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PLASMA PHYSICS WITH GEV ELECTRON BEAMS (PREPARED FOR COMMENTS ON PLASMA PHYSICS)

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Recently approved plasma accelerator and lens experiments at the Stanford Linear Accelerator Center (SLAC) will explore the acceleration and focusing of high-current high-energy electron beams (i.e., multi-GeV) interacting with a plasma. These experiments represent a new regime of relativistic plasma and beam physics. Some of the rich array of physical phenomena that can be explored are described here including high-gradient electron acceleration in the blowout regime, transverse beam dynamics (betatron motion and emittance evolution) in a long plasma, electron hose instability and saturation mechanisms, wakefield transformer ratios that violate the fundamental wakefield theorem, impact ionization and associated beam modulation and acceleration, and guiding of lasers with particle beams.

INTRODUCTION

The last few years have seen a small explosion in the field of plasma-based particle accelerators[1]. Experiments at laboratories around the world, including RAL (UK), KEK/JAERI (Japan), ILE Osaka (Japan), Chalk River (Canada), Ecole Polytechnique (France), UT Austin, U. Michigan, NRL, LLNL, and UCLA have successfully demonstrated the basic viability of ultrahigh gradient acceleration in relativistic plasma waves. Acceleration rates as high as 100 GeV/m have been measured (compared to 20 MeV/m typical of conventional linear accelerators); maximum energies of 100 MeV have been obtained with modest emittances (a few mm-mrad)

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and significant charge (up to nanoCoulombs). All of this high-gradient acceleration has taken place in plasma wakes driven by high-intensity lasers.

Large amplitude plasma wakes may also be driven by a high-current short-pulse particle beam. The wake may then be used to accelerate a secondary beam to higher energy. This is the scheme known as the Plasma Wakefield Accelerator[2]. Unfortunately, there are far fewer laboratories with appropriate beam sources to drive such wakes than there are laboratories with appropriate high-power laser sources. As a result, very few experiments to date have explored particle-driven wakes[3] and none has explored the large amplitude regime of interest for high gradient accelerators. The maximum plasma wake amplitude of an electron bunch scales as current over pulse length ($\tau = 2\sigma_z/c$):

$$eE_z \cong 1\mathrm{GeV/m}\frac{I}{\mathrm{kAmp}}\cdot\frac{4\mathrm{ps}}{\tau} \qquad (1)$$

Thus a 1kAmp in 4 ps pulse is needed to generate for example a 1GeV/m wake. Recently, a proposal to test the Plasma Wakefield Accelerator concept was approved at the Stanford Linear Accelerator Center (SLAC). The SLC beam at SLAC is a 30 GeV* electron beam with sufficiently high current and short pulse length (6.4 nC in $\sigma_z = 2.1$ ps) to excite a high field wake of order 1GeV/m in a plasma of density $2 \times 10^{14}\mathrm{cm}^{-3}$. The main goal of the SLAC experiment (known as E-157) is to accelerate a piece of the beam by 1 GeV over 1 meter of plasma. The availability of such a beam opens the possibility of major advances in advanced accelerators and new horizons for research in plasma physics. In this comment we describe some of the new possibilities that may emerge for acceleration milestones and new plasma physics with GeV electron beams. First, we review the rationale for the proposed SLAC experiment. Then we discuss possible pathways to scaling from 1 GeV to 10 GeV and finally to TeV class accelerators. Such advances necessarily involve new physics and technology issues that have not as yet been addressed experimentally. We identify the major issues and discuss possibilities for experimental exploration of these with the present beam facility.

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* Although such high energy is not needed for this experiment, the stiffness of such high γ beams makes for a cleaner experiment and easier diagnosis of the results.

RATIONALE FOR THE PROPOSED EXPERIMENT

The basic idea of the plasma Wakefield experiment proposed at SLAC is conceptually simple. As illustrated in Fig. 1, the SLC beam's space charge displaces plasma electrons, creating a wake which decelerates the main body of the beam. The tail of the beam sits in an accelerating phase of the wake. A collaboration of researchers[4] from SLAC, USC, UCLA and LBNL have proposed to measure the energy gain of the tail of the beam. Based on particle-in- cell simulations[4,5], the tail is predicted to gain up to 1 GeV in energy over a meter long plasma length. Such an energy gain represents an order of magnitude increase over the largest energy gains in plasma to date, as well as an extension of the scale of high-gradient plasma accelerators from millimeters to a meter. It will also be the first experiment to generate GeV/m gradients in a particle-driven experiment. The nominal parameters of the experiment are given in Table I below.

