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Plasma Wakefield Acceleration of a Positron Beam

Proposal for an Extension of Experiment E-157

Experimenters

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Introduction

SLAC experiment E-157 is a study of plasma wakefield acceleration. The experiment was proposed and approved in 1997 with the goal of measuring acceleration by an electron beam-driven plasma wave. This is a proposal to extend these measurements to a positron beam-driven plasma wave where the physics is qualitatively different. There are strong motivations for proposing this extension

- The study of positron wakefield acceleration is a unique scientific opportunity.
- The E-157 apparatus is complete and performing as designed.
- The SLAC schedule is such that the experiment could be performed this Fall.

E-157 is performed in the SLAC FFTB. The present experiment is designed to have a 30 GeV electron beam with 4×10^{10} particles and a bunch length σ_z = 2 ps. This beam is incident on a 1.4 m long Li plasma with a density ~ 4×10^{14} cm^{-3} produced by laser ionization of a neutral Li vapor. The front of the bunch excites a plasma wave, and the plasma electrons in the underdense plasma are blown-out of the beam core. Roughly one plasma period later they rush back into the beam and accelerate particles in the tail of the bunch.

Physics Motivation

If plasma based accelerators are to have any relevance to future colliders one has to show high gradient acceleration of positrons as well as electrons. The dynamics of a positron beam in a plasma can be studied only at SLAC, and the proposed extension is a unique and timely opportunity.

There is no experimental data on wakes generated by intense positron beams in a plasma that could be used for accelerating charged particles. The physical mechanism behind generating such wakes with positrons is different than with electrons. In the regime of linear wakefield theory, the wavelengths and amplitudes of wakes from positron and electron beams are identical, but when the beam density is larger than the plasma density, linear theory has broken down and there is an asymmetry between the electron and positron cases. In the electron case the beam electrons blow out the plasma electrons whereas in the positron case the plasma electrons are sucked in.

For the positron beam parameters available at the FFTB, $N^+ \sim 2\times10^{10}$, $\sigma_z \sim 0.63$ mm (2 ps), $\sigma_r \sim 50$ μm, and a plasma density of 2×10^{14} cm^{-3} the bunch density is larger than the plasma density, i.e. in the so-called "underdense" regime. The plasma electrons are sucked in and then relax back out in a controlled manner leading to a linear wakefield that is in contrast to an electron beam where plasma electrons are completely blown-out and generate a large, highly

non-linear wakefield on their return. Consequently, the wakes are not in the grossly nonlinear regime and the peak accelerating gradients and the transformer ratio are both considerably lower.

Figure 1 shows the results of a simulation (which is not optimized for maximum gradients) with the NOVO code for a positron beam with the above mentioned parameters. The peak accelerating gradient is about 170 MeV/m whereas the peak decelerating gradient is about 145 MeV/m. In 1.4 m length of our oven we expect to see energy gains of up to 238 MeV for positrons in the latter half of the positron bunch. Such energy gains are easily detectable with our detection system. At higher densities 6×10^{14} cm^{-3}, the positron beam is expected to break up into two pieces longitudinally as the positrons sample different parts of a shorter wavelength wakefield. This should give us a clear signature on our streak camera diagnostic and help compare the experiment with theory.

Finally, if these experiments are successful they will be a prelude to acceleration of a witness positron bunch in a much more intense wake produced by an electron bunch.

