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RADIATION DIAGNOSTICS FOR AWA AND FACET-II FLAT BEAMS IN PLASMA

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Abstract

In electron beam facilities like FACET-II and Argonne Wakefield Accelerator facility (AWA), beams with highly asymmetric emittance are of interest because they are the preferred type of beam for linear colliders (LC). That is ultimately the motivation: building a plasma based LC. In the flat beam case, the blowout radius is no longer equal in the two transverse planes. Focusing is required to keep the particles within the tight apertures, and characterizing these accelerators shows the benefits of employing ultra low beam emittances. Beams with high charge and high emittance ratios in excess of 100:1 are available at AWA. If the focusing is not equal, then we will have different radiation signatures for the flat and symmetric beams in the plasma. We use QuickPIC and OSIRIS particle-in-cell codes to compare various scenarios including a weak blowout and a strong blowout. Further, we determine the radiation generated in the system by importing particle trajectories into a Liénard Weichert code. We discuss future steps towards full diagnostics of flat beams using radiation.

INTRODUCTION

When relativistic electrons oscillate transversely in a nonlinear plasma ion column they emit synchrotron radiation which is also known as betatron radiation [1]. With the advances of plasma and laser techniques, betatron radiation from plasma wakefield accelerators has brought these goals of imaging and beam profile reconstruction closer to being achieved, and also could serve as an important beam diagnostic tool. For an accelerator with a bunch of few-GeV energy, few-fs pulse duration, few-mm-rad emittance, and significant energy spread, methods like pepper pot [2] and quadruple scan [3] are less effective emittance diagnostic methods because they are statistical rather than single shot and are destructive. We need sophisticated methods to measure the emittance in Plasma WakeField Accelerators (PWFAs) because the plasma vacuum boundaries can change the transverse phase space and divergence of the beam [2]. In comparison to a round beam, a flat beam suppresses the beamstrahlung at the interaction point in a linear collider and also breaks the symmetry of betatron motion in x and y planes. Flat beam generation was experimentally demonstrated a decade earlier [4, 5] and was proposed as an alternative to damping rings in linear colliders. The generated flat beam at AWA has few nC charge, MeV energy and µm spot size. Similar scenarios will be explored at FACET-II. There are three main regimes of beam-based PWFA: the linear, quasi-nonlinear and non-linear (or blowout) regimes [6]. In the linear regime, plasma electrons are not completely removed from the center of the wake. In the blowout case, the strong electric fields of the beam force the plasma electrons outward, resulting in a pure ionic column. The scenario for the case of the axisymmetric beam has been studied extensively [7, 8]. However, we don't fully understand the physics behind flat beams, and there is not much information available in the literature. This leaves unanswered questions like asymmetric blowout, plasma based lenses, transverse correlation and associated radiation [9]. In this paper, we systematically investigate the betatron radiation effect in the flat beam case considering realistic beam and plasma parameters. Radiation from the 10 GeV FACET-II and 50 MeV AWA beam diagnostics are explored. Betatron radiation diagnostics for flat and round beams could be used to measure the emittance, spot size, and energy gained by the accelerated electron bunch within the plasma. Studies are being done to examine the transverse profile of the electron beam [10].

AWA FLAT BEAM

Numerical simulations of drive bunch acceleration are carried out with the three-dimensional (3D) quasi-static particle-in-cell (PIC) code QuickPIC and the full PIC code OSIRIS for the parameters shown in Table 1. For the purpose of beam profile and emittance reconstruction, the complete spatial distribution of the beam is needed [11]. Therefore, it is very effective to look at the spatial distribution of betatron photons, as the radiation pattern on the screen is axisymmetric for an axisymmetric electron bunch. Space charge particularly affects the defocusing forces over the length of the bunch and changes the achievable phase space density, which also has a great impact on the betatron motion of the particles. Emittance of the bunch could be significantly improved by optimizing the magnetic field parameters and the beam.