TABLE I List of beam parameters for the E-157 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

	E-157	*Standard SLC*
Bunch intensity (*)	3.5–4.0 10^{10} electrons	3.5–4.0 10^{10} electrons
Bunch length (*)	0.6 mm	0.6–1.1 mm
Rate into the FFTB	10 Hz	1 – 120 Hz
Beam energy	30 GeV	46.6 GeV
Emittance $\gamma\varepsilon_x$	60 mm-mrad	45 mm-mrad
Emittance $\gamma\varepsilon_y$	15 mm-mrad	8 mm-mrad
Spot Size σ_x	< 100 μm	23 μm
Spot Size σ_y	<100 μm	37 μm

Beyond its advanced accelerator milestone goals, the experiment has several physics goals. There are three critical issues for advancing plasma accelerator research that can be addressed with the setup of the proposed experiment. These are:

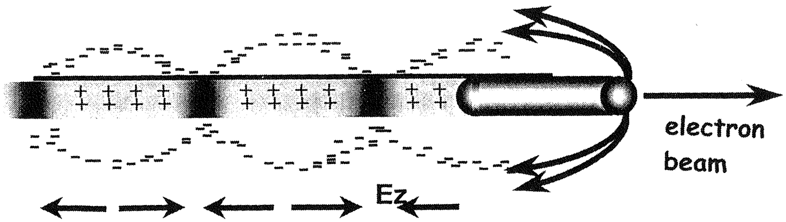


FIGURE 1 Physical Principles of the Plasma Wakefield Accelerator

Accessing the good field structure properties of the nonlinear or "blowout" regime of Wakefield accelerators;

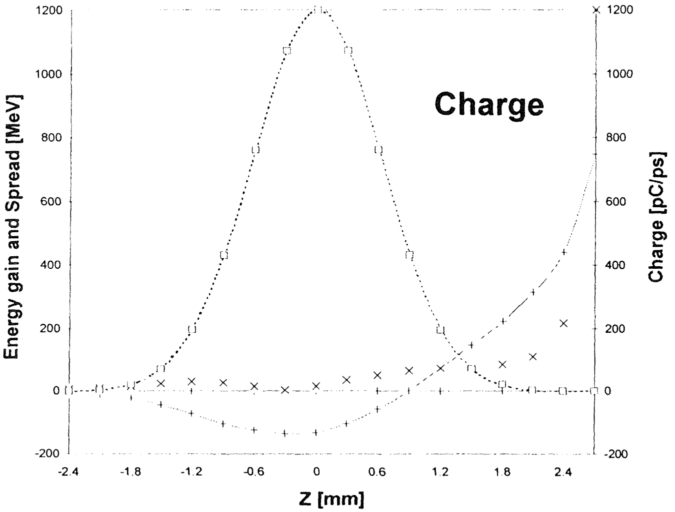
Measuring the transformer ratio (ratio of the accelerating electric field behind the beam to the decelerating field within the beam);

Studying transverse beam dynamics and beam propagation in a long plasma.

Each of these is described briefly below.

i. *The "blowout" regime*[6]. When the drive beam density exceeds the plasma density, the response of the plasma becomes nonlinear. The plasma electrons are radially expelled by the head of the beam, leaving the heavier ions in the beam's path. The ions provide a net focusing wake $W_\perp$ (= force per unit charge) $\approx 2\pi n_0 er$ everywhere along the blowout region (i.e. independent of z). From the Θ-component of Faraday's Law, the longitudinal wake W_{11} is related to $W_\perp$ by $\partial W_{11}/\partial z$. Since $W_\perp$ is independent of z, W_{11} is constant in r. Such a field structure is ideal for accelerating beams of the highest quality. For example, there is no contribution to energy spread from particles sampling different accelerating fields (W_{11}) at different radii. In the proposed experiment, the nominal beam density is five times the background plasma density and will be strongly in this blowout regime.

ii. *The Transformer Ratio.* The transformer ratio determines the ultimate limit on the energy gain of a trailing beam as a function of the drive beam's energy. Linear symmetric beams are limited to a transformer ratio of[7] 2; i.e., a trailing beam particle can gain at most twice the energy of the particles in the drive beam. By using a streak camera to slice the SLC beam energy diagnostic at 1 ps intervals, it will be possi-



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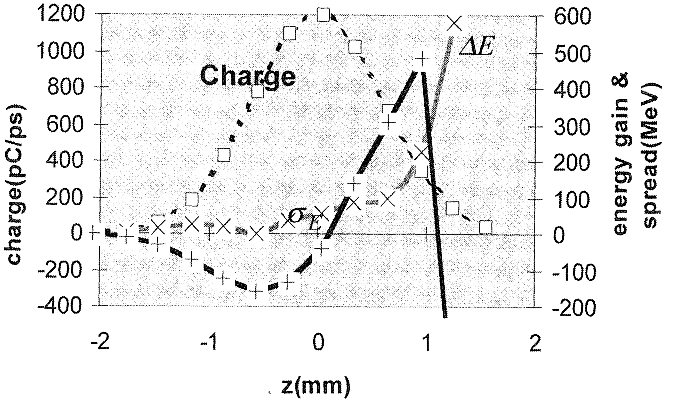