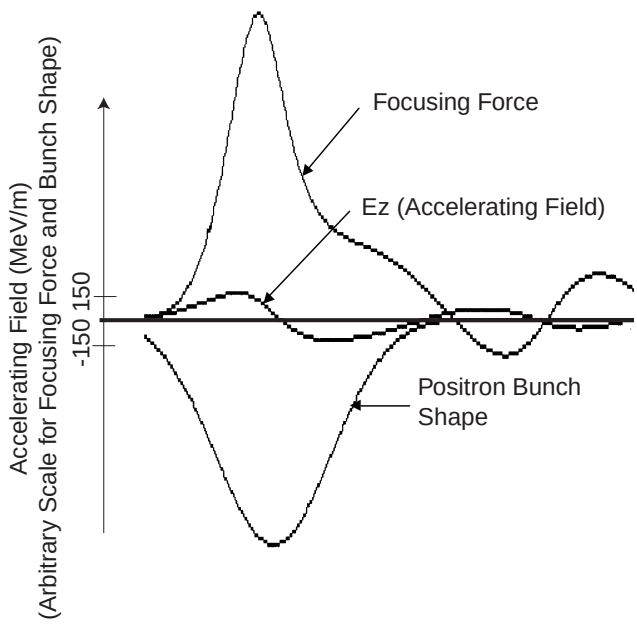

Figure 1: Accelerating field and focusing force for a positron beam with N ~ 2×10^{10} , σ_z ~ 0.63 mm, σ_r ~ 50 μm, and a plasma density of 2×10^{14} cm^{-3}

Proposed E-157 Extension

The third E-157 run with electrons is scheduled for August 16 through September 6. We anticipate that the experiment described in the original proposal will be completed at the end of that run.

With this proposal we are requesting two more three week long runs for studying positron-driven plasma waves. There are radiation safety issues that need to be resolved before the FFTB can be switched to positrons, and we would like to expeditiously analyze and publish some of the results from our running with electron beams. Given these issues and preferences

and given the tentative SLAC schedule that has a two-week long shutdown in October, we would like to have these two runs scheduled after the October shutdown and before the shutdown for the winter holidays.

E-157 Experimental Apparatus

A 1.4 m long Li heat pipe oven, installed at IP1 of the FFTB, produces a Li vapor with a density $\rho_0 \sim 3\times10^{15}$ cm^{-3}. The vapor is contained by a He buffer gas and thin Be windows. The plasma is produced by ionizing the vapor with a 193 nm ArF excimer laser located nearby. The laser is injected into and extracted from the plasma by thin pellicles that are also traversed by the electron beam. Roughly 15% of the vapor is ionized. The plasma recombination time is 15 μs, and varying the time between the laser pulse and electron beam provides a convenient control of plasma density. The initial plasma density is measured by means of the incident UV energy on a shot-by-shot basis.

The pellicles provide another key feature of the experiment. One side is coated with a multi-layer UV reflector, and the other side is coated with Al. Transition radiation from the electron beam passing through the Al is detected both upstream and downstream of the plasma. This transition radiation allows us to align the electron and laser beams by viewing the transition radiation and UV fluorescence with common TV cameras. In addition, the upstream transition radiator allows monitoring of the incident electron beam profile and gives the information needed for measuring and removing beam tails. The downstream transition radiator allows study of plasma focusing by beam size measurement after the plasma.

The plasma is followed almost immediately by the FFTB permanent magnet dump which introduces energy dispersion in the vertical. An aerogel Cerenkov radiator with index of refraction n = 1.009 is located after the dump magnets. The dispersion at the aerogel is $\eta_y = 100$ mm. Light from this radiator is transported out of the FFTB tunnel to an optical table where the time integrated spot size and the time dispersed vertical profile are measured. The latter is done with a streak camera, and the time dispersed vertical profile gives the energy distribution of the beam with 1 ps time resolution. This time resolved energy measurement is the key to studying the energy changes within the bunch.

Data is acquired with shot-by-shot correlations. The upstream and downstream OTR images, the time integrated Cerenkov image, the streak camera image, and laser and beam data are acquired on each shot, and information from these different diagnostics can be combined for filtering and sorting of data

Preliminary E-157 Results

There have been two E-157 runs. The first was about two weeks long and was devoted to developing data acquisition procedures, diagnostics, and necessary techniques such as alignment of the various optical systems. Large transverse effects caused by beam-plasma interactions were observed.

The major change from the first to the second run is that the ionization laser was moved into the FFTB tunnel to increase the laser fluence by reducing losses and by simplifing the laser beam transport. A substantial portion of the second run was spent improving data acquisition, diagnostics, and experimental techniques. Towards the end of the run we had perfected the crucial technique of aligning the laser and electron beams and had convinced ourselves that the various images, the laser data, and the beam data were properly correlated.

