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Betatron Radiation from a Beam Driven Plasma Source

M. Litos, S. Corde

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

Abstract. Photons produced by the betatron oscillation of electrons in a beam-driven plasma wake provide a uniquely intense and high-energy source of hard X-rays and gamma rays. This betatron radiation is interesting not only for its high intensity and spectral characteristics, but also because it can be used as a diagnostic for beam matching into the plasma, which is critical for maximizing the energy extraction efficiency of a plasma accelerator stage. At SLAC, gamma ray detection devices have been installed at the dump area of the FACET beamline where the betatron radiation from the plasma source used in the E200 plasma wakefield acceleration experiment may be observed. The ultra-dense, high-energy beam at FACET (2×10^{10} electrons, $20\times20\,\mu\text{m}^2$ spot, $20-100\,\mu$m length, 20 GeV energy) when sent into a plasma source with a nominal density of $\sim 1\times10^{17}\,\text{cm}^{-3}$ will generate synchrotron-like spectra with critical energies well into the tens of MeV. The intensity of the radiation can be increased by introducing a radial offset to the centroid of the witness bunch, which may be achieved at FACET through the use of a transverse deflecting RF cavity. The E200 gamma ray detector has two main components: a $30\times35\,\text{cm}^2$ phosphorescent screen for observing the transverse extent of the radiation, and a sampling electromagnetic calorimeter outfitted with photodiodes for measuring the on-axis spectrum. To estimate the spectrum, the observed intensity patterns across the calorimeter are fit with a Gaussian-integrated synchrotron spectrum and compared to simulations. Results and observations from the first FACET user run (April-June 2012) are presented.

Keywords: Betatron Radiation, Plasma, Wakefield
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INTRODUCTION

The strong radial focusing fields inside an ion column generated by an electron drive beam as it travels through an under-dense plasma cause the electrons in the bunch to undergo rapid betatron oscillations. As a result, broadband synchrotron radiation is emitted with characteristic energies of tens of MeV. Depending on the plasma density and beam parameters, the flux can grow to be quite large, with upwards of ten photons produced per electron. This unique radiation source may find potential applications in the research world, and more immediately serve as a non-destructive, shot-by-shot diagnostic for the beam-plasma interaction in plasma wakefield acceleration (PWFA) experiments.

A scintillating screen and a photo-diode stack calorimeter were installed at the dump area of the FACET beamline at SLAC to observe the transverse and spectral characteristics of the betatron radiation emitted by the plasma source of the E200 PWFA experiment. The design considerations for the betatron radiation diagnostics and preliminary results from early data are discussed.

PLASMA WIGGLER PARAMETERS

The parameters that describe the behavior of a beam electron in the radial electric fields of an ion column can be analogized with those of a conventional magnetic wiggler. Equation 1 gives the equivalent magnetic field and Equation 2 gives the magnetic wiggler strength for an electron undergoing betatron motion in a non-linear plasma wake [1, 2],

$$B_0 = 3.0\times10^{-17} n_p[\text{cm}^{-3}] r_0[\mu\text{m}]\,\text{T} \tag{1}$$

$$K = \gamma k_\beta r_0 = 1.3\times10^{-10}\sqrt{\gamma n_p[\text{cm}^{-3}] r_0[\mu\text{m}]} \tag{2}$$

where B_0 is the equivalent magnetic field, r_0 is the maximum radial amplitude of the electron during a single betatron oscillation, n_p is the plasma density, K is the equivalent wiggler strength, γ is the relativistic Lorentz factor of

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the electron, $k_\beta = k_p/\sqrt{2\gamma}$ is the betatron wavenumber of the electron, $k_p c = \omega_p = (4\pi n_p e^2/m_e)^{1/2}$ is the plasma frequency, c is the speed of light in vacuum, and e and m_e are the charge and mass of the electron, respectively.

A plasma wiggler emits electromagnetic radiation in a broadband, synchrotron-like spectral pattern. The critical energy of the betatron radiation emitted by a single electron is given by [2]

$$\hbar\omega_c = \frac{3}{2}\gamma^3 \hbar c r_0 k_\beta \simeq 5.2\times 10^{-24}\gamma^2 n_p[\mathrm{cm}^{-3}] r_0[\mu\mathrm{m}]\,\mathrm{keV} \tag{3}$$

where the critical energy is defined as the energy corresponding to the frequency above and below which half of the total radiation is emitted. The number of photons emitted by a single electron over a distance of N_β betatron periods can be estimated by dividing the total radiated energy by the critical energy [2]:

$$< N_{\gamma,\hbar\omega_c} > \simeq \frac{2\pi}{9}\frac{e^2}{\hbar c} K N_\beta \simeq 5.6\times 10^{-3} K N_\beta \tag{4}$$

The divergence of the betatron radiation has an angular spread of $\Delta\theta_{||} \sim K/\gamma$ in the plane of oscillation and $\Delta\theta_\perp \sim 1/\gamma$ in the orthogonal plane.

