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Single-shot betatron source size measurement from a laser-wakefield accelerator

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ABSTRACT

Betatron radiation emitted by accelerated electrons in laser-wakefield accelerators can be used as a diagnostic tool to investigate electron dynamics during the acceleration process. We analyze the spectral characteristics of the emitted Betatron pattern utilizing a 2D x-ray imaging spectroscopy technique. Together with simultaneously recorded electron spectra and x-ray images, the betatron source size, thus the electron beam radius, can be deduced at every shot.

1. Introduction and motivation

In recent years research on laser wakefield acceleration [1] which is considered as a promising concept for compact electron accelerators has shown tremendous development in terms of electron beam energy and stability. This scheme benefits from a large accelerating field gradient of up to a few hundreds Gigavolts per meter generated in the wake of a high intensity laser pulse as it propagates in a transparent plasma. Together with the advent of Petawatt-class laser systems, generation of multi-GeV electron beams have been demonstrated at acceleration distances of only a few centimeters [2–4].

Besides the strong accelerating field, there exists also a strong focusing field in the wakefield. As a consequence injected electrons perform transverse (betatron) oscillations around the wakefield axis while being accelerated. This results in the emission of bright, broadband and femtosecond short beams of hard x-rays with small source sizes [5,6]. Such a compact and cost effective x-ray source can serve as a versatile tool for applications such as x-ray phase contrast imaging [7] and novel x-ray probe for high-energy-density physics [8].

Betatron radiation can also be utilized as a powerful diagnostic method to investigate the acceleration process inside the wakefield since the source depends directly on the dynamics of the accelerated electrons. Various x-ray imaging and spectroscopy techniques have been used to characterize the electron trajectories, the beam emittance and size [9–12]. In this paper we report our initial betatron generation experiments in the self-injected bubble regime. We analyze the spectral characteristic of the betatron pattern using a 2D x-ray imaging spectroscopy technique. Since the regime relies on highly non-linear laser-plasma interaction, very sensitive to the fluctuation of experimental parameters, electron parameters can vary strongly for each shot. Therefore the source size at the exit of a plasma target is estimated on a single-shot basis. Finally we compare the result with the edge contrast technique.

2. Radiation from relativistically accelerated charges

The spectral flux radiated by a relativistically moving electron at position $r(t)$ at the time t is described by the general expression [13]:

$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2}{4\pi^2 c} \left| \int \frac{\vec{n} \times [(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \vec{\beta} \cdot \vec{n})^2} e^{i\omega\left(t - \vec{n} \cdot \frac{\vec{r}(t)}{c}\right)} \, dt \right|^2 \tag{1}$$

which yields the energy radiated in the direction $\vec{n}$ on the frequency ω within a bandwidth of $d\omega$ and a solid angle of $d\Omega$. $\vec{\beta}$ is the electron velocity normalized to the speed of light c and $\dot{\vec{\beta}}$ is its temporal derivative. As seen by the dot product the radiated energy is maximized for relativistic electron velocities $\beta \approx 1$ in the forward direction of the moving electron. The cross products indicate that acceleration is essential for radiation and a transversely applied acceleration produces orders of magnitude more efficient radiation than longitudinal acceleration [13].

Consequently, an x-ray source based on such scheme has to enforce relativistic electrons to oscillate transversely to produce efficient radiation. This is the principle of synchrotron facilities

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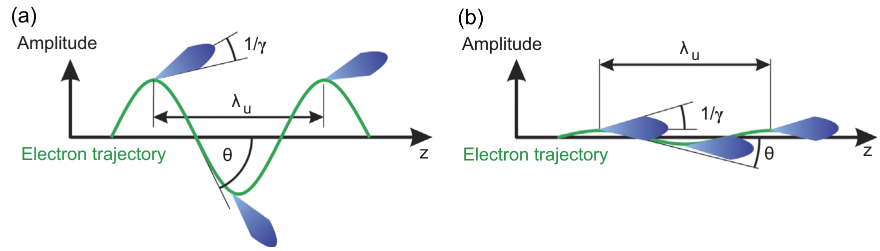

Fig. 1. Wiggler (a) and undulator regime (b): For strong oscillations the opening angle of the radiation cone is identical with the maximum deflection angle θ of the electron orbit. Small oscillations with $\theta < 1/\gamma$ still have a minimum opening angle of $1/\gamma$.

operating with alternating magnetic fields with periodicities λ_u which is typically tens of centimeters.

Regarding the strength of the oscillation with respect to longitudinal motion, two different regimes can be distinguished as shown in Fig. 1. These are quantified by the dimensionless parameter $K = \gamma\theta$ with θ as the maximum angle of the electron orbit and γ as the relativistic Lorentz factor. For $K < 1$ the radiation is emitted at the fundamental wavelength $\lambda = \lambda_u/(2\gamma^2)$. At $K \approx 1$ more harmonics appear in the spectrum. In the wiggler regime with $K > 1$ the number of harmonics increases enormously and the emitted spectrum changes to broadband continuum.

3. LWFA and betatron radiation

In a laser-wakefield accelerator a femtosecond short and high intensity laser pulse is propagating through an underdense plasma. The ponderomotive force of the pulse expels plasma electrons from the high intensity regions leaving the massive and, thus, immobile ions behind. Due to the Coulomb attraction, plasma electrons start to oscillate forming plasma cavities with the plasma wavelength λ_P. In the self-injection regime, background plasma electrons can be trapped at the backside of the first cavity and accelerated toward relativistic energies [14].

