SLAC–PUB–7679
April 1998

Proposal for a One GeV Plasma Wakefield Acceleration Experiment at SLAC[†]

R. Assmann[*], P. Chen, F.J. Decker, R. Iverson, P. Raimondi, T. Raubenheimer, S. Rokni, R. Siemann, D. Walz, D. Whittum
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

S. Chattopadhyay, W. Leemans
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

T. Katsouleas, S. Lee
University of Southern California, Los Angeles, CA 90089

C. Clayton, C. Joshi, K. Marsh, W. Mori, G. Wang
University of California – Los Angeles, Los Angeles, CA 90024

Abstract

A plasma-based wakefield acceleration experiment E-157 has been approved at SLAC to study acceleration of parts of an SLC bunch by up to 1 GeV/m over a length of 1 m. A single SLC bunch is used to both induce wakefields in the one meter long plasma and to witness the resulting beam acceleration. The experiment will explore and further develop the techniques that are needed to apply high-gradient plasma wakefield acceleration to large scale accelerators. The one meter length of the experiment is about two orders of magnitude larger than other high gradient plasma wakefield acceleration experiments and the 1 GeV/m accelerating gradient is roughly ten times larger than that achieved with conventional metallic structures. Using existing SLAC facilities, the experiment will study high gradient acceleration at the forefront of advanced accelerator research.

Presented at 13th Advanced ICFA Beam Dynamics Workshop on Second Generation Plasma Accelerators and the 1st JAERI-Kansai International Workshop on Ultrashort-Pulse Ultrahigh-Power Lasers and Simulation for Laser-Plasma Interactions.
July 14-18 1997, Kyoto, Japan.
To be published in Nucl. Instr. Meth.

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

[*] Invited speaker. Present address: CERN-SL, CH-1211 Geneva 23, Switzerland

Proposal for a One GeV Plasma Wakefield Acceleration Experiment at SLAC

R. Assmann*, P. Chen, F.J. Decker, R. Iverson, P. Raimondi, T. Raubenheimer, S. Rokni, R. Siemann, D. Walz, D. Whittum†
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

S. Chattopadhyay, W. Leemans
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

T. Katsouleas, S. Lee
University of Southern California, Los Angeles, CA 90089

C. Clayton, C. Joshi, K. Marsh, W. Mori, G. Wang
University of California – Los Angeles, Los Angeles, CA 90024

A plasma-based wakefield acceleration experiment E-157 has been approved at SLAC to study acceleration of parts of an SLC bunch by up to 1 GeV/m over a length of 1 m. A single SLC bunch is used to both induce wakefields in the one meter long plasma and to witness the resulting beam acceleration. The experiment will explore and further develop the techniques that are needed to apply high-gradient plasma wakefield acceleration to large scale accelerators. The one meter length of the experiment is about two orders of magnitude larger than other high gradient plasma wakefield acceleration experiments and the 1 GeV/m accelerating gradient is roughly ten times larger than that achieved with conventional metallic structures. Using existing SLAC facilities, the experiment will study high gradient acceleration at the forefront of advanced accelerator research.

I. INTRODUCTION

The energies of most interest for high energy physics today have reached the multi-TeV level. Linear colliders offer the only possibility to access this energy regime with e+e- collisions. Practical limitations on the size and the cost of linear colliders can only be overcome if the acceleration per unit length is significantly increased. While there are attempts to push the gradients in conventional metallic structures to 1 GeV/m, plasma-based acceleration concepts have attracted considerable interest. By replacing the metallic walls of conventional structures with *plasma-walls* many limitations are avoided and very high gradients can be achieved. A recent laser-driven plasma wakefield acceleration (LWFA) experiment has measured an accelerating gradient of 100 GeV/m [1].

Although plasma-based experiments have shown impressive advances in their accelerating gradients, they are quite short, extending over only a few mm. The SLAC experiment E-157 aims at demonstrating high gradient acceleration in a 1 m long plasma cell, based on beam-driven plasma wakefield acceleration (PWFA). Plasma modules of 1 m length would be well suited for building a future linear collider. The use of the existing SLAC linac limits the achievable gradient to about 1 GeV/m. Though not as high as achieved by other plasma-based experiments, this gradient is much larger than in any metallic structure. It would be the first time that plasma-based structures accelerate particles by one GeV. In the following sections we describe the basic philosophy and the goals for the experiment. More details can be found in the actual 50 page proposal E-157 [2].

II. OVERVIEW

The basic idea for the experiment is to use a single SLC bunch to both excite the plasma wakefield (head of the bunch) and to witness the resulting acceleration (tail of the bunch). For many reasons, the SLC beam is the ideal driver for a plasma acceleration test. It has high energy; it is very stiff and is not subject to distortion or depletion over the length of the proposed experimental section. In addition, neither the driving particles nor the accelerated particles will significantly phase slip over the length of the experiment. All of these factors suggest the possibility for a clean test of plasma wakefield acceleration and the opportunity to make detailed comparisons to theoretical models.

The experiments discussed here will assess the viability of wakefield transformers based on beam-driven plasmas. The plasma wakes excited by particle beam and laser drivers are similar. However, the physics of beam propagation (self-focusing, stability, optimal profile shapes, etc.) are quite different. Moreover, particle beam and

---

[*] Invited speaker. Present address: CERN-SL, CH-1211 Geneva 23, Switzerland.

[†] Work supported by Department of Energy contract DE-AC03-76SF00515.