PWFA DIAGNOSTIC

Information about the beam-plasma interaction is encoded in the betatron radiation, thus allowing it to be used as a non-destructive, shot-by-shot diagnostic tool in PWFA experiments. By observing the transverse profile and spectral characteristics of the betatron radiation, such effects as beam matching into the plasma, hosing instabilities, and the relative alignment of drive and witness bunches in a two-bunch PWFA scenario can be measured. It is conceivable that a betatron radiation diagnostic could be of great use to a future PWFA collider.

For a beam that is well matched into the plasma [3], the transverse profile of the betatron radiation should be relatively round with a radial profile that is roughly gaussian. When the beam is mismatched in a single plane, the transverse extent of the radiation in that plane will increase, as will the critical energy. This is also true for a beam that is hosing or for a misaligned witness bunch. If the beam is mismatched in both transverse planes, the distribution of the betatron radiation then becomes round again, but falls off at a rate of roughly $1/r$.

EXPERIMENTAL SETUP

FACET is a new experimental test facility at SLAC that utilizes the first two kilometers of the SLAC linac to generate high energy, high density electron beams for advanced accelerator experiments, with an emphasis on plasma wakefield acceleration. The first user run took place between April 27 and July 5, 2012 with typical beam parameters listed in Table 1. The corresponding plasma wiggler parameters for FACET are listed in Table 2. An electron with a maximum radial offset of $r_0 = \sigma_r = 20\,\mu$m oscillates as if in a wiggler with the following parameters: $B_0 = 60$ T, $K = 170$, $\hbar\omega_c = 16$ MeV, and $< N_\gamma >= 10$ (corresponding to $\sim 10^{11}$ photons in total). Field strengths of this magnitude are beyond the reach a conventional magnetic wiggler.

TABLE 1. FACET Beam parameters for 2012.

Energy	20 GeV
Charge	3 nC
σ_r	20 μm
σ_z	20 μm
Species	e^-

Figure 1 shows a schematic of the experimental setup for the betatron radiation diagnostics of the E200 PWFA experiment at FACET. A $30\times 35\,\mathrm{cm}^2$ KODAK LANEX phosphor screen is imaged by a CCD camera to observe the transverse profile of the betatron radiation, located roughly 25 m downstream of the plasma source. Attached to the upstream side of the screen is a 1 mm thick sheet of copper foil which is used as a converter. A 5 cm wide slot is cut out of the lower middle portion of the screen and converter foil to allow the vertically dispersed and deflected electron beam to pass through with minimal contact.

TABLE 2. Plasma wiggler parameters for typical FACET plasma source.

γ	40000
n_p	$10^{17}\,\mathrm{cm}^{-3}$
L_p	30 cm
N_β	10
B_0/r_0	$3\,\mathrm{T}/\mu\mathrm{m}$
K/r_0	$8.4/\mu\mathrm{m}$
$\hbar\omega_c/r_0$	$800\,\mathrm{keV}/\mu\mathrm{m}$
$< N_\gamma > /r_0$	$0.5/\mu\mathrm{m}$

In addition, a stack calorimeter located ~ 30 cm behind the phosphor screen is used to measure the betatron radiation spectrum. It consists of 12 two-inch thick bricks of alumina with a single two-inch thick lead brick in the rearmost position to block back-scattered radiation emitted from the dump. Between each brick layer is a card with a $5 \times 5 \times 0.5\,\mathrm{mm}^3$ silicon photo-diode. Each doide is covered in black tape to reduce background noise due to transient lighting. Photos of the phosphor screen and the stack calorimeter are shown in Fig. 2.

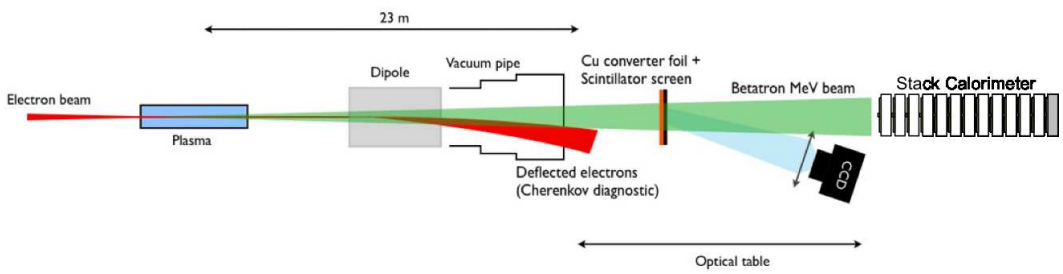

FIGURE 1. Schematic of experimental setup. Screen is located 25 m downstream of plasma source, 10 m downstream of spectrometer dipole. Stack is 30 cm downstream of screen. Beam dump is located immediately downstream of stack (not shown).

