Progress Report
For the period
Since November 15, 2002

for

**“Program for Plasma-Based Concepts for
Future High Energy Accelerators”**

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Program for Plasma-Based Concepts for Future High Energy Accelerators

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Progress Report

The progress made under this program in the period since November 15, 2002 is reflected in this report. The main activities for this period were to conduct the first run of the E-164 high-gradient wakefield experiment at SLAC, to prepare for run 2 and to continue our collaborative effort with CERN to model electron cloud interactions in circular accelerators. Each of these is described briefly below. Also attached to this report are papers that were prepared or appeared during this period.

Highlights of the accomplishments during this contract period:

1. E-164 run I. The first run of the E-164 experiment took place from March 17 to April 28 2003. For this run electron bunch length was shortened from $\approx 700 \mu\text{m}$ to $\approx 100 \mu\text{m}$ in order to bring the expected gradient from a few hundred MeV/m to the GeV/m level. To optimize the accelerating gradient the plasma density had to be increased by the bunch length reduction factor squared, or a factor of about 50 to $n_e \approx 6 \times 10^{15} \text{cm}^{-3}$. The pre-ionized plasma is obtained by laser photo-ionization. This high density could be reached only over a distance of $\approx 30 \mu\text{m}$ with the available laser beam energy and fluence. However, experimental results showed that, for most of the beam parameters (radius $\approx 25 \mu\text{m}$ at the plasma entrance, $> 1.3 \times 10^{10}$ electrons per bunch), the beam radial field were sufficiently large to field ionize the ambient neutral lithium vapor in the plasma source. Field ionization is a threshold process which, when the threshold is exceeded, leads to full ionization of the neutral vapor density n_0 ($n_e = n_0$), therefore leading to a plasma density much larger than the one expected for laser ionization ($\approx 10\%$ of n_0). Images of the beam dispersed in energy showed that the energy loss by the beam in the field-ionized plasma was extremely large, exceeding 1.5 GeV over the 30 μm plasma length, therefore corresponding to decelerating gradients well exceeding 4 GeV/m. Ionizing the vapor to a low density prior to the beam arrival led to more of the beam charge losing energy, but did not increase the maximum energy loss. Clear thresholds for the ionization process were observed as a function of the number of particles in the bunch, bunch radius, and bunch length. The electron bunch enters the plasma with a correlated energy spread resulting from the strong longitudinal linac wakefields. The full width of energy chirp is of the order of $\approx 3\%$ of the incoming energy (or $\approx 1 \text{ GeV}$), with the head of the bunch at the higher energies. In previous long bunch experiments the energy spectrum was dispersed in time to observe energy gains in the back of the bunch, with magnitudes smaller than the incoming chirp. With 100 μm long bunches (1/3 ps), time resolution is not available and only energy gains larger than the incoming energy chirp can be observed on time integrated energy spectra. No clear energy gain was observed during

the experiment. Numerical simulations indicate that when the beam parameters are close to the ionization threshold, the dynamics of the field ionization and of the wake excitation compete along the bunch. This competition does not suppress the energy loss expected in the high density plasma. However, the return of the plasma electrons on axis to create the accelerating part of the wake is suppressed, and very little energy gain is observed. Numerical simulations also indicate that for bunch parameters such that the radial field far exceeds the ionization threshold field, field ionization appears early enough in the bunch so that the wake formation process similar to that observed in a pre-formed plasma is recovered. Large energy gains are therefore expected for shorter bunches (20-100 fs) that are now available at SLAC. The E-164 run II will therefore use shorter bunches than originally planned for E-164.

2. E-164 run II preparation. A number of upgrades were undertaken for run 2 of E-164 including a new plasma source, new simulation models and new diagnostics.

E-164 run I results indicate that pre-ionization of the gas/vapor is not necessary when using short bunches. Numerical simulations we performed during this contract period indicate that to allow for the field-ionization and the wake excitation to happen within the electron bunch, the optimum plasma density (for a given bunch length) is significantly larger (2 to 3 times) than indicated by the linear theory in a preformed plasma. Lithium neutral densities in the $3 \times 10^{16} \text{ cm}^{-3}$ range are optimal, which would require temperatures exceeding 1000 K to reach the appropriate vapor densities. Therefore a cesium oven is under development to reach similar neutral densities and vapor pressures in the 500-600 K range. The field-ionization process was added to the OSIRIS code in the previous contract period (see progress report for 2002) in order to model the short bunch experiments. Extensive simulations have been performed to identify the parameters that will be required to observe energy gain in this experiments. Differences between lithium (5.4 eV ionization potential) and cesium (3.5 eV ionization potential) have also been identified. Calculations show that hydrogen can be ionized by the shortest and most focused bunches available, and simulations show that large amplitude wakes can be driven. A field-ionized plasma offers a possible solution for the $\approx 10 \text{ cm}$ long plasma source required for a plasma afterburner. A hydrogen cell with differential pumping with respect to the accelerator vacuum was also developed. This cell will allow us to cover a large range of plasma densities simply by changing the hydrogen pressure and will also allow for the variation of the plasma length simply by moving the exit pinhole along the beam axis. This feature is very important since the energy acceptance of the FFTB dump line is limited. The energy gain will be maximized (at a plasma density or accelerating gradient) by adjusting the plasma length so as to fill the FFTB dump line energy acceptance.

Numerical simulations using the longitudinal dynamics beam code LiTrack have also been performed in collaboration with Paul Emma at SLAC. The goal is to minimize the incoming beam energy spread, and also to create a population of particles trailing the core of the short bunch in order to more efficiently populate the accelerating phase of the wake. These particles also have an energy close to that of the beam head, so as to minimize the amount of energy gain necessary for them to rise above the head particles energy and become visible on the time integrated energy spectra. Graduate student Erdem Oz and a visiting science teacher from the LA Unified School District, Bill

Quilinan, performed an extensive parameter search to find conditions for linac operation that optimize the plasma acceleration experiment. Mr. Oz and graduate student Suzhi Deng have begun to integrate the LiTrack output with the OSIRIS input module to give a complete simulation from damping ring to plasma exit.

A key parameter for the experiment is the electron bunch length. We are developing a coherent transition radiation (CTR) interferometer to attempt to measure the incoming bunch length. The interferometer will be used to monitor the bunch length and to optimize the linac parameters to achieve the shortest possible bunches. An imaging optical spectrometer will also be installed to look at the plasma light. The intensity of atomic lines (in lithium or cesium) provides information about the energy lost by the beam in the plasma, and observation of Cherenkov radiation on the long wavelength side of atomic emission lines can provide information about the plasma density. Other improvements such as thinner optical transition radiation foils will also be included in the upcoming experiment.

Finally, graduate student Jitendra Kulshresta has begun a pilot project to parallelize the data acquisition and analysis procedure in the E-164 laboratory. A prototype 3-node cluster computer has been built from used processors at USC and networked. We are using a temporary license from an outside vendor to test a parallel Windows environment. Although, we have greater experience in our computational group with linux clusters, using a Windows cluster will obviate the need to extensively re-write the lab software which is windows based. Our goal is to have a 3-node demonstration of the “superbatch” data analysis routine by the end of this contract period with a goal of having a full 10-node cluster ready for E-164X experiments next year. Ultimately, this will reduce the turnaround time for basic data analysis during data taking from over 30 minutes to under 3 minutes. At that timescale, results can be interpreted in real time rather than sometimes long after a shift.

3. Electron Cloud Instability Modeling. During this period graduate student Ali Ghalam has further developed our model for beams interacting with electron clouds in a circular accelerator. It is built on the algorithm for QuickPIC that we use for modeling plasma wakefield accelerators (the e-cloud is after all a non-neutral plasma problem). The QuickPIC code is based on Viktor Decyk’s Framework for developing parallel PIC codes. This includes highly optimized components and parallelization.

First physics results from the model were obtained this contract period and the results recently published in Phys. Rev. STAB (attached). The current effort is aimed at benchmarking the model against others at CERN and Japan. The QuickPIC model is now the most sophisticated model for beam-cloud interactions in the world today. We are seeing good agreement between our model and others when some of the features in our model that are not in the other models are removed for comparison purposes. However, when the full physics is included in the QuickPIC model, the results change, suggesting that only the QuickPIC model can potentially reproduce experiments with high fidelity.

APPENDIX: Attached Reprints

1. S. Deng, *et al.*, “Plasma Wakefield Acceleration in Self-ionized Gas or Plasmas,” To appear in **Physical Review E** 68
2. G. Rumolo, *et al.*, “Electron Cloud Effects on Beam Evolution in a Circular Accelerator,” **Physical Review Special Topics – Accelerators and Beams**, Volume 6, 081002 (2003)
3. C. Joshi and T. Katsouleas, “Plasma Accelerators at the Energy Frontier and on Tabletops,” **Physics Today**, June 2003.
4. K.A. Marsh *et al.*, “Positron Beam Propagation in a Meter Long Plasma Channel,” **Particle Accelerator Conference Proceedings**, 2003.
5. R. Bingham, “In the Wake of Success,” **Nature**, Vol. 424, July 17, 2003.
6. B.E. Blue, *et al.*, “Plasma-Wakefield Acceleration of an Intense Positron Beam,” **Physical Review Letters**, May 30, 2003.
7. T. Katsouleas, “The New Hot Rods of the Physics World,” **Physics World**, February 2003.
8. P. Schewe, *et al.*, “Plasma Wakefields Accelerate Positrons,” **Physics News Update**, Number 637 #1, May 14, 2003.

Plasma wakefield acceleration in self-ionized gas or plasmas

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Tunnel ionizing neutral gas with the self-field of a charged particle beam is explored as a possible way of creating plasma sources for a plasma wakefield accelerator [Bruhwiler *et al.*, Phys. Plasmas (to be published)]. The optimal gas density for maximizing the plasma wakefield without preionized plasma is studied using the PIC simulation code OSIRIS [Vahedi and Surendra, Comput. Phys. Commun. **87**, 199 (1995)]. To obtain wakefields comparable to the optimal preionized case, the gas density needs to be seven times higher than the plasma density in a typical preionized case. A physical explanation is given.

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Recently, there is great interest in a plasma wakefield accelerator (PWFA) as a possible energy doubler (or afterburner) for a linear collider [1]. In the afterburner as well as in an upcoming experiment at SLAC (E164) [2], a high-density short bunch is used to drive nonlinear (blowout regime [3]) plasma wakes and multi-GeV peak accelerating gradients. One critical issue for both experiments is the need for long homogeneous plasma sources of high density—up to 10 meters of $2 \times 10^{16} \text{ cm}^{-3}$ plasma for the afterburner. For UV single-photon ionized metal vapors, laser ionization typically can ionize gases up to a density-length product of order $10^{15} \text{ cm}^{-3} \text{ meters}$ per 100 mJ of laser energy.

