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Synchrotron x-ray radiation from laser wakefield accelerated electron beams in a plasma channel

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Abstract. Synchrotron x-ray radiation from laser wakefield accelerated electron beams was characterized at the HERCULES facility of the University of Michigan. A mono-energetic electron beam with energy up to 400 MeV was observed in the interaction of an ultra-short laser pulse with a super-sonic gas jet target. The experiments were performed at a peak intensity of 5×10^{19} W/cm^2 by using an adaptive optic. The accelerated electron beam undergoes a so called “betatron” oscillation in an ion channel, where plasma electrons have been expelled by the laser ponderomotive force, and, therefore, emits synchrotron radiation. We observe broad synchrotron x-ray radiation extending up to 30 keV. We find that this radiation is emitted in a beam with a divergence angle as small as 12×4 mrad^2 and can have a source size smaller than 3 microns and a peak brightness of 10^{22} photons/mm^2/mrad^2/second/0.1% bandwidth, which is comparable to currently existing 3rd generation conventional light sources. This opens up the possibility of using laser-produced “betatron” sources for many applications that currently require conventional synchrotron sources.

1. Introduction

Laser wakefield acceleration (LWFA) is an active research field since it can potentially enable compact, energy tunable and cost-effective sources of high-energy electron beams [1-3]. One attractive application of those electron beams is the use as an x-ray source for imaging applications. “Betatron” motion of electrons in a plasma with respect to x-ray generation has been studied experimentally [4-5] and theoretically [6]. In this article, the experimental characterization of a synchrotron x-ray source from LWFA is reported.

2. Experimental configurations

The experimental geometry is shown in Figure 1. The HERCULES facility of the University of Michigan [7] provided an interaction pulse (λ = 800 nm, 30 fs) which irradiates supersonic He gas-jets. A 10 cm laser beam was focused by a 1 m focal length off-axis parabolic mirror after wavefront correction with a deformable mirror to a spot size of 10 μm (FWHM) containing 40 % of the energy. The laser beam wavefront was corrected at a low energy (~ 0.35 mJ) by the method described in [8]. A focused peak intensity of 8×10^{19} W/cm^2 can be reached for 100 TW laser power. For these experiments the temporal contrast at the nanosecond time scale was 10^{-8}. A probe pulse was split-off from the interaction pulse by a 2 μm thick pellicle and sent through the plasma orthogonally to the interaction pulse in order to measure the plasma density via a shearing interferometer.

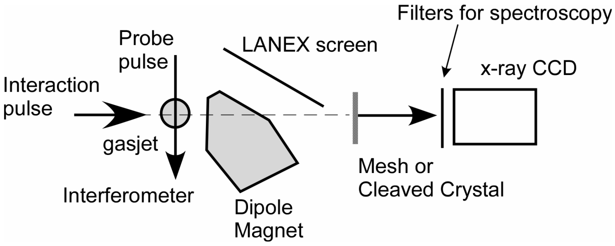

Figure 1. Experimental configuration

Accelerated electrons were deflected by a dipole magnet and sent to a LANEX (Kodak) scintillating screen and the signal was read by a CCD camera. A tracking code using the measured magnetic field map was used to relate the deflection of the electron beam on the LANEX screen to an electron energy. X-rays from the plasma were detected by an x-ray CCD camera. In some experiments, a mesh, a cleaved crystal or filters were inserted between the interaction region and the x-ray CCD camera in order to measure the x-ray beam divergence, source size or x-ray spectrum respectively.

