ELECTRON ACCELERATION VIA POSITRON DRIVEN PLASMA WAKEFIELD ACCELERATOR*

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Abstract

We show that a positron bunch with parameters accessible at FACET can excite a stable plasma wakefield over a few meters and a witness electron bunch experiences an accelerating gradient on the order of 10 GeV/m. Initial simulations show that the positron drive bunch is strongly affected by the transverse components of the wakefield: the positron bunch evolves significantly, which affects both the wakefield and witness bunch dynamics. Various solutions are presented, of which the positron-electron train shceme generates a desirable wakefield.

INTRODUCTION

The Large Hadron Collider (LHC) has brought high energy physics into the multi-TeV energy range. Building a lepton collider that operates at this scale would require a linear machine many kilometers-long if conventional acceleration techniques (with gradients 10-100 MeV/m) are used. The machine must be linear due to the intense radiation of highly relativistic leptons. However, if a new acceleration scheme that provides very high gradients (1-10 GeV/m) were used, the machine could be much shorter. The E-167 experiment [1] at SLAC has shown that a plasma wakefield accelerator (PWFA) can produce such high accelerating gradients. If a lepton collider is to use this technology to bring 10^{11} particles to 1 TeV (per particle), the drive bunch for the PWFA would have to carry at least 16 kJ, based on the transformer ratio measured in the E-167 experiment [2]. The proton bunches produced by the LHC contain seven times this much energy.

Accelerating electrons in a PWFA driven by a relativistic proton bunch has been shown via simulation [3], provided a proton bunch is used with $N_b = 10^{11}$ and $\sigma_{x,y,z} = 430, 430, 100\ \mu m$ in a plasma density of $n_p = 6 \times 10^{14}\ cm^{-3}$. This gives $k_p\sigma_z = 0.46$, where $k_p = c/\omega_p = c\sqrt{\frac{m_e\epsilon_0}{e^2 n_p}}$ is the plasma wavenumber and ω_p is the plasma frequency. Current σ_z values for LHC proton bunches are on the order of $12\ cm$, two orders of magnitude longer than the value used in [3]. A non-linear PWFA requires $k_p\sigma_z \leq 1$; values larger than this will lead to the longitudinal self-modulation of the bunch, an effect that has been proposed as a scheme for generating proton bunches on the $100\mu m$ scale [4]. A high-gradient PWFA experiment showcasing the proton driven PWFA will have to wait until a proton bunch on the order of a few hundred microns can be created.

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POSITRON DRIVEN PWFA

Despite the size limitation with proton bunches, relativistic positron bunches can be compressed to tens of microns at SLAC's Facility for Advanced aCcelerator Experimental Tests (FACET) and used to drive a PWFA [5]. In addition, an electron witness bunch with varaible charge and delay will also be available [6]. Given the positron's charge, these bunches can be used to simulate a proton driven PWFA and provide insight into the physics of a PWFA driven by a positively charged bunch. We study this case here using numerical simulations with beam and plasma parameters that will be achievable at FACET.

Positrons vs. Protons

The main difference between positrons and protons considered here is the relativistic gamma factor γ, which is over 1800 times larger for a positron, given the same energy. This leads to much slower de-phasing rates given by $\frac{\Delta Z}{Z} = \frac{\Delta\gamma}{\gamma^3}$, where Z, ΔZ, and $\Delta\gamma$ are total propagation distance, difference in positon and difference in γ of the bunch/wakefield, respectively. For the plasma length scale to be used at FACET ($Z \approx 1\ m$), there will be negligible dephasing for 23 GeV positron bunches. Also, the transverse properties of positron bunches will be more dynamic when compared to protons: shorter betatron period, stronger focusing/defocussing, etc.

Positron vs. Electron

Simulations with QuickPIC [7] show that a positron bunch will generate a wakefield identical to that of a proton bunch and similar to an electron bunch, up to a phase factor. Figures 1a and 1b show the plasma response from short, tri-gaussian positron ($\sigma_{x,y,z} = 50, 50, 15\ \mu m$) and electron ($\sigma_{x,y,z} = 10, 10, 50\ \mu m$) bunches, respectively. Both bunches contain $N_b = 2 \times 10^{10}$ particles and propagate in a plasma density $n_p = 1 \times 10^{16}\ cm^{-3}$. The geometry of both wakes are identical (bubble radius and length) up to a phase difference, which causes the plasma electrons to pass through the back of the positron bunch. Electron densities in this region are typically $4n_p$, which means the back of the positron bunch sees three times as much opposite charge as the electron bunch and this electron charge is non-uniform (unlike the plasma ion column for the electron bunch). This leads to changes in the transverse distribution and size of the positron drive bunch as well as a shift in the wakefield phase; these will be explored in the next section.