Recently, Bruhwiler *et al.* [4] proposed the possibility of creating plasma sources by tunnel ionizing neutral gas with the self-field of the driving beam. There have also been some previous experiments that showed evidence of ionization by short pulse beams in gases, although the mechanism for those was impact ionization [5,6]. In this paper, we revisit this topic, and extend the work of Bruhwiler *et al.* by studying the optimal gas density for maximizing the plasma wakefield. The ionization and wake generation are modeled with the PIC code OSIRIS [7]. We find that for parameters typical of the above experiments, the wakefield is much smaller than in the preionized case when the gas density is equal to the

optimal plasma density [8]. Increasing the gas density by a factor of about seven yields wakefields comparable to the optimal preionized case. A physical explanation for this behavior is given.

The physical problem and nominal parameters modeled in this paper are the following: A 50 GeV beam consisting of 2×10^{10} electron particles has a Gaussian distribution with rms radius $\sigma_r = 20 \text{ } \mu\text{m}$ and length $\sigma_z = 63 \text{ } \mu\text{m}$. The beam is incident upon neutral (un-ionized) gas. Initially the gas (here we use Li gas) density is set to be $n_0 = 1.4 \times 10^{16} \text{ cm}^{-3}$, which approximately maximizes the wakefield amplitude in a preformed plasma (according to the linear theory, the optimal density corresponds to $\omega_p \sigma_z / c = 2^{1/2}$ [8]). As described in Ref. [4], the self-fields of the drive beam are so strong that they can ionize the neutral gas and create plasma when the beam passes through the neutral gas. But the wakefields created are much smaller than in the preionized case because the electrons are not created quickly enough through ionization to respond resonantly to the drive beam. One way to solve this problem is to use a higher-density drive beam. Here we consider another solution—increasing the gas density. Two-dimensional (2D) PIC simulations are done with the OSIRIS code, which includes an ionization package. The ADK tunnel ionization model [9] is used in the code.

FIG. 1. (a) Real space r vs z of ionized electrons. (b) 2D contour of E_z field. [Axes in both (a) and (b) are in units of c/ω_p . Here $c/\omega_p = 44.8 \text{ } \mu\text{m}$.]

The simulation parameters are the following:

d_t	$t_{\max}$	System size		Grid size		Beam center position	
$0.037/\omega_{p0}$	$52.2/\omega_{p0}$	$z = 48c/\omega_{p0}$	$r = 8c/\omega_{p0}$	$z = 400c/\omega_{p0}$	$r = 200c/\omega_{p0}$	$z = 35c/\omega_{p0}$	$r = 0c/\omega_{p0}$

Here $\omega_{p0} = 6.69 \times 10^{12}$, corresponding to a plasma density $n_0 = 1.4 \times 10^{16} \text{ cm}^{-3}$. The same n_0 and ω_{p0} will be used throughout this paper.

We did six runs separately with gas density $n_{\text{gas}} = 1n_0, 3n_0, 6n_0, 7n_0, 8n_0, 10n_0$, as well as six runs with a pre-ionized (fully ionized) plasma. Sample simulation results are shown in Figs. 1–4.

Figure 1 shows the real space of ionized electrons and 2D contours of the accelerating wake electrical field E_1 for $n_{\text{gas}} = 3n_0$.

Figure 2 shows the amplitude of the wakefield versus gas or plasma density. The wakefield is scaled with the cold non-relativistic wavebreaking field $(mc\omega_p/e)E_p = 11.4 \text{ GV/m}$ at a plasma density of $1n_0$. The amplitude of the wakefield is quite small at $n_{\text{gas}} = n_0$. The amplitude increases with the gas density, and peaks around $n_{\text{gas}} = 7n_0$, while in the pre-ionized case, the wake peaks around $3n_0$. So the optimal density for maximizing the wakefields is higher for the self-ionization case than for the preionized case. (As expected even in the preionized case, the optimal density is larger than the linear theory optimal density n_0 because the nonlinear wake drives the plasma electrons relativistically, increasing their mass and decreasing the plasma frequency. The density must be higher to compensate for this frequency decrease.)

This behavior can be understood as follows. As the beam enters the neutral gas, the head of the beam cannot ionize the gas until its electric fields reach a threshold value. The rapidly ionized plasma “sees” an effectively shortened beam, because it does not see the head of the beam (i.e., it does not experience any electric forces from the head of the beam; for

relativistic beams the transverse electric field at any axial position depends only on the beam density at that position). In Fig. 4, the start position of the wake shows this effect clearly—the start position of the wake is delayed in the self-ionized case until a threshold value is reached. The effectively shorter beam then needs a higher gas density to match the plasma period (wavelength) to the effective pulse length. For threshold ionization near the peak of the beam density, the beam is effectively shortened by half its length. We may then expect the matched plasma density to be larger by a factor of 4 (to shorten the wavelength by two). Transverse effects may favor further increasing the gas density. The reason for this is this decreases the transverse area of the plasma that needs to be ionized to support the wake (proportional to the plasma blowout radius squared and inversely proportional to plasma density). These qualitative arguments are consistent with the simulations in which the optimal gas density was seven times the linear theory and 2.5 times the pre-ionized optimum density.

The wavelength in a wakefield accelerator is important to know both for optimizing the wakefield and for optimally loading a second beam of particles to be accelerated. Figure 3 shows the change of wake wavelength with density. The wavelength is normalized to $\lambda_p = 2\pi c/\omega_p$, where $\omega_p = (4\pi ne^2/m)^{1/2}$ and $n = n_{\text{gas}}$ or n_{plasma} for the self-ionized and preionized cases, respectively. For $n_{\text{gas}} = 1n_0$ to $4n_0$, the wakefield is not strong enough to fully ionize the neutral gas, so the plasma density is in fact smaller than the gas density, which leads to a longer wavelength. As the gas density increases, both the plasma density and the wakefields increase. The wakefields in turn cause more ionization. After the gas

FIG. 2. Scaled amplitude of the longitudinal electric field E_z/E_p vs gas or plasma density, $E_p = 11.4 \text{ GV/m}$ E_z/E_p .

FIG. 3. Scaled wavelength vs gas or plasma density, $\lambda_p = 2\pi c/\omega_p$, where $\omega_p = (4\pi ne^2/m)^{1/2}$ and $n = n_{\text{gas}}$ or n_{plasma} .

FIG. 4. Comparison of the longitudinal electric field of the preionized case and the self-ionized case. (The z axis is in units of c/ω_p . Here $c/\omega_p = 44.8 \mu\text{m}$.)

density increases to some point (around $4n_0$), the change of the wavelength with density for the self-ionization case parallels that of the preionized case: λ increases due to nonlinear effects and peaks at a density corresponding to the peak wake amplitude (around $n_{\text{gas}} = 7n_0$ for the self-ionized case and $n_{\text{plasma}} = 3n_0$ for the preionized case).

The above results support the thesis that self-ionization can be used as a way to create plasma sources for plasma wakefield accelerators. The beam wakefield can be made

comparable to the preionized plasma case if the gas density is increased appropriately.

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Electron cloud effects on beam evolution in a circular accelerator

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The interaction between a low-density electron cloud in a circular particle accelerator with a circulating charged particle beam is considered. The particle beam's space charge attracts the cloud, enhancing the cloud density near the beam axis. It is shown that this enhanced charge and the image charges associated with the cloud charge and the conducting wall of the accelerator may have important consequences for the dynamics of the beam propagation. The tune shift due to the electron cloud is obtained analytically and compared to a new numerical model (QUICKPIC) that is described here. Sample numerical results are presented and their significance for current and planned experiments is discussed.

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I. INTRODUCTION

Electron clouds have been shown to be associated with limitations in particle accelerators performance in several of the world's largest circular proton and positron machines [1]. Electrons accumulate in the vacuum chamber where a positively charged bunched particle beam propagates because of a multipacting process which involves primary electron generation (e.g., from residual gas ionization or from photoemission at the inner pipe wall due to synchrotron light) and their multiplication through secondary emission at the wall [2]. If the average secondary emission yield of the chamber material is greater than unity, the primary electrons accelerated in the field of the passing bunch can reach the pipe wall with a high enough energy to produce more electrons. The number of electrons in the pipe will then grow until an equilibrium is reached between the production rate (dominated by secondary emission) and the loss rate progressively increased by low energy electrons quickly repelled to the wall because of the high space charge field from the cloud itself. The presence of an electron cloud inside the beam chamber can deteriorate the vacuum [3,4], causing interference on the electrodes of beam pickup monitors [2] and make the beam unstable via bunch-to-bunch or head-tail coupling [5–8].

Although a number of beam-cloud interaction models that can satisfactorily explain many of the observations have been developed [9–15], the exact dynamics that leads to beam degradation (e.g., emittance growth, beam loss) is still under study for a more detailed understanding. In particular, previous models have been limited in that they treat the cloud in an impulse approximation [12] (giving a single kick per turn) Also, the conducting boundary of the pipe (and hence image forces of the cloud and beam charge) has not been included in the treatment

of the dynamics of the beam in these models although it may have been considered in the cloud buildup process [16–18]. In addition, there are discrepancies between the analytic models to date and the experimentally observed tune shifts.

In this paper we apply techniques from plasma physics and plasma wake field accelerator models to the study of the non-neutral plasma-beam interaction. We describe analytic and numerical models for the interaction between a positively charged beam and an electron cloud in a circular accelerator. Our model takes into account the effect of cloud image charges from the conducting beam pipe on the beam dynamics for the first time. We show that (i) the cloud space charge force is the dominant force in contributing to the coherent tune shift. (ii) The cloud compression on the axis of the beam along with its image charges on the conducting walls of the accelerator may not contribute to the coherent tune shift, but instead, play an important role in configuring the steady state beam dynamics. The simulation model is adapted from a particle in cell (PIC) plasma model of wake field accelerators in the quasistatic approximation [19]. The full description of the simulation tool and the modifications to adapt it to circular accelerator environment are given in Sec. II. The forces on the beam by the electron cloud and the cloud and beam image charges in the conducting wall are analyzed in Sec. III. In Sec. IV, the interaction between these forces (we study how these forces interact with each other) and their effects on the dynamics of the beam are studied. Section V is devoted to the tune shift due to the electron cloud. An analytic expression for the tune shift is derived and compared to the PIC simulation results. Finally, emittance growth and beam instabilities due to the beam-cloud interactions are discussed in Sec. VI.

II. DESCRIPTION OF THE SIMULATION MODEL (QUICKPIC) WITH THE SYNCHROBETATRON OSCILLATIONS

QUICKPIC is a new 3D PIC code based on the quasistatic or frozen field approximation [19–21]. This approximation is specifically useful for studying wakes. It requires that the beam does not evolve significantly on the time scale that it takes the beam to pass by plasma particles, or in other words, $\beta \gg \sigma_z$, where β is the average beta function and σ_z is the axial length of the beam viewed in the lab frame. This is typically well satisfied in the models discussed in this paper. The basic equations for QUICKPIC follow from the wave equations for A and ϕ in the Lorentz gauge as illustrated in the box in Fig. 1.

