SLAC-PUB-8189
July 1999

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Presented at IEEE Particle Accelerator Conference, 3/29/99—4/2/99, New York, NY, USA

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Work supported by Department of Energy contract DE–AC03–76SF00515.

PROGRESS TOWARD E-157: A 1 GeV PLASMA WAKEFIELD ACCELERATOR*

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Abstract

A plasma based wakefield acceleration (PWFA) experiment, scheduled to run this summer, will accelerate parts of a 28.5 GeV bunch from the SLAC linac by up to 1 GeV over a length of 1 meter. A single 28.5 GeV bunch will both induce the wakefields in the one meter long plasma and witness the resulting acceleration fields. The experiment will explore and further develop the techniques that are needed to apply high-gradient PWFA to large scale accelerators. This paper summarizes the goals of the first round of experiments as well as the status of the individual components: construction and diagnosis of the homogeneous lithium oven plasma source and associated ionization laser, commissioning of the electron beam, simulated performance of the electron beam energy measurement, and first PIC simulations of the full meter long experiment.

1 INTRODUCTION

In the experiment known as E-157 [1], a 28.5 GeV electron bunch is used to both excite and witness a large amplitude wake in a meter long plasma cell. The experiment has a rich physics agenda which includes demonstrating high-gradient plasma acceleration over meter scales, measuring large amplitude wakes of order GeV/m in the blowout regime of plasma acceleration [2], and studying beam propagation issues such as betatron oscillations important for future 1-10 GeV stages based on the PWFA mechanism. To accomplish these objectives requires special attention to all three of the key experimental components: the beam, the plasma and the beam diagnostics (see Fig. 1). The construction of each component is well underway in preparation for the scheduled experimental run this summer. This paper describes progress on each of the three experimental components plus recent advances in simulating the experiment over a full meter with parallel PIC simulations.

*Work supported by USDOE: #DE-AC03-76SF00515 and others.

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Simulation support from F. Tsung and D. Gordon is gratefully acknowledged. We thank L. Archambault, S. DiMaggio and J. Dougherty (LBNL) for their technical support.

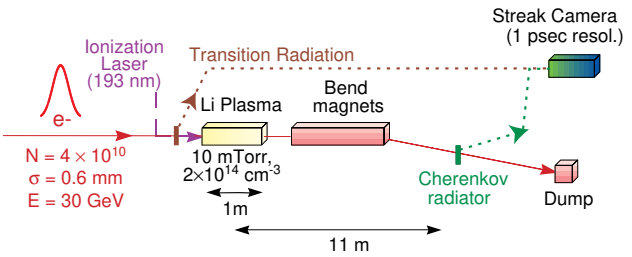
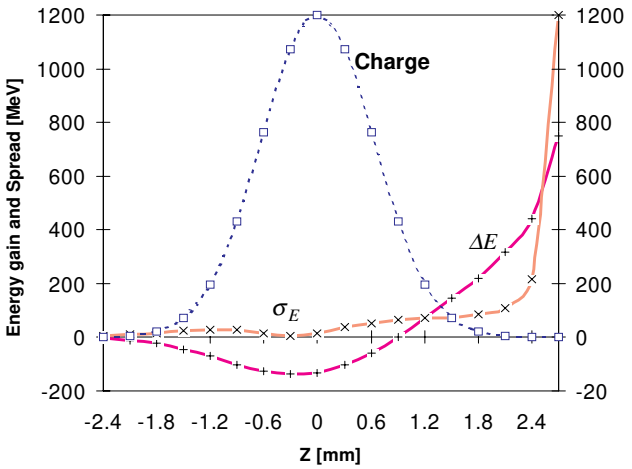


Figure 1: Layout of E-157.

2 EXPERIMENTAL COMPONENTS

In this section each of the three main experimental components is described: the beam diagnostics, the plasma source and the beam. For more detail on each, see the accompanying individual papers [3, 4, 7-9] in these proceedings.

2.1 Beam Diagnostics



Energy change(–+–) and absolute energy spread(–×–) of 1ps slices along the bunch

Figure 2: Simulated time resolved measurements.

As shown in Fig. 2, the electrons in the tail of the drive bunch experience the accelerating field of the plasma wake and gain an energy of about half a GeV over the meter long plasma. Since only the electrons in the tail experience the highest energy gains, their measurement requires time resolved diagnostics on fast time scales (~1ps) and at the highest sensitivities (<10^7 electrons Below we describe the strategies we have developed for accomplishing this.

