SIMULATIONS OF POSITRON BEAMS PROPAGATING IN PLASMA

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Abstract

Studies on propagation of electron beams in plasma have shown that in the blowout regime of the plasma wakefield accelerator (PWFA), the emittance of the incoming beam is preserved because of the linear focusing force exerted by a uniform ion column [1]. However, for positron beams the focusing force is nonlinear and they suffer emittance growth. We simulated the propagation of a positron beam in the uniform plasmas with different densities. We calculated the beam emittance from the simulation results and observed the beam size and emittance grow with increasing plasma density. Simulation results agree well with that of previous work.

INTRODUCTION

The PWFA offers potential high accelerating gradient compared to traditional radio frequency accelerators. The energy doubling of 42 Gev trailing particles of an e^- beam has been achieved in an 85 cm of plasma section [2]. From the point of view of an electron-positron (e^-/e^+) collider, preservation of the beams' emittance is vital in order to reach the luminosity required for physics discovery.

For an e^- beam whose density n_b is comparable to plasma density n_p ($n_b \geq n_p$), the relatively heavy plasma ions are immobile and form a uniform ion column that exerts an ideal focusing force on the electron bunch. The focusing force varies linearly with radius (free of geometrical aberrations), and is constant along the beam propagation axis. Therefore, the emittance of electron bunch is preserved along the acceleration process. However, when a positron beam travels along a plasma, the plasma e^- are attracted toward the positron bunch. The plasma e^- flow through the e^+ bunch and their density can exceed that of the positron bunch. This creates a nonlinear focusing force that causes a growth of the positron bunch emittance. In a uniform plasma, the preservation of the positron bunch emittance is not achieved as in the e^- bunch cases.

Simulations and experiments on the propagation of an ultra-relativistic positron bunch with an energy of 28.5 GeV, traveling in 1.4 meter-long plasma with a density of 0.1-5×10^{14} cm^{-3} have been performed [3]. In that case, the incoming emittance of the positron beam in x and y directions were ε_{xN}=390×10^{-6} m-rad and ε_{yN}=80×10^{-6} m-rad, respectively. The initial beam sizes in the two traverse directions were the same at the plasma entrance: σ_x=σ_y=25 μm. The beam transverse size on a screen located approximately 1 m downstream from the plasma exit were obtained from experimental and simulation's images of the beam. Excellent agreement was found between simulation and experiment results. Simulations showed that as the positron bunch travels along the plasma, its emittance in both directions grows rapidly over the first 10 cm of plasma [3]. After the 1.4 m-long plasma, the emittances grow by a factor of 8 in the x and 38 in y directions. That is, the positron bunch exits the plasma with about the same emittance in both planes, even if the initial emittances are a factor of 4.8 different. This work also showed that a charge halo forms around the bunch core. This halo formation and the emittance growth of the positron bunch are caused by the coupling interaction between the positron bunch and the background plasma e^-, which results in a nonlinear focusing force.

The purpose of this paper is to investigate the emittance growth of a positron beam traveling in 1.4 meters plasma section with densities in the 0-2×10^{14} cm^{-3} range. Simulation results are presented.

SIMULATION RESULTS

Table 1 shows the beam and plasma parameters used in the simulations. The simulations were performed with the fully electromagnetic, and fully relativistic 3D version of the particle in cell code OSIRIS [4]. Table 2 shows the simulation parameters for the plasma density n_p=1×10^{14} cm^{-3} case. For other plasma densities, the simulation box size is scaled with $n_p^{1/2}$. The bunch emittance is calculated from the phase space of simulation particles using the rms expression:

$$\varepsilon_{xN} = \langle\gamma\rangle\left(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right)^{1/2} \qquad (1)$$

In this expression, <…> stands for the average over the simulation particles, x is the transverse coordinate, $x'=p_x/\langle p_z\rangle$ is the particle trajectory angle in the x plane, and γ is the particle relativistic factor. A similar expression was used for the y direction.

