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# Petawatt Laser Synchrotron Source

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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 [1]. 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 converted into x-rays.

At high intensity, the ponderomotive force of a laser, propagating through underdense plasma, expels plasma electrons, leaving an ion channel. Electrons inside the channel can undergo oscillations at the betatron frequency $\omega_\beta = \omega_p \sqrt{2\gamma_{z0}}$ where $\omega_p$ is the plasma frequency and $\gamma_{z0}$ is the Lorentz factor associated with the electrons' motion along the channel. Electrons resonant with the laser frequency gain net energy along the channel axis from the transverse electric field of the laser [1]. The radiation that results from such oscillations can be classified into two regimes. For small betatron strength parameters $a_\beta = \gamma_{z0} r_\beta \omega_\beta / c \ll 1$ (undulator limit), the radiation spectrum will be narrowly peaked about the resonant frequency $\omega_1$, where $2r_\beta$ is the oscillation amplitude. As $a_\beta \to 1$, 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) [1]:

$$\frac{dI}{d(\hbar\omega)} \cong \sqrt{3}\frac{e^2}{\pi\varepsilon_0} N_\beta \gamma_{z0} \frac{E}{E_{crit}} \int_{2\xi}^{\infty} K_{5/3}(\xi')d\xi' \tag{1}$$

$N_\beta$ 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, with mean energy of $E_{crit}$, radiated by $N_e$ electrons, scales as:

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

where $n_e$ is the plasma density. The radiation is confined to a cone around $\vec{\beta}$ with opening angle $\theta \approx a_\beta/\gamma_{z0}$.

The experiments were performed using the Vulcan Petawatt laser with central wavelength $\lambda_0 = 1.055\,\mu\text{m}, f/3$ ($f/5$) focusing, a pulse length of $\tau_l = 630$ fs ($\tau_l = 760$ fs), a near diffraction limited $1/e^2$ spot radius of $w_0 = 3.2\,\mu$m ($w_0 = 5.3\,\mu$m) and a maximum energy on target of 280 J (90 J). This yielded laser parameters $9 < a_0 < 29$. The laser was focused on the front edge of a supersonic Helium gas jet of diameter 1 to 5 mm. A magnetic spectrometer measured electrons with energies from 20 to 200 MeV. X-rays were measured with suitably filtered image plate detectors in the direct forward direction after the electrons had been deflected by the magnet.

By changing the laser energy on target, an intensity scan was carried out for a 2 mm nozzle for $n_e = (1.6 \pm 0.2) \times 10^{19}$ cm$^{-3}$. Two markedly different types of electron spectra were observed (fig. 1a). At moderate $a_0 = 13$, the spectrum is clearly non-maxwellian. Non-maxwellian spectra are regularly observed in (self-modulated) laser wakefield acceleration (LWFA) [1]. At high $a_0 = 20, 25, 27$, 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 characteristic of direct laser acceleration (DLA) [1]. The variation of maximum electron energy and temperature $T_{eff}$ with increasing $a_0$ though is strongly indicative of DLA.

The simultaneously measured x-ray radiation emitted directly forward was found to increase with laser intensity, for a set of filters (5 $\mu$m Al, 20 $\mu$m Ni, 1.5 mm Al) with different cut-off

