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SIMULATION STUDY OF BETATRON RADIATION FOR PERTURBED BEAMS IN PLASMA

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Abstract

Plasma wakefield acceleration (PWFA) is a method for accelerating charged particles using large electric fields sustained by plasma waves (up to hundreds of GV/m) for the accelerating longitudinal fields. In this project, we will evaluate the impact of perturbations on basic particle motion. These perturbations are affected by any number of terms of the equations of motion. The most important perturbations derive from the fact that the particle beams are not quite monochromatic, the finite spread of energies about the nominal energy. We will discuss the hosing which is a transverse instability due to perturbations. The prototypical parameter set was perturbed in several ways. The main goal of this research is to be able to diagnose the parameters of a beam from the spectral and angular distribution of the betatron radiation which encodes information about the beam-plasma interaction.

INTRODUCTION

The Betatron technique involves analyzing the radiation emitted by a beam as it undergoes betatron oscillations in the presence of a plasma wakefield. This radiation carries valuable information about the properties of the beam, such as its energy and transverse emittance, which can be used for beam and plasma diagnostics. We specifically focus on the effects of a perturbed beam on the dynamics of betatron radiation and its spectral features.

The study reveals that the critical betatron photon energy and the overall angular distribution of the emitted radiation can provide insights into the beam profile and dynamics of the witness electron bunch. However, in practical experiments, it can be challenging to separate the radiation generated from the driver and witness beams. Therefore, the analysis focuses on identifying differences in the radiation spectrum for different scenarios, which can predict the behavior of the radiation spectrum.

Furthermore, the study demonstrates that precise matching of the electron beam to the plasma ion column is challenging due to various errors in beam transportation. This mismatch can result in beam perturbations that affect the stability of plasma-based accelerators, which are crucial for transverse betatron oscillations. Even a slight tilt in the beam can coherently couple to the plasma wake, affecting the electron oscillation amplitude and leading to changes in the radiation spectrum. The study utilizes PIC (Particle-in-Cell) simulations to identify differences in the angular spectra and radiation spectrum of perturbed beams compared to unperturbed ones using models explained in [1, 2]. It perturbs the parameter sets of FACET-II PWFA experiments in various ways to identify the experimental signals using betatron radiation emitted by the witness beam. The findings of this study have the potential to improve the design and operation of PWFA experiments, ultimately advancing our understanding of plasma physics and high-energy particle acceleration.

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SIMULATION SETUP

Drive and witness separation : In Fig. 1, we notice that the separation between the driver and the witness beam affects the accelerating gradient. A separation study of 6 data sets has been done for δ varying 200 µm, 180 µm, 160 µm, 140 µm, 120 µm, 100 µm. 200 µm has the highest accelerating gradient of 10 GeV/m. When the plasma density is less in the starting, the beam decelerates to -2 GeV/m and accelerates when the plasma density increases. The spectra of radiation generated by the witness beam for a range of different separation gaps is shown in Fig. 2.

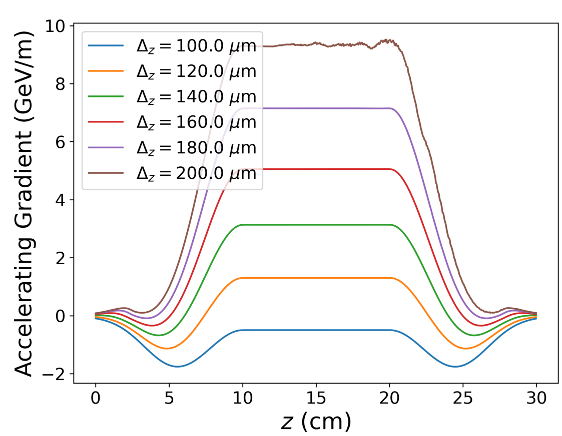

Figure 1: Separation of drive and witness beam affects the accelerating gradient of the witness beam. 200 µm has the highest accelerating gradient of 10 GeV/m.