The quasistatic approximation assumes that the wakes are functions of $z-ct$ only so that the full set of Maxwell's equations reduces to equations for the wake potentials ϕ and $\Psi = \phi - A_{\parallel}$ that involve only solving 2D Poisson equations. The QUICKPIC cycle is illustrated in Fig. 2. The Poisson equations are solved on a 2D slab of plasma (using a well-established bounded 2D PIC code BEPS [22] as a subroutine) with conducting boundary conditions. The longitudinal motion of the cloud electrons and $V \times B$ force and the B field terms arising from their motion are neglected in the present implementation. This is typically valid as long as the spot size of the beam is significantly less than the collisionless skin depth of the cloud, c/ω_p , where ω_p is the plasma frequency associated with the cloud electrons, and the cloud particle velocities remain nonrelativistic. Both of these assumptions are valid here. The full quasistatic equation including relativistic and electromagnetic corrections is currently being implemented and will be available for future studies. Having assumed that the beam particles are moving relativistically and the cloud particles are nonrelativistic, the contribution of the longitudinal cloud particle's current density to the total current density is negligible although no assumption is made for the relative

FIG. 2. (Color) QUICKPIC cycle. A 2D Poisson solver is used to calculate potentials and update positions and velocities in the plasma slab. After the slab is stepped through the beam, the stored potentials Ψ and ϕ are used to push the 3D beam.

magnitude of the cloud and beam charge densities. No electron production is currently implemented in the code and cloud electrons are elastically reflected from the conducting walls of the chamber. The cloud is assumed to be generated by the preceding bunches and is assumed to be initially uniform and cold.

The wakes are stored and used to update the plasma in the slab and the slab is then pushed back a small step through the beam. After transiting the beam, the stored values of ψ are used to find the force on the beam (treated as a 3D PIC model) and it is pushed through a large step (of the order of $\beta/30$). In a standard electromagnetic PIC model the time step, Δt , is nearly cell size divided by the speed of light, $\Delta z/c$. For this quasistatic code, the time step is $\beta/30$ leading to 2 or 3 orders of magnitude fewer time steps and an identical savings of computing time. The code is highly optimized on a single processor and both the 3D outer layer and the 2D inner layer of the code are fully parallelized to allow domain decomposition along z and y , respectively.

As mentioned, the code is used for modeling plasma wake field accelerators. In order to enable QUICKPIC to simulate a bunch in a circular accelerator, some extra features were added to correctly model the bunch evolution. In particular, betatron and synchrotron oscillations of the beam particles are introduced. These oscillations

Maxwell equations in Lorentz gauge

$$\left(\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2\right) \mathbf{A} = \frac{4\pi}{c} \mathbf{j}$$

$$\left(\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2\right) \phi = 4\pi\rho$$

$$\mathbf{j} = \mathbf{j}_b + \mathbf{j}_e \approx \mathbf{j}_b = c\rho_b \hat{z} \quad (\mathbf{A} = A_{\parallel} \hat{z})$$

$$\Psi = \phi - A_{\parallel}$$

Reduced Maxwell equations

$$-\nabla_{\perp}^2 \mathbf{A} = \frac{4\pi}{c} \mathbf{j}$$

$$-\nabla_{\perp}^2 \phi = 4\pi\rho$$

Local-- ϕ, A at any z -slice depend only on ρ, j at that slice!

Forces:

$$plasma: \quad F_{e\perp} = -e\nabla_{\perp} \phi$$

$$beam: \quad F_{b\perp} = -e\nabla_{\perp} \Psi$$

FIG. 1. (Color) Quasistatic or frozen field approximation used in QUICKPIC.

are due to the external fields of the magnets and rf power in the accelerator. Under the effect of these forces, individual particles (and the bunch as a whole, if off centered) execute oscillations in all three spatial coordinates. The frequency of the transverse oscillation of the single particle has been made dependent upon its longitudinal momentum offset to take into account also chromatic effects that seem to play an important role in the unstable evolution of the beam [12]. The equations of motion of a single beam particle in transverse and longitudinal directions implemented in QUICKPIC are as follows:

$$\frac{d^2x}{dt^2} + \left[Q_x + \Delta Q_x \left(\frac{\delta p}{p_0} \right) \right]^2 \omega_0^2 x = \frac{1}{m_p \gamma} F_{cl_x},$$

$$\frac{d^2y}{dt^2} + \left[Q_y + \Delta Q_y \left(\frac{\delta p}{p_0} \right) \right]^2 \omega_0^2 y = \frac{1}{m_p \gamma} F_{cl_y},$$

and

$$\begin{cases} \frac{dz}{dt} = -\eta c \left(\frac{\delta p}{p_0} \right), \\ \frac{d}{dt} \left(\frac{\delta p}{p_0} \right) = \frac{Q_z^2 \omega_0^2}{\eta c} z + \frac{1}{p_0} F_{cl_z}. \end{cases}$$

In these equations Q_x and Q_y are, respectively, the horizontal and vertical tunes; ΔQ_x and ΔQ_y represent the chromatic shifts proportional to the particle relative momentum offset ($\delta p/p_0$); ω_0 is the angular revolution frequency of the beam in the circular accelerator (which for ultrarelativistic beams can be written as c/R_0 , R_0 being the average machine radius); $F_{cl} = (F_{cl_x}, F_{cl_y}, F_{cl_z})$ is the total force exerted by the cloud on each beam particle; p_0 is the nominal particle momentum; γ is the relativistic factor; η is the slippage factor, which can be positive if the machine is operating above transition energy, thus causing more energetic particles to move backwards within the bucket and vice versa. For simplicity, in our model we have replaced the alternating gradient focusing, on which most of the real machines are based, with constant and uniform focusing in both transverse directions. The longitudinal equations of motion represent in linearized form the rf bucket that focuses the beam longitudinally.

Unless otherwise specified, the simulation parameters used in the simulation throughout the entire paper are matched to CERN Super Proton Storage (CERN-SPS) parameters. These parameters are summarized in Table I.

The simulation box is 40 mm in the vertical direction, 80 mm in the horizontal, and 2.5 m in the longitudinal direction. There are 64–128 cells in each direction and 4–8 particles (electron cloud particles) in each cell; the total number of beam particles in the simulation box is 524 288.

TABLE I. SPS parameters used in the simulations.

rms horizontal spot size (mm)	2
rms vertical spot size (mm)	2
rms bunch length (cm)	30
Horizontal box size (mm)	80
Vertical box size (mm)	40
Bunch population	10^{11}
Horizontal emittance (μm)	0.1
Vertical emittance (μm)	0.1
Momentum spread	2.48×10^{-3}
Beam momentum (GeV/c)	26
Circumference (km)	6.9
Horizontal betatron tune	26.22
Vertical betatron tune	26.18
Synchrotron tune	0.005
Electron cloud density (cm^{-3})	$10^6\text{--}10^7$

III. FORCES ACTING ON THE BEAM

As the model equations indicate, the fields on each longitudinal piece of the beam and cloud come from 2D Poisson equations. So, all forces can be viewed as if from long line charge or current densities. There are three space charge forces to consider. First, there are the direct image charges of the beam with line charge density and line current equal and opposite to the beam. For relativistic beams, the electric and magnetic forces from these images cancel to order $1/\gamma^2$ and as we will show later they can be neglected. Second, there is a direct force from the cloud on the beam. When the cloud is unperturbed (uniform density) this gives a restoring force proportional to the electric field:

$$E_{d1} \approx \frac{n_{cl} e y}{2\epsilon_0}. \quad (1)$$

When a positively charged bunch passes through an electron cloud it sucks in the cloud towards its axis, creating cloud compression near the axis of the beam. Figure 3 shows QUICKPIC results for a positively charged beam passing through an electron cloud and the corresponding cloud density at early times. Each image is a color contour plot of the density for an x - z plane with y at the center of the beam. As can be seen from the cloud density figure, there is a high concentration of cloud close to the beam axis, increasing toward the tail of the beam. The pinched cloud exerts a force to an unperturbed beam and focuses the beam toward its own axis.

The situation becomes more complicated when the beam is tilted as in Fig. 4. In this case, the compressed cloud is not aligned perfectly with the beam axis. As shown in Fig. 4, this creates an electric field and a force on the beam tail in a direction that pulls the tail back to the not-tilted axis. Approximating the pinched cloud as a uniform line density much longer than the bunch length, and also assuming the tilt amount is less than the cloud

FIG. 3. (Color) (a) Positively charged beam density. (b) The corresponding cloud density. Cloud compression on the axis of the beam is evidenced from this figure. The color bars show the beam and cloud densities. The unperturbed (uniform density) cloud density is 10^6 cm^{-3} and c/ω_p is 5.3 m.

compression cross section, the electric field due to the line density at distance y from the axis can be written as

$$E_{cl,y} \approx -\frac{\lambda_{cl}y}{2\epsilon_0 A}. \quad (2)$$

Here, A is the cross section area of the pinched cloud near the axis of the beam and λ_{cl} is the line charge density of the compressed cloud.

When we have conducting boundary conditions, there is yet another restoring force acting on the displaced beam. The pinched cloud on the axis of the beam produces its own image charges of like sign of the beam in a conducting pipe and hence in a direction as to restore the beam to the pipe axis [20]. These images are not moving relativistically and hence there is no corresponding cancellation of their effect by the magnetic forces as was the case for the beam images.

To quantify the image cloud forces acting on the beam we consider a negative line charge density $-e\lambda_{cl}$ located at $a/2, b/2 + y$ inside a rectangular box of dimensions a and b , as shown in Fig. 5.

This charge models the accumulation of electrons around a slightly displaced beam. Its images will act

FIG. 4. (Color) A cartoon showing a tilted beam and the electric field on the tail of the beam due to cloud compression on the axis. The beam is moving up.

back on the beam. We assume that the displacement y of this charge from the center of the box is small compared to the box vertical size b . Neglecting the electric field from the image charges in the vertical conducting pipe ($b \ll a$), the total electric field from the images evaluated at the location where the source charge is can be written as

$$E_{\text{image}_y}(y) = \frac{\lambda_{cl}e}{2\pi\epsilon_0} \left(-\frac{1}{b-2y} + \frac{1}{b+2y} - \frac{1}{3b-2y} + \frac{1}{3b+2y} - \dots \right).$$

For $y \ll b$, the field becomes

$$E_{\text{image}_y}(y) = -\frac{2y\lambda_{cl}e}{\pi\epsilon_0 b^2} \sum_{n \text{ odd}} \left(\frac{1}{n^2} \right) = -\frac{\pi\lambda_{cl}e}{4\epsilon_0 b^2} y. \quad (3)$$

Each bunch particle (proton or positron) will feel a focusing force given by $F_{\text{image}_y}(y) = eE_{\text{image}_y}(y)$.