3. “Betatron” motion in electron spectrum

Electron spectra as a function of plasma density are shown in Figure 2. The length of the plasma was approximately 2.5 mm. At a fixed laser power (30 TW), the electron spectra could be categorized into three types depending on the plasma density. First, a broad spectrum with multiple peaks is observed at high densities (e and f). Second, the spectra showed a sinusoidal shape in space, potentially due to “betatron” motion of the accelerated electron beam, and are observed at medium densities (b, c and d). Third, quasi-monoenergetic spectra are observed at the lowest densities (a). Observed “betatron” motion in the electron spectrum is similar to the one reported in the reference of 9. In the reference, the experimentally observed “betatron” motion of accelerated electrons was interpreted by 2D-PIC simulations as a consequence of off-axis injection in the radial direction, i.e., orthogonal to the laser propagation direction. The experiments and simulations showed that the asymmetrical laser intensity profile in radial direction might lead to an asymmetrically shaped wake and off-axis electron injection. More studies are required in order to fully understand the source of the “betatron” motion.

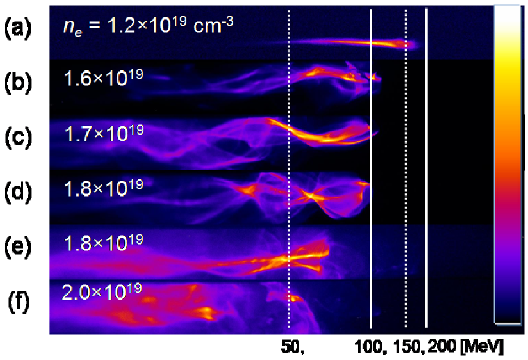

Figure 2. (color online) Image of electron spectrum as a function of plasma density. The color intensity scale is normalized by the peak intensity for each individual image.

4. X-ray characterization

A mesh was set behind the magnet and x-rays originating from the interaction region cast a shadow of the mesh on the x-ray CCD camera as shown in Figure 3. The size of the plasma was 5 mm in diameter and the plasma density was 5×10^{18} cm^{-3}. In the particular shot shown below, the laser power was 70 TW on target which yields an intensity of 5.3×10^{19} W·cm^{-2}. The x-ray image shows a 12×4 mrad^2 beam divergence which corresponds to a K parameter ($K \sim \theta\cdot\gamma$) of $K_x = 5$ and $K_y = 1.5$, where θ, γ, x and y are the beam divergence of x-rays, Lorentz factor of the electron beam, horizontal direction and vertical direction, respectively. Here, the electron beam energy was simultaneously measured to be 220 MeV was used.

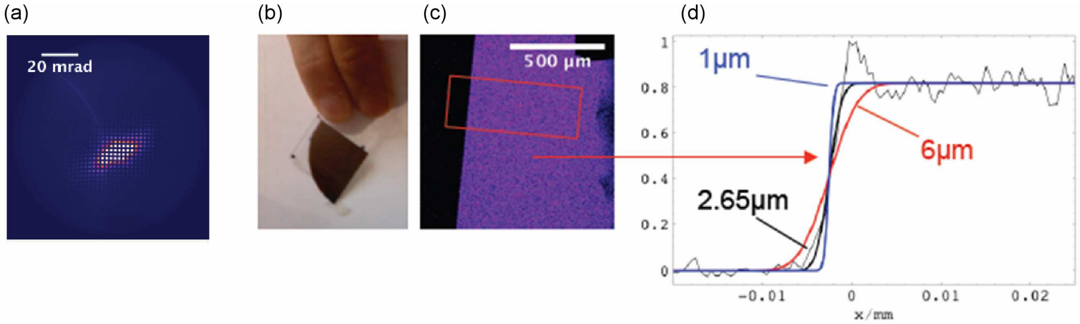

Figure 3. (color online) (a) Image of a mesh illuminated by the synchrotron x-ray radiation from a LWFA electron beam. The beam divergence is as small as 12×4 mrad^2. (b) InSb cleaved crystal, (c) Image of the crystal illuminated by the synchrotron x-ray radiation from a LWFA electron beam. (d) Line outs of the x-ray image with the experimental profile. Fitting curves by use of various source sizes are overlaid.