In order to eliminate the influence of the head erosion seen, an examination of the back 50% of the beam particles was employed as shown in Figure 1. Betatron radiation and the electron dynamics are inter-related; hence, we may be able to use betatron radiation to indirectly measure the evolution of the beam size creating asymmetric blowout shown in Fig. 2 or even beam profile inside the plasma chamber. There are several difficulties in the study and the application of betatron diagnostics for electron and proton wakefield

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Table 1: Parameters for AWA

Parameter	Value	Unit
Beam		
Peak density, n_b/n_0	6.54	-
Energy, E_b	50	MeV
σ_z	674	µm
σ_x, σ_y	113, 11.3	µm
$\epsilon_{n,x}$, $\epsilon_{n,y}$	200, 2	řad
Plasma		
Species	H	-
Density, n_0	1.4×10^{14}	cm^{-3}
Particles per cell	4	-
Simulation		
Simulation window (x,y,z)	(8, 8, 14)	k_p^{-1}
Grid	$(1024)^3$	-
Timestep	0.25	ω_p^{-1}
Beam particles	1.68×10^7	-

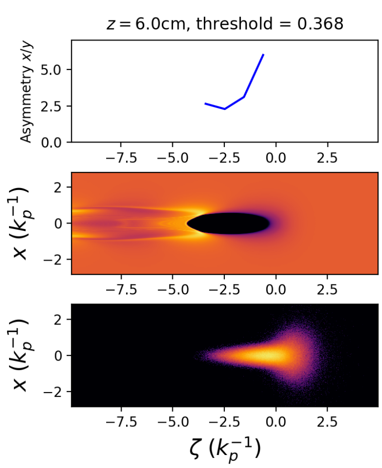

Figure 1: The blowout asymmetry is tracked at several slices along with a corresponding display of the plasma shown in top and beam as shown below. The scales are in kp^{-1} calculated using plasma density.

acceleration experiments. The main problem is for accelerating beams, which change the characteristics of the betatron radiation emitted at each moment along the acceleration path. When these betatron photons emitted from different electrons at different times are accumulated on the screen of the spectrometer, the integrated radiation spectrum can no longer be simply characterized by the single electron betatron radiation theory.

We used the Quasi-Static code QuickPIC to simulate betatron radiation. While QuickPIC and OSIRIS do not directly compute radiation, we modified it to output particle trajectories and input those trajectories into a code based on the Liénard–Wiechert code discussed in [12, 13]. Rather than compute radiation from every particle trajectory output by QuickPIC, a subset of those trajectories was randomly sampled and the result was scaled to the number of physical particles. This approach is similar to the method used to compute betatron radiation. In order to get the measure of performance of the flat beam, beam dynamics simulations were performed using Quasi-static and Osiris PIC codes.

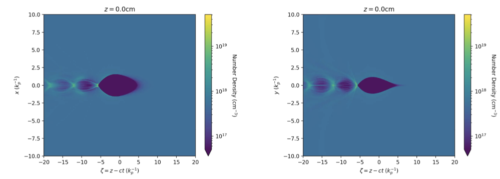

Figure 2: Plasma electron densities for the symmetric AWA case at the initial time step. Different blowouts are formed due to asymmetric beams in x and y. We notice the wide and narrow channel due to asymmetric emittances.

Table 2: Parameters for FACET-II

Parameter	Value	Unit
Beam		
Peak density, n_b/n_0	186	-
Energy, E_b	10	GeV
σ_z	20	µm
σ_x, σ_y	3.7, 0.37	µm
$\epsilon_{n,x}$, $\epsilon_{n,y}$	100, 1	řad
Plasma		
Species	H	-
Density, n_0	1.5×10^{17}	cm^{-3}
Particles per cell	4	-
Simulation		
Simulation window (x,y,z)	(10, 10, 11)	k_p^{-1}
Grid	$(2048)^2 \times 1024$	-
Timestep	2.5	ω_p^{-1}
Beam particles	3.36×10^7	-

FACET-II FLAT BEAM

Figure 3 for AWA and FACET-II show the total intensity of photons emitted during the acceleration, which is almost linearly increasing during the beam propagation. In the transverse plane, where the beam is small, the beam is completely submerged in the ion cavity and strongly focused by the linear focusing forces which are linear and stronger in this dimension. In the other plane, the beam is larger than the ion column due to the weak blowout, causing head erosion of the beam electrons outside of the blowout region. The part of the beam inside the ion column is still linearly focused, but the scaling factor of the focusing force is smaller.

