

Acceleration and Focusing of Electrons and Positrons Using a 30 GeV Drive Beam

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Abstract. A series of plasma wakefield acceleration (PWFA) experiments are being conducted with a 30 GeV drive beam from the Stanford Linear Accelerator Center (SLAC). These experiments continue to address the application of meter-scale plasmas to focus and accelerate electrons and positrons in the context of future applications to high-energy accelerators.

INTRODUCTION

Extraordinarily high fields are generated in beam plasma interactions. Accelerating fields as high as 100 GeV/m [1] and focusing gradients larger than 1 MT/m [2] have been observed. These high fields have only been sustained over mm scale distances however, and many questions remain as to the applicability of plasmas to high-energy accelerators and colliders. A university-national laboratory collaboration is addressing some of these questions via an ongoing series of experiments at the Final Focus Test Beam (FFTB) facility at the Stanford Linear Accelerator Center (SLAC). Experiment E-157 [3] was the first experiment to study Plasma Wakefield Acceleration (PWFA) of electrons over meter scale distances. The physics for positron beam drivers is qualitatively different (flow-in vs. blow-out regimes). Substantial changes to the experimental hardware based on experience from E-157, as well as the desire to study the physics of positron beam drivers led to experiment E-162. Finally, the opportunity for dramatically shorter bunches, and correspondingly higher accelerating gradients (>GeV/m), led to experiment E-164, scheduled to begin running in April 2003.

In the PWFA, the space charge fields of a relativistic particle bunch exert a radial force on the electrons of a neutral plasma and drive a large amplitude plasma wake at the electron plasma frequency $\omega_{pe} = (n_e e^2 / \epsilon_0 m_e)^{1/2}$ where n_e is the plasma electron density, e and m_e are the electron charge and rest mass, and ϵ_0 is the vacuum permeability. The radial component of the wake focuses or defocuses the particle

bunch and the longitudinal component de-accelerates or accelerates particles in the bunch. The experiments at SLAC are conducted using a single bunch, and the plasma acts as an energy transformer, taking energy from the particles in the head of the bunch that drive the plasma wake, and transferring this energy to particles in the tail of the same bunch.

In the linear theory, valid when the beam density, n_b , is larger than the plasma density n_e , the amplitude of the longitudinal electric field is given by [4]:

$$eE_z = 240(\text{MeV}/m) \left(\frac{N}{4 \times 10^{10}} \right) \left(\frac{0.6\text{mm}}{\sigma_z} \right)^2 \quad (1)$$

where N is the number of particles in the drive bunch and σ_z is the root mean square (r.m.s.) bunch length of the Gaussian bunch. The maximum gradient is obtained when the plasma wavelength is roughly equal to the drive bunch length:

$$\lambda_{pe} = \frac{2\pi c}{\omega_{pe}} \approx 4\sigma_z \quad (2)$$

For parameters typical delivered to the SLAC FFTB (see Table 1), accelerating gradients greater than 100 MeV/m can be achieved. Equation 1 also illustrates one of the most attractive features of the PWFA – the scaling of accelerating gradient with the inverse square of the longitudinal bunch length: $eE_z \propto 1/\sigma_z^2$.

The experiments discussed in this paper are conducted in a regime where the beam density, n_b , is larger than the plasma density n_e . The head of the bunch expels all of the plasma electrons from the bunch volume leaving a pure ion column for the remainder of the bunch, giving rise to the name “blow-out regime”. In this regime the wakefields become highly non-linear with a non-sinusoidal or spiky amplitude structure. Although the wakefield scaling given in Equation 1 is not strictly valid in this regime, simulation with 2-D and 3-D particle in cell (PIC) simulations have indicated that the peak on access accelerating field roughly follows this dependence well into the non-linear regime. Quantifying the wakefield amplitude dependence on bunch length, for a fixed charge and appropriate plasma density (see Equation 2) is one of the primary goals of these experiments.

The transverse behavior of the bunch will be dominated by the combined drive-bunch and ion column electric fields. For the portion of the beam in blow-out, the ion column acts as a geometric-aberration free lens with a radial electric field given by:

$$E_r(r) = \frac{1}{2} \frac{n_e e}{\epsilon_0} r \quad (3)$$

where r is the radius from the center of the ion column.

EXPERIMENTAL LAYOUT AT THE SLAC FFTB

The experimental layout is shown in Figure 1 and discussed briefly below.

