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POSITRON PWFA SIMULATIONS FOR FACET*

S. J. Gessner†, E. Adli, S. Corde, J. England, J. Frederico, M. J. Hogan, S. Li, M. Litos,
T. Raubenheimer, D. Walz, Z. Wu, SLAC, Menlo Park, CA, 94025, USA
W. An, W Mori, UCLA, Los Angeles, CA, 90095, USA

Abstract

When a positively charged beam enters a plasma, plasma electrons are drawn in toward the beam axis, creating a region of extremely large charge-density with complicated, nonlinear fields. Few analytic solutions exist to describe these fields, and this necessitates the use of simulations to model positively charged beam-plasma interactions. In this paper, we study the evolution of a positron beam as an analogous model for the proton driven plasma wakefield experiment proposed by Caldwell.

INTRODUCTION

The interaction between a positively charged beam and a plasma is different than an electron beam-plasma interaction in the non-linear regime. A high charge-density electron beam will expel plasma electrons from a small region surrounding the beam. A positively charged beam will do the reverse, drawing plasma electrons into the core of the beam. This has the effect of modulating and focusing the beam. This process leads to a complicated non-linear wake structure following the beam that appears to be less favorable for accelerating a witness beam when compared to the electron driver scenario. Nevertheless, there is increased interest in a positively charged drive beam due to the availability of TeV scale proton beams at CERN [1].

The FACET accelerator test facility at SLAC gives us an opportunity to explore the dynamics of positively charged drive beams using positron bunches. The plasma wakefield acceleration (PWFA) dynamics for protons and positrons are identical if the relativistic factor γ and the plasma density n_0 are the same. Even if γ and n_0 are not the same, we can compare the two cases through appropriate scaling parameters.

SCALING RELATIONS

Protons vs. Positrons

Scaling relations are an incredibly important tool for comparing plasma wakefield acceleration (PWFA) scenarios at different plasma densities and beam energies. In this case, we seek to replicate the results from Lotov's proton simulations using a positron beam in a FACET-like plasma [2]. Specifically, we match the normalized length scales $k_p\sigma_r$ and $k_p\sigma_z$ for the proton and positron cases, where k_p is the plasma wavenumber and $\sigma_{r,z}$ are the radial and longitudinal beam dimensions of the incoming gaussian beam. The proton beam in Caldwell's proposal is notable for having an extremely small value of $k_p\sigma_z$ at 0.46 compared to the linear optimum value of $\sqrt{2}$. The maximum longitudinal bunch compression for a beam with 2×10^{10} particles at FACET is $\sim$10 μm which sets the plasma density for this positron simulation [3]. Table 1 compares the plasma and beam parameters for Lotov's proton beam simulation and our positron beam simulation.

Table 1: Beam and Plasma Parameters

Beam	n_0	γ	σ_r	σ_z
Proton	1×10^{15} cm^{-3}	1066	420 μm	100 μm
Positron	5×10^{16} cm^{-3}	40000	60 μm	14 μm

Focusing Length

In addition to matching beam length scale parameters, we also need to consider the scaling of the focusing lengths for the beam in the plasma. In Lotov's simulation, the proton beam has to propagate through meters of plasma before driving a non-linear wake. FACET plasmas are on the order of a meter long, so we need to confirm that this length is sufficient to observe the evolution of the positron beam. The appropriate scaling parameter in this case is the betatron wavelength in the plasma, given by

$$\lambda_b = 2\pi\sqrt{\frac{2\epsilon_0\gamma m_b c^2}{n_0 e^2}} \tag{1}$$

where m_b is the beam particle mass. λ_b will change as the plasma density evolves, but calculating this value at the beginning of the plasma allows us to estimate the scale of this effect. For Lotov's proton beam, $\lambda_b = 2.09$ m and for the positron beam at FACET, $\lambda_b = 4.22$ cm. This indicates that we will be able to observe driver evolution in our meter scale plasma.

Energy Depletion

The rate at which energy is depleted from positron beam is related to the decelerating field strength of the wake. The peak decelerating field in the plasma is

$$E_d = \frac{m_e c\omega_p}{e}. \tag{2}$$

The plasma frequency ω_p scales with the square root of the plasma density n_0. The plasma density at FACET is 50 times as dense as the plasma in Lotov's simulation so we expect the peak decelerating field to be $\sim$ 7 times stronger in this scenario. The calculated values are $E_d = 3$ GeV for the proton beam and $E_d = 21.5$ GeV for the positron

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† sgess@slac.stanford.edu

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beam. Positron beams produced at FACET have an energy of roughly 20 GeV when they enter the plasma, so we expect a portion of the positron beam to be depleted of almost all its energy by the time it exits a meter long plasma.