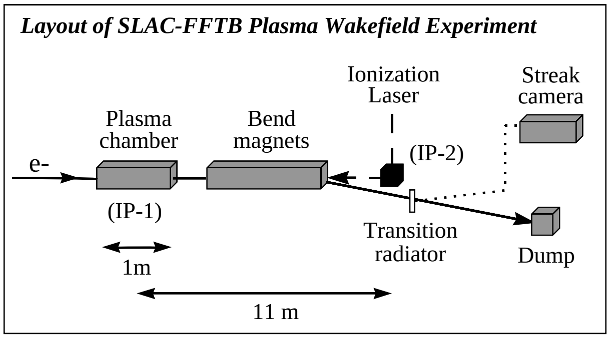

FIG. 1. Schematic sketch of the proposed experiment.

Parameter	PWFA	Standard SLC
Bunch intensity*	3.5-4.0$\cdot 10^{10}$ e$^-$	3.5-4.0$\cdot 10^{10}$ e$^-$
Bunch length*	0.6 mm	0.6-1.1 mm
Repition rate	10 Hz	1 - 120 Hz
Transv. rms jitter (end of linac)	$< 50\mu$m	$< 30\mu$m
$\gamma\epsilon_x$ at plasma IR	60 mm-mrad	45 mm-mrad
$\gamma\epsilon_y$ at plasma IR	15 mm-mrad	8 mm-mrad
σ_x at plasma IR	$< 100\mu$m	23 μm at $1 \cdot 10^{10}$ e$^-$
σ_y at plasma IR	$< 100\mu$m	37 μm at $1 \cdot 10^{10}$ e$^-$

TABLE I. List of beam parameters for the PWFA experiment. The parameters are compared to the SLC standard performance at 46.6 GeV. The first two parameters (indicated by *) determine the plasma wakefield acceleration and are fundamental for the proposed experiment. Other parameters (the transverse beam emittances) are not critical for our experiment and can be worse. The IR is the beam-plasma interaction region at IP-1.

laser drivers have different scalings for energy gain per stage and efficiency, which may make particle drivers more attractive at ultra-high energies. By designing flexibility into the plasma source and/or drive bunch length, we will be able to explore some of the most important phenomena. Specifically, we can measure the transformer ratio (i.e. the decelerating and accelerating fields within the bunch), transverse focusing fields, and the dependence of the gradient on plasma density, bunch length, beam and plasma radius. Furthermore, increasing the plasma density or bunch length will enable a first test for electron hose instability [3]. A secondary benefit of the experiment will be the opportunity to explore the new physics and technology issues associated with particle beam rather than laser drivers.

We plan to place a meter-long plasma of appropriate density in the path of the SLC beam at the so-called IP-1 of the Final Focus Test Beam (FFTB) [4,5] at SLAC. The PWFA experiment will replace the E144 [6] (nonlinear Compton scattering) experimental setup at IP-1. A schematic sketch of the experiment is shown in Figure 1. The beam parameters needed for the proposed experiment are routinely achieved during standard SLC operation. Most important are a beam intensity of between 3.5 to 4×10^{10} electrons and a suitable bunch length ($\sigma_z = 0.6$ mm) and shape. It will be shown that the high current longitudinal bunch profiles in the SLC linac are well suited. Normalized emittances and transverse beam jitter are not critical and can be significantly larger than the standard SLC values at 46.6 GeV.

In order to minimize the impact and cost of the experiment we plan for parasitic running at 10 Hz during operation of the SLAC B-factory (PEP-2) [7]. PEP-2 will already accelerate the linac beams to 30 GeV for positron production. We avoid additional costs for the maintenance and operation of the RF in the last third of the linac by only requiring 2-3 sectors of acceleration downstream of the positron extraction point. The additional acceleration is needed in order to maintain efficient BNS damping and a small final energy spread. The beam energy in the FFTB will be 30 GeV. Minor modifications in the dumpline transport will allow safe operation of the FFTB with a high current 30 GeV beam. Though planning for 30 GeV, it is important to note that the PWFA experiment can always be carried out at 46.6 GeV, if appropriate.

The experiments are envisioned to take place in stages. The first stage will simply place a meter-long plasma of appropriate density in the path of the SLC beam near the end of the FFTB. We expect the head of the bunch to be decelerated by about 0.2 GeV while tail particles are accelerated by up to 1 GeV. The resulting change in energy distribution, will be detected by a time-resolved energy measurement with a streak camera. The wakefield will be diagnosed in detail by subtracting the energy distribution signals with and without the plasma. We note that the peak accelerating gradient in the experiment is expected to increase from 1 GeV/m to 2.5 GeV/m if the SLC RMS bunch length can be reduced from 0.6 mm to 0.4 mm. A second set of experiments will vary the plasma density, plasma length, and/or beam bunch length to test scaling laws for wake amplitudes and electron hose instability.

III. THE SLC DRIVE AND WITNESS BEAM

The experiment described in this paper was designed for the SLC high current beam as a wakefield driver. The operating ranges for the SLC beam parameters are well known and constrain the feasible plasma-wakefield acceleration design. Table I lists the SLC drive beam parameters that are used in the design of the SLAC-PWFA experiment. The numbers are compared to the standard performance during SLC operation at 46.6 GeV, demonstrating that the PWFA experiment could be done easily at 46.6 GeV. The important constraints for plasma-wakefield acceleration arise from the minimum achievable bunch length and the highest possible bunch intensity. This will be discussed in more detail in the next section. We note that it was confirmed that the parameters from

