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Measurement of the betatron radiation spectrum 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 electron 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 $1.5\times10^{18}\,\mathrm{cm}^{-3}$) 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 spectra measurements with a two screen spectrometer allowing to fix the ambiguities due to electron deflections at the plasma exit. We have measured monoenergetic electron beams above 300 MeV. Furthermore a forward directed x-ray beam is observed. The measured betatron spectrum agrees well with the calculated spectrum in the synchrotron asymptotic limit (SAL) using the measured electron beam parameters.

Keywords: Laser wakefield electron acceleration, x-ray radiation
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EXPERIMENTAL SETUP

Experiments were performed using the Ti:sapphire amplifier based Callisto system at the Jupiter Laser Facility, LLNL. The system is optimized to deliver an energy E $>$ 10 J on target in $\tau < 100$ fs. An f/8 off-axis parabolic mirror focuses the 800-nm laser pulse down to a best focus approximately twice the diffraction limit (the 1/e diameter is $\sim 8\,\mu$m). The plasma density is dependent on the nozzle and gas jet backing pressure and has been measured with a Llyod interferometer between $\sim 1.6\times10^{18}$ and $2\times10^{19}\,\mathrm{cm}^{-3}$ for the experiment discussed here.

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 over a 20×8 cm area and the magnetic field drops to 0 within a few mm outside of the magnet structure. 40 μm aluminium filter is used to block the laser light in the forward direction. 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 deviated by the magnet. The IPs measure electrons energies from 5 MeV to 2 GeV. The two front image plate, 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 [2]. The energy range measured by IP(a) goes from 78 MeV to ∞ and from 128 MeV to ∞ for IP(b). The third IP(c) measures low energy electrons [3-70] MeV.

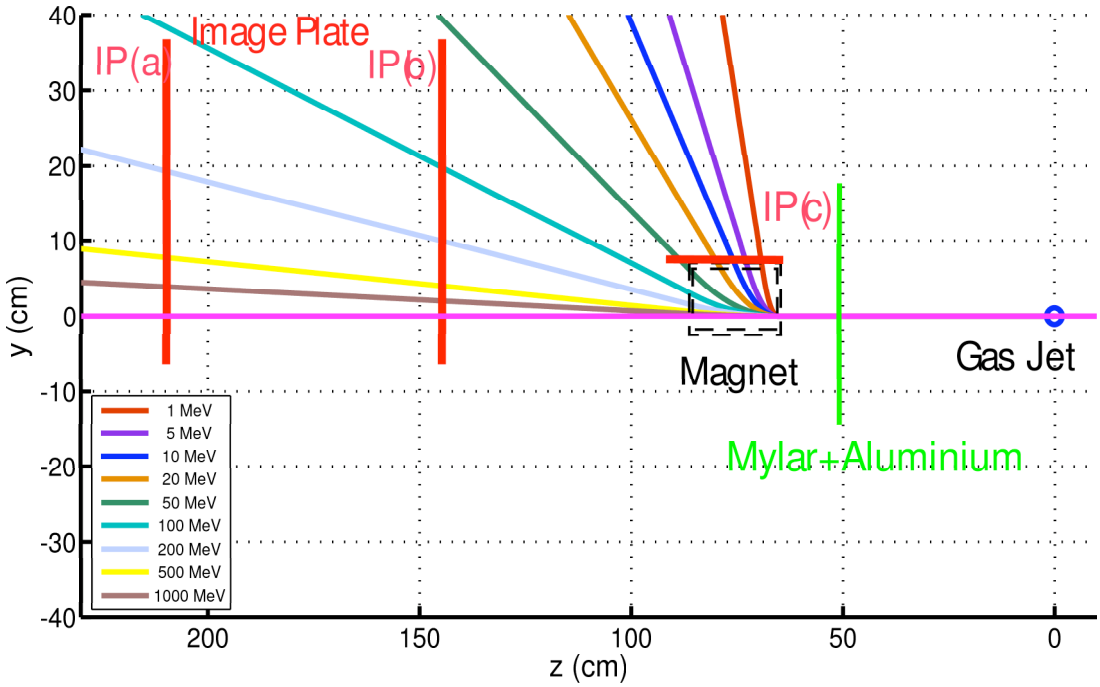

FIGURE 1. Electrons trajectories, at indicated energies, after deflection by a magnetic field of 4800 G. The electron are detected on three different imaging plates. The center of the gas jet is at $z = 0$ and the laser is propagating along the increasing z.