The cloud line charge λ_{cl} can be expressed as

$$\lambda_{cl} = H_{cl}(z)n_{cl}eA, \quad (4)$$

where A is the cross sectional area of the cloud density enhancement on the beam axis, and H_{cl} is the cloud compression enhancement factor. H_{cl} can be estimated from simulations or an analytic expression found in the

FIG. 5. (Color) Electrons attracted by a vertically displaced beam are modeled as a line density whose images with respect to the perfectly conducting wall act back on the beam. The green box is the conducting cavity.

Appendix:

$$H_{cl}A = 2\pi\sigma_r^2\left(\frac{\omega_{pb}\sigma_z}{c}\right)^2, \quad (5)$$

where ω_{pb} is the electron plasma frequency associated with the beam density.

In the next section, we give a qualitative description of beam dynamics based on the interaction between the forces on the beam.

IV. EFFECT OF CLOUD AND CLOUD IMAGE FORCES ON BEAM DYNAMICS

Because of the nonlinearities involved in the problem, describing the interaction between the three forces on the beam due to the cloud by analytic expressions is complex; however, a simple description of the scenario is as follows:

Imagine a beam off centered from the axis of the pipe but not tilted. The beam experiences a force due to the unperturbed space charge of the cloud that deflects it toward the axis and therefore shifts the betatron tune. In addition, the cloud compression exerts an added force that focuses but does not displace the beam (since the beam is not tilted). The forces due to image charges though, exert a force (F_{image_y} in Fig. 4) on the beam towards the axis of the pipe. This force tends to be larger at the tail than it is at the head due to cloud compression near the tail. So, the tail tends to dephase from the head causing the beam to tilt. As soon as the beam tilts, the force due to direct cloud compression (F_{cl_y} in Fig. 4) acts on the tail trying to pull it back towards the beam axis as shown in Fig. 4. So, there is an equilibrium angle at which the force due to the direct cloud and its images cancel each other at the tail. A lower bound on the tilt angle could be found by setting the forces due to image cloud compression and the direct cloud compression [Eqs. (2) and (3) with y replaced by $D - y \approx D$ in Eq. (3)] to be equal. Using Eq. (2) as a force due to direct cloud compression implies that the compression is assumed to be completely parallel to the axis of the pipe,

but, in reality cloud compression lies somewhere between the axis of the beam and the axis of the pipe. Thus Eq. (2) sets up an upper limit to the force from the pinched cloud and therefore sets up a lower limit for the equilibrium tilt angle:

$$\alpha > \frac{\pi^2\sigma_x\sigma_y D}{b^2\sigma_z}, \quad (6)$$

where, D is the displacement amount and b is the vertical pipe size. In deriving this equation, the cross section area of the cloud density compression in Eq. (2) is approximated as $\pi\sigma_x\sigma_y$.

Before proceeding further we make two side comments. (1) In this discussion, we have neglected the image forces due to the unperturbed cloud. Numerically we found that these contribute a correction of less than 20%. (2) We are typically considering a regime in which the bunch is sufficiently short or the box size is sufficiently large such that electrons are not depleted on either side of the beam. From the Appendix, Eq. (A3), this is $(\omega_{pb}\sigma_z/c) \leq (b/\sigma_r)$.

To test the physical picture explained here, we look at the force on the tail of a beam using QUICKPIC simulations. Figure 6 shows the force at the tail of a beam versus tilt angle for different beam displacements. As can be seen, the force on the tail crosses zero at some tilt angle for each displacement amount. This angle is the equilibrium angle. The more the beam is deflected the bigger the image charge forces on the beam would be and therefore the bigger the equilibrium angle is. From the figure we see, for example, for the displacement of 5 mm, the equilibrium angle is around 5°; estimating this angle by (6) will give the tilt amount of about 0.2°.

As a comparison to previous models [9–12] which did not include conducting boundaries [15–19], we show as a dashed curve in Fig. 6 the force on the beam, displaced 7.5 mm from the center, but with periodic boundary conditions. As seen this force is quite different from

FIG. 6. (Color) Forces on the beam as a function of the tilt angle for different displacement amounts.

FIG. 7. (Color) Three snapshots of beam evolution over CERN-SPS. (a) At $t = 0$; (b) at $t = 136 \mu\text{s}$ (6 turns); (c) at $t = 0.8 \text{ ms}$ (35 turns). c/ω_p for all the snapshots is 1.67 m.

the corresponding force on the beam with conducting boundary conditions. This difference between the two cases shows the importance of proper boundary conditions of the cloud image forces on the beam.

To verify the above argument we look at the long-term propagation of a beam along CERN-SPS. The physical parameters chosen in the simulation are matched to the CERN-SPS physical parameters. The cloud density is chosen to be 10^7 cm^{-3} . As an initial perturbation, the beam is tilted but on axis at the beginning of the simulation (with a slope of $1\sigma_x$ per $1\sigma_z$). Figure 7 shows three snapshots of the beam during the simulation. At the beginning of the simulation [Fig. 7(a)], there is a force due to direct cloud compression acting on the beam. This force is much greater at the tail than it is at the head due to the fact that charge compression reached its maximum close to the tail of the beam. Neglecting the force on the head compared to the tail, we can say that the force tends to line up the tail with the head later in time. Figure 7(b) shows the beam density after six turns (36 km). As can be seen, the beam is not tilted anymore but it is deflected from the center due to the fact that the tail has lined up with the head. Since the head was initially off axis, there is an overall displacement to the beam. At still later times, the beam develops a slight equilibrium tilt angle described in the previous section. This is shown in Fig. 7(c) which is the beam density after 35 turns around the accelerator ring.

The amount of displacement from Fig. 7 is about 6.8 mm and the tilt angle amounts to 9° . This amount of tilt is consistent with that predicted by Fig. 6 which is between 5° and 10° for 6.8 mm of displacement.

V. EFFECTS OF CLOUD AND CLOUD IMAGE FORCES ON THE TUNE SHIFT

As mentioned earlier, there is a force due to unperturbed cloud space charge on the beam. Assuming that the bunch goes through an initial uniformly distributed electron cloud, the head of the bunch feels the field (1) and consequently experiences a tune shift:

$$\Delta Q_y = \frac{e^2 n_{cl} R_0^2}{4\epsilon_0 m_p c^2 Q_y \gamma}. \quad (7)$$

Moreover, the study in [10] suggests that in open space, if the cloud size is much larger than the beam size, the coherent tune shift can be evaluated by naively using this expression applied to the whole bunch even in the dynamical regime while the electron cloud gets distorted by the passing bunch. This was a result of numerical simulations and was explained as an effect from electrons at large amplitudes, which perform slow nonlinear oscillations around the bunch and hence give rise to a static force acting on the bunch at any time.

We may expect the forces due to direct cloud compression and its images to be inconsequential to the tune shift or tune spread as they tend to cancel each other at steady state as shown before. To test this, we examine the tune shift and spread using QUICKPIC. Figure 8 shows the results for vertical tune lines for 10^6 and 10^7 cm^{-3} cloud densities, the two representative values of what is expected at the CERN-SPS. The tune line for no cloud case is also depicted for the sake of comparison.

The tune lines are obtained by taking the fast-Fourier transform of the beam centroid motion over 150 turns of beam propagation. From the figure the tune shift for 10^6 cm^{-3} cloud density is 0.007 while that of 10^7 cm^{-3} cloud density is 0.077 which is almost 10 times as big as the low-density case. This tune shift and the linear proportionality of the tune shift with density are consistent with Eq. (7), the result for simple unperturbed cloud.

There is relatively little tune spreading observed in the tune lines of Fig. 8 (i.e., tune spread is much less than the tune shift), suggesting that the cloud compression and its image forces, although large contribute little to tune shift or tune spread of the accelerator. We note, however, that at this point our model does not include gradients in the cloud density along the ring (e.g., gradients in magnetic field) and that these variations may disrupt the equilibrium scenario described in the previous section and may lead to tune spread. This is a subject for further work.

FIG. 8. Vertical tune for different cloud densities.

VI. EFFECTS OF ELECTRON CLOUD ON BEAM INSTABILITY

Next, the effects of the electron cloud on the emittance growth of the beam are studied. The simulations are performed based on the CERN-SPS parameters for 70 turns of the SPS ring. The beam is initially untilted but off axis 1 mm in the vertical direction. Over this length, there is no emittance growth in our model in the absence of electron cloud and negligible emittance growth for cloud densities up to 10^6 cm^{-3} [Fig. 9(a)]. This is a typical value for cloud density obtained from the simulations of electron cloud buildup for the CERN-SPS ring [17]. However, at cloud densities 10 times higher, the emittance growth of the beam becomes apparent. Figure 9(b) shows the spot size of the beam in this high cloud density. As seen from the figure, the spot size grows 50% after 70 turns. Figure 9(c) shows that the beam centroid oscillation also grows.

Figure 10 shows three snapshots of the beam after 18 turns over half a betatron period for the high cloud density case. It is interesting to compare Fig. 10(c) with Fig. 7(c) where the beam was initially tilted. We see in

both cases the beam shows similar behavior: oscillating around the axis of the pipe with the tail slightly tilted toward the center line with respect to the head toward the axis. This shows that no matter how the beam is initially perturbed, the beam ends up having a similar long-term dynamic.

Work is in progress to further study the longer term evolution of the beam (over a few hundred turns).

VI. DISCUSSION

We have presented new analytic and numerical models for the dynamics of electron clouds and beams in a circular accelerator. Our new parallelized model allows continuous modeling (i.e., resolution less than beta function) of the beam along the accelerator and includes the effects of image forces of the cloud on the beam dynamics for the first time. Results of the model for tune shift and tune spread are in fair agreement with previous work. However the emittance growth seen in QUICKPIC is a factor of a few times slower than that seen in other models [12] for which the cloud was treated as a single

FIG. 9. (Color) QUICKPIC simulation of beam propagation over 70 turns of CERN-SPS (a) and (b) spot sizes for cloud densities 10^6 and 10^7 cm^{-3} , respectively. Some oscillation is observed initially in (a) that is because the beam is not matched initially. (c) Beam centroid in the vertical plane for 10^7 cm^{-3} of cloud density.

FIG. 10. (Color) Three snapshots of the beam over the CERN-SPS ring. (a) At $t_0 = 0.4$ ms (18 turns); (b) at $t_1 = t_0 + T_B/4$; (c) at $t_2 = t_0 + T_B/2$, where T_B is the nominal betatron period ($\approx 0.9 \mu\text{s}$). c/ω_p for all the snapshots is 1.67 m.

slab at one point in the ring. This suggests that accurate modeling of beam-cloud interaction requires the kind of continuous model described here. Further work is planned to include external magnetic fields on cloud dynamics and on cloud density variations along the ring.