Witness offset : The simulations in this study investigated the effects of an offset in the witness beam's x centroid on its dynamics and radiation signature. Five different values of

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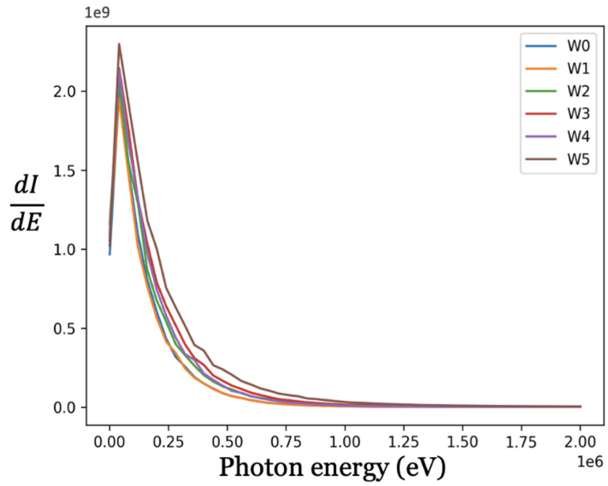

Figure 2: The spectra of radiation generated by the witness beam for a range of different separation gaps show the radiation spectrum generated by the witness beam.

Δx ranging from 0 µm to 20 µm were scanned over as shown in Fig. 3. The prototype simulation corresponds to the case where $\Delta x = 0$ µm. The results of the simulations showed that larger offsets in the witness beam's x centroid resulted in increased emittance growth and x spot size growth. Additionally, the larger offset beams experienced some charge loss, although this loss was only significant for the case with the largest offset. Surprisingly, the larger offset beams exhibited a slightly smaller energy spread compared to the prototype simulation, with the case of $\Delta x = 20$ µm showing a lower energy spread compared to the case of $\Delta x = 0$ µm.

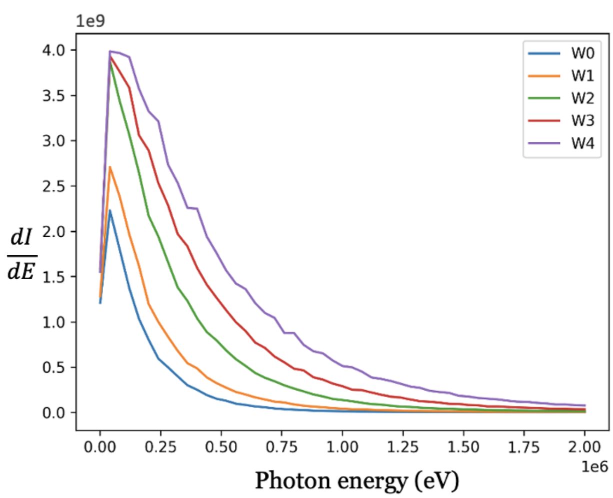

Figure 3: Radiation spectrum of drive and witness together when witness beam is offset for few different cases.

Banana beam : The study investigated the effects of different types of drive beam perturbations on the betatron radiation. This simulation aimed to investigate the effects of a beam head centroid perturbation, where A and B are coefficients controlling the displacement of the beam centroid in the x and y directions, respectively. The transverse and longitudinal sizes of the beam were given by σ_x, σ_y, and σ_z, respectively. Additionally, a non-perturbed simulation was conducted as a baseline for comparison with the perturbed simulations using the parameters shown in Table 1 and 2.

Table 1: Prototypical Parameters for a FACET-II PWFA

Parameter	Value	Unit
Plasma		
n_0	1.79×10^{16}	cm^{-3}
L_p	30	cm
Drive Beam		
Q	1.5	nC
E	10	GeV
$\sigma_{x,y}$	5	µm
σ_z	5	µm
$\epsilon_{nx,ny}$	3.2	µm
Centroid change		
$0(D0)$	$2 * real - centroid$	-
$1(D1)$	$4 * real - centroid$	-
$2(D2)$	$6 * real - centroid$	-
$3(D3)$	$8 * real - centroid$	-
$4(D4)$	$10 * real - centroid$	-
$5(D5)$	$no - change$	-

Table 2: Parameters and Total Radiated Energy for 6 Simulations for Banana Beams

Simulation	A	B	Energy Radiated(eV)
1	100	100	2.013×10^{16}
2	300	300	1.952×10^{16}
3	500	500	9.643×10^{15}
4	700	700	6.485×10^{15}
5	900	900	6.486×10^{15}
6	0	0	1.232×10^{16}

In Fig. 4, the beam centroid in x is plotted, while y is eight times the real centroid. The energies relevant for FACET-II PWFA experiments range from 1 to 20 GeV, with plasma density typically chosen near $10^{17} - 10^{18}$ cm^{-3}. The corresponding photon energies can range from a few keV to the MeV level, which must be accommodated through spectrometer and detector design. To deduce the emittance from the radiation spectrum, the amplitude distribution of critical energies is required. In Fig. 5 folder 0 has the highest change others are in decreasing order at a multiple of 0.8, 0.6, 0.4, 0.2, with no change.