The laser beam - electron beam alignment was found to be the factor that determined whether we observed large, dramatic transverse effects or relatively benign ones. When the beams are misaligned, large deflections and distortions of the electron beam are measured. In

fact, it is striking what this 1.4 m long plasma can do to a 30 GeV electron beam. However, when the beams are aligned, there is only modest changes in rms sizes and there is virtually no beam deflection. This is illustrated in Figure 2 which shows successive time integrated Cerenkov images when the laser alternately fires ~1 μs before (labeled "plasma on") and ~2.5 μs after ("plasma off") the electron beam.

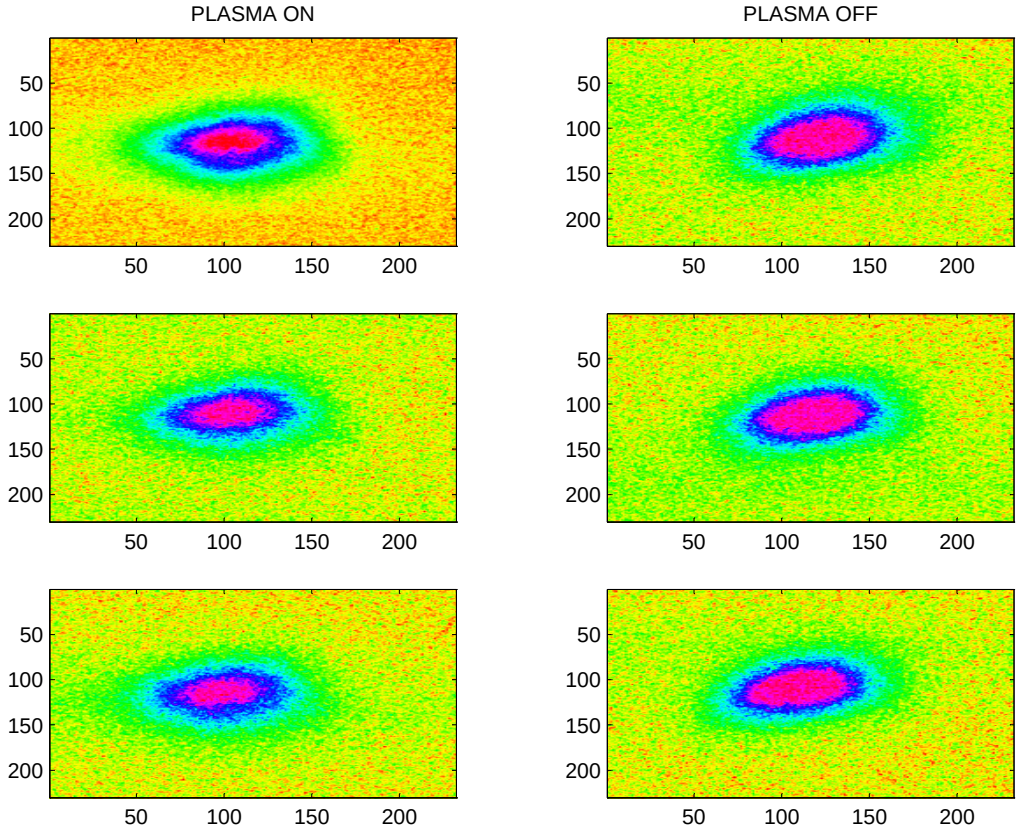

Figure 2: Successive plasma on - plasma off beam profiles from the time integrated Cerenkov images. The image is rotated 90° so the vertical direction is horizontal in the images. This figure shows that there is only a small amount of steering between plasma on and plasma off conditions.

Two figures from the original E-157 proposal are reproduced below to show what was expected and to allow comparison with data taken during the second run. The energy gain along the bunch is plotted in Figure 3. Energy is extracted from the head and center of the bunch producing the plasma wave and the longitudinal fields that accelerate particles in the tail. Figure 4 shows the transverse focusing gradient. It grows from zero to a constant value, ~ 6000 T/m, as the electrons are blown out of the beam core.