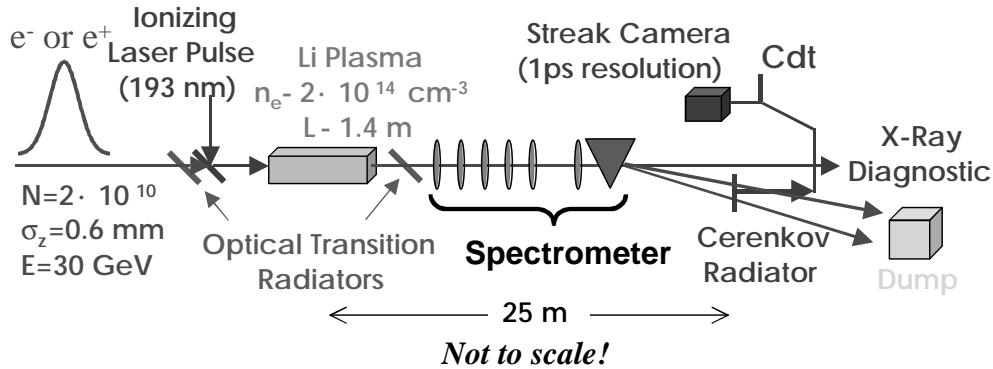


FIGURE 1. Experimental layout of the PWFA experiments at the SLAC FFTB.

A beam (electrons or positrons) of parameters given in Table 1 is propagated down the 3km long SLAC linac into the FFTB beamline where it is focused down at the entrance of the plasma. The plasma is created by single photon ionization of lithium vapor created in a heat-pipe oven. The ionization laser is coupled into the lithium vapor by a 45° pellicle mirror made of $150\mu\text{m}$ thick fused-silica with a high-reflectivity coating for the 193nm ultra-violet (UV) laser pulse. By controlling both the position the laser hits the pellicles, and the subsequent angle of the pellicle, the laser (and thus the plasma) can be aligned to the drive beam trajectory. Changing the amount of energy in the UV laser pulse changes the plasma density. Thin titanium foils ($37\mu\text{m}$) upstream and downstream of the plasma provide optical transition radiation (OTR) that is used to monitor the beam transverse profile before and after the plasma with a resolution of typically $2\text{-}9\mu\text{m}$. Beginning in experiment E-162, the plasma source was moved to the focal point of the FFTB. This new location provided quadrupole magnets downstream of the plasma source, that are used in conjunction with the dipole magnets, to form an imaging magnetic energy spectrometer. The spectrometer images the beam at the plasma entrance or exit onto a 1mm thick piece of aerogel some 25 meters downstream. The imaging condition allows differentiation of the transverse effects (focusing & deflection) from the longitudinal effects (energy loss & gain). When the imaged beam passes through the aerogel it emits Cherenkov radiation that is used to form both a time-integrated image of the beam as well as a streak camera generated time resolved image with 1ps resolution. The dipole magnet disperses the beam according to energy in the vertical direction such that particles with more energy end up high and particles with less energy end up low. The Cherenkov system has an energy resolution of $\sim 30\text{MeV}$ and a time resolution of $\sim 1\text{ps}$. Finally the suite of standard FFTB beam instrumentation (BPM's, torroids, ADC's) is combined with the OTR's and the Cherenkov system to characterize the beam, before and after the plasma, on a single pulse basis.

TABLE 1. Typical beam and plasma parameters delivered for E-162 and predicted for E-164.

Parameter	Symbol	Value (E-162/E-164)
Beam Energy	E	28.5 GeV
Relativistic Factor	γ	55686
Number of Particles per Bunch	N	2×10^{10}
Bunch Length	σ_z	650 μm /100 μm
Bunch Radius at Plasma Entrance	σ_r	25 μm
Plasma Density	n_e	$< 2 \times 10^{14} \text{ e}^-/\text{cm}^3$
Plasma Length	L	1.4m/30cm

EXPERIMENTAL RESULTS WITH ELECTRONS

Beam Focusing / Plasma Lens Effect

As stated in the introduction, we operate in a regime where the beam density is greater than the plasma density. Consequently, the front half of the beam blows out all of the plasma electrons leaving behind an ion column that focuses the back half of the bunch. The ion column is a near-ideal lens with no geometric aberrations (although it still has chromatic) and a focusing force that is constant along the back half of the bunch. For beam parameters in Table 1, the maximum focusing gradient is on the order of 4,000 T/m at the beam radius. For comparison, the maximum focusing gradient of the final focus quadrupoles in the FFTB is on the order of 0.1 T/m. The focal length of the plasma is shorter than the length of the plasma for densities well below the maximum, resulting in multiple foci within the plasma. Although the beam size cannot be measured in the plasma, an equivalent measurement is made by measuring the spot size at the downstream (DS) OTR as a function of plasma density. The measurements are in good agreement with a simple beam envelope model that treats the plasma as a thick quadrupole that focuses in both planes [5]. The electrons in the head of the bunch, that expel the plasma electrons, experience a focusing force that is both weaker than the blow-out value, but also is evolving along the length of the bunch as more and more plasma electrons are blown out. This time dependent focusing has also been found to be in good agreement with theoretical and numerical models [6].