The angular dependence of the spectrum is related to the beam dynamics inside the plasma. An on-axis symmetric bunch performing mismatched oscillations in the plasma will lead to betatron radiation with a much higher critical energy in the center than on the side of the photon beam. However, if the beam is matched, there will be no correlation between the angle and spectrum in the very high K_u limit. The DDS diagnostic system can provide simultaneous

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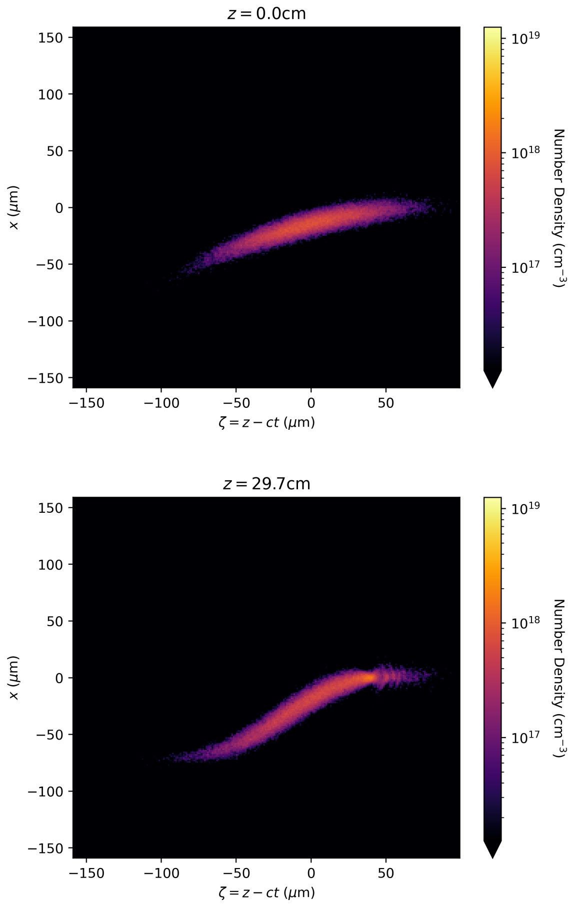

Figure 4: Eight times the real centroid in x at z=0 cm and z= 29.7 cm.

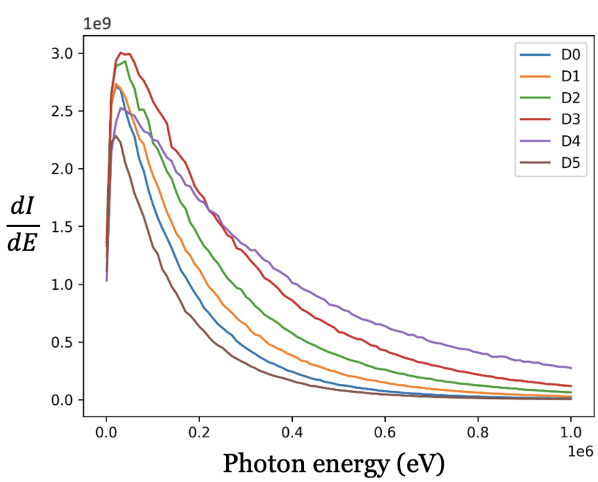

Figure 5: Synchrotron radiation spectra for banana beam for six different cases.

information regarding matching and betatron amplitudes, allowing constraints on the transverse phase space, particularly the beam emittance. If the bunch is asymmetrical and asynchronous, the x and y oscillations impact the DDS, and LW simulations are required to interpret and deduce beam parameters and phase space. The betatron radiation diagnostics could achieve this by indirectly measuring the emittance inside the plasma.

CONCLUSION

By conducting parametric scans on various beam perturbations, valuable insights can be gained into how these perturbations affect the spectral and angular distribution of betatron radiation. Previous PIC simulations have shown that betatron radiation can play a role in mitigating emittance for PWFAs. Additionally, advancements in betatron radiation diagnostics can aid in detecting beam misalignment in the transverse direction, as well as other important beam parameters. The results from these scans can contribute to a better understanding of the behavior of betatron radiation in PWFAs and pave the way for more effective diagnostics and control of beam parameters in future experiments.

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