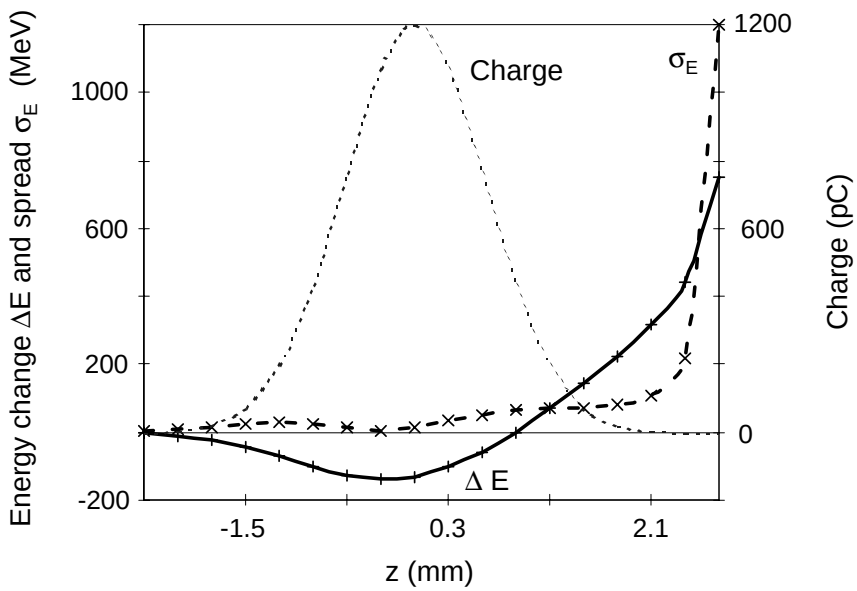

Figure 3: Simulated change of energy (solid line) and absolute energy spread (dashed line) of 1 ps slices along the bunch. The charge distribution is indicated by the dotted line. The energy gain and energy spread curves summarize the signature of plasma wakefield acceleration as expected to be measured. (Figure 5 from the original E-157 proposal).

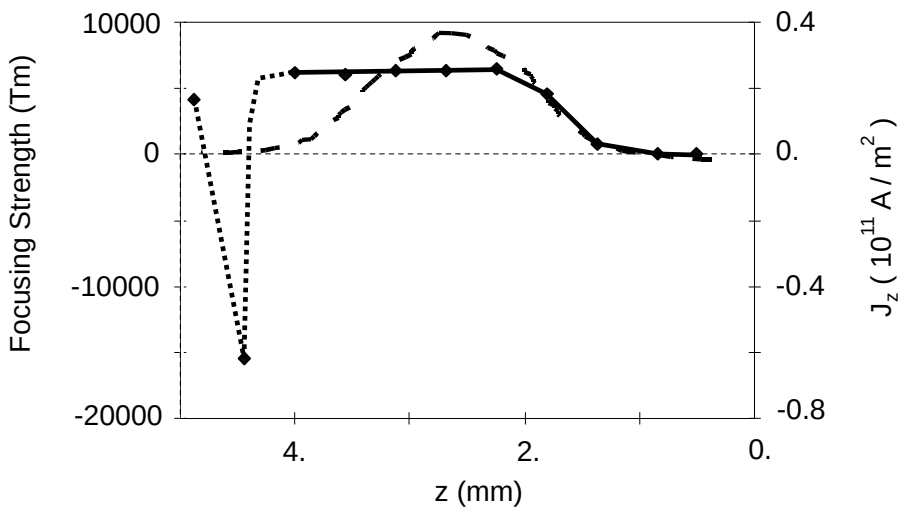

Figure 4: Focusing strength (solid) and axial current (dashed) vs position in the bunch. (The head and tail are interchanged from Figure 3.) Note that there is a strong defocusing peak in the far tail of the bunch. (Figure 11 from the original E-157 proposal).