ELECTRON ENERGY SPECTROMETER

Measuring the vertical difference between the electron impact on the two consecutive IPs allows a measurement of both the electron energy and the transverse beam deflection at the plasma exit.

Figure (2a) shows an electron bunch detected on the near forward screen (IP(a)) at 308 MeV with a 10 % FWHM and 4 mrad of angular divergence [Fig. (2b)]. The main incertitude in the energy measurement comes from the y axis measurement uncertainties, $\Delta y \simeq 2$ mm, which corresponds to an error in the energy measurement $\Delta E \simeq 10$ MeV at 308 MeV. The far forward screen [IP(b)] detected an electron bunch at 310 MeV with a 12.3% FWHM, indicating a diffusion of the electron beam by the IP(a). The angle of the electron beam leaving the plasma is α=-1.75 mrad for that shot: electrons are

emitted down with the angle α and are then deflected up by the magnetic field. In this experiment, image plate are used to estimate the absolute number of electron [4]. The charge contained in the monoenergetic bunch shown in Fig. (2a) is 9.32 pC.

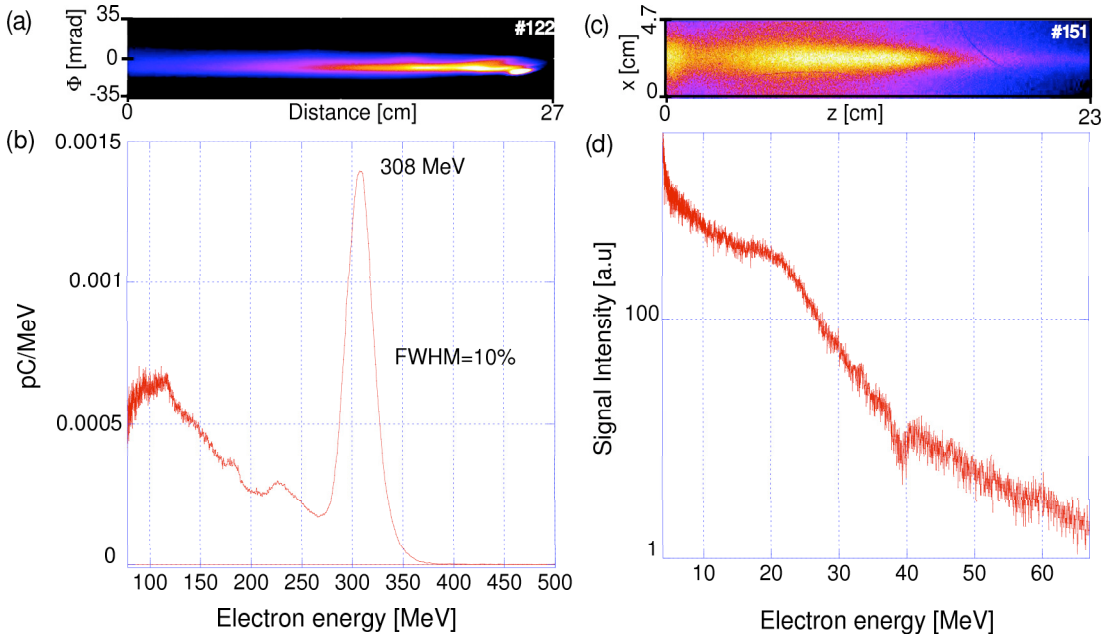

FIGURE 2. (a) Raw electron spectrum obtained on the IP(a) placed 144.6 cm from the gas jet and its corresponding electron spectrum (b). An electron bunch is detected at 308 MeV with 10 % FWHM and 4 mrad of angular divergence. (c) Raw electron spectrum obtained on the IP(c) for a different shot and its corresponding electron spectrum (d).

