that is well described in the synchrotron asymptotic limit.

The experiments were performed using the Vulcan Petawatt laser with central wavelength $\lambda_0 = 1.055 \mu\text{m}$. The focusing geometry could be changed from $f/3$ to $f/5$ by reducing the beam diameter before focusing. This yielded a pulse length of $\tau_l = (630 \pm 120)$ fs and a near diffraction limited $1/e^2$ spot radius of $w_0 = 3.2 \mu\text{m}$ for the $f/3$. For the $f/5$, the corresponding values were $\tau_l = (760 \pm 120)$ fs and $w_0 = 5.3 \mu\text{m}$. The laser was focused on the front edge of a supersonic gas jet with a plastic nozzle of diameter 1 to 5 mm. The maximum energy on target was 280 J for $f/3$ and 90 J for $f/5$. This yielded laser parameters $9 < a_0 = 0.89 \times I^{1/2} [10^{18} \text{ Wcm}^{-2}] \lambda_0 [\mu\text{m}] < 29$, where I is the peak focused intensity. Helium was used as a target gas and electron densities up to $1.4 \times 10^{20} \text{ cm}^{-3}$ could be achieved.

A magnetic spectrometer in the forward direction (0° to the laser axis) measured electrons with energies from 20 - 200 MeV. The x-rays were measured with suitably filtered imaging plate detectors at 0° after the electron where deflected by the magnetic spectrometer. The image plates were absolutely calibrated [10]. Initially, a grid of metal wires was placed a few centimeters from the target. A radiograph consisting of a shadow of the wire grid was observed indicative of a sub-millimeter source of x-ray radiation close to the laser focus.

To quantify the source dimensions more accurately, penumbral images were taken of a knife-edge. The $1/e$ x-ray source size is found to increase almost linearly with plasma density both in the horizontal and vertical direction, consistent with enhanced laser filamentation at high densities. For $n_e = 1.6 \times 10^{19} \text{ cm}^{-3}$, we find a $1/e$ source size of $90 \mu\text{m}$, for $n_e = 1.4 \times 10^{20} \text{ cm}^{-3}$, it is $250 \mu\text{m}$. Varying the interaction length by changing the nozzle length at constant density did not affect the x-ray source size appreciably. Replacing the plastic nozzle with a high Z brass nozzle indicates that the contribution of bremsstrahlung from the nozzle is negligible.

X-ray yields were measured through various metal foils

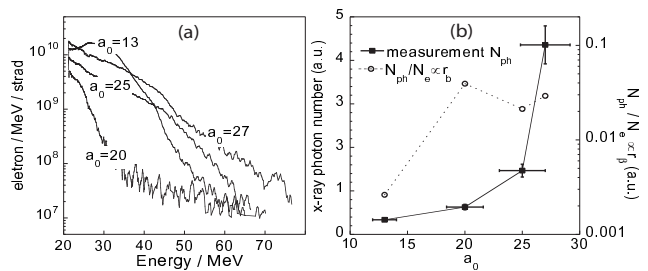


FIG. 1: Electron energy distribution (a) and x-ray photon yield (b) for different laser parameters a_0 . The measured x-ray signal is fitted in the SAL (b). Shots were taken with $f/3$ focusing on a 2 mm nozzle at $1.6 \times 10^{19} \text{ cm}^{-3}$.

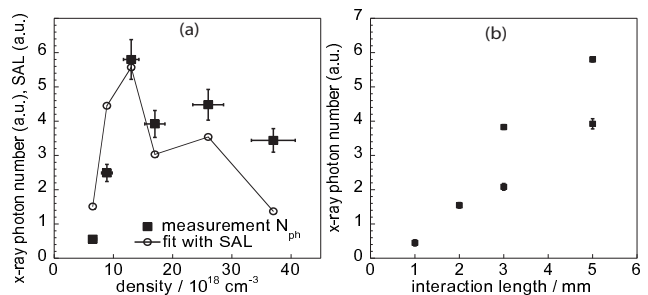


FIG. 2: X-ray photon signal as a function of plasma density (a) and interaction length (b) for $f/5$ focusing and a laser parameter of $a_0 = 10$.

with $1/e$ cutoff energy ranging from keV to tens of keV. Foils were chosen with identical transmission characteristics except for a narrow energy range around their K-edges, to create a pair of differential filters, usually called Ross filters. From the measurements, the total number of photons per steradian per energy bin can be deduced. By using a number of filters, a spectrum of the x-rays could be constructed. This was measured simultaneously with the spectrum of relativistic electrons.