Figure 5 shows a single streak camera image for a beam with 2×10^{10} electrons. The time axis is 70 ps full scale. The image shows many of the features expected. The plasma density was such that the main portion of the beam undergoes an integer number of betatron oscillations when the plasma focusing of the core is taken into account. However, the head of the bunch is mismatched and defocused. The tail of the beam shows a clear enhancement in the energy gain direction. Note that the tail does not extend below the centroid, which would indicate defocusing

rather than acceleration. Measurement of the smaller energy loss of the core requires more analysis to correct for beam jitter.

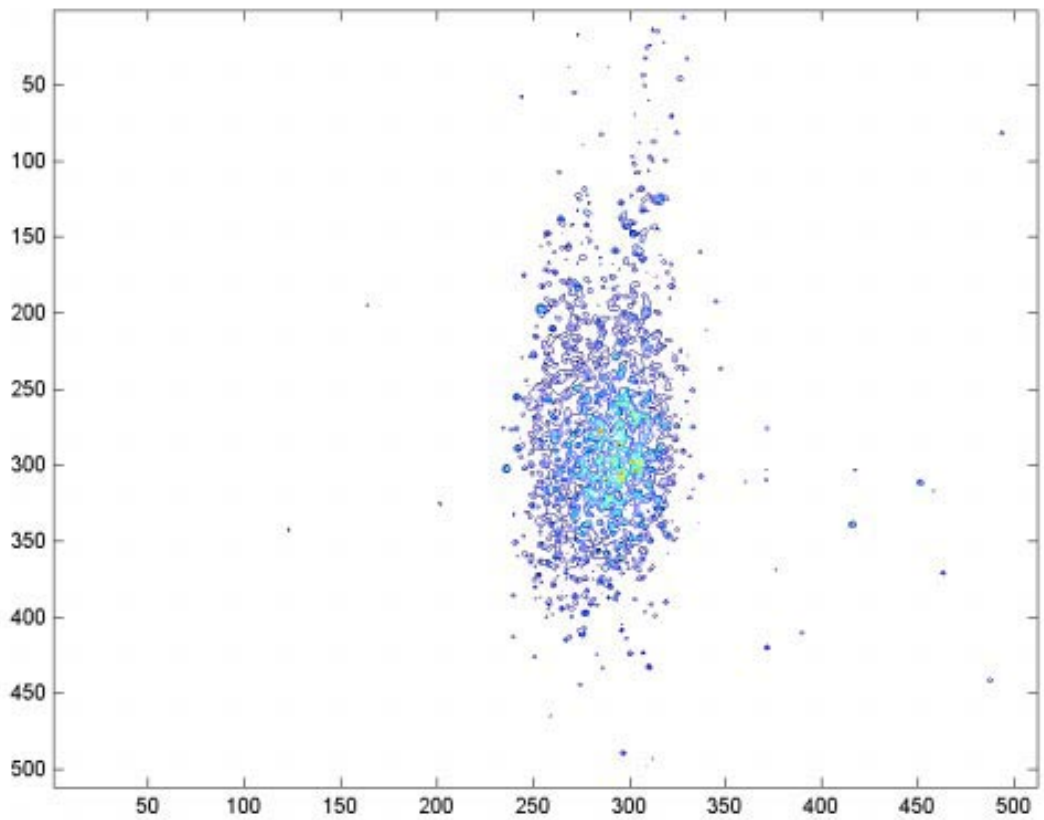

Figure 5: A single streak camera image. The units are pixels on a CCD camera. The horizontal scale corresponds to 70 ps, and the vertical dimension is the vertical profile of the beam with increasing energy towards the top of the figure.

Figures 6 and 7 shows multiple images summed after correction for the streak camera trigger jitter. The two bright regions separated by a less intense band in the "plasma off" case, Figure 6, are due to a ×5 neutral density filter appropriately placed to reduce the light from the beam core and thereby eliminate space charge effects in the streak camera. In contrast, the "plasma on" case, Figure 7, shows a clear acceleration tail. This is just the signal expected and is what we plan to quantitatively measure and study as various beam and laser parameters are varied during the third E-157 run with electrons.

Summary

There is a high probability of obtaining data on the generation of plasma wakefields using the positron beam at the FFTB. The apparatus and diagnostics for doing this are ready, as is a high caliber team of scientists and engineers. SLAC FFTB is the only place in the world where such an experiment can be performed. We request that this proposal be approved for two, three week long periods in November and December 1999.