BETATRON X-RAY ENERGY MEASUREMENT

In nearly all LWFA experiments, the conditions are such that the betatron radiation spectrum is in the synchrotron asymptotic limit (SAL) [5]. Indeed, the strength parameter for an electon 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 [3, 6]; typically, $a_\beta \gg 1$ for usual LWFA parameters.

The radiation spectrum along the axis is then given by [5]:

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

where $\alpha_f = 1/137$, and $K_{2/3}^2$ is a modified Bessel function with argument $\xi = \omega/\omega_c$, where $\omega_c = 3 a_\beta \gamma_{z0}^2 c k_\beta$ is the critical frequency.

To measure the x-ray spectrum, we used a set of filters with transmission functions that provides a narrow energy band transmitted ΔE_n (n=1,2,3) around the materials

K edges (typically called Ross filters). The difference of energy deposed through two associated Ross filters provides an estimate of the number of photons per keV per 0.1%BW $\frac{dI}{dE}$ within a defined energy band [Fig. (3a)]. Indeed the energy deposed on the IP due to the x-ray radiation is $I = \frac{dI}{dE} \times T_{tot} \times \Delta E_n$ where T_{tot} is the total x-ray transmission up to the detector (Aluminium, Mylar, air, Ross filter and polypropylene used as the filters support).

Figure (3a) shows the three transmission gates created using six different filters (33 μm of Saran, 5.5 μm of Ti, 20 μm of Cu, 19 μm of Zn, 30 μm of Zr and 20.5 μm of Mo) on E_1=3.9 keV, E_2=9.3 keV and E_3=19 keV with respectively ΔE_n (n=1,2,3) of 2.1 keV, 0.65 keV and 2 keV of energy bandwith. A 5 μm precision in the filter thickness measurements allow an estimate in the number of photons transmitted. The experimental x-ray spectrum deduced from Ross filter measurement, as shown in Fig. (3b), is integrated over 22 mrad. The spatial distribution of the x-ray spot is also measurable through the filters analysis.

For this shot, Fig. (2c) shows a measured Boltzmann electron distribution with a 1.52 MeV temperature and a 1 pC charge. The laser pulse was 11.7 J in energy and $\sim$ 100 fs in pulse length focused on the upstream edge of a 5 mm long gas jet of Helium. The plasma density was measured to be 7×10^{18}cm^{-3} by a Llyod interferometer.

We compare this experimental measurement with the theoretical calculations [Fig. (3b)]. The theoretical calculations use the measured electron energy and charge and the plasma density. The calculation assumes electrons propagating in a blow-out channel and no acceleration is included yet. As the electron propagation length in the plasma changes only the total flux (by allowing more betatron oscillation),not the shape of the spectrum, this propagation length is assumed to be 1 mm in the simulation.