By changing the laser energy on target, an intensity scan was carried out for a 2 mm nozzle for $n = (1.6 \pm 0.2) \times 10^{19} \text{ cm}^{-3}$. Two markedly different types of electron spectra were observed, as shown in figure 1(a). At moderately relativistic a_0 , the spectrum is clearly non-Maxwellian. Non-Maxwellian spectra are regularly observed in (self-modulated) laser wakefield acceleration (LWFA) [11]. At highly relativistic a_0 , the spectra become more Maxwellian, with a steadily increasing effective temperature T_{eff} for increasing a_0 . The thermalization could be due to phase rotation of electrons once they became dephased in a plasma wave, but is also a consequence of direct laser acceleration (DLA) mechanisms [7, 12]. The variation of maximum electron energy and temperature T_{eff} with increasing a_0 though is strongly indicative of the presence of DLA.

The simultaneously measured x-ray radiation emitted directly forward is found to increase with laser intensity, for a set of filters ($5\mu\text{m}$ Al, $20\mu\text{m}$ Ni, 1.5mm Al) with different cut-off energies (1.2keV, 7keV, 22keV). In figure 1(b), the photon yield per solid angle through a $20\mu\text{m}$ Ni filter is plotted. For this case, the x-ray yield can be easily compared with that predicted by the SAL. Equation 2 reduces to $N_{ph} \propto N_e r_\beta$, since the plasma density is constant, and the number of betatron oscillations for a constant interaction length scales as $N_\beta \propto \lambda_\beta^{-1} \propto n_e^{1/2} \gamma_{z0}^{-1/2}$. The electron number N_e was measured. N_{ph}/N_e which is proportional to the betatron oscillation amplitude r_β is plotted in figure 1(b), on the secondary axis. This ratio, i.e. r_β , is found to increase dramatically from weakly relativistic a_0 to highly relativistic a_0 . Wakefield acceleration is at odds with the observed scaling of r_β with a_0 (figure 1(b)). If electrons were merely accelerated by a wakefield, the amplitude r_β would not depend strongly on a_0 . An increase in betatron oscillation amplitude r_β however is consistent with electrons accelerated in the regime of DLA, where higher laser intensities drive larger transverse oscillations [7]. For low a_0 , the acceleration is mostly axial and the radiation per electron due to transverse oscillations in the channel is negligible, i.e. r_β is small. This is a strong indication that the acceleration at moderate a_0 is mostly wakefield driven.

Indeed this transition from wakefield dominated to DLA dominated acceleration is also indicated by spectral analysis of the transmitted laser radiation. The spectra are more severely modulated at moderate intensity than at ultra-relativistic intensities. This has also been observed previously by Walton et al. [13]. Simulations indicate that cavitation due to increasing a_0 serves to reduce the efficiency of Raman processes [6].

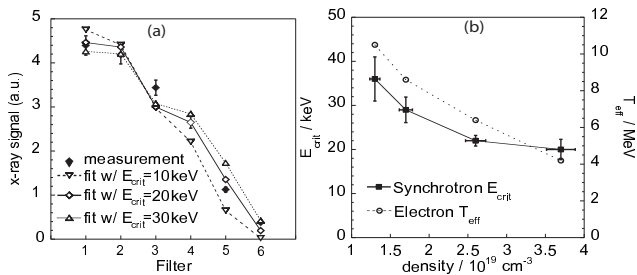


FIG. 3: (a) Measured and modeled x-ray signal for different filters. The filters, from left to right, are V $20\mu\text{m}$, Ti $30\mu\text{m}$, Ni $20\mu\text{m}$, Fe $30\mu\text{m}$, Al 1.5mm and Cu $270\mu\text{m}$. The modeling is based on a SAL spectrum with different E_{crit} . (b) Scaling of E_{crit} of the synchrotron radiation and T_{eff} of the electron distribution with density n_e . Shots were taken with $f/5$ focusing on a 5mm nozzle at $a_0 = 10$.

Figure 2(a) plots the x-ray signal through a $20\mu\text{m}$ Ni filter for a scan of density conducted with a 5mm nozzle for $a_0 = 10$. Below a certain density, the x-ray yield vanishes rapidly. For high densities, the x-ray signal stays

high and drops slowly. A similar behavior was observed for the other filters. The density scaling is fundamentally different from other radiation mechanisms such as bremsstrahlung or non-linear Thomson scattering. The former scales $\propto n_e^2$ when observed on axis and the latter $\propto n_e$ [5]. A comparable scaling of the x-ray intensity with plasma density was found from a laser wakefield accelerator and was attributed to synchrotron radiation from electrons undergoing betatron oscillations in the plasma wake [3]. In our case, SAL (equation 2) reduces to $N_{ph} \propto N_e n_e r_\beta$. Setting r_β constant, the SAL estimate using the measured electron number N_e and plasma density n_e fits the measured x-ray yields reasonably well, as shown in figure 2(a). As discussed above, the oscillation amplitude r_β is a measure of the strength of DLA. An upper limit of r_β is the size of the plasma channel, which will decrease with increasing n_e . However, if anything, the SAL underestimates the emission at higher density, suggesting that DLA dominates LWFA at higher densities [14] and that resonant coupling between the laser field and the transverse oscillations lead to an effective increase of r_β with density.