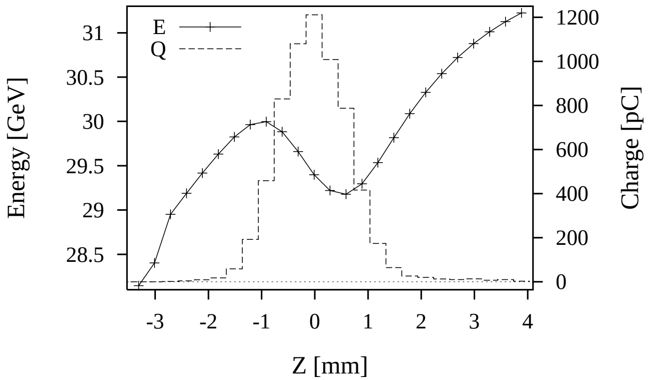

FIG. 2. Simulated Energy variation along the bunch length at the end of the SLC linac. The dashed curve shows the charge distribution for the shortest possible SLC bunch (0.6 mm).

Table I satisfy radiation safety and beam containment requirements in the FFTB [2].

The assumed performance is well established from the SLC experience. However, in order to minimize the impact and cost of the experiment, a beam operation at 30 GeV is assumed, as PEP-2 will already accelerate beams up to this energy. The interleaved operation with PEP-2 and the linac and FFTB issues at 30 GeV are discussed in the detailed proposal [2]. An important parameter is the energy spread at the end of the linac. Fig. 2 shows a LIAR [8,9] simulation of the energy along the longitudinal direction of the bunch for a modified 30 GeV BNS damping. The simulation is compared to the measured longitudinal charge distribution for minimal bunch length (0.6 mm rms). Even at 30 GeV the rms energy spread in the FFTB can be constrained to 1% or 300 MeV. This energy spread allows to achieve reasonably small spot sizes in the FFTB and to diagnose the expected energy gains and losses.

IV. BEAM-PLASMA INTERACTION

The basic concept of the plasma wakefield accelerator is to use a high-current drive-beam to excite a large plasma wake that can accelerate trailing particles. The wake is created when the space charge of the drive beam displaces plasma electrons in much the same way that a boat creates an ocean wake by displacing water. In this case the plasma ions provide the restoring force on the displaced electrons and the wake phase velocity is at the beam velocity ($\approx c$). This creates a high-gradient accelerating structure with a wavelength λ_p set by the plasma density n_0:

$$\lambda_p \approx 1 \text{ mm} \cdot (10^{15} \text{ cm}^{-3}/n_0)^{1/2} \, . \tag{1}$$

For the case of dense ($n_b > n_0$) and narrow ($\sigma_r < c/\omega_p$) beams the plasma response is highly non-linear and is dominated by the radial blow out of all the plasma electrons within a radius $\sigma_r(n_b/n_0)^{1/2}$ [10]. Here, n_b is the beam density, σ_r the radial beam size, c the light velocity and ω_p the plasma frequency. The plasma ions move relatively little on a short time scale, creating a uniform focusing wakefield W_r in the blowout region. A large longitudinal wakefield is possible when (after the passage of the beam) the ion space charge force pulls the electrons back, creating a large density spike on axis. The fields in front of the density spike have attractive properties for an accelerating structure. They provide linear focusing W_r that is independent of the longitudinal coordinate z (i.e., $\partial W_r/\partial z = 0$) from which it follows that the accelerating field W_z has a uniform profile (i.e., $\partial W_z/\partial r = 0$). For beam currents such that Nr_e/σ_z approaches one, the accelerating field is large, on the order of

$$W_z \approx 100 \cdot \sqrt{n_0} \text{ V/m.} \tag{2}$$

Although groups at UCLA, ANL and LBNL plan experiments to access the blowout regime, there has been no experimental test of this regime to date due to the relatively dense beams required.

The fully non-linear fluid equations for the plasma response to a beam are analytically tractable only in 1-D (valid for very wide beams). In 2-D the non-linear fluid equations in cylindrical geometry (r–z) have been solved numerically by B. Breizman in the simulation model Novocode [11]. We used the fluid models to quickly survey a large parameter space; however, to more accurately model the final parameters we turn to particle-in-cell (PIC) simulations. The PIC simulations use fully self-consistent 2-1/2D relativistic codes that are computer time intensive but have proven to be accurate models of experiments. The simulation results shown in the following were all obtained with the PIC code MAGIC [12]. We point out that the PIC results agree to better than 20% with results from Novocode simulations.

A. Longitudinal wakefield beam acceleration

Sample results of a 2-1/2D PIC simulation in cylindrical geometry using the code MAGIC are shown in Figure 3. The parameters correspond to the expected beam parameters (as described before) and optimized plasma settings. The optimized plasma density is 2.1×10^{14} cm^{-3}. Figure 3a shows the real space of the plasma electrons in which blowout and crossing of streamlines ("wavebreaking" [13]) are clearly visible. Figure 3b is a snapshot of the longitudinal wake W_z 6 mm into the plasma. The peak accelerating field is 900 MeV/m. Figure 3c shows the axial current density J_z versus z. The beam's current profile and the plasma current (a large spike near the peak accelerating field) are clearly visible.