DRIVER EVOLUTION

The evolution of the positron bunch is essential for driving a strong non-linear wake in the plasma. Although the drive beam is relatively short given the plasma density, it is also very large in the radial dimension with $k_p\sigma_r = 2.52$. For a positron bunch with 2×10^{10} particles, the 1σ beam density is only half of the plasma density, which means it will not drive a strong plasma wake. However, this situation is rectified by the strong focusing of the bunch as it propagates through the first few centimeters of plasma.

Bunch Focusing

The positron bunch enters the plasma with a 3D gaussian distribution. A plasma electron at a radius of r from the core of the beam will see an integrated field of

$$E(r) = \frac{Ne}{(2\pi)^{3/2}\epsilon_0\sigma_z}\left(\frac{1-e^{-r^2/2\sigma_r^2}}{r}\right) \qquad (3)$$

as the beam passes by.

The peak value of field occurs at $r = 1.585\sigma_r$, and a plasma electron at this radius experiences an enormous focusing force of 52.9 GV/m. Even though the beam is only $\sim$ 100 fs long, the particle will move $\sim$ 40 μm during this time. This displacement strongly alters the plasma density near the core of the beam. Furthermore, this process is iterative. The increase in plasma density in the core of the beam causes the positron beam to contract in response, so that plasma electrons will experience the peak field at a position closer to the beam axis.

Note that the head of the bunch is always propagating into a neutral region of plasma, so that the process described above as iterative in time is actually iterative along the bunch length. Subsequent slices of the bunch will see a larger plasma density than the proceeding slice and therefore see a stronger focusing force. Positrons in the core and rear of the bunch will be the most tightly focused part of the beam, and will in turn drive the strong non-linear wake needed for PWFA.

The dynamic focusing of positrons has been studied previously at the E157 experiment at SLAC and aspects of the processes described above were observed [4] [5].

Head Erosion and Energy Depletion

The bunch focusing described above occurs extremely rapidly, in roughly one betatron wavelength. The subsequent beam evolution is much slower and driven by two different effects. The first process is head erosion, which is driven by the emittance of the beam. The head of the beam sees no focusing force from the plasma, so it diverges due to the angular spread of the beam. If an incoming positron beam with a normalized emittance of 50 mm mrad is focused down to a spot size of 60 μm it will diverge at an angle of 0.02 mrad. Over 1 m of plasma, the spot size will grow by 20 μm which significantly reduces the bunch density at the head of the beam. As the beam propagates further into the plasma, plasma electrons will not be as strongly focused into the core of the beam and the positron beam will defocus due to its own space charge.

The second process, energy depletion, occurs as the positron beam transfers its energy into the plasma to drive the wake. The focused tail of the beam which is driving the wake experiences a decelerating field of $\sim$ 20 GeV/m. The positron beam enters the plasma at 20 GeV so a significant portion of the beam will lose most of its energy by the time it exits a 1 m plasma.

SIMULATION

The driver evolution process described in the previous section does not easily yield an analytic description due to its iterative nature and the extremely non-linear fields it produces. However, particle-in-cell (PIC) codes have proven to be an extremely powerful and accurate tool for simulating PWFA dynamics. We use the UCLA's QuickPIC code [6] to simulate the evolution of the positron driver and the wake produced by the beam. In this simulation, $\epsilon_x = 50$ mm mrad and $\epsilon_y = 5$ mm mrad, corresponding to the ideal emittance for a FACET beam.

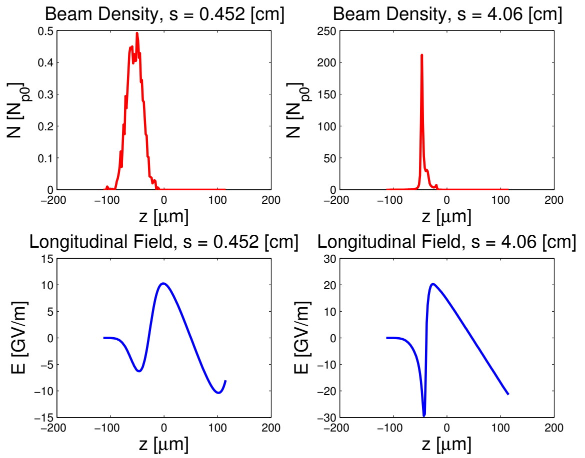

Figure 1: Evolution of bunch density and longitudinal field along the beam axis.

Results and Analysis

Figure 1 compares the bunch density and longitudinal wakefield of the beam at the entrance of the plasma and after 4.06 cm of propagation in the plasma. Full movies of the simulation are available at [7]. The drastic increase of the peak bunch density along the beam axis gives us a sense of the powerful focusing effect of the plasma. The simulation confirms the scaling hypothesis that λ_b sets the length scale of beam evolution in the plasma.