Figure 3 shows a calculated spectrum for a gaussian beam with normalized emittance in x and y of $\varepsilon_x = 500\,\mathrm{mm}\cdot\mathrm{mrad}$ and $\varepsilon_y = 50\,\mathrm{mm}\cdot\mathrm{mrad}$, respectively. The beam is assumed to be well matched into a plasma with a density of $2.7 \times 10^{17}\,\mathrm{cm}^{-3}$. The resulting spectrum is a synchrotron spectral profile integrated over a gaussian radial distribution. Two fits were performed on the calculated spectrum: the first fit was a least squares minimization of the absolute difference between a simple synchrotron spectral function and the calculated betatron radiation spectrum; the second fit used the same function but instead minimized the relative difference, *i.e.*, the difference weighted by the magnitude of the calculated betatron spectrum. The former minimization best fits the low energy core of the spectrum with a critical energy of 17.5 MeV, while the latter minimization best fits the high energy tail with a critical energy of 26.8 MeV.

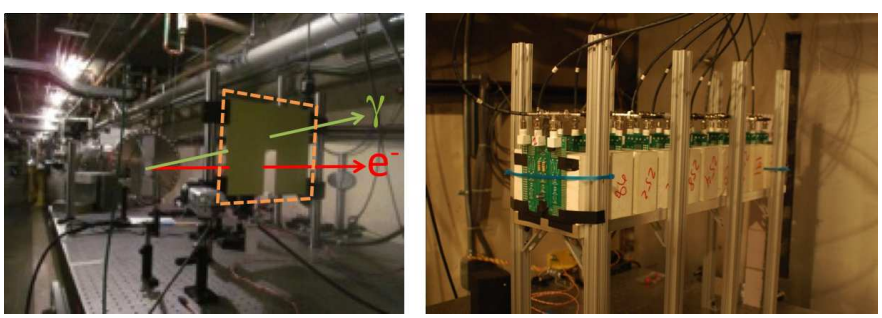

FIGURE 2. Left: Photograph of phosphor screen. Right: Photograph of stack calorimeter.

The design of the stack calorimeter was guided by an electromagnetic showering simulation using the EGS4 [4] code, where a synchrotron function was given as input to a 3-D model of the stack. Figure 4 shows the simulated energy deposition in the silicon photo-diode of each layer of the stack over a wide range of critical energies. The difference between the deposited energy in a given layer for the different critical energies corresponds to how well

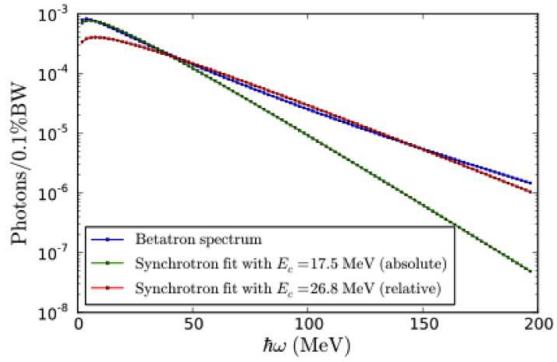

FIGURE 3. Calculated gamma ray spectrum for a matched gaussian electron beam in the E200 plasma source with $n_p = 2.7 \times 10^{17}\,\mathrm{cm}^{-3}$.

the detector can resolve the incoming radiation. The choice of alumina as the absorber material for the stack came as a compromise between the expected resolution and the total space needed to contain the entire length of the shower. Other materials considered were carbon, tungsten, and aluminum, of which carbon gives the best resolution, but at the cost of twice the space.

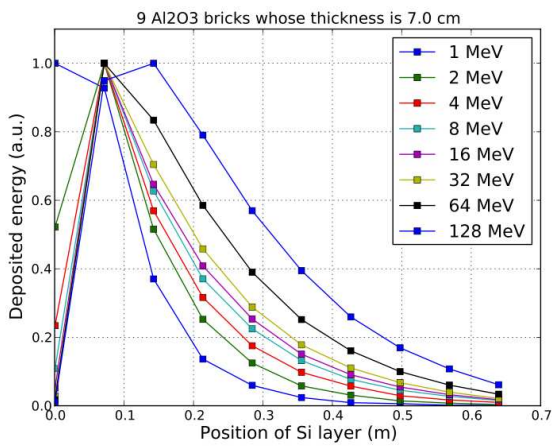

FIGURE 4. Simulated response of stack calorimeter for critical energies $1-128\,\mathrm{MeV}$.

