BETATRON RADIATION FROM AN OFF-AXIS ELECTRON BEAM IN THE PLASMA WAKEFIELD ACCELERATOR *

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Abstract

In a plasma wakefield accelerator in the nonlinear regime the accelerated bunch electrons oscillate in a pure ion column. They emit strong synchrotron, also known as betatron radiation, in the keV to MeV photon range [1]. In previous experiments with a single electron bunch the oscillating electrons where distributed symmetrically about the beam axis or the ion column axis. However, with a drive/witness bunch system, the witness bunch can be injected into the ion column with a transverse momentum component or with a radial offset. In this case the witness bunch oscillates about the beam axis resulting stronger radiation. Since the ultra-relativistic bunches do not suffer dephasing, the energy loss to radiation can be compensated for by the energy gain from the wakefield. We explore the characteristics of the witness bunch oscillations and of the betatron radiation through numerical simulations and calculations.

INTRODUCTION

When an electron bunch propagates through plasma and its density n_b is larger than the plasma density n_e, i.e. in what is known as the blowout regime of the plasma wakefield accelerator (PWFA), a pure ion column is generated. The focusing force of the ion column $-eE_r$, ($E_r = ½\, e n_e r/\varepsilon_0$) increases linearly with radius and causes the beam electrons to oscillate (betatron oscillations) and therefore radiate (synchrotron radiation called betatron radiation in this case).

An individual electron within the beam has a simple harmonic motion (small oscillation amplitude) about the ion column axis with betatron frequency $\omega_\beta = \omega_{pe}/\sqrt{2\gamma}$, where $\omega_{pe} = (n_e e^2/\varepsilon_0 m_e)^{½}$ is the plasma frequency, γ is the electrons relativistic Lorentz factor. The electron bunch has a finite transverse size (r_0) and each electron within the bunch oscillates with a different amplitude. Since the radiated power (per electron) scales as r_0^2, the electrons that are oscillating close to the axis ($r_0 << r_{0max}$) do not radiate as much as those far way from the axis. The spectrum of the radiation is therefore tends to be broad. Also, due to the conservation of energy, electrons also radiate at harmonics of the betraton frequency.

We explore the possibility of using a small radius, short witness bunch offset from the drive bunch propagation (or ion column) axis that oscillates "off-axis" for betatron radiation generation through numerical simulations. Such a witness bunch oscillates as a "macro electron" in the ion column.

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SIMULATION

We employ the UCLA particle in cell code QUICKPIC [2] to numerically simulate the betatron oscillation of the drive/witness bunches. We use the typical SLAC 25.5 GeV beam parameters in our simulation as shown in table1. We choose the simulation box size to be several c/ω_p (c/ω_p =53μm). We also run simulations with different resolutions.

Parameters

We have the simulation input parameters listed below in table 1.

Table 1: Simulation Input Parameters

Parameters	Symbols	Values
Number of particles in the drive/witness bunch	N	6.5×10^9/ 6.5×10^8
Plasma density	n_b (cm^{-3})	1×10^{16}
Beam length	σ_z (μm)	14/ 7
Horizontal beam size Vertical beam size	σ_x (μm) σ_y (μm)	10/ 5 10/ 5
Relativistic Lorentz factor	γ	50000
Horizontal and vertical normalized emittance	ε_{Nx} (m-rad) ε_{Ny} (m-rad)	5×10^{-6} 5×10^{-6}
Box sizes	(μm)	220,220,340
Drive/witness bunch position	x,y,z (μm)	110,110,60 /130,110,220
Grid numbers in x, y, z directions		2^6, 2^6, 2^7
Number of macro beam/ plasma particles per cell		8 / 64

Results

Figure 1 shows a composite image of the plasma electron density and of the two electron bunches density in the simulation box at various position along the plasma. All densities are normalized to the electron plasma density. The witness bunch oscillates in the pure ion column (normalized electron density equal zero) induced by the drive bunch. First, as expected, the witness bunch, initially offset from the ion column axis in this case, oscillates about it with the betatron period. Second because the witness bunch has a finite transverse size, it is also focused along its betatron trajectory. Third, as the witness bunch progresses along the plasma it acquires a longitudinal tilt. Because the witness bunch has a finite longitudinal size, different z-slices gain different amounts of energy. Since the oscillation frequency depends on the electrons energy (γ), different slices eventually oscillate at different frequencies, and dephase. Finally it also shows that different longitudinal slices of the drive bunch experience different number of betatron oscillations, as previously observed [3]. This is mainly due to the fact that the focusing force increases from the very head of the driven bunch where it is zero to the full ion column focusing force. The witness bunch could be placed at a longitudinal position where the energy gain from the longitudinal wakefield can compensate for the energy loss due to betatron radiation. The figures show that the oscillation of the drive bunch generates small asymmetries in the second wakefield bucket ($z > 4.4c/\omega_p$ in Figure 1). However, the propagation of the two bunches remains stable over long plasma distances and not seem to seed significant hosing instability [4].