Changing the interaction length was investigated by varying the nozzle diameter D from 1 to 5 mm in steps of 1 mm, with all other parameters constant. The electron spectra exhibit two markedly different shapes, similar to those plotted in figure 1(a). For $D = 1$ and 2 mm nozzles, the distribution is non-Maxwellian. An increase to $D = 3$ and 5 mm yields increasingly Maxwellian spectra. The x-ray yield is found to increase almost linearly with D (figure 2(b)). This is consistent with the anticipated scaling of yield in the SAL due to a linear increase in N_β .

To obtain an energy spectrum of the emitted x-rays up to six filters were used simultaneously per shot with $1/e$ cut-off energies from keV to tens of keV allowing for a reliable reconstruction of the critical energy E_{crit} . In the SAL the spectrum can be approximated by a generalized form of equation 1. Convolving the spectrum with the filter transmission $T(E)$ and the image plate response $R(E)$, the x-ray energy deposition P can be calculated for each filter i and proportionality factor α , $\int \frac{d^2 I}{dE d\Omega} T_i(E) R(E) dE = \alpha P_{calc,i}$. Minimizing $\chi^2 = \sum_i (\alpha P_{calc,i} - P_{measured,i})^2$ yields the best fit parameter E_{crit} . Figure 3(a) shows an example of a least squares fit giving $E_{crit} = 20\text{keV}$. The critical energy of the synchrotron spectrum E_{crit} decreases with plasma density (figure 3(b)) and increases with nozzle length. The maximum electron energy and effective Maxwellian temperature T_{eff} of the electron distribution are also found to decrease with density for the same shots as plotted in figure 3(b), on the secondary axis. Consequently the measured x-ray signal is a direct diagnostic of the dynamics of the electrons.

In the case of a monoenergetic electron beam, $E_{crit} = 3\hbar\gamma_{z0}^2\omega_p^2 r_\beta / 2c$. Even for electron beams with a broad spectrum, not all electrons contribute to the radiation

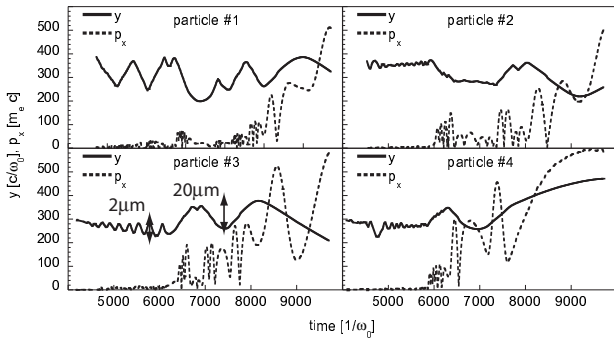


FIG. 4: Sample electron trajectories from the PIC simulation showing transverse deflection y and axial momentum p_x .

equally. Low energy electrons are more abundant but high energy electrons will radiate γ_{z0}^4 times more energy per solid angle. Considering for example the shot at $1.6 \times 10^{19} \text{ cm}^{-3}$ with $E_{crit} = 29 \text{ keV}$ from figure 3(b), the product of these two effects is maximized for electrons with $60 < \gamma_{z0} < 80$. Hence $r_\beta = (30 \pm 10) \mu\text{m}$ can be estimated. Previously oscillation amplitudes of $r_\beta \cong 2 \mu\text{m}$ have been reported in a LWFA dominated regime [15]. An r_β of $30 \mu\text{m}$ corresponds to $a_\beta = \gamma_{z0} r_\beta k_\beta \cong 130 \gg 1$ which not only justifies the treatment of radiation in the framework of SAL but also represents the most violent optical plasma wiggler realized to date. With a_β and γ of order 100, the divergence angle of the synchrotron radiation $\theta \sim a_\beta/\gamma \simeq 60^\circ$ can be estimated. For comparable laser and target parameters, a divergence angle of $50^\circ - 95^\circ$ was experimentally determined [17].