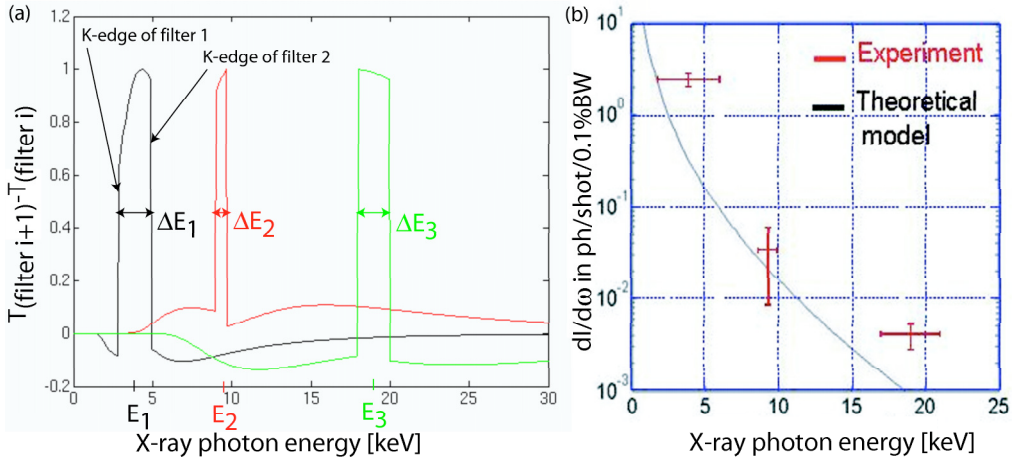

FIGURE 3. (a) Transmission gates are created by a set of filters. Two filters having their K-edge different by ΔE_n allow a measure of the x-ray energy deposed at $E_n \pm \Delta E_n/2$. (b) Experimental (red marks) and theoretical (black line) x-ray spectrum are shown. The electron spectrum, simultaneously measured for that shot, shows a Boltzmann distribution with a 1.5 MeV temperature and a 1 pC charge.

EXPECTED RESULTS AND FUTUR WORK

The next experiment will be using an x-ray spectrometer with 9 transmitted energy bandwidth, as shown in Fig. (4a), given by the measure of the energy deposed through 15 filters. This x-ray spectrometer will spatially and spectrally resolve the x-ray spectrum.

A scale for the expected betatron spectrum in LLNL, shown in Fig. (4b), is calculated for a 0.3, 1 and 3 GeV electron beam in a gaussian energy distribution with 10% FWHM, having a charge of 0.1 nC and a beam radius of 5 μm, propagating through a 1 cm long blown-out ion channel with a constant energy. The spectrum depends on the observation direction from axis. The spectrum integrated over all angles shows a peak near 80 keV and a flux of $\sim 10^4$ photons per shot and per 0.1 % BW for the 1 GeV electron energy. Figure (4b) shows the influence of the electron energy on the emitted radiation.

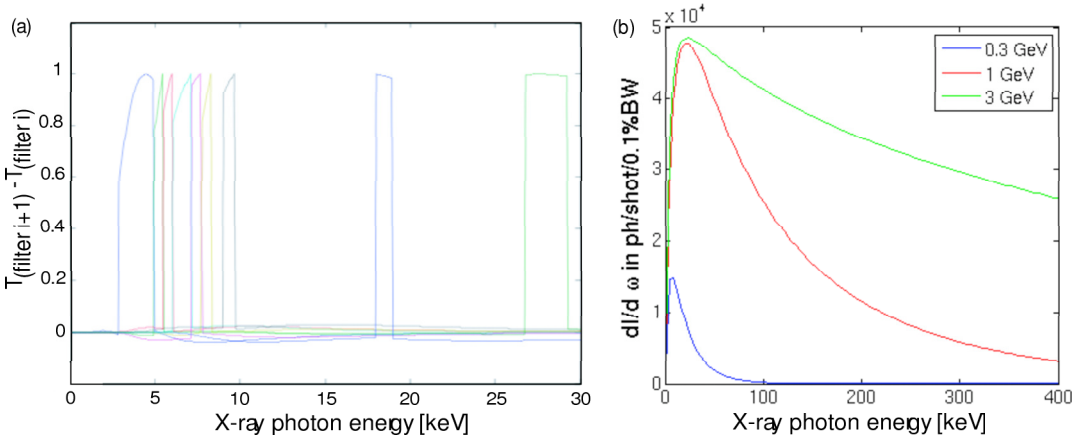

FIGURE 4. (a) 9 transmission gates are created by a set of 15 filters which will allow a spatially and spectral resolved x-ray spectrum. (b) Expected betatron spectrum emitted by a 0.3, 1 and 3 GeV electron bunch in a gaussian energy distribution with 10 % FWHM, having a 0.1 nC charge propagating along a 1 cm blown-out ion channel with an electron amplitude of motion of 5 μm.

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 above 300 MeV. The x-ray spectrum was deduced from Ross filter spectrometer and indicates photons at a few keV. Diagnostic developments are in progress to allow a more detailed electron and x-ray spectra to be measured and to pursue the development of a betatron x-ray source for radiography applications.

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