In anticipation of the time-resolved diagnostic of energy change described later, we simulated the experimental observables in Figure 4. We show the beam charge

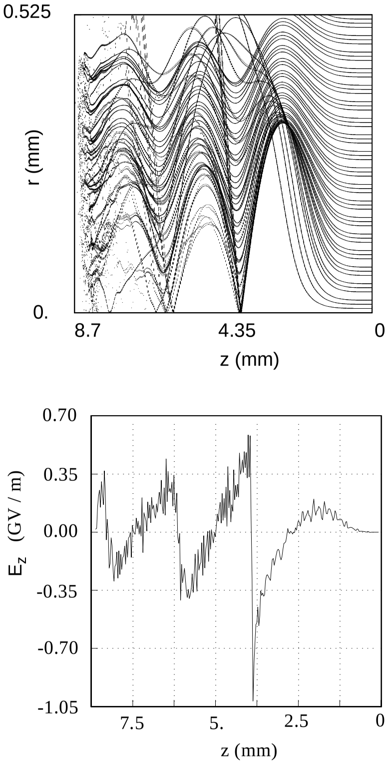

FIG. 3. MAGIC PIC simulation of plasma wake for the shortest SLC bunch ($\sigma_z = 0.6$ mm) and plasma density 2.1×10^{14} cm^{-3}. (a) Real space r–z of plasma electrons; (b) axial electric field E_z.

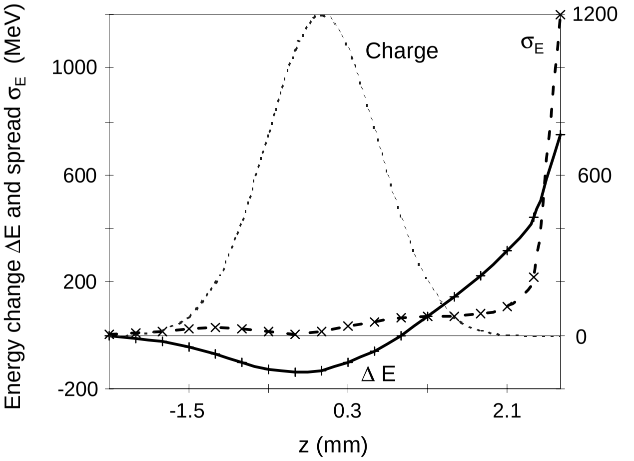

FIG. 4. Simulated change of energy (solid line) and absolute energy spread (dashed line) of 1 ps slices along the bunch. This calculation was done for the same parameters as Figure 3. The two curves summarize the signature of plasma-wakefield acceleration as expected to be measured with the proposed diagnostic setup. The charge distribution is indicated by the dotted line.

and the simulated beam energy change and beam energy spread in 1 ps intervals as they would be resolved with a streak camera. Even though some particles in the simulation gain over 1 GeV, the 1 ps window captures particles on either side of the acceleration peak. As a result, the energy change of the center of the last ps bin shown is roughly 800 MeV with a spread of 1200 MeV. Note that decelerating and accelerating fields within the bunch are well resolved with 1 ps diagnostic intervals. The core of the bunch is decelerated by roughly 150 MeV.

To determine the optimal beam and plasma conditions for the experiment as well as to test the sensitivity of the experiment to variations in the plasma and beam parameters, we have performed a number of simulations similar to the one shown in Figure 3. The complete simulation results are given in the proposal [2]. It is shown there that the peak accelerating gradient is roughly proportional to the beam current and does almost not depend on the radial size of the SLC bunch. It is also shown that the wake amplitude begins to degrade for plasmas narrower than 300 μm in radius. This corresponds roughly to the maximum outward excursion one would calculate for the plasma electrons ejected by the beam. One other consequence of a finite width plasma is the need for alignment of the beam and plasma axis. If the plasma is very narrow and the beam is off axis, the expulsion of plasma electrons by the beam will produce an ion column centered on the plasma axis which will deflect the beam. At the other extreme of a very wide plasma, the axis of the ion column is defined by the beam itself and no deflection of a collinear beam occurs. A transition between these two types of behavior occurs for our parameters and a beam jitter of approximately 50 μm at a plasma radius of 250 μm. Thus a plasma of radius 300 μm or greater will simultaneously avoid wake degradation and beam deflection.

Changing the bunch length from 0.6 mm to about 1 mm we have calculated that the peak accelerating gradient drops from 1 GeV/m to about 0.2-0.4 GeV/m. It is therefore essential to use the shortest possible SLC bunch. If the bunch length is reduced to 0.4 mm the expected peak gradient reaches 2.5 GeV/m with a plasma density of 10^{15} cm^{-3}. Figure 5 shows the peak wake amplitude as a function of plasma density. The peak gradient is 900 MeV/m ± 100 MeV/m at a plasma density of 2.1×10^{14} cm^{-3}. The uncertainty quoted is due to numerical noise in the simulations. Also shown is the number of particles accelerated within 70% of the peak gradient versus the plasma density. We note that for the highest possible gradient only a small number of particles sees maximum acceleration.

B. Transverse beam focusing

As seen in the simulations in Figure 3a, the head of the drive beam rapidly blows out the plasma electrons leaving a positive ion column in the beam path. In this case, the transverse wake on the main body of the beam is particularly simple and takes the value given by a uniform positive cylinder of charge density n_0: $W_r = 2\pi n_0 e^2 r$.

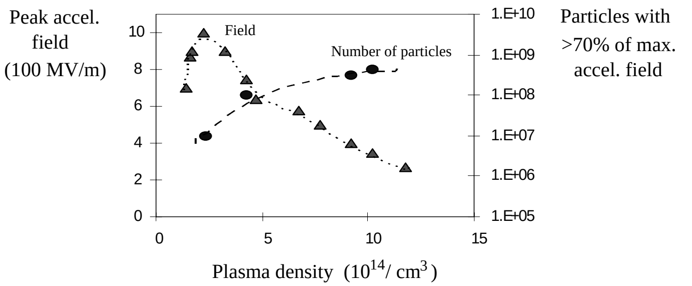

FIG. 5. Peak wake amplitude versus plasma density with $\sigma_z = 0.6$ mm and (dotted) number of particles experiencing 70% or more of the peak gradient.