FIGURE 2 Energy change (..+..) and absolute energy spread (.x.) of 1 ps slices along the bunch for plasma densities of 4 × 10^{14}cm^{-3} (a) and 2 × 10^{14} cm^{-3} (b)

ble to measure the wakefield experienced by each slice along the beam. This enables direct confirmation of the transformer ratio limit of two. Moreover, by changing the plasma parameters, we can move the experiment to nonlinear regimes where the transformer ratio limit of 2 no longer applies. The PIC simulations by Seung Lee in Fig. 2 compares simulated Wakefield measurements at two operating points for the plasma density. In the first ($n_o = 4 \times 10^{14}\text{cm}^{-3}$), the transformer ratio is slightly above 2. In the second ($n_o = 2 \times 10^{14}$ cm^{-3}), the transformer ratio is 4.7. In addition to the magnitude of the transformer ratio, its shape is very important since it determines the potential efficiency of the PWFA. That is, a decelerating wake that is fairly flat (independent of z) will slow all the drive beam particles at the same rate and extract the greatest energy from the beam before it stops or distorts. The streak camera diagnostic in E-157 enables experimental investigation of the profile of the decelerating wake in plasma wakefield accelerators.

iii. *Transverse Beam Dynamics*[8] The drive beam in the PWA is strongly pinched by the mechanism described in part (i) above (essentially, the plasma lens effect). This raises many questions about the transverse dynamics of this beam. Based on the envelope equation of beam optics with the underdense plasma lens focusing force, the drive beam is nominally expected to undergo 3 oscillations over a one meter plasma length. By varying the density-length product of the plasma, the theoretical scaling of the betatron wavelength can be measured. In future plasma accelerators it will often be desirable to avoid betatron oscillations of the beam. This can be done by matching the beam beta function to the beta associated with the focusing force in the plasma. In the SLAC experiment the matching of the beam and plasma could be done by spoiling the emittance of the beam (e.g., by passing it through a thin foil of appropriate thickness). In this case, the main body of the beam should propagate the full meter at a stable radius without oscillating. Such an experiment would be an important step in demonstrating control over transverse beam dynamics in plasma accelerators.

FUTURE EXPERIMENTS IN THE DEVELOPMENT OF THE PWFA

As described above, the proposed experiment will test many issues important to a 1-GeV module of a future plasma accelerator. It is reasonable then to ask what is the next step and how far away is it? As it turns out, not far at all.

(i) Bunch Munching and Pulse Length Scaling

Based on the scaling in Eq. (1), for a fixed bunch charge, the wake gradient scales inversely with the *square* of bunch length; thus in principle a simple reduction in pulse length from σ=.63mm to σ=.2mm could increase the wake by a factor of ten. Then it becomes possible to create a 10 GeV module that is one meter long. Thus an important physics experiment is a test of the scaling law in Eq. (1). It may be possible to study such scalings using "bunch munching" techniques (via rf induced correlated energy spreads on the drive beam) to vary the length of the SLC beam.

(ii) Electron Hose Instability[9]

To achieve still higher energies in a plasma accelerator there are at least two options: One is to stage the 1–10 GeV modules. The second is to employ a longer drive beam (more than a plasma wavelength $\lambda_p = 2\pi c/\omega_p$) and shape its longitudinal profile to increase the transformer ratio. Such longer beams, however, are subject to instabilities such as the electron hose instability. Thus a critical physics experiment is the study of electron hosing of GeV beams. The growth rate for this instability is given in various limits. An asymptotic scaling for the number of e-foldings is

$$N_e \sim \frac{6}{\gamma^{1/6}} \left(\frac{z}{\lambda_p}\right)^{1/3} \left(\frac{c\tau}{\lambda_p}\right)^{2/3}$$

z is the plasma length ≈ 1m. For the nominal parameters of the E-157 experiment N_e is only five and hosing should occur weakly if at all. However, simply raising the plasma density by an order of magnitude yields $N_e = 50$ and strong hosing may be expected. Thus, it should be possible by raising the plasma density to study the onset and growth of electron hosing. Moreover, stabilization can be studied. For example, narrowing the plasma channel is expected to limit hose growth. This can be done in the experiment by using a narrower laser beam to ionize the plasma source.

(iii) Bunch Shaping and High Transformer Ratio Experiments

If the hosing can be overcome, then bunch shaping to achieve large transformer ratios may be feasible. Bunch shaping techniques and transformer ratio diagnostics are important topics to be explored by present and/or follow-on experiments. For example, linear theory predicts that wake amplitudes of 10 GeV/m and a transformer ratio greater than 10 could be obtained in principle from a SLAC bunch if it could be reshaped into a half-Gaussian with the same rise length (σ_+ = .6 mm or 2ps) and short cut-off length (σ_- = .06mm or .2ps).