X-ray Emission

As the electrons undergo betatron oscillations, the strong focusing coupled with an ultra-relativistic beam results in synchrotron radiation in the X-ray spectrum from 5-30 keV. Such radiation has been observed previously, at longer wavelengths and when there were enough oscillations for the particles to begin to act coherently, and was referred to as the ion channel laser (ICL) [7]. In our experiments the number of oscillations is small and the radiation is in the spontaneous regime where the total radiated power scales as the square of the plasma density. The X-rays are emitted in a narrow cone in the forward direction with a high brightness [8].

Beam Steering/Refraction

As mentioned in the experimental layout section, the beam and plasma are made to be co-linear by steering the ionization laser on to and off of the upstream UV pellicle. As long as the electron beam is within the UV laser (and thus the plasma column) for the entire length of the plasma, the focusing forces will be axis-symmetric with no net steering force. If the plasma and the electron bunch are not aligned, when the electron bunch approaches the edge of the plasma column, the focusing force will no longer be axis-symmetric due to the lack of plasma electrons on the non-ionized vapor side, resulting in a net deflection of the trailing particles back towards the plasma. This beam steering phenomena can be modeled in analogy with the refraction of light crossing a boundary from a medium with a relatively higher index of refraction to a medium with a relatively lower index of refraction. This phenomena is illustrative of the power of collective behavior – a particle beam capable of burning a hole through solid steel, can be made to bounce off an interface between a low-pressure gas and a plasma where the electrons can act collectively. A non-linear Snell's law has been derived that models the qualitative behavior and is in good agreement with estimates from PIC codes [9]. At shallow angles, the bunch undergoes total internal reflection within the plasma and the angle of deflection is equal to the angle of incidence. At larger angles, the beam breaks through the surface with a deflection angle eventually dropping to zero for normal incidence to the boundary.

De-Acceleration/Acceleration

For the single bunch case studied in these experiments, the particles in the head of the bunch that do work on the plasma and blow-out the plasma electrons will lose energy. When the blown-out plasma electrons rush back in one plasma period later, they in turn do work on the particles in the bunch tail causing them to gain energy provided the condition stated in Equation 2 is satisfied. The maximum expected energy gain is given by Equation 1.

In E-157, the beam exited the plasma and drifted 12 meters to the Cherenkov with no magnetic focusing, just the dipole magnet providing energy dispersion. The magnetic center of the plasma-lens is defined by the head of the bunch that blows out the plasma electrons. If the bunch enters the plasma with a tilt (radial-longitudinal correlation), the back half of the bunch will not be at the magnetic center and thus will experience, in addition to the strong focusing forces, a strong dipole force resulting in a kick when the beam exits the plasma. Coupled with a 12 meter drift, deflection angles on the order of 10 μ rad could produce offsets equivalent to 30 MeV of energy change and made isolation of the energy gain (acceleration) signal difficult.

E-162 removed this problem by relocating the experiment upstream such that there were now quadrupoles downstream of the plasma that could be combined with the dipole to form an imaging magnetic energy spectrometer. The imaging condition ensures that the beam size in the dispersed (or energy) plane at the Cherenkov is independent of the beam deflection at the exit of the plasma. Preliminary analysis shows un-ambiguous de-acceleration (energy loss) of the beam core and acceleration (energy gain) of the beam tail with gradients in excess of 100MeV/m [10]. Although

these gradients are somewhat smaller than those predicted by PIC simulations of the experiment, recent attempts to include both non-ideal beam and plasma conditions as well as diagnostic effects in the simulations, have indicated that such “real world” factors can account for up to a factor of two difference [11].

EXPERIMENTAL RESULTS WITH POSITRONS

Although the physical mechanisms of the PWFA are fundamentally different for positron beams (flow-in) as compared to electron beams (blow-out), many of the behaviors are similar. Specifically, the PWFA can operate with a positron drive beam and can again both focus and accelerate particles [12].

Focusing

Unlike the electron beam driven PWFA, the positron beam driven PWFA does not blow-out the plasma electrons, rather it sucks them in. The focusing force in the blow-out regime is limited to the ion column density which equals the ambient plasma density. Once all the plasma electrons have been blown out, the focusing force will remain linear in r and constant in z until the plasma electrons come rushing back in one plasma period later. In contrast, a positron beam may suck in plasma electrons from out to one skin-depth resulting in plasma electron densities (and corresponding focusing forces) orders of magnitude stronger than for the blow-out case. Although the stronger forces are in principle attractive, the forces are aberrated as they continually vary in z and do not necessarily vary linearly in r . Preliminary analysis of the data indicates that indeed, for a given plasma density, the focusing forces on the positron beam are much stronger than for an electron beam. The aberrations in the focusing result in initially Gaussian transverse profiles developing a tightly focused core with a set of not as well focused wings in the distribution. At higher densities, the strong longitudinal variation in focusing will result in phase mixing and emittance dilution. The longitudinal variation in focusing has been observed, but unlike in the blow-out regime, there is no simple analytic model as yet, and we must rely on comparison with simulations. Quantifying the emittance dilution as well as trying to preserve it through techniques such as hollow channel plasmas are areas of active inquiry [13].