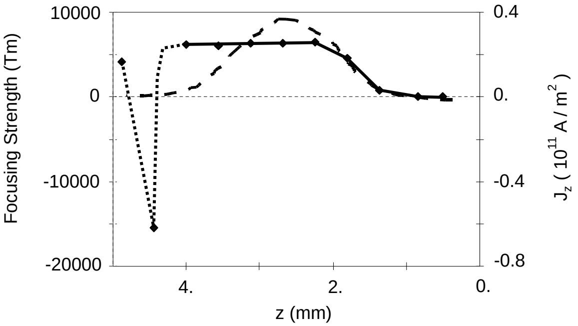

FIG. 6. Focusing strength (solid) and axial current j_z (dotted) versus longitudinal position z for the PIC simulation of Figure 3. The points indicate the simulation results. Note that there is an important defocusing peak in the far tail of the bunch. Its width is unconstrained within the binning used for this simulation. However, it occurs only after the peak accelerating field. The axial current shows the longitudinal bunch distribution.

This corresponds to an effective quadrupole focusing strength (in both planes) of

$$\frac{W_r}{r} = 960\,\pi \ \mathrm{T/m} \cdot \frac{n_0}{10^{14}\ \mathrm{cm}^{-3}}\,. \tag{3}$$

The variation in the transverse focusing strength along the bunch in a PIC simulation is shown in Figure 6 (for $r = \sigma_r = 75\,\mu$m). From this we see the time-dependent focusing rising at the head then asymptoting to the theoretical value from the above equation (6400 T/m for this case). The simulation assumed immobile ions which is a good approximation for large beam sizes. The β-function for such the focusing channel is $\beta = \sqrt{2\gamma}c/\omega_p$, and the matched beam condition ($\beta = \sigma_0^2/\epsilon$) occurs for an equilibrium radius of $\sigma_0 = 4\,\mu$m and $\beta = 12$ cm ($\gamma\epsilon = 10$ mm-mrad, $\gamma = 6 \times 10^4$ and $n_0 = 2.5 \times 10^{14}$ cm^{-3}).

Since the SLC beam will enter the plasma at a waist larger than this value, the spot size will over focus ("plasma lens"). Figure 7 shows a simulation of the beam size propagation inside the plasma with a focusing gradient of 6000 T/m. The horizontal and vertical beam sizes perform 5/4 oscillations within the plasma. We note, that for the minimum spot size, the plasma ions are not completely immobile anymore and they start modifying the focusing forces. This is presently being studied. If the betatron phase advance within a plasma is a multiple of π, then the outgoing beam divergence is minimized and the design beam sizes downstream are maintained. This is illustrated in Figure 8. It shows the spot sizes at the location of the energy diagnostics (at so-called IP-2, 12 m downstream of IP-1) for different plasma densities (quadrupole gradients). Due to betatron phase mixing the mismatch effect increases with higher plasma density. However, local maxima in beam size reflect the condition that the phase advance in the plasma cell is a multiple of π. In order to handle the strong transverse plasma focusing we clearly need to adjust the total phase advance in the plasma to a multiple of π. This can be done straight forwardly by minimizing the measured spot size.

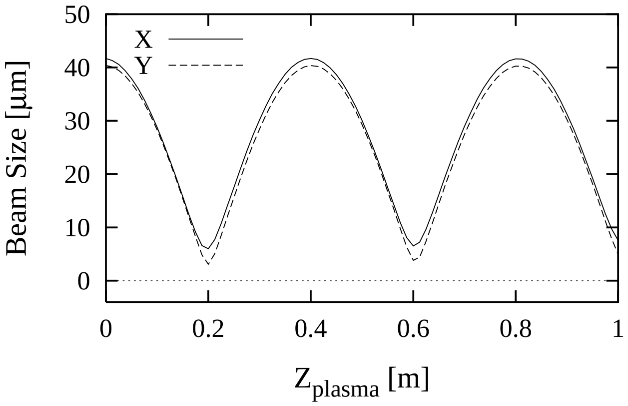

FIG. 7. Horizontal (solid) and vertical (dashed) beam size within the 1 m long plasma cell for a plasma density of 2×10^{14} cm^{-3}. (solid line). The corresponding quadrupole strength is 6000 T/m.

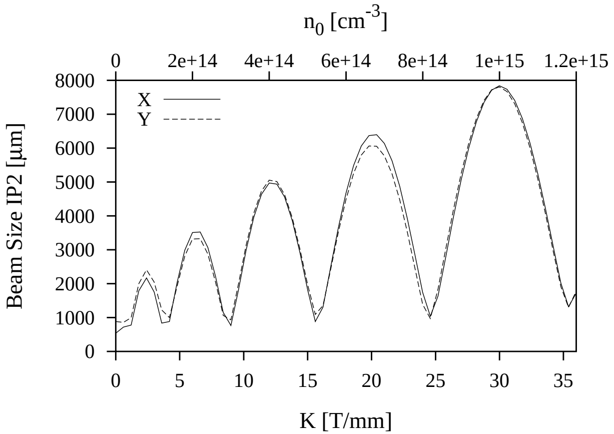

FIG. 8. Horizontal and vertical beam size at IP-2 versus plasma focusing strength K (plasma density n_0). Several plasma densities allow the study of plasma wakefield acceleration while the downstream beam blowup is kept small. The calculation was done with a relative energy spread of 1%.