Inside the plasma cavity with a diameter of typically tens of micrometers, the electrons experience two field components, namely a transverse focusing field and a longitudinal accelerating field, which can be described by the equation of motion [15]

$$\frac{d\vec{p}}{dt} = -\frac{m_e}{2}\omega_P^2 \vec{r}_\perp + m_e c \omega_P \vec{u}_z. \tag{2}$$

Here $\omega_P = 2\pi c/\lambda_P = \sqrt{n_e e^2/m_e\varepsilon_0}$ is the plasma frequency, n_e is the electron density of the plasma, e is the charge of an electron with the mass m_e, ε_0 is the vacuum permittivity, $\vec{r}_\perp$ is the position vector from the channel axis to the electron and $\vec{u}_z$ is the unit vector along the plasma channel axis.

Electrons injected with an offset to the laser axis sense a restoring force towards the axis due to the transverse focusing field. This results in a transverse oscillation around the wakefield axis. The harmonic motion as shown in Fig. 2 has the fundamental betatron frequency $\omega_\beta = \omega_P/\sqrt{2\gamma}$ and the wavelength $\lambda_\beta = 2\pi c/\omega_\beta$ which is analog to λ_u. Betatron radiation possesses the fundamental wavelength $\lambda = \lambda_\beta/(2\gamma^2)$ [16].

For a plasma wiggler K is given by $K = \gamma r 2\pi/\lambda_\beta$. In practical units this is:

$$K = 1.33 \times 10^{-10}\sqrt{\gamma n_e[\mathrm{cm}^{-3}]}r\,[\mu\mathrm{m}]. \tag{3}$$

For the experiments described here, K is typically between 6 and 10, so the accelerated electrons radiate in the wiggler regime and thus emit a broadband spectrum. During the longitudinal acceleration, the effective electron mass γm_e grows and therefore the betatron period λ_β increases and the betatron amplitude r decreases. r may shorten to less than half of its original value [15].

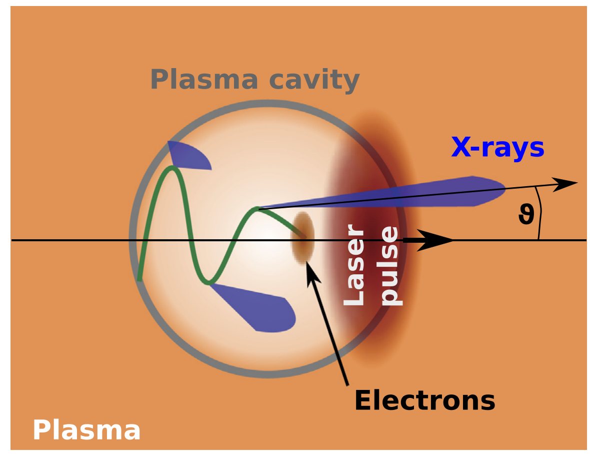

Fig. 2. Betatron radiation: The space charge separation of the ions inside the plasma cavity creates a transverse electrostatic field. This is sensed by the injected electrons as a radial force towards the main propagation axis. They undergo betatron oscillations and, as in a magnetic wiggler, synchrotron radiation is emitted in the laser forward direction.

At the end of the acceleration process the electron energy maximizes and dominates Eq. (3). Therefore the parameter K is maximized.

The typical spectral distribution for an infinitely small detector placed on the laser axis ($\Theta \approx 0$) derived from Eq. (1) is given by [16]:

$$\left.\frac{d^2 I}{dE\,d\Omega}\right|_{\Theta=0} \simeq N_\beta \frac{3e^2}{2\pi^3\hbar c\varepsilon_0}\gamma^2\left(\frac{E}{E_{crit}}\right)^2 K_{2/3}^2\left(\frac{E}{E_{crit}}\right) \tag{4}$$

where $\hbar$ is the reduced Planck constant, N_β is the number of betatron oscillations of one electron and $K_{2/3}(E/E_{crit})$ is the modified Bessel function of the second kind. For photon energies around the critical energy E_{crit} the spectrum is proportional to $\gamma^2(E/E_{crit})^{2/3}$. With increasing energy ($E \gg E_{crit}$) the spectra decay exponentially with $E/E_{crit}\exp(-2E/E_{crit})$ to zero [13]. The critical energy E_{crit} is defined as $E_{crit} = 3/2\hbar\gamma^3 k_\beta^2 r$ [17]. In more practical units this gives:

$$E_{crit}\,[\mathrm{keV}] \simeq 5 \times 10^{-24}\gamma^2 n_e\,[\mathrm{cm}^{-3}]r\,[\mu\mathrm{m}]. \tag{5}$$

Fig. 3 shows typical betatron spectra for different betatron radii, e.g. 0.5 μm and 1.0 μm. The final electron energy and the plasma density are 200 MeV and $n_e = 9.8 \times 10^{18}\ \mathrm{cm}^{-3}$.

4. Experimental setup

The experiments were performed using the DRACO Ti:Sapphire laser system with a pulse width of 30 fs FWHM and an energy of 3.6 J on target. A schematic of the setup is shown in Fig. 4. The laser beam was focused with an f/20 off-axis parabolic mirror to a vacuum focal spot size of $w_0 = 23.8$ μm reaching a peak intensity