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APPENDIX: ANALYTIC EXPRESSION FOR THE CLOUD DENSITY COMPRESSION ON THE AXIS OF THE BEAM

The electron cloud line density $\lambda_{cl}(z)$ around the beam can be alternatively expressed as a neutralization factor $\eta_c(z)$ multiplied by the bunch line density (usually

Gaussian) or in terms of the unperturbed cloud density through multiplication by an appropriate enhancement factor $H_{cl}(z)$. Note that $\lambda_{cl}(z)$ is a function of the longitudinal coordinate along the bunch z according to

$$\lambda_{cl}(z) = H_{cl}(z)n_{cl}eA, \quad (\text{A1})$$

where A is the cross sectional area of the cloud density enhancement on the beam axis, and n_{cl} is the unperturbed cloud density. The enhancement factor H_{cl} can be obtained from simulations or an approximate analytically as we show next. A typical profile of the cloud density enhancement along the bunch for CERN-SPS ($n_{cl} = 10^6 \text{ cm}^{-3}$, $N_b = 10^{11}$ protons in a Gaussian bunch with $\sigma_x \approx \sigma_y \approx 2$ mm, $\sigma_z \approx 0.3$ m, and chamber vertical size $b = 4$ cm) with two different bunch intensities is illustrated in Fig. 11.

An approximate analytic expression for H_{cl} can be found from the argument below.

The cloud density enhancement is limited by the amount of charge within the vicinity of the beam. By “in the vicinity” we mean within a radius such that it has time to reach the beam axis before the beam passes by.

FIG. 11. (Color) Electron cloud line density along the bunch normalized to the unperturbed density for two different values of SPS bunch current. (a) 10^{11} p/b case. The transverse density profile is taken along the center of the beam (b) 3×10^{10} case. The profile is taken at the location of maximum cloud compression which is close to the center of the beam. By definition, these figures show the longitudinal profile of the enhancement factor $H_{cl}(z)$. In both cases c/ω_p is 5.3 m.

The time it takes a cloud electron to reach the axis from an original radius r_0 is given by [23]

$$t = \frac{\sqrt{\pi} r_0}{\omega_{pb} \sigma_r}, \quad (\text{A2})$$

where $\sigma_r = \sigma_x \cong \sigma_y$ is the beam radius (assumed round) and ω_{pb} is the electron plasma frequency associated with the beam density (i.e., $\omega_{pb}^2 = 4\pi n_b e^2 / m_e$ and n_b is the peak beam density, $n_b = [N_b / (2\pi\sqrt{2}\pi\sigma_x\sigma_y\sigma_z)]$). This analytic result was obtained for a uniform beam profile but proved to be reasonably accurate by comparing it to numerical solutions for Gaussian beams. To effect the core of the bunch, this time must be less than the bunch length σ_z/c . Thus the maximum radius is

$$\frac{r_0}{\sigma_r} = \omega_{pb} \sigma_z / c, \quad (\text{A3})$$

giving rise to a maximum charge density enhancement

$$n_{\max}/n_0 = H_{cl} \frac{A}{2\pi\sigma_r^2} = \left(\frac{r_0}{\sigma_r}\right)^2 = \left(\frac{\omega_{pb}\sigma_z}{c}\right)^2. \quad (\text{A4})$$

For the example parameters of Fig. 11, this gives $H_{cl}A/2\pi\sigma_r^2 = 17$ and 6, respectively. This compares reasonably with the values 17 and 8.5 obtained from the simulations.

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Plasma Accelerators at the Energy Frontier and on Tabletops

Charged particles surfing on electron density waves in plasmas can experience enormous accelerating gradients.

Chandrashekhhar Joshi and Thomas Katsouleas

(See the articles in PHYSICS TODAY by Andrew Sessler, January 1988, page 26, and by Jonathan Wurtele, July 1994, page 33.)

The impact that much smaller low-energy particle accelerators have had on other branches of science and

Experiments using charged-particle accelerators have led to remarkable discoveries about the nature of fundamental particles and the behavior of nuclear matter. These breakthroughs have been made possible by dramatic advances in our understanding of the physics and technology of particle acceleration.¹ Accelerator beam energies increased exponentially—by an order of magnitude every decade—for half a century after the pioneering days of John Cockcroft and Ernest Lawrence in the early 1930s, as established technologies were pushed to their limits and superseded by new ones (see figure 1).

The present state of the art for proton synchrotrons is the Large Hadron Collider (LHC), under construction at CERN on the French–Swiss border. Its 7-TeV proton beams will, in effect, provide experiments with constituent quark energies on the order of 1 TeV. Looking further ahead, particle physicists are already planning for an electron–positron collider with 250-GeV beams, a neutrino factory, and even a TeV muon collider. These energies represent the so-called energy frontier, where particle physicists confidently expect to discover fundamentally new phenomena.

Although the accomplishments of accelerator-based physics have been spectacular, there is much more to do. The accelerators now in operation or contemplated are expected to lead the way beyond the present manifestly incomplete standard model of particle physics. In particular, they should unearth new classes of particles and enhance our understanding of the asymmetry between matter and antimatter, the masses of the quarks and fundamental leptons, and the transition to the primordial quark–gluon plasma.

We must ask, however, whether the rapid pace of discovery can continue without further breakthroughs in accelerator technology. Irrespective of accelerator topology or the types of particles being accelerated, the fact remains that high-energy accelerators that rely on radio-frequency technology are simply getting too big and too expensive. (See the article by Maury Tigner in PHYSICS TODAY, January 2001, page 36.) Is there a different paradigm for building particle accelerators at the energy frontier while dramatically reducing their size—and hopefully their cost?

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technology has been equally impressive. Accelerators are being used, among other applications, for materials science, structural biology, nuclear medicine, fusion research, food sterilization, transmutation of nuclear waste, and cancer therapy. The requirements for such machines are very different from those of high-energy accelerators, and they vary from one application to another. Nonetheless, many low-energy applications would benefit from extremely compact “tabletop accelerators” that could provide beams of GeV electrons, protons, or ions with energies of a few hundred MeV per unit charge.

In this article, we survey new approaches to charged-particle acceleration by collective fields in plasmas. These approaches show considerable promise for realizing plasma accelerators at the energy frontier as well as tabletop electron and ion accelerators. The plasmas would not only provide unprecedentedly high acceleration gradients; they would also serve to focus the accelerated beams down to very small spot sizes.

Surfing on plasma waves

Instead of using RF waves to accelerate charged particles, as conventional accelerators do, plasma accelerators use plasma-oscillation waves excited by lasers or by “driver beams” of charged-particles. The accelerating gradients and focusing strengths that have been demonstrated in plasma experiments have been orders of magnitude greater than those achieved thus far by RF accelerators. The greater the accelerating gradient—if it can be maintained over sufficient distance—the shorter would be the accelerator required to reach a given energy. The impressive plasma-acceleration results already demonstrated in experimental structures raise hopes that this revolutionary technology may miniaturize future accelerators in the same way that semiconductor processors miniaturized electronics.

In addition to the customary “Livingston curve” that charts the progress of working particle physics accelerators over the decades, figure 1 also indicates the highest energies achieved in various plasma acceleration experiments over the past 10 years. Admittedly, plasma schemes have a long way to go before they can produce beams with sufficiently high intensity and low energy spread and “emittance” (that is, angular spread) to be useful for doing high-energy physics. Nevertheless, one can see from figure 1 that the peak energy gain in plasma experiments has been increasing by an order of magnitude every five years.

Figure 1. Exponential growth of accelerator beam energy, traditionally depicted by the Livingston curve (green), began tapering off around 1980 as conventional radio-frequency technology approached its limits. The extrapolation to 2010 ends with the 250-GeV electron and positron beams of the 30-km-long Next Linear Collider (NLC), which particle physicists are proposing to build with state-of-the-art RF technology. Progress toward a more radical solution that might eventually reach the high-energy frontier with much shorter linear accelerators is indicated by the red dots, which mark energies already obtained in some of the plasma-acceleration experiments in the US, Japan, and Europe. (Institutional abbreviations are spelled out in the text.) They all represent electron acceleration, except for E162 at SLAC, which is for positrons. The blue dot marks the record electron energy anticipated from a plasma experiment now in progress.

We describe here the ideas and developments that have led to these promising results, as well as the considerable challenges that lie between proof-of-principle experiments and the realization of useful plasma accelerators.

Generating the waves

John Dawson of UCLA has aptly been called the father of plasma-based accelerators. (See his obituary in *PHYSICS TODAY*, July 2002, page 78.) The four plasma acceleration schemes invented by Dawson and coworkers all share a common underlying principle: Charged particles are accelerated by surfing on the longitudinal electric field of a relativistically propagating electron plasma wave. Relativistic propagation means that the wave's phase velocity is very close to c , the speed of light, so that the particle cannot quickly outrun the accelerating electric field of the wave and therefore interacts with it over a long distance.

The electric field intensity in volts per centimeter is approximately given by the square root of the plasma's electron density ρ in cm^{-3} . But the characteristic wavelength of plasma oscillation decreases with increasing density like $\rho^{-1/2}$. Thus, a plasma with $\rho = 10^{16}/\text{cm}^3$ can support a wave that has a peak field of about 10^8 V/cm. That's orders of magnitude more than the 10^5 to 10^6 V/cm accelerating gradient of existing and proposed RF electron linacs. But such high gradients are achieved at the expense of ever shorter wavelengths. For $\rho = 10^{16}/\text{cm}^3$, the plasma wavelength is only $300 \mu\text{m}$.

Figure 2 illustrates the different plasma accelerator schemes for exciting a plasma wave:

► In a *laser wakefield accelerator* (LWFA), as shown in figure 2a, the radiation pressure of a short, intense beam of laser photons pushes plasma electrons forward and aside. As the laser pulse passes, these displaced electrons snap back and overshoot their original positions because of the restoring force exerted by the heavier, less mobile ions. The displacement sets up a plasma density oscillation behind the laser pulse, much like the wake of a ship. In a dilute plasma, the photon pulse propagates with a group veloc-

ity very close to c , and therefore the phase velocity of the wake oscillation is also near c . The wake's electric field—the so-called wakefield—thus accelerates the relativistic particles over a long distance before they finally outrun it. So the particles' energy gain is substantial.²

► In a beam-driven *plasma wakefield accelerator* (PWFA), a high-gradient plasma wakefield is excited by a short, high-charge, relativistic beam of charged particles rather than by laser photons (see figure 2b). Now it is the Coulomb force of the beam's space charge that expels the plasma electrons (or, in the case of a positron driver beam, pulls them in). Again, they rush back and overshoot when the driving beam passes, setting up a plasma oscillation.³ In both the LWFA and PWFA schemes, the optimum length of the drive pulse turns out to be approximately half a wavelength of the plasma wave. For $\rho = 10^{16}/\text{cm}^3$, the optimum drive pulse length is about 500 femtoseconds.

► The *plasma beat-wave accelerator* (PBWA) scheme (figure 2c) was one of two approaches devised to address the difficulty that, until recently, subpicosecond photon and electron bunches powerful enough to drive a high-gradient plasma wake did not exist. The PBWA makes use of a beat wave produced by the interference of two higher-frequency laser beams whose frequency difference is exactly equal to the natural frequency of the plasma oscillation.⁴ The amplitude-modulated beat wave looks like a series of short pulses that can resonantly drive the plasma wave. One can then use lasers of much lower intensity than one needs in the LWFA case.