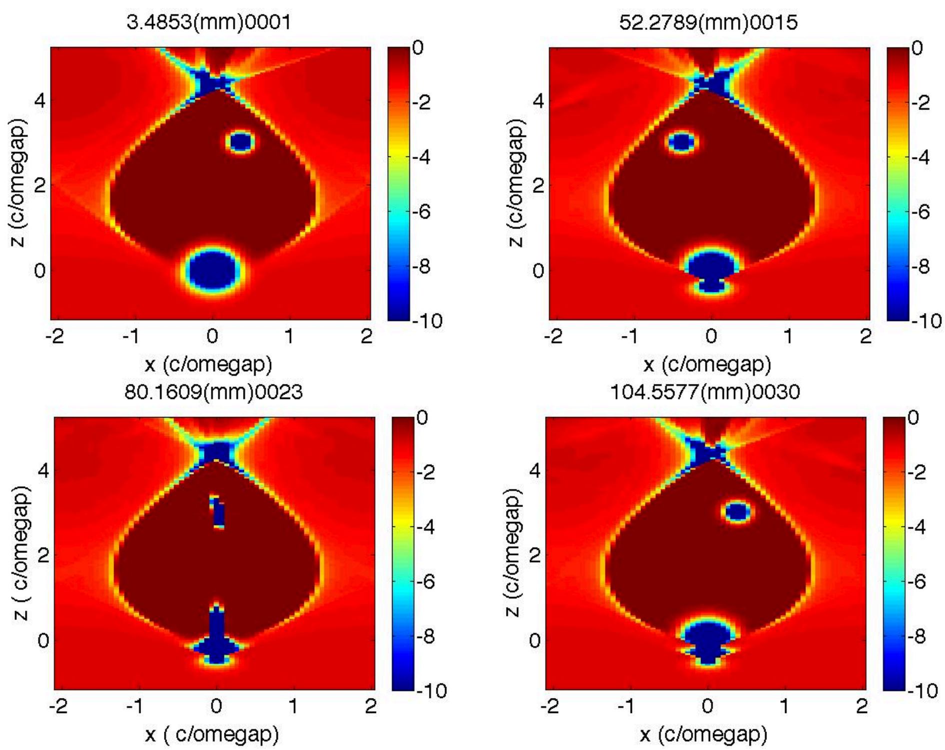

Figure 1: Plasma beam density profile at different propagation distances in the plasma. All densities are normalized to the initial electron plasma density (neutral plasma =-1). The color table is saturated to evidence the plasma density variations since the two bunches density are much larger than the plasma density.

RADIATION

We analyzed the X-ray generation process in the high harmonic generation regime; the synchrotron-like broadband spectrum is generated. The uniform ion column has a "wiggler strength" K given by $K=\gamma_0 k_\beta r_0$. Here for a plasma wiggler, different radia result in different K; if K >>1 (large radius), the bunch emits a quasicontinuous broadband spectrum, similar to the synchrotron spectrum. The averaged radiation power by one electron undergoing one betatron period is given by [5],

$$\langle P_s \rangle \approx {e^2 c}/{12} \gamma^2 k_{pe}^4 r_0^2 \quad (1)$$

Thus the energy loss for one electron per unit distance (n_e [cm^{-3}], r_0 [μm]) is

$$Q = {\langle P_s \rangle}/{c} \approx 1.5\times10^{-45} \left(\gamma n_e r_0\right)^2 {MeV}/{cm} \quad (2)$$

which shows that 4.25 GeV/m radiation is resulted from a E = 28.5 GeV electron with r_0 = 10 μm and n_{pe} = 3×10^{17} cm^{-3}. With a beam, electrons at different radii have different betatron amplitudes r_0 and hence different resonant frequencies. For a monoenergetic, axisymmetric Gaussian beam, $f(r)=\exp[-(r_0-r_c)^2/2\sigma_r^2]$ and $\int f(r)2\pi r=1$,