Simulations with the particle-in-cell (PIC) code OSIRIS have been performed to study if and under what conditions such large oscillation amplitudes can occur. Trajectories of test electrons were tracked. All of the tracked electrons exhibit oscillations across the channel, but the motion is not a simple betatron resonance oscillation. A set of sample trajectories are shown in figure 4. For most of the interaction, particle 2, 3 and 4 oscillate with small amplitudes on the order of several μm without picking up significant amounts of axial momentum. Any radiation produced in this pre-acceleration phase will contribute little to the measured x-ray yields. After a certain time, the oscillation amplitude starts to rise and suddenly increases to $10 \mu\text{m}$. At the same time, the transverse electron energy is found to increase, indicative of a resonant coupling with the laser field. This transverse energy is transferred to the axial momentum via the $\mathbf{v} \times \mathbf{B}$ force. These particles only perform very few oscillations before they lose phase with the laser due to relativistic mass increase. Only particle 1 performs several oscillations with large amplitudes. For electrons that hit the betatron resonance, oscillation amplitudes in excess of $10 \mu\text{m}$ are regularly observed and are only limited by the channel diameter. This is in good agreement with the oscillation

amplitude deduced from the electron and synchrotron spectra.

Making use of the x-ray measurements with differential filters, absolute photon numbers can be determined. Under some conditions, the total number of photons is found to be more than $5 \times 10^8 \text{ ph/mrad}^2/0.1\%$ bandwidth (BW) in the spectral range from 7 keV to 12 keV where the typical electron charge is 2 nC for electrons with $40 < \gamma < 160$. This is about ten times more photons per electron than previously achieved with a keV synchrotron source in a regime dominated by LWFA [16]. In our work, the electron acceleration is strongly influenced by the very high $a_0 > 10$. Direct laser acceleration, i.e. resonant driving of the transverse electron oscillations leads to an increase in the oscillation amplitude. This becomes manifest in the observed synchrotron spectra with E_{crit} as high as $(36 \pm 5) \text{ keV}$ and divergence $\theta > 50^\circ$. The x-ray beam typically contains a total energy of 2 mJ, i.e. $\sim 5 \times 10^{-2}$ of the total energy in the electron beam or $\sim 5 \times 10^{-5}$ of the total energy in the laser pulse. 10% of the x-ray energy is emitted above 50 keV. The peak brightness of the x-ray beam is estimated from the pulse duration of the laser and the x-ray source size to be $1 \times 10^{17} \text{ ph/s/mm}^2/\text{mrad}^2/0.1\% \text{ BW}$, similar to 2nd generation wigglers.

In conclusion, we have demonstrated that electron acceleration in a DLA dominated regime produces a plasma wiggler with much higher strength parameter as compared to the wakefield regime. This leads to an x-ray source that extends to much higher energies than previously achieved while sharing the benefits of brightness, short pulse duration and laser-synchronization with other all optical synchrotron sources [15] [16]. A hard x-ray synchrotron source could significantly expand the current scope of x-ray diffraction and absorption studies in ultrafast x-ray science.

The authors acknowledge the assistance of the staff of the Central Laser Facility at the Rutherford Appleton Laboratory. SK acknowledges EUROLEAP for financial assistance.

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- [1] N. Patel, *Nature* **449**, 133 (2007).
 - [2] S. P. D. Mangles et al., *Nature* **431**, 535 (2004); J. Faure et al., *Nature* **431**, 541 (2004); C. G. R. Geddes et al., *Nature* **431**, 538 (2004).
 - [3] A. Rousse et al., *Phys. Rev. Lett.* **93**, 135005 (2004).
 - [4] D. H. Whittum et al., *Phys. Rev. Lett.* **64**, 2511 (1990).
 - [5] K. T. Phuoc et al., *Phys. Rev. Lett.* **91**, 4 (2003).
 - [6] S. P. D. Mangles et al., *Phys. Rev. Lett.* **94** (2005).
 - [7] A. Pukhov et al., *Phys. Plasmas* **6**, 2847 (1999).
 - [8] E. Esarey et al., *Phys. Rev. E* **65**, 15 (2002).
 - [9] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1999), 3rd ed.
 - [10] S. G. Gales and C. D. Bentley, *Rev. Sci. Instr.* **75**, 4001 (2004).

- [11] B. Hidding et al., Phys. Rev. Lett. **96**, 105004 (2006).
- [12] G. D. Tsakiris et al., Phys. Plasmas **7**, 3017 (2000).
- [13] B. R. Walton et al., Physics of Plasmas **13** (2006).
- [14] C. Gahn et al., Phys. Rev. Lett. **83**, 4772 (1999).
- [15] K. T. Phuoc et al., Phys. Rev. Lett. **97**, 225002 (2006).
- [16] K. T. Phuoc et al., Phys. Plasmas **12**, 8 (2005).
- [17] This measurement was performed in a later experiment on the Vulcan laser, fielding two x-ray detection channels at 0° and 45° from the laser axis.