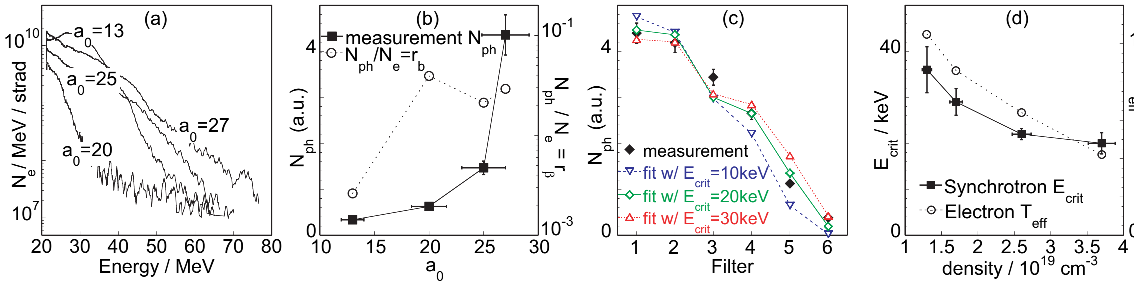


Figure 1: (a) Electron energy distribution and (b) x-ray photon yield $N_{ph}$ (solid square) and $N_{ph}/N_e$ (open circle) for different $a_0$ with $f/3$ focusing, $D = 2$ mm and $n_e = 1.6 \times 10^{19}\,\mathrm{cm}^{-3}$ (c) Measured and modeled x-ray signal for different filters for $n_e = 3.7 \times 10^{19}\mathrm{cm}^{-3}$. The filters, from left to right, are V 20 $\mu$m, Ti 30 $\mu$m, Ni 20$\mu$m, Fe 30 $\mu$m, Al 1.5 mm and Cu 270 $\mu$m. Modeling is based on a SAL spectrum with different $E_{crit}$. (d) Scaling of $E_{crit}$ and $T_{eff}$ with $n_e$. Shots were taken with $f/5$ focusing on a $D = 5$ mm nozzle at $a_0 = 10$.

energies (1.2 keV, 7 keV, 22 keV). In fig. 1b, the photon yield per solid angle through a 20 $\mu$m Ni filter is plotted. For this case, the x-ray yield can be easily compared with that predicted by the SAL. Eq. 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 $N_\beta \propto \lambda_\beta^{-1} \propto n_e^{1/2}\gamma_{z0}^{-1/2}$, with $\lambda_\beta = 2\pi c/\omega_\beta$. The electron number $N_e$ was measured. $N_{ph}/N_e$ which is proportional to the betatron oscillation amplitude $r_\beta$ is also plotted in fig. 1b. This ratio and therefore $r_\beta$ increases dramatically, by over one order of magnitude, from the lowest $a_0$ to higher $a_0$. It would be thought that if electrons were wakefield accelerated, the amplitude $r_\beta$ would not depend strongly on $a_0$. The observed increase in betatron amplitude $r_\beta$ correlated with the change in the electron spectra strongly suggests a transition to a regime where electrons are accelerated by DLA. In this scenario, the higher laser intensities drive larger transverse oscillations [1]. For moderate $a_0$, the acceleration is mostly axial (i.e. $r_\beta$ is small) and the radiation per electron due to transverse oscillations in the channel is negligible. This indicates that the acceleration at moderate $a_0$ is mostly wakefield driven. This transition from wakefield dominated to DLA dominated acceleration is also indicated by analysis of the transmitted laser spectra [1].

To obtain a spectrum of the x-rays up to six filters were used simultaneously, allowing for a reliable reconstruction of the critical energy $E_{crit}$. In the SAL the spectrum can be approximated by a generalized form of eq. 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 $\alpha$, $\int \frac{d^2I}{dEd\Omega} T_i(E)R(E)dE = \alpha P_{calc,i}$. Minimizing $\chi^2 = \sum_i(\alpha P_{calc,i} -$

$P_{meas,i})^2$ yields the best fit parameter $E_{crit}$. Fig. 1c shows an example of a least squares fit giving $E_{crit} = 20$ keV. The critical energy $E_{crit}$ decreases with plasma density (fig. 1d) 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 (fig. 1d).

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 equally. Low energy electrons are more abundant but high energy electrons will radiate ${\gamma_{z0}}^4$ times more energy per solid angle. Considering for example the shot at $1.6\times10^{19}$ cm$^{-3}$ with $E_{crit} = 29$ keV from fig. 1d, the product of these two effects is maximized for electrons with $60 < \gamma_{z0} < 80$. Hence $r_\beta = (30 \pm 10)\,\mu$m can be estimated. Previously oscillation amplitudes of $r_\beta \cong 2\,\mu$m have been reported in a LWFA regime [1]. An $r_\beta$ of 30 $\mu$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. Particle-in-cell simulations were conducted to confirm large oscillation amplitudes $> 10$ $\mu$m as the result of a betatron resonance [1].

Under optimum conditions, the total number of photons is found to be more than $5\times10^8$ 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 $40 < \gamma < 160$ [1]. This is about ten times more photons per electron than previously achieved with a keV synchrotron source in a regime dominated by LWFA [1]. 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 $(36\pm5)$ keV. The x-ray beam typically contains a total energy of 2 mJ, i.e. $\sim 5\times10^{-2}$ of the total energy in the relativistic electrons. 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 $1\times10^{17}$ ph/s/mm$^2$/mrad$^2$/0.1% 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.

## References

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