To quantify the source dimensions more accurately, penumbral images were taken by replacing the mesh by a cleaved edge crystal (Figure 3b). The image of the half-shadow due to the edge was obtained at a magnification of 30 (Figure 3c). The half-shadow is the result of the convolution of the source function and the aperture function. If they are assumed to be a Gauss function and a step function, respectively, the convolution takes the shape of an error function. Fitting error functions to the lineout across the half-shadow yields the best fit for the source size. Preliminary results reveal an unprecedented small FWHM x-ray source size smaller than 2.7 μm (Figure 3d) which changes little with plasma density [10].

In order to obtain the x-ray spectrum, the x-ray yield was measured through a set of metal foil filters of different material and thickness. Various spectral distributions were compared with experimental results until the agreement between predicted and measured x-ray yield is satisfactory. The actual spectrum can be assumed to have a synchrotron-like shape [6], and we consequently vary the critical energy E_{crit} to maximize the agreement between measured and predicted x-ray yield. We used up to six filters 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}. Figure 4 shows various typical synchrotron spectra from a range of conventional light sources together with our experimental result. Based on spectral measurement and x-ray beam divergence measurements, the highest total photon number observed in our experiment is of the order 10^8 photons per shot. The peak brightness is normalized to the source size, the divergence, 0.1 % bandwidth and the x-ray pulse duration, which is assumed to be the laser pulse duration. It is due to the unprecedented small source size and good collimation of the x-ray beam that the source yields a brightness comparable to currently existing 3rd generation conventional light sources. Small source size and divergence in turn are the merit of quasi-monoenergetic electron beams and their unique injection and acceleration dynamics.

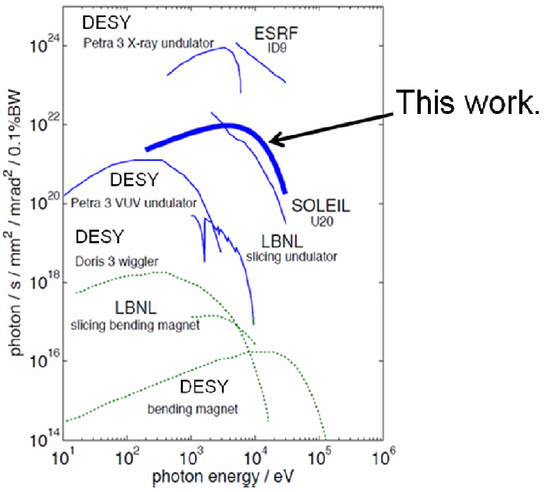

Figure 4. (color online) Normalized x-ray peak brightness for a typical shot for a selection of conventional 2nd (green dashed lines) and 3rd (blue lines) generation light sources [11].

5. Summary

Synchrotron x-rays from mono-energetic electrons were fully characterized. The x-ray divergence was found to be as small as 12x4 mrad^2 and the x-ray source size can be smaller than 3 µm. A peak brightness of more than 10^{22} [ph/s/mm^2/mrad^2/0.1%BW] comparable to 3rd generation light sources was inferred from the above mentioned observations.

References

[1] S. P. D. Mangles, et. al, Nature **431**, 535 (2004)
[2] C. G. R. Geddes, et. al, Nature **431**, 538 (2004)
[3] J. Faure, et. al, Nature **431**, 541 (2004)
[4] A. Rousse, et. al, Phys Rev Lett **93**, 135005 (2004)
[5] S. Kneip, et. al, Phys Rev Lett **100**, 105006 (2008)
[6] E. Esarey et. al, Phys. Rev. E **65**, 056505 (2002)
[7] V. Yanovsky, et. al, Opt Express **16**, 2109 (2008)
[8] S. W. Bahk, et. al, Opt Lett **29**, 2837 (2004)
[9] Y. Glinec, et. al, A Letters Journal Exploring The Frontiers of Physics **81**, 64001-p1 (2008)
[10] S. Kneip, et. al, Proc. of SPIE Vol. **7359**, 73590T-1 (2009)
[11] A. Rousse, et al, European Physical Journal D **45**, 391(2007)

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