Table 1: Beam and Plasma Parameters

Parameter	Symbol	Value
Beam Energy	E (GeV)	28.5
Beam Relativistic Factor	γ	55686
Number of e^+ per Bunch	N	1.9×10^{10}
Bunch Length	σ_z (um)	720
Bunch Radius	σ_x ,σ_y (um)	25,25
Bunch Density	n_b (cm^{-3})	2.68×10^{15}
Normalized Beam Emittance	ε_{xN} (m-rad)	390×10^{-6}
	ε_{yN} (m-rad)	80×10^{-6}
Plasma density	n_p (cm^{-3})	0-2×10^{14}
Plasma Length	L (m)	1.4

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Table 2: Simulation Parameters for $n_p=1\times10^{14}$ cm^{-3}

Parameter	Symbol	Value
Simulation Box Size (c/w_p)	X	3
	Y	3
	Z	10
Grid Size(c/w_p)	dx	0.015
	dy	0.015
	dz	0.04
Number of Simulation e^+ per Bunch	N_e	1.28×10^7
Number of Plasma Particles	N_p	1.024×10^8
Number of CPU nodes	Node	64

Figure 1 shows the plasma e^- density and e^+ beam contour plot. The e^+ beam has traveled 1cm in the plasma. The plasma density is $n_p=1\times10^{14}$ cm^{-3}. The figure shows that the plasma e^- density is very non-uniform along and across the e^+ bunch and can reach values much larger that the initial plasma and bunch densities. The plasma e^- density inside the e^+ bunch determines the focusing force that is expected to be very non-linear in this case.

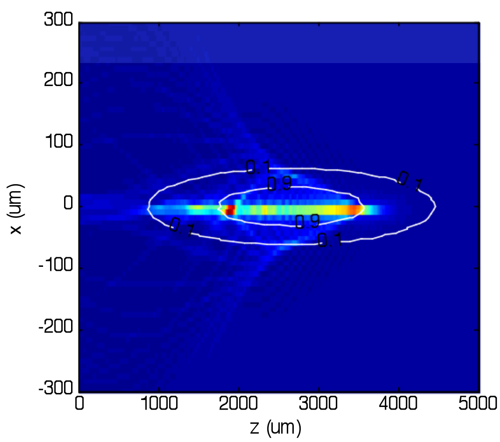

Figure 1: Plasma density and beam contour plot at z=1cm. The plasma electron density color map is normalized to the uniform plasma density n_p. The two contours show the 10% and 90% beam charge levels.

The corresponding focusing force is shown on Figure 2. The beam is centered at 0 in x direction and its range is from $-3\sigma_x$=-75um to $+3\sigma_x$=75um. The focusing force is non-linear across the whole beam transverse direction.

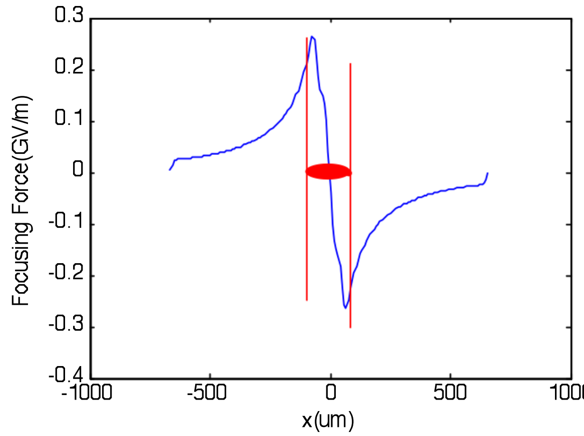

Figure 2: plasma focusing force on the e^+ beam at z=1cm for $n_p=10^{14}$ cm^{-3}, evaluated in the middle of the bunch (z=2500 μm on Fig.1).

Figure 3 shows the evolution of the positron bunch emittance in both transverse directions along the plasma. The emittances are normalized to their value at the plasma entrance. The final emittances are about a factor of 3 in x and a factor of 11 in y direction larger than at the plasma entrance.