INITIAL DATA

Figure 5 shows one of the first images of betatron radiation on the phosphor screen captured at FACET. The betatron gamma rays create the bright spot in the middle of the phosphor screen (feature a.). This spot disappears when the plasma source is removed from the beamline. Also visible is a portion of the unfocused tail of the electron beam near the bottom of the screen on either side of the slot (feature b.). Synchrotron radiation from the final spectrometer dipole is present on the screen in the form of a vertical stripe traveling downward from the center of the betatron spot, though it is overwhelmed by the betatron radiation in this particular image.

There are three major apertures that restrict the visibility of the betatron radiation on the phosphor screen. The most restrictive aperture is the width of the 2 mm thick rectangular aluminum window mounted in the center of the 4 cm thick steel exit flange of the vacuum beampipe (feature c.). The only advantage to the presence of this aperture is that it allows us to measure the relative flux of gamma rays through the aluminum and the steel. We observe a 70% reduction of intensity due to the steel, which confirms that we are indeed observing gamma rays in the expected MeV energy range on our phosphor screen. The remaining two apertures come from the size of the gap in the spectrometer dipole (feature d.), and the size of the circular vacuum beampipe (feature e.).

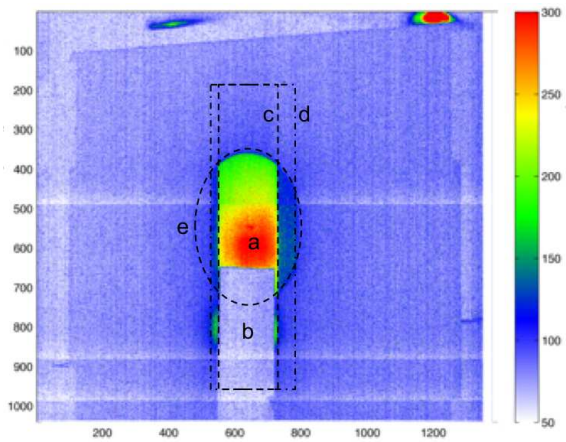

FIGURE 5. Transverse profile of beam-driven PWFA betatron radiation on phosphor screen. Image features: a. betatron radiation gamma rays, b. unfocused tail of electron beam, c. exit window aperture, d. spectrometer dipole aperture, e. vacuum beampipe aperture.

A lineout was taken along the central vertical axis of the image to analyze the radial profile of the betatron radiation. Figure 6 shows a gaussian curve fit to the data. The HWHM of the radiation is about 5 cm, which agrees with a naive order of magnitude estimation based on the calculated angular divergence and the distance to the screen. The fact that the gaussian curve does not fit the data well indicates that the beam was not well matched into the plasma in the vertical direction. The round shape of the radiation in Fig. 5 further tells us that the beam was also unmatched in the horizontal direction.

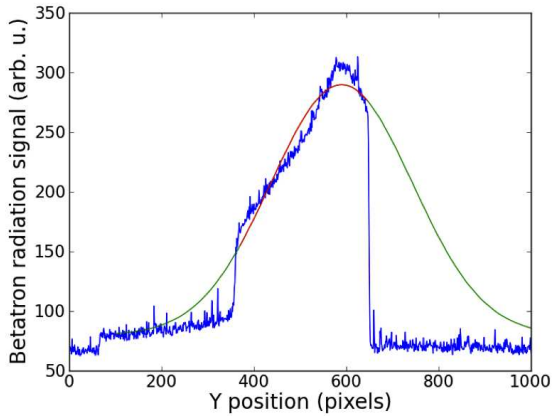

FIGURE 6. Vertical lineout of data from Fig. 5 with gaussian fit overlaid. Pixel 0 represents the top of the screen, and pixel 1000 represents the bottom of the screen. The beampipe aperture blocks radiation up to about pixel 380. The slot in the screen covers pixels above 650.

At the time of this conference, the stack calorimeter had yet to see beam and thus had not yet collected any data.

SUMMARY

The strong radial focusing forces in the plasma source for the E200 PWFA experiment at FACET behave similarly to a wiggler with a strength of $K > 100$. This will produce betatron radiation with critical energies in the tens of MeV, and with a photon yield of at least ten photons per electron. The transverse profile and spectrum of the betatron radiation can give insight into the beam-plasma interaction on a shot-by-shot basis, thus making it a valuable diagnostic for PWFA experiments.

To measure the properties of the betatron radiation produced in the E200 PWFA experiment at FACET, a phosphor screen and stack calorimeter were installed in the FACET beamline upstream of the beam dump. The design of the stack was based on simulations of radiation with critical energies ranging from 1 to 100 MeV.

Analysis of the initial data from the phosphor screen confirms that betatron radiation is being produced in the MeV energy range. Further, we can deduce that the beam was not well matched into the plasma at the time the initial data was taken based on the radial profile of the radiation. No spectral data from the stack calorimeter was available at the time of this conference, but the stack was installed in time to collect data before the end of the 2012 FACET user run and analysis is forthcoming.

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