Upstream of the plasma, OTR is used to diagnose the properties of the incident beam. The ability of OTR to provide the required resolution in spot size and divergence at 28.5 GeV has been experimentally verified. Results from a quadrupole scan are shown in Figure 3, in which 50 micron waists in both axes were resolved using near field OTR images. Beam divergences of 100 μrad have been measured using the two-foil far field interference pattern for a foil separation of 0.5 meter [4]. Use of a streak camera to study the time evolution of the beam spot size and divergence is planned, building on experiments at lower beam energies [5,6].

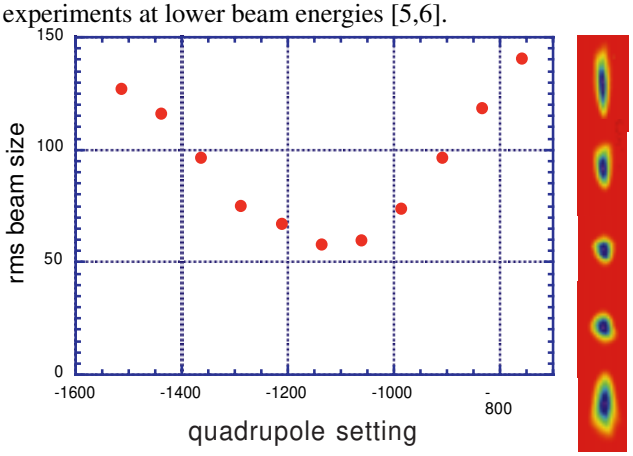


Figure 3: Quadrupole scan (left) in electron beam spot size measured with OTR (images on right) at 28.5 GeV.

After the plasma (Fig. 1), the electron beam is dispersed in energy by a series of deflecting magnets. Eleven meters downstream, the dispersion D in the vertical plane is about 3 mm/GeV. At this location the beam is sent through a low index of refraction transparent material to generate Cherenkov radiation (CR) in the visible wavelength range. The CR and OTR radiators can be imaged onto a CCD camera to produce a time integrated image of the beam, or onto the slit of a streak camera (slit in the energy dispersion plane) to produce an energy versus time spectrum of the beam.

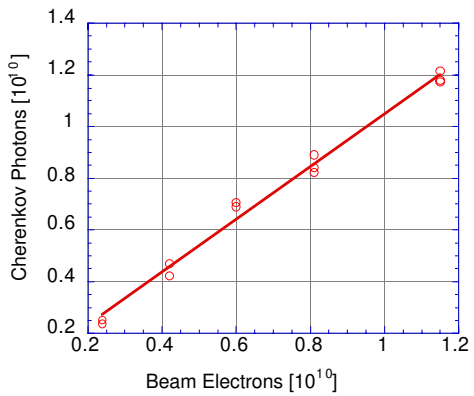


Figure 4: Photon yield vs. number of electrons.

For the Cerenkov material we chose to use silica aerogel, approximately 3mm thick. This material has an index of refraction of 1.009 and overcomes difficulties associated with lower index materials such as air (requiring a thick target and introducing depth of focus issues for imaging) or higher index materials such as glass (having a large Cerenkov angle making it difficult to collect and transport all of the light). However, the new material posed uncertainties concerning its photon yield and survivability. To address these, preliminary tests were performed. [Fig. 4] The photon yield is approximately one photon per electron. Calibration of photon yield assumed 50% quantum efficiency of the CCD and neglects any losses through collection optics. This is more than an order of magnitude higher than that from OTR and enables measurement of charge down to the level of 100fC. In addition the aerogel showed no signs of deterioration over the two week testing period.

2.2 Plasma Source

The requirements on the plasma represent a significant advance over what has been achieved previously: one meter length, minimum transverse size of 1 mm, density of 2-4x10^{14} cm^{-3} uniform to within 10% with a density times length-squared product tuned to within 2% [10]. In addition the plasma must be either fully ionized or sufficiently low Z that beam impact ionization does not cause a significant plasma density increase.

The plasma parameters necessary for the experiment have been achieved in a short version of a Li heat-pipe oven [3]. The neutral density was n_0=2×10^{14} cm^{-3} over a length of L=25 cm. The product n_0L was measured by the hook method, and by uv and white light absorption. The length of the vapor column was inferred from longitudinal temperature profile measurements. The Li vapor was ionized by a uv ArF laser pulse through a single photon absorption process. The plasma density was measured by uv absorption and by CO_2 laser and visible laser interferometry. As expected the plasma density varied linearly with the incident fluence, and reached a maximum value of ≈3×10^{14} cm^{-3}, corresponding to a fractional ionization of 15%. The time for the plasma density to drop by a factor of two from its maximum value was 12 μs. In the experiment the plasma density will be adjusted on a shot-to-shot basis by changing the delay between the ionizing laser pulse and the electron beam. The length of the vapor/plasma column can be changed over a longer time scale by adjusting the heating power delivered to the source.

Based on these results, a 1-meter long source has been built and is being tested [9]. Similar neutral and plasma density values are expected from this longer source.