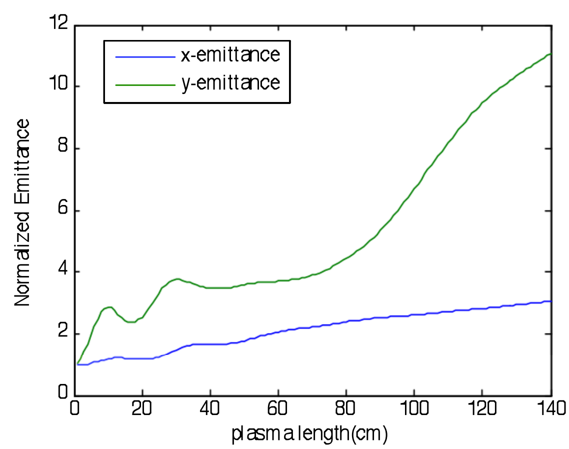

Figure 3: emittance growth of positron bunch along the plasma. The normalized emittances (see Eq. 1) are also normalized to their values at the plasma entrance.

We also investigated the emittance growth as a function of the plasma density. For these simulations, the plasma density range is from 0 to 2×10^{14} cm^{-3} with an interval of 0.25×10^{14} cm^{-3}. All the emittances are normalized to the initial emittances: 380×10^{-6} m-rad in x and 80×10^{-6} m-rad in y direction.

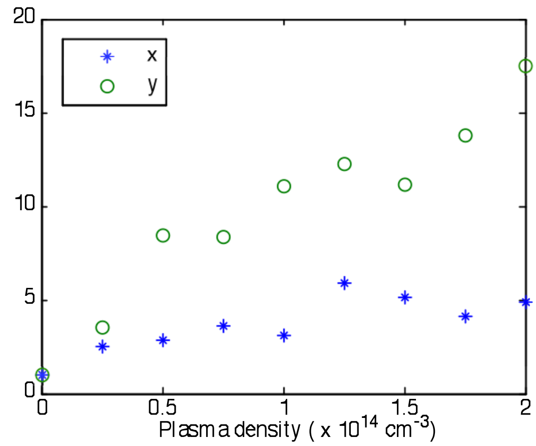

Figure 4: Emittance of the positron bunch at the end of the 1.4 m long plasma as a function of the plasma density.

Figure 4 shows that both final emittances increase with plasma density. However, the relative emittance growth is larger in the low incoming emittance y plane than in the x-plane. At a plasma density of 2×10^{14} cm^{-3}, the emittance in y direction is about 17 times larger than its initial value, but only 5 times larger in the x direction. The effect of the nonlinear plasma focusing force is therefore to bring the emittance in the two planes to similar values. It was also observed in experiments that the transverse beam sizes at the plasma exit are also essentially equal. Note that the emittances obtained in these simulations are slightly lower than those obtained in previous simulations [3]. This difference will be investigated through one to one simulations. However, the trends and main conclusions remain the same in both cases.

A possible means to minimize or suppress the emittance growth may be to use a hollow plasma channel rather than the uniform plasma that was used in the experiments and in the simulations presented here. It was already shown numerically that positron bunches propagating in hollow plasma channels drive larger accelerating fields that in uniform plasmas [5]. Future experiments and simulations will use a drive and witness bunch train (instead of a single bunch) in order for the accelerated particles (witness bunch) to exit the plasma with a narrow energy spread. In this case the hollow plasma electrons may cross the beam axis between the two bunches and therefore allow for the witness bunch to propagate in a much lower plasma electron density than in the uniform plasma described in this paper. This possibility is currently being explored in numerical simulations.

SUMMARY

We have shown from numerical simulations that the emittance growth suffered by positron bunches propagating in dense, long uniform plasma increases with plasma density. Emittance growth has to be minimized for PWFA applications to a future e^-/e^+ linear collider. We are studying means to achieve this goal.

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