► The *self-modulated laser wakefield accelerator* (SMLWFA) is the other scheme originally designed to address the absence of sufficiently powerful subpicosecond bunches. It was already known to plasma physicists in the 1970s, but its potential for acceleration was not appreciated until the 1980s. In this scheme, a long, intense pulse modulates itself into something like a beat-wave structure (figure 2d) via the Raman forward-scattering instability, so called because it resembles the Raman scattering of light from molecules. But in this case, it is a parametric instability in

which the scattered light and the plasma wave grow exponentially at the expense of the pumping radiation.⁵ The incident electromagnetic wave couples its energy into a relativistically propagating plasma wave and two electromagnetic daughter waves with frequencies shifted up and down by the plasma frequency.

The interaction between a short, intense laser pulse and a plasma can also be used to accelerate ions.⁶ For instance, at the Rutherford Appleton Laboratory (RAL) in England, a 50-terawatt laser focused on a solid target has generated a collimated beam of 10 to 400 MeV protons and other ions. The laser's electric field first ionizes the target atoms, and the electrons are then accelerated forward by the laser magnetic field's Lorentz force. The space charge of the electrons, in turn, accelerates the ions leaving the target's surface.

The ions can also be accelerated by the shock front that propagates through the solid material after it is hit by the laser pulse. The efficiency of converting laser energy into high-energy ions can exceed 10%. With petawatt lasers now becoming available, ion beams with energies up to a GeV can be expected from such a relatively simple device. Protons and ions in this energy range are well suited for a variety of applications: radiography for nuclear stockpile stewardship, drivers for fast-ignition fusion, generation of medical isotopes, and perhaps even as injectors for conventional accelerators.

Recent experiments with electron acceleration

The first excitation of relativistic plasma waves by the PBWA technique was accomplished in 1985 by the UCLA group led by one of us (Joshi).⁷ In the 1990s, electron acceleration by the PBWA scheme was demonstrated by the UCLA group and by groups at Chalk River Laboratories in Ontario, the Ecole Polytechnique near Paris, and the Institute for Laser Engineering (ILE) in Osaka, Japan. From the observed energy gains of the electrons in those experiments, one could infer acceleration gradients in excess of a gigavolt per meter, confirming the theoretical predictions of extremely high electric fields for relativistic plasma waves.⁸

In the early 1990s, the use of chirped-pulse amplification to produce high-power pulses with Nd:glass lasers led to laser systems that could generate 100-TW pulses. Christine Coverdale and coworkers at Lawrence Livermore National Laboratory (LLNL) showed not only that such a laser focused in a plasma produced Raman forward scattering, but also that the plasma wave accelerated some of the electrons from the plasma itself. And in the mid-1990s, pioneering experiments on the SMLWFA scheme were done at the RAL by a collaboration led by Bucker Dangor of Imperial College, London.⁹

Those experiments demonstrated that, in a plasma of electron density $10^{19}/\text{cm}^3$, one could produce a 5-nanocoulomb beam of electrons with energies up to 100 MeV. Amazingly, that energy gain occurred in less than a millimeter. That's the highest terrestrial acceleration gradient ever achieved—almost 200 GeV/m. Subsequently, groups from the US Naval Research Laboratory, the University of Michigan, Lawrence Berkeley National Laboratory (LBNL), and KEK, Japan's high-energy accelerator laboratory, demonstrated similarly impressive results.¹⁰

With the emergence of Ti:sapphire lasers in the late 1990s, it has become possible to generate 50-fs, 100-TW

Figure 2. Four different kinds of driver pulses (red, propagating from right to left) that can excite a relativistic electron density wave (blue) in a plasma accelerator. (a) In a laser wakefield accelerator, the radiation pressure of a short, intense laser pulse pushes plasma electrons away to initiate the accelerating plasma wakefield. (b) In a plasma wakefield accelerator, the plasma electrons are pushed away by the Coulomb force of a short, high-charge relativistic bunch of electrons from a linac. (c) In a laser-driven plasma beat-wave accelerator, the interference between two high-frequency lasers produces a laser beat wave whose frequency equals the plasma's natural oscillation frequency. (d) In a self-modulated laser wakefield accelerator, a long, intense laser pulse interacting with the plasma acquires a beat-wave-like amplitude modulation by the Raman forward-scattering instability.

pulses at a high repetition rate. So now one can, at last, realize the promise of the LWFA scheme as it was originally conceived. Recently, Victor Malka's group at the Ecole Polytechnique's Laboratoire d'Optique Appliquée (LOA) has used wakefield acceleration to obtain extremely promising results: a maximum electron energy of 200 MeV in just a millimeter (see figure 3).¹¹ Having measured the angular divergence of the accelerated electrons at various energies, the group concluded that the highest-energy electrons also have the smallest emittance.

Tabletop prospects

How might one further increase the energy of electrons in laser-driven schemes to produce a GeV tabletop plasma accelerator? To go from 200 MeV in a couple of millimeters to a GeV and beyond, one needs to increase the length of the plasma wave by guiding the intense laser pulse. A particularly promising approach is the use of a preformed plasma channel. The channel would have an electron density minimum along its axis. The refractive index is higher on the axis of the channel than at its edges and therefore the channel acts like an optical fiber to guide light beams.

How to produce such plasma channels for guiding ultra-intense laser pulses while exciting a wakefield is an active area of research that is meeting with some success.¹² For instance, Michael Downer's group at the University of Texas in Austin has propagated 80-fs laser pulses with peak intensities of $2 \times 10^{17} \text{ W}/\text{cm}^2$ over 1.5 cm. That distance is 60 times the characteristic diffraction length in such a plasma channel. At such intensities, however, the wake amplitude is not large enough to accelerate electrons from the plasma itself. In any case, such plasma electrons would have too large an energy spread. Most applications require a nearly monoenergetic electron beam.

For monoenergetic acceleration, an extremely short electron bunch must be phase-locked to the accelerating

Figure 3. Tabletop laser wakefield acceleration of electrons to a few hundred MeV. (a) A typical tabletop setup would fire focused ultrashort laser pulses into a laminar-flow gas jet to produce a plasma and excite a wakefield. The wakefield traps plasma electrons and accelerates them to about 100 MeV in just a millimeter. (b) Recent results with 50-fs, 100-TW laser pulses at the Laboratoire d'Optique Appliquée (LOA) in France demonstrate acceleration of electrons to 200 MeV in 1 mm of plasma.¹¹ (c) The angular distribution of the electrons in the LOA experiment, for three energy ranges, shows that the spread of exit angles, and therefore the emittance of the accelerated beam, decreases with increasing electron energy. For each energy range, the blue outer circle indicates the full width at half maximum of the angular distribution for that range. (Courtesy of V. Malka.)

plasma waves, whose wavelengths may be only tens of microns at the requisite ultrahigh accelerating gradients. Fortunately, several all-optical injection schemes have been proposed that use two or more laser beams: one to excite the plasma wake and the other(s) to inject electrons into the wake with femtosecond precision.¹³

In one such scheme, Donald Umstadter and coworkers at the University of Michigan have suggested that a second ultra-intense laser pulse, propagating at right angles to the first, could perturb the orbits of the electrons

in the wakefield excited by the first pulse and thus cause them to be trapped and accelerated while maintaining a relatively small energy spread. Combining plasma guiding with all-optical injection is thought by many to be the most promising route toward GeV electron beams in centimeter-scale plasmas.

Scaling up to the energy frontier

How hard is it to extend these centimeter-scale acceleration techniques to the meter scales needed for approaching the energy frontier? One approach to higher energies would be to stage hundreds of smaller laser-plasma acceleration modules, each providing a gain of a few GeV. The problems associated with staging, however, are enormously complicated and beyond the scope of this article. But if one could make a single, ultrahigh-gradient plasma-acceleration stage several meters long, staging could be greatly simplified—or even rendered unnecessary.

Such issues have been investigated in recent experiments on beam-driven plasma-wakefield acceleration at Argonne National Laboratory, Fermilab, and at SLAC.¹⁴ The work at SLAC was done by a collaboration of scientists from SLAC, UCLA, the University of Southern California, and LBNL. A series of experiments at SLAC (designated E157 to E162) has demonstrated a prototype, 1.4 meters long, of a positron and electron PWFA stage.¹⁵ This is a very significant accomplishment, because the particle physics community has assigned its highest priority to a linear electron-positron collider at the energy frontier (see PHYSICS TODAY, September 2001, page 22).

The drivers of the plasma wakefield in the SLAC experiments were 4-ps-long beam bunches of 28.5-GeV positrons and electrons from the laboratory's 3-km linac, with peak currents of nearly a kiloamp. The passage of the intense electron beam through a 1.4-m-long lithium plasma not only excited the plasma wave but also accelerated a significant amount of charge from the back end of the same drive bunch.¹⁵

These experiments also showed that beam propagation over 1.4 meters of plasma is controllable, despite the strong focusing forces that arise in the plasma. (Those forces are comparable to what one would get in a 6000-T/m quadrupole electromagnet.) Aside from energy loss and gain, the experiments have quantitatively verified many of the other predicted phenomena, such as periodic focusing of the beam and x-ray emission due to the wiggling motion of electrons about the axis of the wakefield.

For plasma waves that are not too large, a plasma wakefield accelerates positrons in much the same way as it accelerates electrons—except, of course, that the positrons are carried along on the opposite phase of the plasma wave. For the strongly driven plasma waves of interest for the highest accelerating gradients, however, the physical mechanism for wakefield excitation and acceleration turns out to be different for electrons and positrons. In plasma-wakefield acceleration with an intense electron-beam driver, the Coulomb force of the beam's space charge completely expels the plasma electrons. But the space charge of a positron beam pulls in plasma electrons laterally, thus creating an electron density on axis that far exceeds the initial plasma density. In a uniform plasma, the wakes produced by an otherwise identical positron beam tend to be somewhat smaller than those produced by an electron beam.

Figure 4 compares the energy change of the positron beam observed in the SLAC experiments with the prediction from the self-consistent three-dimensional computer code OSIRIS.¹⁵ The agreement between experiment and simulation is excellent: The bulk of the beam loses about

Figure 4. Observation and simulation of positron energy changes resulting from traversal of a 1.4-m-long plasma. (a) In a plasma wakefield experiment at SLAC,¹⁵ energy changes were recorded for different temporal slices of the 10-ps relativistic positron beam pulse. Whereas the bulk of the pulse (near $t = 0$) showed energy loss of about 55 MeV, its tail (t later than +1 ps) demonstrated energy gain of as much as 80 MeV. This was the first demonstration of high-gradient plasma acceleration of positrons. (b) A computer simulation of the SLAC experiment group predicted much the same pattern of deceleration of the pulse's head followed by acceleration of its tail. (Adapted from B. Blue, et al., *Phys. Rev. Lett.*, in press.)