(iv) Positron Acceleration

Since the SLC is an electron-positron collider facility, the possibility exists for accelerating positrons in the wake of an electron bunch (though not in the current location of the experiment). This could demonstrate the viability of positron acceleration in plasmas as well as improve the diagnostic resolution of the experiment. In addition, there is the very interesting possibility of studying non-linear wakes excited by positron beams. In the positron counterpart to the nonlinear blowout regime, the positron wake will be created by sucking in rather than blowing out the plasma electrons. Positron beams open a whole new arena for non-linear plasma research.

FUTURE EXPERIMENTS ON ACCELERATOR APPLICATIONS AND BASIC PLASMA PHYSICS

(i) Energy Spread Compensation

Linacs such as the SLC and the future NLC purposely design and spread from the head to the tail of the beam in order to damp beam breakup instabilities. This energy spread is undesirable at the final collision. For the NLC design the spread is quite large, approximately 5 GeV with the head at higher energy than the tail. S. Heifets and T. Raubenheimer have proposed the use of a plasma wake to accelerate particles in such a way as to cancel the energy spread of the beam[10]. This scheme may become a near term application for plasma engineering in next generation accelerators. Since the present SLC beam has a similar correlated energy spread, it is possible to test this scheme with the SLAC experimental setup. By slightly raising the plasma density to shorten the wake wavelength, the wake can be made to decelerate the head and accelerate the tail half of the beam. Thus, it is possible to design a passive plasma such that placing it in the path of the beam reduces the beam's energy spread and improves its beam quality. An improvement on this concept would be a two bunch experiment in which the first bunch excites a wake that is used to remove the energy spread on the second bunch.

(ii) Plasma Lenses

As the energy of linear colliders increases, so too does the length and complexity of the final focusing system just prior to the interaction point. Paper designs for the NLC (next linear collider) are kilometers long. This length requirement could be greatly reduced if the focusing strength of the final lenses were much greater than what is possible with conventional quadruple magnet technology (of order 10kG/cm). The focusing strength associated with a plasma lens[11] scales as $3\text{x}10^4 \mathrm{kg/cm} \times \frac{\mathrm{n}}{10^{16}\mathrm{cm}^{-3}}$, where n is the smaller of the beam density and the plasma density. For the parameters of the SLC at a spot size of 5µm, and a plasma density of $10^{17}\mathrm{cm}^{-3}$ the focusing strength in the plasma would be 300 MG/cm. An experiment to test just such a plasma lens has been approved at SLAC (designated E-150)[12]. The goal of this experiment is to focus a 5µ beam to approximately 1µ by passing it through a 1–3 mm thick plasma. Such a test is an important step toward realizing a plasma lens in a future linear collider.

(iii) Beam-induced Ionization and Self-modulated Acceleration

In analogy with current laser experiments in the self-ionized, self-modulated regime, it will be of interest to perform the corresponding experiment with a GeV beam. The idea is to replace the plasma source with a high-density neutral gas. Beam-neutral collisions will begin to ionize the gas. The beam space charge will accelerate these electrons radially causing them to produce further ionizations (secondaries). When the plasma density is high enough, instabilities will begin to modulate the driving beam. The modulated beam can then resonantly excite a large plasma wake which may in turn self-trap and accelerate electrons. This is a rich and complex regime of plasma Wakefield acceleration that has yet to be explored.

(iv) Laser Guiding by a GeV Beam in a Plasma

As mentioned previously, current laser experiments are limited to mm scale lengths. This is mainly because of the short diffraction length of the focused lasers. Accordingly, techniques for optically guiding the intense lasers over long distances, such as the use of preformed channels are actively being pursued[13]. Instead of using a channel it is of interest to use a high density particle beam to guide the laser. The guiding mechanism is as follows. The GeV beam displaces plasma electrons until the beam is neutralized or all plasma electrons are expelled (if the beam density is high). This causes the index of refraction in the beam region to be $\eta = (1 - \omega_p^2/\gamma\omega^2)^{1/2}$, where γ is the Lorentz factor of the beam. For a GeV beam, $\gamma \sim 10^3 \gg 1$ and η approaches 1. Outside the beam $\eta = (1 - \omega_p^2/\omega^2)^{1/2} < 1$, SO the beam can be guided. It will be of interest to overlap a long laser pulse (e.g., 1 ns) with the 4 ps particle beam, co-propagating in the plasma. All but the overlapping portion of the laser will diffract strongly. Thus a short (<4 ps) piece of the laser will be effectively chopped out and transported up to a meter.

SUMMARY

In summary, the interaction of GeV beams and plasmas represents a new regime for basic and applied plasma and beam research. The possibilities for new experiments and new discoveries are rich and varied.

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