If the beam has a head-tail offset, then the tail of the beam will be deflected toward and oscillate about the axis defined by the head. This leads to an angular deflection. For typical head-to-tail offset of 25 μm we expect a maximum 2 mm offset 10 m downstream. Choosing the phase advance in the plasma cell to be exactly a multiple of 2π, however, will cause the plasma to be completely transparent to the beam with respect to its transverse dynamics.

V. THE PLASMA SOURCE

The experiment requires a plasma source that is about 1 to 1.5 meters in length whose plasma density can be varied from 10^{14} to 10^{15} electrons per cm^3 and one that is quasi-uniform. The latter requirement can be somewhat quantified by assigning a density scale length $L = (1/n_e(dn/dx))^{-1}$ where n_e is the mean electron density. For a linear density profile, $n_e(x) = n_0(1 + z/L)$, a 25% variation in density over 1 meter of length of the source will lead to a 12% variation in the wavelength of the plasma wave accelerating structure. This in turn will cause a phase slippage between the particles and the wave, which is quite acceptable. Thus, the density scale length should be greater than 4 m. The next requirement is that the plasma source should be fully electron ionized so that any further electron impact ionization by the beam will not induce time-dependent variation in the plasma density in the frame of the electron beam. At the same time, there should not be a significant emittance increase of the electron beam due to collisions.

The ideal plasma source that fits all these requirements would be a fully ionized, meter long hydrogen plasma. However, hydrogen plasmas in this density range and of such lengths are very difficult to make. The same is true of a helium plasma. Furthermore, large of helium are required and are difficult to pump. A sophisticated differential pumping system would have to be employed to guard against failure of any containment foil, especially if helium is being flowed through the plasma. We have therefore decided on a lithium plasma source that can simultaneously satisfy all the requirements on the range of required plasma densities, homogeneity, scalability (length), and that minimizes the problems of electron beam scattering and impact ionization.

Lithium, an alkali metal, is a solid at room temperature with extremely low vapor pressure. However, at 180°C it becomes a liquid and the vapor pressure of the liquid increases rapidly as the liquid approaches its boiling point of 1300°C. The required plasma densities between 2×10^{14} and 1×10^{15} cm^{-3} can be obtained by singly ionizing the lithium atoms ($E_i = 5.9$ eV). The vapor pressure required for this range of densities is 20 to 100 mTorr, which can be obtained at temperatures between 560 and 630°C. Meter long lithium vapors have been produced at these and far higher (Torr-range) pressures in heat pipes for atomic physics and spectroscopy experiments [14]. In fact, a vast body of literature exists on producing sealed lithium heat pipes and producing and diagnosing lithium plasma using photoionization and spectroscopy/interferometry, respectively. After surveying the literature, we have designed such a source for our present application.

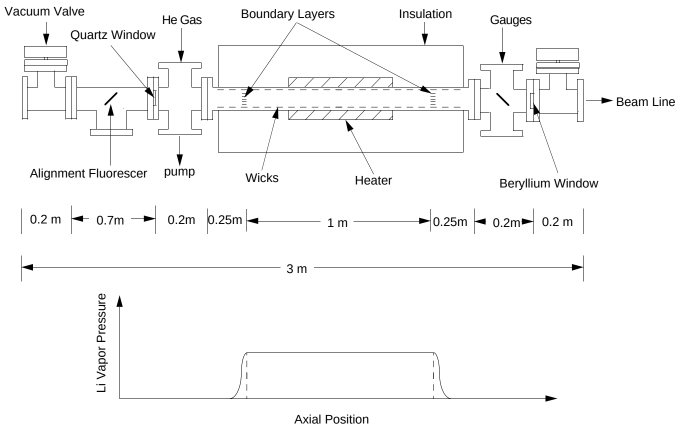

FIG. 9. Schematic layout of the proposed lithium plasma source and its connection to the FFTB beamline.

Figure 9 shows the schematic of the lithium plasma source. The first thing to note is that it is a completely sealed system with a few micron thick quartz window [15] on the upstream and a 25 mm thick beryllium window on the downstream end. Quartz was chosen because of its ability to transmit the 6 eV photons that are needed to photoionize the lithium vapor. The second thing to note is that upstream of the source is a 0.5 m ion tube with its own turbo-molecular vacuum system and a fast, feedback controlled vacuum valve that will isolate the FFTB beam line should the windows fail. In a lithium oven, the lithium vapor is confined in the heated region by a buffer gas, which in this case will be helium. Since the lithium can only exist as high pressure vapor in the heated region, pressure balance requires helium to move away into the colder region of the source. Thus, there is a boundary region where transition from mainly lithium (on the hot side) to mainly helium (on the cold side) occurs. This boundary layer is typically 10 cm long, exists on both sides of the heated region and serves to confine the hot lithium vapor.

An advantage of this arrangement is that the lithium vapor is homogeneous and adjustable in length. Furthermore, the windows need not be heated making it very easy to make a vacuum seal. The 6 eV laser photons, contained in an approximately 5 ns long, 25 mJ pulse, are brought in from a mirror, approximately 11 meters downstream from the plasma chamber. The optical beam side is so arranged as to produce a focal spot radius of about 300 μm. The Rayleigh range of this beam is over 2.7 meters, so it will not spread appreciably over the length of the plasma column. The amount of laser energy needed to fully ionize the lithium vapor to Li$^+$ can be easily estimated. Since the ionization is a one photon ionization process, the laser energy needed simply depends on the ionization cross-section σ_I and the total number of atoms that are to be ionized. Taking $\sigma_l = 10^{-18}$ cm^{-2} at 6 eV, we estimate the total energy needed to be less than 5 mJ for the higher densities (10^{15} cm^{-3}) that are to be produced. Therefore, a laser pulse containing 25 mJ at 0.2 μm should be more than adequate. Details about the laser source can be found in the proposal [2].

