ULTRA-SHORT X-RAY RADIATION COMING FROM A LASER WAKEFIELD ACCELERATOR*

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Abstract

A Laser Wakefield Accelerator (LWFA) is under development at Lawrence Livermore National Laboratory (LLNL) to produce electron bunches with GeV class energy and energy spreads of a few-percent. The ultimate goal is to provide a bright and compact photon source for high energy density physics. The interaction of a high power (200 TW), short pulse (50 fs) laser with neutral He gas can generate quasi-monoenergetic electrons beams at energies up to 1 GeV [1]. The laser pulse can be self-guided over a dephasing length of 1 cm (for a plasma density of 1.5×10^{18} cm^{-3}) overcoming the limitation of vacuum diffraction. Betatron radiation is emitted while the accelerated electrons undergo oscillations in the wakefield electrostatic field.

Here we present electron spectrum measurements with a two screen spectrometer allowing to fix the ambiguities due to unknown angle at the plasma exit. We have measured monoenergetic electron beams at energies around 110 MeV. Furthermore a forward directed x-ray beam is observed. The peak energy of the measured synchrotron spectrum is reconstructed based on the energy deposited after different sets of filters, assuming x-ray radiation described in the synchrotron asymptotic limit (SAL) and is found around 6 keV.

EXPERIMENTAL SETUP

Experiments were performed using the Ti:sapphire based Callisto amplifier at the Jupiter Laser Facility at LLNL, optimized to deliver an energy E > 10 J on target in $\tau < 100$ fs. An f/10 off-axis parabolic mirror focuses the 800-nm laser pulse down to approximately twice the diffraction limit. The spot size is then $\sim 8\,\mu$m at focus. The plasma density is dependent on the nozzle and gas jet backing pressure and has been measured with a Llyod interferometer between $\sim 1.6 \times 10^{18}$ and 2×10^{19} cm^{-3}.

Three image plates (IP) track electrons dispersed by a permanent magnet, as shown in Fig. (1). The permanent magnet is capable of producing 10 kG depending of its gap. The magnetic field drops to 0 within a few mm outside of the magnet structure. An aluminium filter is used to block the laser light on the forward IP. Polyethylene blocks are placed in the target chamber to help reduce Bremstrahlung radiation due to electrons hitting the aluminium target chamber wall. Figure (1) shows the electron trajectory at indicated energies deviated by the magnet set at 4800 G. The IPs can measure electrons energies from 5 MeV to 1 GeV.

The two front IPs, IP(a) and IP(b) in Fig. (1), measure overlapping ranges of electron energies in order to allow the reconstruction of the bunch angle when electrons are leaving the plasma; indeed, it has been shown that the energy measure can be significantly affected if the electron bunch exits the plasma with an angle [3].

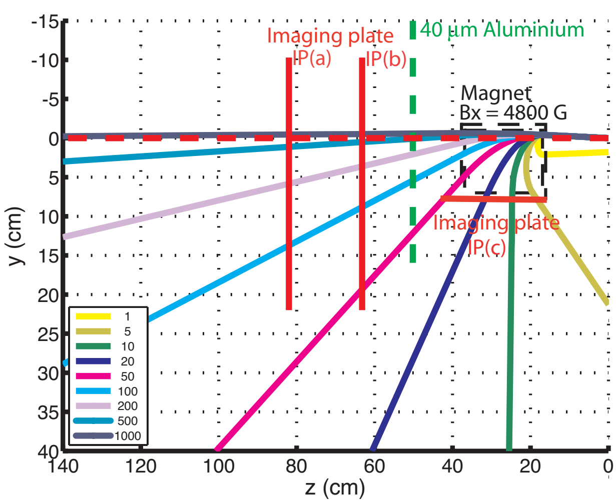

Figure 1: Electrons trajectories, at indicated energies (in MeV), after deflection by a magnetic field of 4800 G. The electron are detected on three different imaging plates. The center of the gas jet is at $z = 0$ and the laser is propagating along the increasing z.

A slit selects the energy range measured by both IP(a) and IP(b), from 80 MeV to ∞. The third IP(c) measures low energy electrons, in the [5-50] MeV range.