Now, we extend the flat beam case to possible application at the FACET-II facility [14] (see Table 2 for simulation parameters) and explore the case where the beam density is much larger than the plasma density, $n_b \gg n_0$. The beam and strong blowout wake in this case are shown in Fig. 2 and it is significantly different from the AWA case, as the

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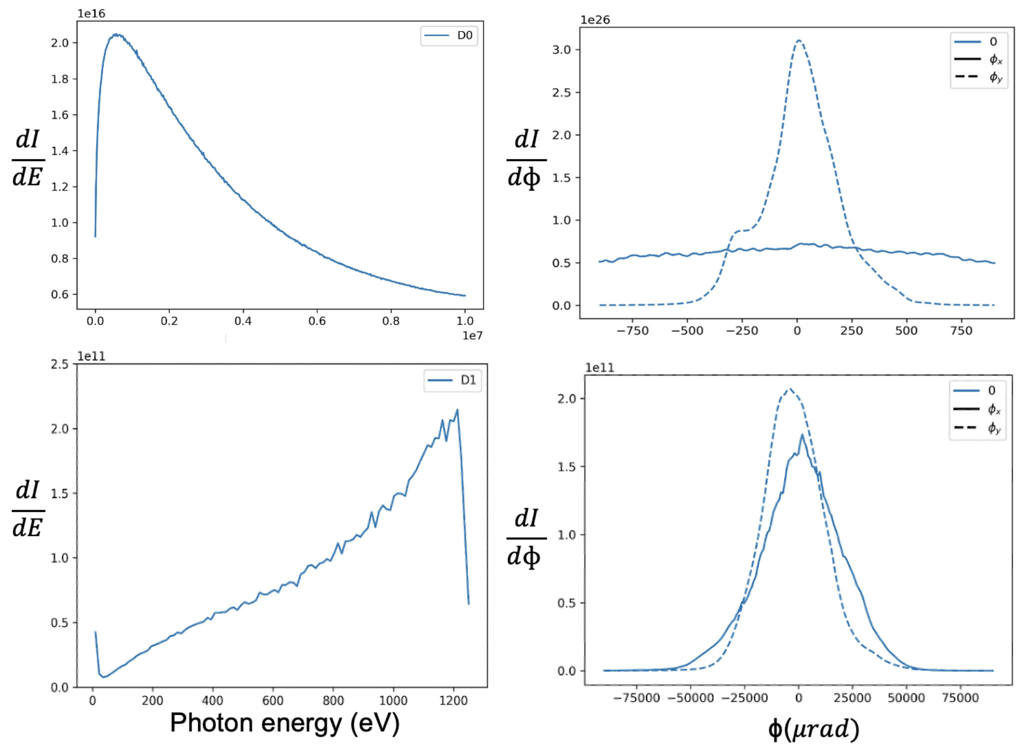

Figure 3: Betatron radition and 1D angular distribution for AWA beam using QuickPIC and LW code.

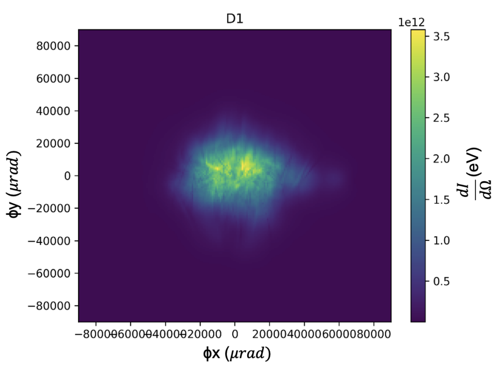

Figure 4: Double differential spectrum for the AWA flat beam. We notice the asymmetric patterns in the double differential because transverse axis have different spot sizes

wake is quite axisymmetric. This is the main reason we clearly see the difference in 1D spectrum for FACET-II case as shown in Fig. 3 and in double differential as shown in Figure 4. The plasma wake initially overlaps with the beam but gradually increases in size, reaching a maximum point in both the transverse planes. Due to the intense beam density, there is significant asymmetric ion motion [15] which would have nonlinear asymmetric effects. After the development of a system of matching equations for an asymmetric electron beam sent through plasma, QuickPIC and OSIRIS simulations were performed to check that these equations indeed result in better matching than their symmetric counterparts. Our work provides a further understanding of the betatron radiation properties in the FACET-II experiments and contributes to the study of betatron radiation diagnostics by understanding the double differential spectra, spot size in the accelerator and emittance growth.

CONCLUSION

In this paper we have discussed the physics associated with asymmetric wakes with weak blowout driven by flat beams having 100:1 transverse emittance ratio. Understanding the plasma wakefield structure corresponding to these flat beams is important as these beams are demanded for future linear collider scenarios to mitigate beamstrahlung at the interaction point. Betatron radiation is a powerful diagnostic to experimentally assess emittance growth, beam parameters, and the presence of instabilities, which are of key importance for the next generation of PWFA experiments. Lower plasma densities are also being explored to create a more suitable point to inject the witness, which should allow the validity of the matching model to more easily be seen. Experimental work will likely accelerate soon as well. With successful vacuum chamber tests and a new valve that needs testing, there is an ample supply of work to be done on the capillary discharge setup.

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