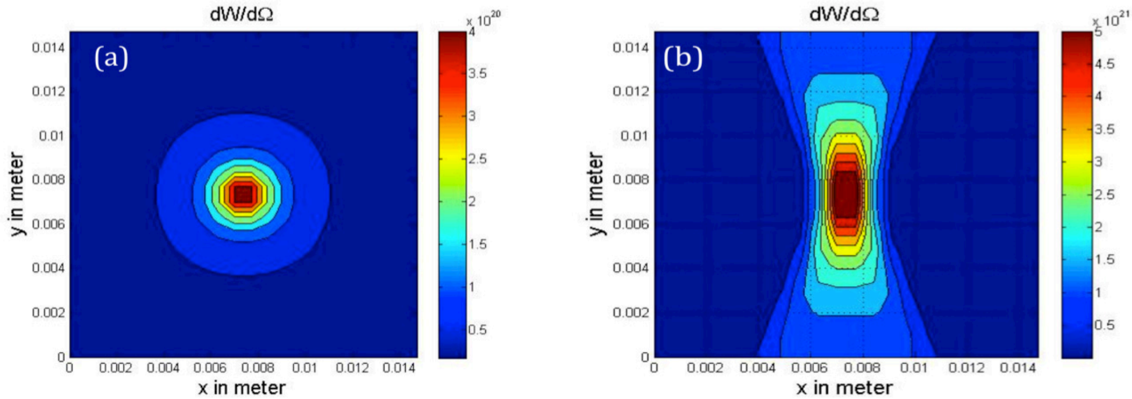

Figure 2: Radiation Pattern integrated in frequency (a) on axis, and (b) off axis witness bunch case.

$$\langle P_{total}\rangle \approx \int 2\pi r f(r) dr \frac{e^2 c}{12}\gamma^2 k_{pe}^4 r_0^2 = 2\pi \frac{e^2 c}{12}\gamma^2 k_{pe}^4 4\sigma_r^4 [\frac{1}{2} + \frac{3\sqrt{\pi}}{4}\bullet (\frac{r_c}{\sqrt{2}\sigma_r}) + \frac{3}{2}(\frac{r_c}{\sqrt{2}\sigma_r})^2 + \frac{\sqrt{\pi}}{2}(\frac{r_c}{\sqrt{2}\sigma_r})^3] \quad (3)$$

When r_c=20μm, σ_r=5μm, about 30 times higher radiation is resulted than that of the on-axis case with r_c=0. We use the Saddle-point method to calculate radiation from bunches based on the formula (4) from Jacokson's

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c} | \int_{-\infty}^{\infty} \vec{n} \times (\vec{n} \times \overrightarrow{\beta(t)}) e^{i\omega(t - \vec{n}\bullet\overrightarrow{r(t)})} dt |^2 \quad (4)$$

Electrodynamics book [6] which is simplified as

$$\frac{d^2W}{d\omega d\Omega} = 2N_0 \frac{e^2\eta^2\rho^2\chi^2}{3\pi^2 c}\left[\frac{\sin^2\theta \sin^2\phi}{\chi} K_{1/3}^2(q) + K_{2/3}^2(q)\right] \quad (5)$$

Therefore the off-axis witness bunch radiates more power with a different radiation pattern as shown in Figure 2. In future experiments, total power will be a combined radiation of on-axis drive bunch plus off-axis witness bunch.

POSSIBLE EXPERIMENT

A drive/witness bunch train will be generated at the SLAC National Accelerator Laboratory FACET for PWFA acceleration of the witness bunch with a narrow energy spread [7]. For PWFA experiments the witness bunch trajectory will be aligned as best as possible to that of the drive bunch to reach the best possible final parameters for the witness bunch. In this acceleration process betatron radiation is a deleterious side effect and in general remains a small perturbation for the acceleration process. However, the beam line can be tuned so that the dispersion is zero at the plasma entrance (such that the two bunches enter the plasma at the same radial position), but with the derivative of the dispersion not zero. Since the bunch train generation process [8] relies on a correlated energy spread imposed on the initial train, the two bunches will enter the plasma with different angles, leading to the desired off-axis oscillation of the witness bunch. This effect will be detected as an increase in radiated power when compared to the on-axis injection case. Note that a similar increase in betatron radiation power can be expected if hosing instability occurred, and the same detection method would reveal the instability in conjunction with direct imaging of the beam. Detection of the radiation pattern (Figure 2) using for example a phosphor screen will also be examined. Finally we note that polarized x-ray or gamma rays could be generated if the witness bunch were injected with an azimuthal momentum at that the plasma entrance.

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