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ELECTRON ENERGY SPECTROMETER

Measuring the vertical difference of the electron impact between the two consecutive IPs allows to distinguish an energy variation from a transverse deflection of the electrons at the plasma exit.

An electron bunch is detected on the near forward screen (IP(b)) at 110 MeV with a 9 % FWHM and 6 mrad of angular divergence [Fig. (2)]. The main uncertainty comes from the y axis measurement, $\Delta y \simeq 2$ mm, which corresponds to an error in the energy measurement $\Delta E \simeq 2$ MeV at 110 MeV. The far forward screen (IP(a)) also detected an electron bunch at 110 MeV with the same FWHM, indicating negligible diffusion of the electron beam by the IP(b). The angle of the electron beam leaving the plasma is negligible for that shot (within the ΔE error).

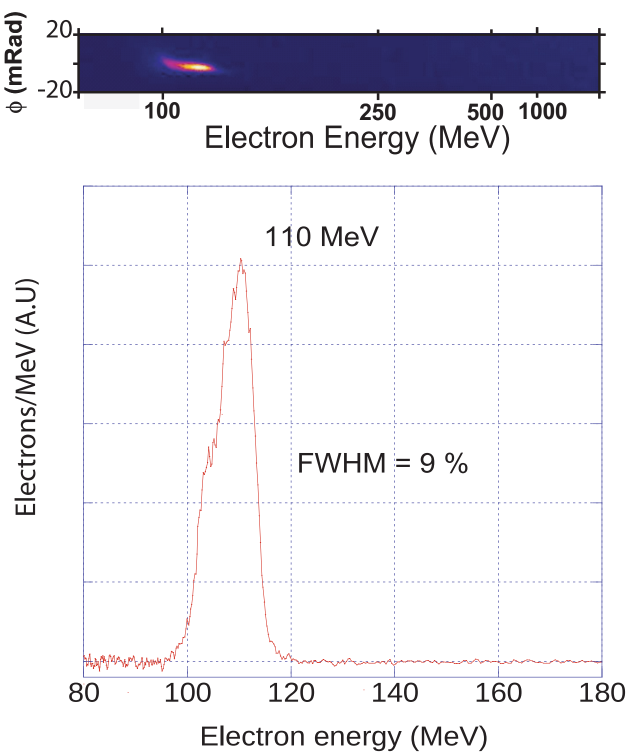

Figure 2: Electron spectrum recorded on the IP(a) placed 63.2 cm from the gas jet in the z direction. An electron bunch is detected at 110 MeV with 9 % FWHM and 6 mrad of angular divergence.

BETATRON X-RAY ENERGY MEASUREMENT

In almost all LWFA experiments so far, the conditions are such that the betatron radiation spectrum is in the synchrotron asymptotic limit (SAL) [6]. Indeed, the strength parameter for an electron undergoing betatron motion in a blown-out ion channel is given by $a_\beta = \sqrt{2\gamma_{z0}} r_\beta/\lambda_p$, where γ_{z0} is the longitudinal Lorentz factor of the electron, r_β the oscillation amplitude in the channel, and $\lambda_p = 2\pi c/\omega_p$ the plasma wavelength [4, 7]; typically, $a_\beta \gg 1$ for usual LWFA parameters.

The radiation spectrum along the axis is then given by [6]:

$$\frac{d^2 I}{d\omega d\Omega} = (6/\pi)^2 \alpha_f N_\beta \gamma_{z0}^2 \xi^2 K_{2/3}^2(\xi), \quad (1)$$

where $\alpha_f = 1/137$, and $K_{2/3}^2$ is a modified Bessel function with argument $\xi = \omega/\omega_c$, where $\omega_c = 3a_\beta\gamma_{z0}^2 c k_\beta$ is the critical frequency. To increase the energy of the radiated photons, it is necessary to increase the critical frequency ω_c via increasing γ_{z0}, n_e, and/or r_β [8].

To obtain the x-ray spectrum, we used a set of filters acting like a step function above a certain energy. The difference between the transmission functions through 150 μm of Ag and 100 μm of Cu gives a transmission function which resembles a step function with a cutoff at 26 keV, with almost zero transmission below 26 keV. This allows us to estimate the x-ray energy above 26 keV for each shot. We also measure the total deposited x-ray energy, and calculate the ratio of the energy above 26 keV to the total energy: $\rho = (I_{Ag} - I_{Cu})/I_{tot}$. We compare this ratio to the one given by theoretical calculations, and estimate an x-ray spectrum from a best fit to the theoretical plot.