Again, in analogy to the electron beam driven case, a positron beam will drive a space charge oscillation in the plasma density causing periodic regions of net longitudinal accelerating and de-accelerating fields. Simulations indicate that in contrast to electron beam driven wakes that scale roughly as Equation 1, positron beam driven wakes are smaller. In the electron bunch case, the plasma electrons tend to converge near a single point in space and time behind the drive bunch, resulting in a large spike in accelerating field. For the positron beam driven case, the plasma electrons that are sucked in arrive at different points in space and time. This phase mixing of arrival times prevents the spike from developing. By creating a hollow channel plasma, such that there is a tube of neutral vapor surrounded by plasma, some of the phase mixing can be eliminated and a partial spike can be developed. PIC simulations suggest that this spike may be optimized when the radius of the hollow

channel has a radius of one c/ω_p . Some experimental data has been taken with a partial hollow channel, but it is still under analysis.

De-Acceleration

Just as in the case of an electron bunch driven PWFA, with a positron bunch, a portion of the bunch must do work on the plasma and lose energy in the process. While experimental data has been taken to look for both energy gain (acceleration) and energy loss (de-acceleration) of a positron beam, it is in the initial stages of analysis. Energy loss is typically the more robust observable since it happens in the core of the bunch where there is the most charge. As an initial attempt to quantify the energy loss, the energy of the core of the positron beam, as measured in a one ps wide slice at the streak camera, was compared on a pulse to pulse basis with the beam energy as measured by a beam position monitor (BPM) in a region of high dispersion prior to the plasma. Preliminary analysis shows the effects of shot-to-shot energy jitter in the linac reproduced on both diagnostics, but the Cherenkov measurement (after the plasma) shows a clear trend of energy loss, peaking at around 75 MeV for a plasma density of $2 \times 10^{14} \text{ e}^-/\text{cm}^3$ and a length of 1.4 m.

FUTURE DIRECTIONS AND UPCOMING EXPERIMENTS

During the SLAC Summer shutdown in 2002, a magnetic chicane is being installed at the 1km point of the linac with the goal of compressing the bunch from the current length of $650 \mu\text{m}$ to a minimum of $12 \mu\text{m}$ [14]. The compression will be done in two stages. The first will utilize an energy chirp put in the beam and the magnetic chicane to compress the beam to a minimum of $50 \mu\text{m}$. After leaving the chicane, the strong longitudinal wakefields created by the short bunch will, over the next 2km, add an additional correlated energy chirp to the beam. The dogleg bend at the entrance to the FFTB will use this additional chirp to compress the beam down to the predicted minimum of $12 \mu\text{m}$.

The availability of dramatically shorter bunches combined with the scaling suggested by Equation 1 led to Experiment E-164. E-164 plans to utilize $100 \mu\text{m}$ long bunches to measure accelerating gradients in excess of 1 GeV/m. To keep the total energy spread on the beam within the acceptance of the FFTB dump line, the plasma length is being shortened to 30 cm from the previous 1.4 m. In addition to such impressive accelerating gradients, E-164 will add an additional data point to the $eE_z \propto 1/\sigma_z^2$ curve, which is essential to understanding the ultimate limits of the PWFA. The first experiment with $100 \mu\text{m}$ bunches is scheduled to begin in April 2003.

SUMMARY AND CONCLUSIONS

PWFA experiments E-157 and E-162 have observed a wide range of phenomena using both 30 GeV electron and positron drive beams, specifically:

- Focusing of electron beams and stable propagation through an extended plasma column.
- Focusing of positron beams.
- Electron beam deflection analogous to refraction at the neutral gas-plasma boundary.
- X-ray generation due to betatron motion in the blow-out plasma ion column.
- Energy loss in the core and energy gain in the tail (> 100 MeV/m) over 1.4 m.
- Energy loss of the core of a positron beam on the order of 75 MeV over 1.4m.

However, there is still much to do before PWFA's can be considered for application to future high-energy accelerators:

- Quantify the bunch length scaling for accelerating field ($eE_z \propto 1/\sigma_z^2$?). Experiment E-164 beginning in April 2003 will add a crucial data point in this area.
- Plasma source development: higher densities ($>10^{16}$ e⁻/cm³) over extended lengths (> 1 m) and hollow channel plasmas for positrons.
- Continued robustness against instabilities such as electron hose.
- Loading of the plasma wake for acceleration with narrow energy spread and high extraction efficiency.

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