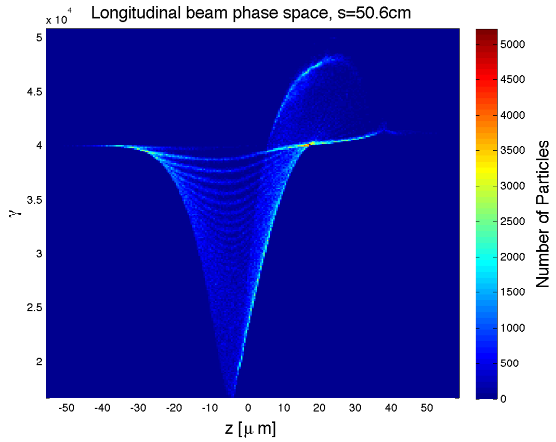

Figure 2: Longitudinal phase space of beam after 50 cm of propagation.

Figure 2 shows the longitudinal phase space of the beam after 50.6 cm of propagation in the plasma. As noted above, the portion of the beam that experiences the largest decelerating fields would be entirely depleted of its energy after 1 m of propagation through plasma. After half a meter of propagation in the plasma, the most decelerated electrons have lost more than half their energy, validating our prediction.

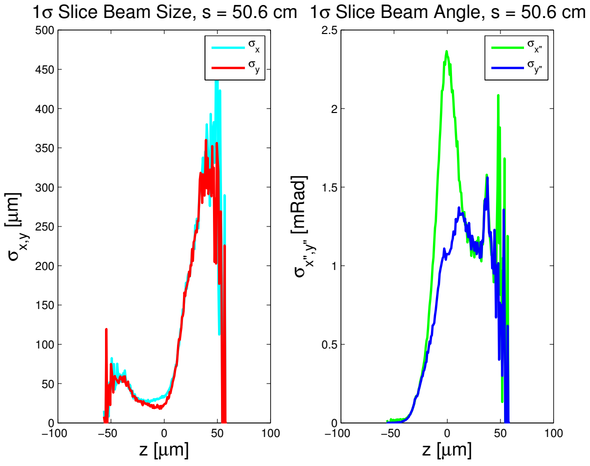

Figure 3: Slice sizes and angles after 50 cm of propagation.

Next we look at the transverse beam distributions to see the effect of strong plasma focusing on the beam. We see that in the left plot of Figure 3, the distributions in x and y have evolved similarly over the length of the plasma. We also notice the effect of head erosion near the front of the beam at $z = -50$ μm where the angular spread of the incoming bunch has caused particles near the head of the beam to drift apart.

The bunch is most strongly focused in the middle near $\sigma_z \approx 0$ μm. This is also the region where the betatron mismatch between the incoming beam and the plasma is most apparent. The over focused core of the beam develops a large angular spread. This is especially true of angular spread in x because the incoming beam emittance was larger in that dimension to begin with.

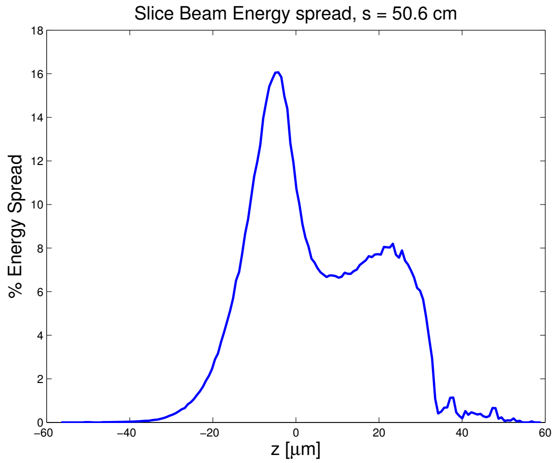

Figure 4: 1σ Energy spread of 0.7 μm beam slices after 50 cm of propagation.

The emittance of the outgoing beam is not a well defined quantity due to the large energy spread of the beam. If we attempt to calculate the normalized emittance of the beam at the exit of the plasma, we are faced with the fact that the beam no longer has a well-defined γ. We could instead calculate the slice emittance for the beam if the slice energy spread is small. However, Figure 4 shows that even when we slice the beam into sub-micron sections, there are still portions of the beam with 20% energy spread.

CONCLUSION

Simulations in QuickPIC have verified our predictions of the beam evolution of the positron driver using scaling relations. QuickPIC supplements our understanding of the beam evolution by providing a detailed picture of the evolved beam.

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