55 MeV, whereas particles in its tail gain a maximum energy of 80 MeV. These results represent the first high-gradient acceleration of positrons using collective plasma fields. Such meter-scale prototype stages for accelerating both electrons and positrons are something of a milestone in the development of plasma accelerators for the energy frontier.

Plasma focusing of particle beams

If one wants a miniature high-energy collider, one must also miniaturize the final-focusing optics that make the colliding-beam cross sections small enough to provide a useful collision rate. Fortunately, plasmas can produce lenses of extremely short focal length for beams of ultrarelativistic charged particles.¹⁶

The physical mechanism of a plasma lens is easily understood. In vacuum, an ultrarelativistic electron beam

Figure 5. Plasma focusing of a 30-GeV positron beam from the Stanford Linear Accelerator. At a fixed distance beyond the plasma lens, the demagnification of the beam diameter, which was initially 50 μm , is plotted against the electron density of the focusing plasma. As the plasma density is increased toward its optimum ($2 \times 10^{12}/\text{cm}^3$), the focusing strength increases and the beam diameter is pinched to half its initial value. But at still higher plasma densities, the beam is overfocused and the spot size grows again. The red error bar indicates the diameter uncertainty of the beam without plasma focusing. (Adapted from M. Hogan et al., *Phys. Rev. Lett.*, in press.)

spreads rather slowly as it propagates. That's because the repulsive space-charge force is nearly balanced at relativistic velocities by the attractive Lorentz force of the charged particles moving in parallel. However, as an electron beam enters a plasma and expels the plasma electrons, the ions left behind exert a focusing force. If the beam density exceeds the plasma density, all the plasma electrons leave. Then the focusing force of the remaining ion column is constant along the beam, and it grows linearly with transverse distance from the axis. In addition to its very short focal length, such a lens has, in principle, no spherical aberrations. That greatly simplifies the final-focusing optics before the collision point, which would otherwise require dozens of focusing elements.

The focusing of a positron beam is, alas, less ideal. The positrons pull in plasma electrons, which tends to neutralize the beam's charge. Plasma electrons from different distances converge on the positron beam at different times. The resultant focusing force is then neither linear in the radial direction nor constant along the beam. Nevertheless, the focusing gradients are orders of magnitude greater than those achievable by traditional magnetic focusing.

Plasma lenses have been shown to focus GeV electron and positron beams. In a set of experiments done by Johnny Ng and collaborators at SLAC,¹⁶ the 7- μm -diameter SLAC positron beam was further focused down to about 5 μm as it passed through a short column of plasma with an electron density of about $10^{18}/\text{cm}^3$. The focusing gradients in these experiments were enormous: 10^6 T/m. Figure 5 shows the focusing of positrons by a plasma lens in a recent experiment at SLAC by Mark Hogan and coworkers. The positron beam diameter is clearly seen to decrease, at a fixed distance beyond the lens, as the plasma density, and therefore the focusing strength, is increased to an optimum value. Beyond this optimum density, the beam is overfocused and the spot size grows again.

Plasma focusing has demonstrated spot-size reduction by a factor of two to four, for both positron and electron

Figure 6. To test the feasibility of plasma-wakefield afterburners added to a high-energy radio-frequency linear collider as an energy doubler, we propose the installation of two 10-m-long plasma afterburners at the ends of the 50-GeV electron and positron beams of the Stanford Linear Collider (SLC), just before the point where the beams are focused to collide with each other (see inset). That would double the collider's e^+e^- collision energy to 200 GeV. Unlike the plasma filling the electron afterburner, the positron afterburner's plasma would have a hollow axial channel. The SLC shares the downstream end of the 3-km-long Stanford Linear Accelerator with the PEP II asymmetric B-meson factory and other facilities.

beams. The logical next step is to demonstrate that plasmas can focus beams to submicron-diameter spots. For the eventual use of plasma lenses in a high-energy electron-positron linear collider, one would have to focus the colliding beams down to a few tens of nanometers.

Toward a plasma afterburner

The demonstration of plasma-wakefield acceleration of electrons and positrons over a meter, and the plasma focusing of multi-GeV e^+ and e^- beams down to spots only a few microns wide has fueled speculation about the scalability of the PWFA scheme to the energy frontier. The theoretical acceleration gradient in a PWFA scales as the electric charge of the driving bunch divided by the square of bunch length. Thus, if the 4-ps pulse length of the drive bunch in present experiments can be contracted by an order of magnitude, we should be able to increase the acceleration gradient from the present 100 MeV/m to something like 10 GeV/m. Using the ultrashort bunch facility at SLAC, we will soon be testing this crucial scaling law in an experiment labeled E164 (see figure 1). Should it prove possible to obtain such extraordinarily high gradients over a few meters without incurring any beam-plasma instabilities, one could contemplate building a single-stage PWFA energy doubler at the downstream end of a high-energy RF linear accelerator.¹⁷

How would such an "afterburner" work? As an illustrative example, figure 6 shows a pair of PWFA energy doublers, installed on either side of the collision point of the Stanford Linear Collider (SLC), that serve to double the energies of the electron and positron beams from the present 50 GeV to 100 GeV. That's the scale of demonstration experiment one would need to prove that the plasma wakefield accelerator is a realistic candidate for a future e^+e^- collider at the energy frontier. Each plasma afterburner in such an experiment would be about 10 m long. These

plasma sections play the role of a voltage transformer, increasing beam energy at the expense of beam current.

In each plasma section, the particle bunch actually consists of two microbunches just 100 fs apart. The first microbunch excites the wake, while the second, containing only a third as many charged particles as its predecessor, is phased to accelerate on the wake of the first. To avoid sacrificing event rate at the SLC's collision point, one would have to offset the reduced number of particles in the accelerated bunch by having correspondingly smaller beam spot sizes. That would be done by placing a high-density plasma lens after each wakefield afterburner section, just before the collision point.

The positron beam's afterburner would be different from the one that boosts the electrons. As shown in figure 6, it would be a hollow channel on the axis, surrounded by plasma. The wakefield excited by a positron beam in such a hollow channel would be more coherent than one could get in a radially uniform plasma column. That's essentially because the positrons would be pulling in electrons from the cylindrically symmetric boundary of the channel.

Preliminary simulation studies of such plasma afterburners have shown that electrons in the second bunch are accelerated at a rate of 8 GeV/m. The 20% energy spread coming out of these simulations is too big for some classes of physics experiments that require a narrowly defined collision energy. But it might be tolerable for experiments that can rely on a robust production signal for the particle being sought—for example, the Higgs boson.

Important accelerator physics issues remain to be resolved. How stable, for example, would the plasma wakefield be over distances much longer than a meter? How efficiently could the accelerating beam extract energy from the wake? Then there are demanding technological issues like the alignment of the colliding beams. Such questions are common to all advanced accelerator schemes. They will

be addressed in the next few years by new 3D computer simulation tools and new, dedicated experimental facilities such as Orion, under construction at SLAC, and the Accelerator Test Facility, already in operation at Brookhaven National Laboratory.¹⁸

The quest for plasma acceleration is making rapid progress (see figure 1). It took accelerator builders 60 years to reach lepton (and quark) center-of-mass collision energies in the range of 200 GeV. If plasma-acceleration technology is to have an impact at the high-energy frontier, it had better make faster progress than that. We must address serious issues such as beam quality, event rates, and overall efficiency.

On the other hand, combining laser and plasma technologies could lead rather quickly to GeV tabletop electron and ion accelerators for a rich variety of applications. The future is, of course, full of challenges and uncertainties, but it is also full of exciting chances to make a difference.

We dedicate this article to the memory of John Dawson. We also thank our many collaborators and colleagues who have contributed to the field that Dawson pioneered.

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POSITRON BEAM PROPAGATION IN A METER LONG PLASMA CHANNEL

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Abstract

Recent experiments and simulations have shown that positron beams propagating in plasmas can be focused and also create wakes with large accelerating gradients. For similar parameters, the wakes driven by positron beams are somewhat smaller compared to the case of an electron beam. Simulations have shown that the wake amplitude can be increased if the positron beam is propagated in a hollow plasma channel (Ref. 1). This paper, compares experimentally, the propagation and beam dynamics of a positron beam in a meter scale homogeneous plasma, to a positron beam hollow channel plasma. The results show that positron beams in hollow channels are less prone to distortions and deflections. Hollow channels were observed to guide the positron beam onto the channel axis. Beam energy loss was also observed implying the formation of a large wake amplitude. The experiments were carried out as part of the E-162 plasma wakefield experiments at SLAC.

Introduction

In the "blow out" regime of the plasma wakefield accelerator (PWFA) a high density electron beam exerts a large radial force on the plasma electrons, creating a nearly uniform ion column. As the beam passes through, plasma electrons rush back to neutralize the ions creating a large amplitude wake following the drive beam. The wake can be used to accelerate electrons in a trailing beam, or electrons in the tail of the drive beam can be used to probe the wake.

The ion column acts as a thick, underdense, plasma lens, with a large focusing strength thus producing multiple betatron oscillations as shown in reference 2. For a uniform ion column the force on the beam is linear with radius. In this case, the beam can propagate without distortion or emittance growth.

In the case of a positron beam, plasma electrons flow in to neutralize the beam in a very dynamic way. As the beam passes through, these plasma electrons rapidly exit leaving a large amplitude wake behind. Due to the large reservoir of plasma electrons surrounding the beam, electrons can be pulled in continuously. Some overshoot and pass through the beam or oscillate about the beam axis. The resulting focusing forces are nonlinear and vary with r and z along the beam as shown in Ref. 3. At best,

nonlinear but symmetric forces, result in emittance growth and beam halo formation.

A radially inhomogeneous plasma can create a deflection or distortion of an electron beam due to the creation of an asymmetric ion column. Similarly, positron beams can be deflected or distorted due to a radially asymmetric flow of plasma electrons to one part of the positron beam or another. Also, electron or positron beams with head to tail tilts can be deflected and distorted. This is because forces on axially misaligned beam slices will have a focusing component plus a transverse deflecting component. These distortions and deflections are experimentally unwanted and have often been observed during E-162 runs.

Hollow channel plasmas can guide a positron beam. Ions on the channel wall repel the beam and confine it on axis. The physical mechanism and results are discussed further below.

Experimental Set Up

The experiment was conducted at SLAC as part of the PWFA work known as E-162. The experiment was located at the Final Focus Test Beam Facility (FFTB). The set up and measurement details are described in many other papers (See references). Here we give only a brief description. The 28.5 GeV positron beam was focused to the entrance of a uv photoionized lithium plasma. Typical beam parameters were, 2×10^{10} positrons per bunch, 600 μm rms bunch length, with a 25 μm beam size at the plasma entrance. The SLAC beam emittance was increased due to scattering from foils and from a thin uv coupling mirror placed in the beam line. The beam emittance at the plasma entrance was about 2×10^9 m-r.