The axial electric fields are also similar ($\approx 10\ GV/m$; see Figure 1c); however, the focusing forces for the

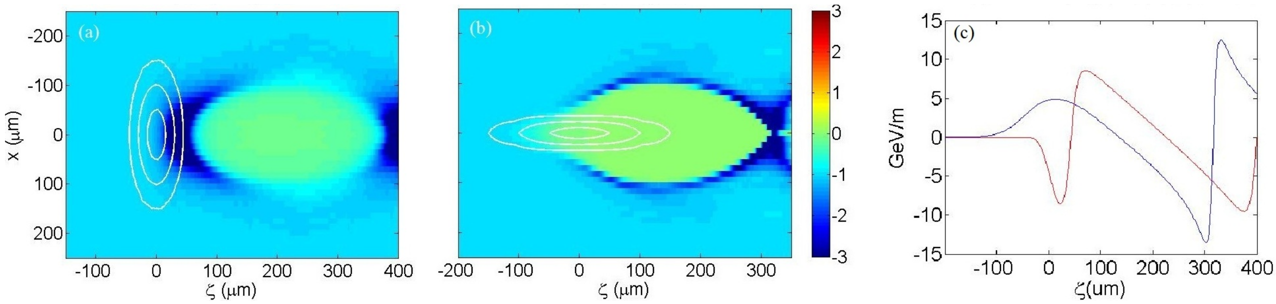

Figure 1: Positron (a) and Electron (b) PWFA Comparison. Axial electric field (c) for electron (blue) and positron (red). ζ is the axial coordinate in the moving frame (moving to the left) measured from the driver center.

positron case are non-linear, which arise from the non-uniform plasma electron density within the bubble (see Figure 1a). Unlike the electron driver, the positron drive bunch is unable to generate a wakefield in the 'blow-out' regime [8] where all plasma electrons are expelled form axis to a similar radii, producing a pure ion channel within the wakefield.

DRIVER SELF-MODULATION

After propagating for a short time ($t < 1/4\tau_\beta$, where $\tau_\beta = \frac{\sqrt{2\gamma}}{\omega_p}$ is the betatron period for an electron), the front of the positron bunch is slightly defocused whereas the tail of the bunch is strongly focused due to the influx of background electrons (see dark region behind driver in Figure 1a). The subsequent density profile is low ($.01n_b$ in the wakefield partial bubble) near the front and increases to a peak ($10n_b$) towards the back. For $t > 1/4\tau_\beta$, the driver envelope and density profile do not undergo any more significant evolution until the driver energy is depleted.

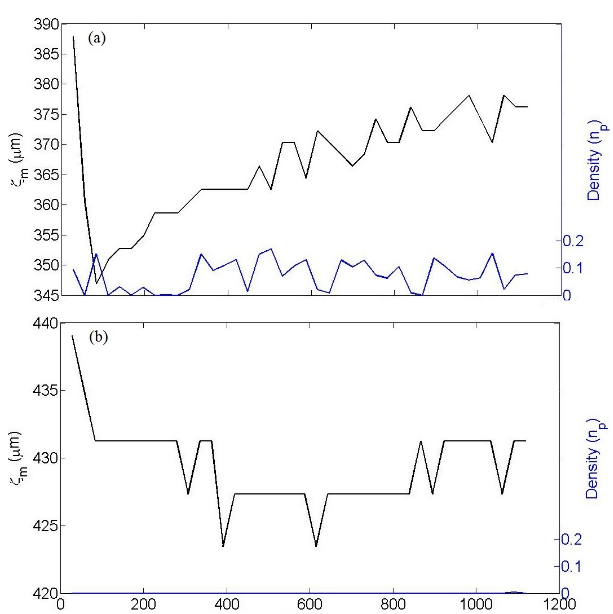

Figure 2: ζ_m (black) and minimum plasma electron density (blue) on axis within the bubble versus Z for single positron (a) and positron-electron train (b) PWFA.

Effect on Wakefield

During this evolution, the wakefield is shifted backward in ζ, resulting in the relative de-phasing of the wake to both the drive and witness bunches. The plasma electron density decreases as the evolution occurs, reaching a steady value close to zero ($\approx 3\%$ of plasma electrons remain); it does not reach blow-out. Figure 2a quantifies this effect: the position, ζ_m, of the maximum axial electric field and density on axis are plotted as functions of propagation distance into the plasma.

Effect on Witness Bunch

The witness electron bunch is loaded in a phase such that the relative de-phasing of the wake from driver self-modulation will bring the witness into the proper phase: large (GeV/m) accelerating and focusing fields present throughout the bunch. Failure to anticipate the wake evolution will leave the witness in the region of a strong defocusing field immediately behind the bubble, resulting in the loss of the witness bunch.