Note that the theoretical calculations are for the very simplified case of an electron beam with a Gaussian transverse distribution of radius r_β at $1/e$, propagating in a blown-out ion channel which density matches our experiment; no acceleration nor decceleration is included yet.

The x-rays are then measured on the same IPs used for the electron spectrum measurement, IP(a) and IP(b).

Since the charge of the electron bunch changes the total flux but not the shape of $d^2I/d\omega d\Omega$, we calculated the ratio $\rho = I_{>26}/I_{tot}$ as a function of r_β and γ_{z0} only, which is shown in Fig. (3). The Llyod interferometer measures a plasma density at $5 \times 10^{18}\,\mathrm{cm}^{-3}$ for that particular shot. The experimental x-ray measurement from the image plates gives $\rho = 0.042$.

We observe that for a realistic electron bunch radius of a few microns, an electron bunch energy of 50 to 100 MeV is needed to recover the measured ratio of 0.042. The electron beam spectrum measured for that shot was centered around 26 MeV. Its energy is lower than the theoretical fit, which can be easily explained as dephasing (i.e. deceleration) of the electron beam before it leaves the plasma and gets measured. Our experiments have not try to match the interaction length to the dephasing length yet, i.e. the electrons do not necesarily exit the plasma at their maximum energy.

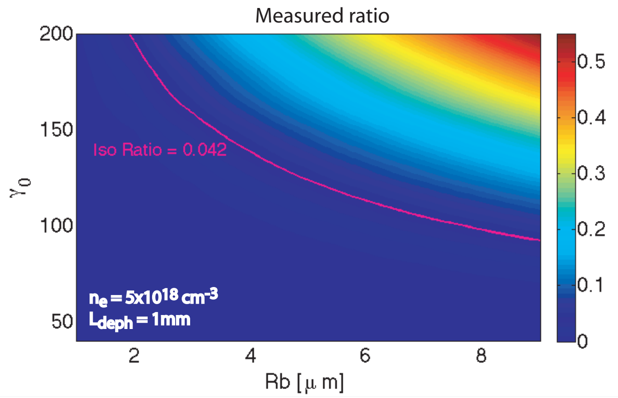

Figure 3: Ratio of the energy deposited above 26 keV over the total energy deposited on the IP as a function of γ_0 and r_β. The ratio measured in our experiment is 0.042.

As a typical example, we show an x-ray spectrum for the set of parameters r_β=3 μm, γ_{z0}=160 ($\simeq$ 80 MeV) $\pm 10\%$ FWHM in Fig. (4). The reconstructed spectrum has a peak energy near 6 keV.

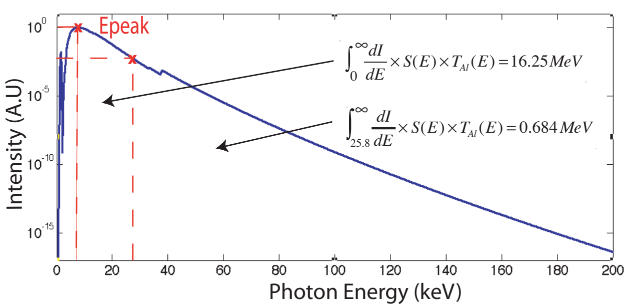

Figure 4: Reconstruction of the x-ray spectrum in the SAL limit based on measured ratio of energy deposited through filters.

CONCLUSION

We have performed the first measurements of accelerated electrons and x-ray spectra at LLNL Jupiter laser facility. We have measured monoenergetic electrons beams at energies around 110 MeV, measured with a two-screen spectrometer. The x-ray spectrum was deduced from fitting with theoretical estimates in the synchrotron asymptotic limit; the measurements indicate that the x-ray spectrum has a peak energy around 6 keV. Diagnostic developments under progress will allow us to measured more detailed electron and x-ray spectra, and to pursue the development of the betatron x-ray source for radiography applications.

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