VI. BEAM ENERGY DIAGNOSTICS

The expected result of the Plasma Wakefield Acceleration Experiment is to observe deceleration and acceleration of up to 1 GeV within a single SLC bunch. Figure 4 shows the simulated changes in beam energy and energy spread due to PWFA for 1 ps slices along the expected SLC bunch. This energy change will overlay the incoming energy variation along the bunch (see Figure 2). It is important to note that the incoming rms energy spread within a 1 ps slice of the bunch will not exceed 100 MeV. From the expected plasma-induced energy change in Figure 4 we draw several conclusions:

- The longitudinal charge distribution is roughly Gaussian with a sigma of 0.6 mm.
- In order to diagnose the experimental results we need a time-resolved measurement of the energy along the bunch. This can be accomplished a streak camera.
- A time resolution of 1 ps is sufficient to precisely analyze the plasma-generated beam deceleration and acceleration.
- Considering particles up to 3 σ_z into the tail we find an expected energy difference between the decelerated head and the accelerated tail of roughly 400 MeV. The 1 ps slice at 3 σ_z in the tail shows an absolute acceleration of about 250 MeV.
- The maximum slice acceleration is about 800 MeV with an induced energy spread of 1.2 GeV. The slice that experiences this maximum acceleration is about 4.5 σ_z out in the tail of the particle distribution. Only very little beam charge can be observed there. We expect to see about 10^7 particles (compare Figure 5).

It will be rather straight forward to measure plasma-induced energy changes within about 2.5 σ_z of the particle distribution. Those measurements will test the plasma theory and simulation in detail. However, in order to diagnose the maximum acceleration we need to reliably measure charges down to 10^7 particles (or about 0.03% of the total bunch charge) without worsening the time resolution of the streak camera.

In order to measure time-resolved energy changes a transition radiator is placed in the electron beam at a point near but downstream from IP-2. Transition radiation is produced at 45°, extracted from the vacuum through a quartz window and brought to an optical diagnostic station external to the radiation shielding. The light will be transported in a (low quality) vacuum. Remotely controlled mirrors for steering the light will be available. The optical diagnostic station will have a Hamamatsu N3373-02 streak camera as the primary detector. A streak camera trigger from the SLAC timing system will be available. The intrinsic resolution of the camera for SLC measurements was determined to be 0.85 psec or 0.26 mm. The intensity of the transition radiation is comparable to the synchrotron light intensity that was used for the SLC measurements. A schematic sketch of the experimental layout is shown in Figure 1.

The width of an optical interference filter at the streak camera determines both chromatic effects and the available light intensity for the streak camera. A 10 nm interference filter was used for SLC linac measurements in order to achieve a 1 ps time resolution. With that charges down to a few 10^8 particles have been measured reliably at SLC. Note that measuring lower intensities was not important for SLC and therefore was not studied. In order to measure 10^7 particles with the SLAC streak camera the filter width would have to be opened by about a factor of ten, leading to 4 ps resolution if the chromatic effect cannot be corrected. At the present time we cannot decide whether it will be possible to open the filter width by a factor of ten while maintaining a time resolution of 1 ps. These effects will be studied further.

Even if we can not understand and avoid the chromatic contribution to the time resolution, we can still measure the tail of the beam with a larger time resolution. Measuring a 4 ps slice in the tail of the bunch, we would see a large energy spread of more than 1 GeV for this slice. Though not measuring the maximum acceleration as an acceleration of a single slice of the beam, we would still measure it directly through the energy spread.

The dispersion at the diagnostics location is about 100 mm. A difference measurement will be made comparing beam pulses with plasma to those without plasma. The beam centroid will shift due to energy gain and dispersion. The dispersive centroid shift can be measured provided the change in spot size due to the mismatch introduced by the plasma is small compared to the centroid shift. Because the streak camera measures the beam in slices of 1 ps, the beam size for a single slice is calculated with a reduced energy spread of 0.3%. Spot sizes with and without the plasma cell are then almost identical for certain plasma densities. The “transparency” condition for the plasma cell was discussed earlier. For minimum mismatch effects we expect a spot size for a single 1 ps slice of about 0.5 mm. The vertical deflection due to an acceleration of 100 MeV is 330 μm, which should be easily measurable. The energy change between the decelerated head and the accelerated tail of the bunch is shown in Figure 4 to be about 400 MeV for particles within 2.5 sigma of the longitudinal distribution. It will be possible to measure the longitudinal wakefield along the bunch in detail. The maximum acceleration of 800 MeV for a 1 ps slice will show itself as a large offset (2.5 mm) and a large vertical beam size (4 mm) due to the large induced energy spread (1.2 GeV). Generally the plasma-induced energy spread for a 1 ps slice is small (<80 MeV) and the vertical beam size is expected to increase by less than ≈15%.

VII. CONCLUSION

A beam-driven plasma wakefield acceleration (PWFA) experiment, named E-157, has been approved at SLAC. The experiment will accelerate parts of an SLC bunch by up to 1 GeV/m over a length of 1 m. A single SLC bunch is used to both induce wakefields in the one meter long plasma and to witness the resulting beam acceleration. The experiment will explore and further develop the techniques that are needed to apply high-gradient plasma wakefield acceleration to large scale accelerators. The one meter length of the experiment is about two orders of magnitude larger than other high gradient plasma acceleration experiments and the 1 GeV/m accelerating gradient is roughly ten times larger than that achieved with conventional metallic structures. Using existing SLAC facilities, the experiment will allow the study of high gradient acceleration at the forefront of advanced accelerator research.