2.3 Beam Production

To achieve the goal of high-gradient acceleration (GeV/m) in the blow-out regime places specific requirements on the drive beam. It must have significant charge ($N = 4 \cdot 10^{10}$), short bunch length ($\sigma_z \leq 0.63$ mm), modest spot size of 25-50 μm and be aligned to within 10 μm [10].

An SLC-like beam with an emittance of 5 in x and $0.3 \cdot 10^{-5}$ m-rad in y seems ideal. The bunch length is a critical factor for plasma acceleration (the wake amplitude scales as charge over bunch length-squared). For E-157 the bunch length has to be reduced from the typical 1.2 mm for minimum energy spread (0.15%) to 0.6 mm or even 0.4 mm. These shorter bunches generate not only a plasma wakefield, but also a strong longitudinal wakefield in the conventional accelerator giving the beam a large double-horned energy distribution of up to 4 % between horns.

A test run in the winter of 98/99 [7] checked the compatibility with PEP-II, where an additional 10 Hz beam was sent to the plasma experiment area. The bunch length was measured with a 36 GHz cavity and optimised to about 0.55 mm at 29.5 MeV compressor amplitude. Figure 5 shows the inverted cavity signal after normalizing it to a toroid reading (stars:*) and scaling it to the expected curve (solid line, for an $R_{56} = 0.7$ m). By reducing the R_{56} to 0.6 m or 0.5 m and raising the compressor strength a shorter bunch is possible.

The transverse beam emittances and stability were after initial difficulties reduced below the required values, but the charge was still only $2.2 \cdot 10^{10}$ particles.

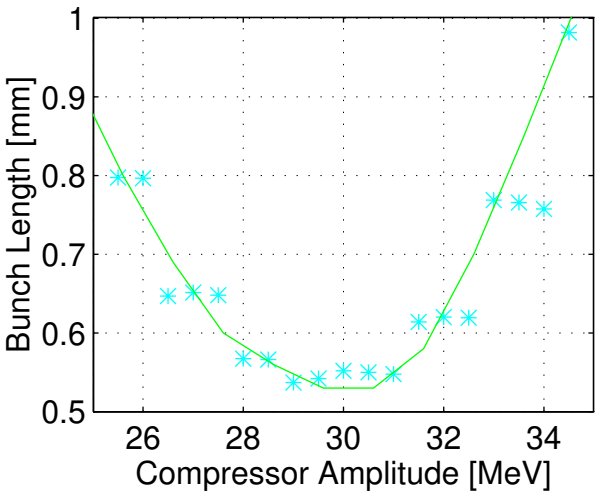


Figure 5: Linac bunch length versus compressor strength.

3 SIMULATIONS

Detailed PIC modeling of plasma wakefield generation has been performed in 2-D [1]. Recently the models have been implemented in a massively parallel object-oriented code on the T3E at NERSC. The parallel implementation had enabled production runs to model the full meter long experiment in two days. The results [8] show the betatron oscillations of the beam at the predicted frequency. The beam undergoes three betatron oscillations reaching sub-micron spot sizes within the plasma (plasma lensing); however, the wake remains stable throughout. Fig. 6 shows the shape of the plasma wake (E_z) near the peak accelerating field (E_z vs. r and z). Note the flattened profile in front of the peak that is characteristic of the blowout regime [2]. The width of the accelerating structure narrows to approximately 50 microns in the last ps before the peak. The height of the peak is approximately 1 GV/m.

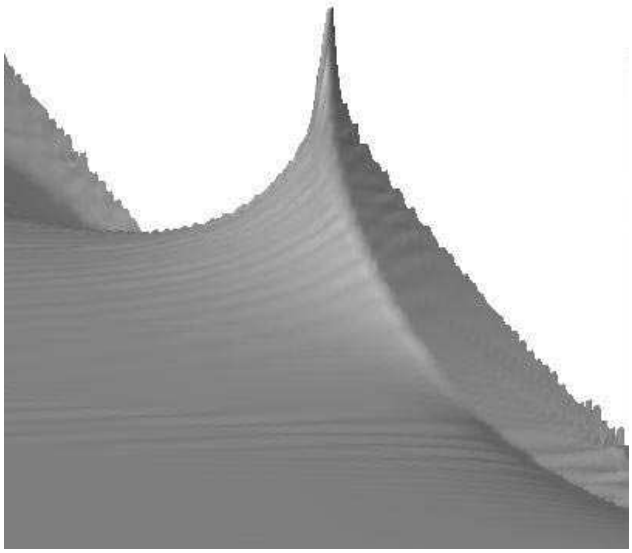


Figure 6: Accelerating wake E_z versus z and r. Wake is moving to the right.

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