Since the positron driven PWFA does not reach blow-out, the witness bunch sees background electrons and creates a second wake within the first, as seen in Figure 2d of [3]. This leads to unfavorable emittance and energy spread. Ideally, the witness will sit in a blow-out regime wakefield so that these problems are minimized.

SCHEMES APPROACH BLOW-OUT

Match Driver Geometry

Shaping the driver to the geometry found after the self-modulation period requires a scheme to produce a density profile similar to the ramped bunch profile found in [9]. Also, the envelope of the bunch needs to be narrow towards the rear of the bunch and fan out towards the front (conical). This approach may result in the decrease of the evolution time by entering the plasma with a transverse profile close to that generated by the plasma; however, this will not fix

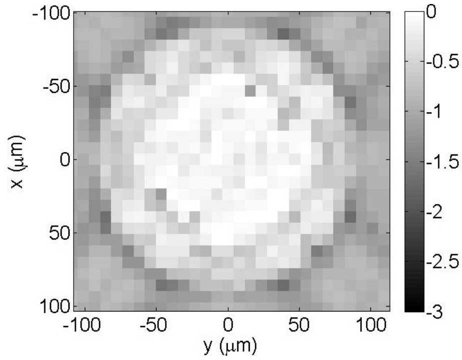

Figure 3: Transverse cross section of plasma electron density for positron train (two bunches) PWFA. Cross section taken at potential witness location.

the non-zero background electron density within the bubble.

Use a Positron Bunch Train

For the electron PWFA, it has been shown in both the linear [10] and non-linear [11] case that a train of bunches can increase transformer ratio. In both cases, the N^{th} electron bunch is placed in the front of the N^{th} bubble (e.g. $N * \lambda_p$ for the linear case). This phase allows the N^{th} bunch to transfer energy to the wake and for the non-linear case, sustain blow-out. In the positron case, this scheme works in the linear regime; however, preliminary simulations in the non-linear regime ($N = 2$, $n_b/n_p = 3.4$) show that the background plasma density becomes transversely non-uniform (Figure 3).

Use an Electron 'Sweeper'

Another possibility is to follow the positron driver with an electron bunch that acts as a 'sweeper' to remove background electrons. For the positron PWFA simulated in Figure 1, an electron bunch $N_b = 1e10$, $\sigma_{x,y,z}$=12,12,15μ m) is placed at ζ=130μm. The positron driver still evolves; however, the wakefield evolution is mitigated by the electron sweeper. This can be seen in the relatively small changes in ζ_m seen in Figure 2b. Blow-out is reached in this case, although this condition is not stable after about one meter due to evolution of the sweeper (small increase in density in same figure). A electron bunch can then be loaded and witness a pure ion column (Figure4).

CONSIDERATIONS

Of these three schemes, the electron 'sweeper' method is the only one to push the positron PWFA into the blow-out regime. This requires injecting each bunch individually or injecting one long electron bunch after the positron bunch and using a method (e.g. a mask [12]) to create the sweeper and witness from the single electron bunch.

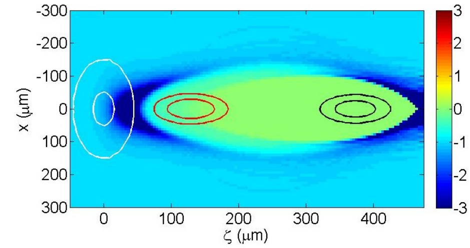

Figure 4: Plasma response and bunch train for 'sweeper' method.

For the proton driven PWFA, the proposed propagation distance is on the order of 100m [3]. A high energy electron bunch ($\approx 10\ GeV$ conventionally accelerated) to be used as a sweeper must sit in a phase with a decelerating gradient of magnitude less than $\approx 1\ GeV/m$, else it will be depleted before the end of the plasma. Unfortunately, the sweeper in Figure 4 sees a gradient of $-5.7\ GeV/m$, but this is for a plasma density of $10^{16}\ cm^{-3}$. If this field is proportional to the wave breaking field, $E_{wb} = c\sqrt{\frac{n_p m_e}{\epsilon_0}}$, then reducing the plasma density to $6 \times 10^{14}\ cm^{-3}$ would reduce this gradient to $\approx 1.4\ GeV/m$. If the sweeper method is to be used, the phase at which it is placed as well as the plasma density must be optimized in order to make this decelerating gradient low enough such that the bunch is not lost before the end of the plasma.

CONCLUSIONSIONS

We have studied the acceleration of a witness electron bunch on the wake driven by positron bunch with beam and plasma parameters that will be achievable at SLAC FACET. It appears that the parameters are suitable to study some aspects of the physics of the acceleration process.

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