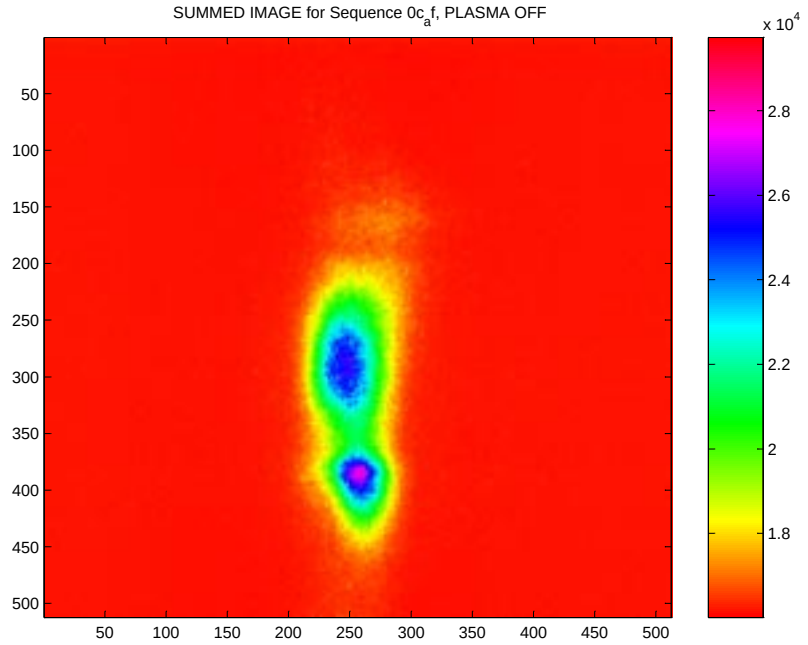

Figure 6: The summed image, removing streak camera trigger jitter, for the plasma off condition. The image structure is explained in the text. The axes have the same meaning as Figure 5.

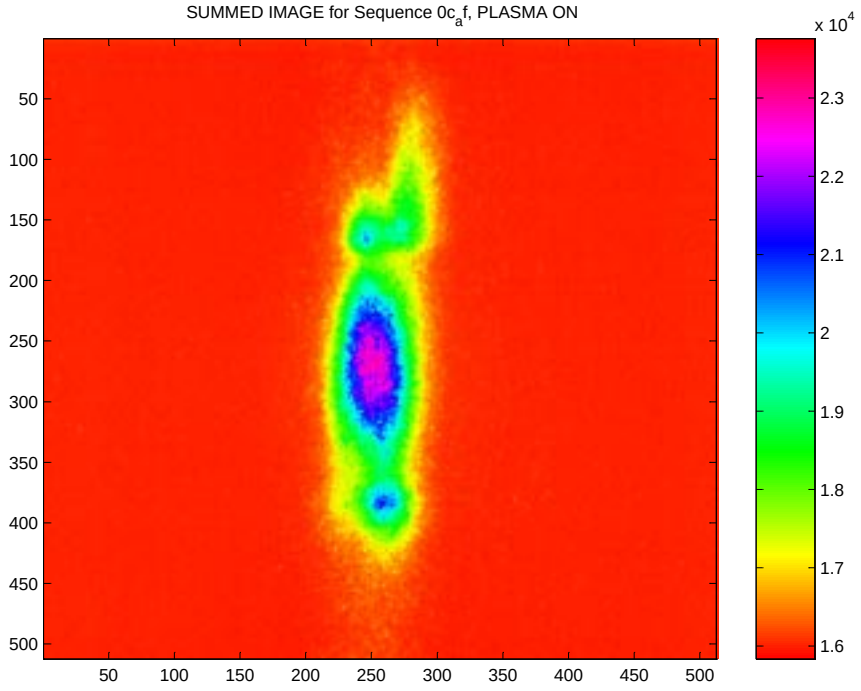

Figure 7: The summed image for the plasma on condition.