The development of the different parts of the experiment is well under way. The proposed plasma cell has been built at UCLA and is presently being tested. The beam-induced plasma wakefields have been modeled at USC. The transport of the SLC beam into the FFTB, through the plasma cell and into the beam dump has been studied carefully at SLAC. Finally, the appropriate beam diagnostic has been specified based on the extensive experience at SLAC and LBNL.

We can envision a rich physics program of follow-on experiments not discussed here. Some of these include tests of beam shaping to demonstrate the possibility of high transformer ratios [16], the use of a separate witness beam with a variable delay to fully probe the wakefields [17], the guiding of laser beams with the SLC beam in a plasma over hundreds of Rayleigh lengths [18] and the outcoupling of the plasma wakes as a unique high-power 100 GHz source [19]. We also note that the peak accelerating gradient in the experiment is expected to increase from 1 GeV/m to 2.5 GeV/m if the SLC rms bunch length can be reduced from 0.6 mm to 0.4 mm. The successful completion of the experiments, hopefully in 1999, will undoubtedly provide a major impetus to advanced accelerator research as well as contribute to the fundamental understanding of plasma and beam physics in a new regime.

---

[1] C. E. Clayton et al, K. Nakajima et al. To be published in Proc. Adv. Accelerator Concepts Workshop, Lake Tahoe, 1996 (AIP, NY 1997), S. Chattopadhay (Ed.).

[2] R. Assmann et al, SLAC Proposal E157.

[3] D. H. Whittum, W. H. Sharp, S. S. Yu, M. Lampe, and G. Joyce, Phys. Rev. Lett. 67 pp. 991-994, 1991; M. Lampe, G. Joyce, S. P. Slinker, and D. H. Whittum, Phys. Fluids B 5, pp. 188-1901, 1993.

[4] V. E. Balakin et al, “Focusing of Submicron Beams for TeV-Scale E+ E- Linear Colliders”, Phys. Rev. Lett. 74 pp. 2479-2482, 1995.

[5] M. Berndt et al, “Final Focus Test Beam: Project Design Report”, SLAC-0376, Mar 1991.

[6] C. Bula et al (E144 Collaboration), “Observation of Nonlinear Effects in Compton Scattering”, SLAC-PUB-7221, Feb 1996. Submitted to Phys. Rev. Lett.

[7] “PEP-2: An Asymmetric B-Factory.” Conceptual design Report, SLAC-418, 1993.

[8] R. Assmann et al, “LIAR: A New Program for the Modelling and Simulation of Linear Accelerators with high Gradients and Small Emittances”, SLAC-PUB-7300, Sep 1996. Talk given at 18th International Linac Conference (Linac 96), Geneva, Switzerland, 26-30 Aug 1996.

[9] R. Assmann et al, “LIAR - A Computer Program for Linear Accelerator Simulations (User’s Guide)”, SLAC/AP-103.

[10] J. B. Rosenzweig, B. Breizman, T. Katsouleas, and J. J. Su, “Acceleration and focusing of electrons in two-dimensional nonlinear plasma wakefields”, Phys. Rev. A. 44, pp. R6189-R6192, 1991; D. Whittum, Ph.D. Thesis, UC Berkeley (1990).

[11] B.N. Breizman, T. Tajima, D.L. Fisher and P.Z. Chebotaev, “Excitation of Nonlinear Wake Fields in a Plasma for Particle Acceleration”. In: “Research Trends in Physics: Coherent Radiation and Particle Acceleration”, edited by A. Prokhorov, AIP Press, New York, 1992, p. 263-287.

[12] MAGIC code, Mission Research Corporation, United States.

[13] J. M. Dawson, “Nonlinear electron oscillations in a cold plasma”, Phys. Rev. 133, pp. 383-387, 1959.; T. Katsouleas and W. B. Mori, “Wave-breaking amplitude of relativistic oscillations in a thermal plasma”, Phys. Rev. Lett. 61, pp. 90-93, 1988; J. B. Rosenzweig, “Trapping, thermal effects, and wave wave breaking in the nonlinear plasma wakefield accelerator”, Phys. Rev. A. 38, pp. 3634-3642. 1988.

[14] C. R. Vidal and F. B. Haller, Rev. Sc. Inst., A2, 1779 (1971). C. R. Vidal, “Experimental Methods in the Physical Sciences”, Vol. 29B. Edited by F. B. Dunning and R. Hulet, Academic Press 1996.

[15] W. Kimura, STI, private communication.

[16] P. Chen, J. J. Su, J. M. Dawson, K. L. F. Bane and P. B. Wilson, “Energy Transfer in the Plasma Wakefield Accelerator”, Phys. Rev. Lett. 56, p. 1252, 1986.

[17] J. B. Rosenzweig et al, “Experimental Observation of Plasma Wakefield Acceleration”, Phys. Rev. Lett. 61, 98, 1988.

[18] G. Shvets and T. Katsouleas, private communication. The displacement of plasma electrons by the SLC beam

increases the refractive index on the beam's axis and enables guiding of the laser light.

[19] J. Yoshii, C. H. Lai, T. Katsouleas, C. Joshi, W. B. Mori, "Cerenkov Radiation from Magnetized Plasma Wakes", submitted to Phys. Rev. Lett., 1997.