A column of lithium vapor, 140 cm, long was produced in a heat pipe oven (Ref. 4). A uv ArF laser was used to single photon ionize the lithium vapor. For these experiments, the plasma density was proportional to uv fluence (J/cm^2). The plasma density ranged from $(0 - 2) \times 10^{14} \text{ cm}^{-3}$. An axially uniform plasma can be produced by focusing the laser to compensate for uv absorption. Axial variations in plasma density do not significantly alter the resulting transverse dynamics of the beam as long as the scale of the density variation is larger than the betatron wavelength. When absorption is taken into account, the radial plasma profile mimics the laser profile.

The plasma channel was produced by placing a mask in the center of the uv laser beam. The mask diameters used were 1 mm and .6 mm. An ideal plasma channel with rigid walls like that described in Ref. 1, would be difficult to produce due diffusion of the plasma. Since the laser fires ~ 200 ns before the positron beam arrives, this allows some time for diffusion to take place. We believe the beam is propagating in something more like a density depression than an ideal rigid channel. In any case this will be referred to as a hollow channel as well. Comparison to the case without a channel was performed for the same conditions by removing the mask.

The beam spot size and location was monitored by optical transition radiators (OTR) located upstream (US) and downstream (DS) of the plasma. Focusing and transverse dynamics were observed on the DSOTR versus a uv count which is proportional to the plasma density. Monitoring of the incoming beam parameters was a simple matter of toggling the uv laser so that no plasma was produced.

An imaging spectrometer was set up to monitor the changes in beam energy after traversing the plasma. A permanent dipole bending magnet was used to disperse the beam and quadrupole lenses were used to image the beam from the plasma exit to an aerogel Cherenkov radiator (CR). Imaging assures that the observed beam energy is true and not due to transverse effects. The magnetic dispersion is about 10 cm or 300 MeV /mm. The CR was imaged onto a CCD camera where changes of the beam energy were observed. CR light was also imaged on to a streak camera (SC) where changes in the beam energy along the pulse were monitored.

The incoming beam has a correlated energy spread of about 350 MeV with the higher energy in the head. Observation of energy gain of tail electrons is difficult unless they gain enough energy to be clearly seen above the energy of the head. By streaking the beam energy in time, we can look at the change in energy along the beam, particularly the energy loss of the middle of the beam and energy gain of the tail electrons.

Results

Figure 1 compares the beam images at the DSOTR with no plasma, to plasma with and without a channel. With the channel the beam propagated and focused without distortion. Without a channel the beam was focused, but has an unwanted distortion. Figure 2 shows the average beam deflection versus uv counts, without the hollow channel. All the points are for the same input beam parameters. The beam was deflected without the channel indicating the plasma profile was radially inhomogeneous and or the beam was tilted. In contrast the beam was not deflected but rather guided with the hollow channel. Guiding occurs when the positron beam is misaligned or at a small angle to the hollow channel axis. The build up

of ions on the channel wall, confine the beam by repelling the beam toward the channel axis.

Figure 1. Comparison of positron beam images at the DSOTR for a) no plasma b) plasma with a hollow channel c) plasma without a channel .

Figure 2. Average beam deflection verses uv counts (proportional to plasm density) for a plasma without a hollow channel.

Random shot to shot misalignment of the beam to the hollow channel axis occurred due to small energy variations of the beam. This resulted in steering from the slightly misaligned final focusing quads. Figure 3 shows the beam trajectory at the US and DS OTR's for 200 shots. The open circles show the correlation between beam location on the OTR's without plasma. The crosses

show the beam guiding with the hollow channel. The beam moves toward the center location in x , which demonstrates hollow channel guiding. Similarly the beam was also guided in y .

Figure 3. Beam guiding trajectory on DS vs. US OTR. The open circles show the correlation between beam location on the OTR's without plasma. Crosses show when the plasma is on the beam moves toward the center location of the channel in x .

As noted above, the homogeneous plasma actually has a radial profile peaked on axis like the uv laser. Beams not on axis with the plasma were deflected. A beam on a trajectory moving across the plasma axis would appear to steer toward the axis. This is not guiding as evidenced by the fact that the beam is deflected further as the plasma density was increased.

The plasma dynamics of a positron beam propagating in a hollow channel are illustrated in Fig. 4a. An annulus of plasma electrons are pulled toward the beam as the beam moves through the channel. Most of the plasma electrons reach the beam axis as it passes by. Therefore very few plasma electrons cross the beam allowing for propagation with low distortion and deflection. Figure 4b, shows the flow in of plasma electrons for the homogeneous case. Plasma electrons cross the beam and some oscillate about the axis leading to nonlinear focusing forces along the beam.

The central portion of the beam loses energy as it propagates through the plasma channel. Figure 5, compares CR images of the energy spectra for no plasma, a low density hollow channel and a high density hollow channel plasma. At low density we see the beam is focused, but no significant energy change. At high density the beam loses significant energy of about 200 MeV. To observe energy gain of the beam tail requires further analysis of the streak camera images.

Figure 4. Illustration of plasma dynamics, a) with and b) without a hollow plasma channel. Beam moves to the left.

Figure 5. Energy spectrum of positron beam a) with no plasma compared to b) low density and c) high density hollow plasma channels.

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predator numbers are high (P_2), prey numbers will crash. The full model for the system will have two equations, one for prey and one for predators, and we know that such two-dimensional models are perfectly capable of displaying cyclic behaviour.

We now see why the observation of the perfectly out-of-phase dynamics demonstrates that the rotifer–algal cycles could not be driven by the classical predator–prey mechanism. So what is the actual explanation? The path taken by the Cornell group to answer this question is an almost textbook example of how science is supposed to be done. First they advanced four competing hypotheses, suggested by various known features of algal and rotifer biology. Next they translated the hypotheses into mathematical models and contrasted model predictions with data. Only one model, based on the ability of algae to evolve rapidly in response to predation, successfully matched such features of data as period lengths and phase relationships⁵. This is a convincing result, and if we dealt with a natural system we would have to stop there because we cannot usually manipulate the genetic structure of field populations.

In the laboratory, however, such an experiment is possible, and the successful test reported by Yoshida *et al.*¹ provides the final and most decisive evidence of the rapid-evolution hypothesis. Thus, the out-of-phase cycles result from the following sequence of observed events: under intense predation, the prey population becomes dominated by clones that are resistant to predators; when most prey are resistant, the predators remain at low numbers even though prey abundance recovers; low predation pressure allows non-resistant clones to outcompete resistant ones; so predators can increase again, leading to another cycle.

The experimental demonstration that rapid evolution can drive population cycles means that ecologists will have to rethink several assumptions. To give just one example, there is a long-standing debate in population ecology on whether natural populations can exhibit chaotic dynamics. Chaos (in the mathematical sense) is irregular dynamical behaviour that looks as though it is driven by external random factors, but in fact is a result of internal workings of the system. Before the discovery of chaos, ecologists thought that all irregularities in the observed population dynamics were due to external factors such as fluctuations of climate. Now we realize that population interactions (including those between predators and prey) can also result in erratic-looking — chaotic — dynamics. Incidentally, the chaos controversy was the main reason why the Cornell group decided to study rotifer population cycles.

Some ecologists have argued that chaotic dynamics cause populations to crash to very

low densities at which the probability of extinction is high, and that natural selection should therefore cause evolution away from chaos⁶. Since this argument was advanced, at least two examples of chaotic behaviour have been discovered: in the dynamics of the incidence of childhood diseases such as measles⁷, and of population numbers of rodents such as voles and lemmings⁸. What is more important, however, is that the argument assumes that evolution occurs on much longer timescales than oscillations. But the results of Yoshida *et al.*¹ show that evolution can be an intrinsic part of oscillations, raising an exciting possibility that some populations might rapidly evolve both towards and away from chaos. Perhaps this is the explanation of the puzzling observation that some Finnish vole populations shift from a stable regime to oscillations, whereas others do precisely the reverse⁹.

This is rank speculation, however, and will have to remain so because we cannot test it experimentally in natural systems. But in

the laboratory much more is possible, as the study by Yoshida *et al.* shows. We can hope that in the near future we will see an experimental investigation of the possibility of rapid evolution to and away from chaos. ■

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Accelerator physics

In the wake of success

Robert Bingham

Particle accelerators tend to be large and expensive. But an alternative technology, which could result in more compact, cheaper machines, is proving its viability for the acceleration of subatomic particles.

Since the construction of the first particle accelerator in 1932, high-energy collisions of accelerated ions or subatomic particles (such as electrons and their antimatter counterpart, positrons) have proved a useful tool in physics research. But the escalating size and cost of future machines means that new, more compact acceleration techniques are being sought. In *Physical Review Letters*, Blue *et al.*¹ report results from a test facility at the Stanford Linear Accelerator Center (SLAC), Califor-

nia, that have great significance for the future of particle accelerators. Their success heralds an entirely new type of technology, the plasma wake-field accelerator.

When charged particles such as electrons or positrons pass across a gradient of electric field, they are accelerated — how much depends on the steepness of the gradient. In conventional accelerators, a radiofrequency electric field is generated inside metal (often superconductor) accelerator cavities. But the gradient can be turned up only so far before

Figure 1 The wake created by a boat is a familiar image, but it is also the inspiration for a new type of particle accelerator. Blue *et al.*¹ have demonstrated that waves in a hot, ionized plasma of gas can create a rippling electric field in their wake, and that this 'wake field' can accelerate subatomic particles.

ALAN SCHEIN/CORBIS

the field breaks down. A more attractive medium for the next generation of particle accelerators is a plasma — a gas of atoms that has been ionized into a soup of electrons and nuclei. Plasmas can support electric fields with strengths of around a hundred gigavolts per metre, which is orders of magnitude higher than conventional accelerators.

At the centre of Blue and colleagues' apparatus¹ is a chamber 1.4 metres long containing a hot plasma created from lithium atoms. The electron density in the plasma is about 1.8×10^{14} per cubic centimetre. When a tightly packed bunch, or pulse, of positrons is fired into the plasma, it creates a rippling electric field behind it, rather like the wake of a boat (Fig. 1), and hence the name 'wake field'. Inside the chamber, the positively charged particles in the pulse 'suck in' negatively charged electrons from the plasma. To restore charge neutrality, the displaced electrons then snap back, away from the pulse, but tend to overshoot their original positions. This oscillation in plasma electron density creates an oscillating electric wake field, moving behind the pulse (Fig. 2).

Roughly the first two-thirds of the positron pulse (which overall comprises about 10^{10} particles) lose energy in setting up the intense plasma wake field. From their initial energy of 28.5 giga-electronvolts (GeV), these positrons decelerate at a rate of 49 mega-electronvolts (MeV) per metre. But the wake field they create accelerates the trailing third of the beam, increasing these particles' energies by almost 80 MeV over the length of the chamber, which corresponds to an accelerating gradient of 56 MeV per metre. The results are in excellent agreement with a three-dimensional simulation of the process, which predicted a peak energy gain of 78 MeV.

This is the first experiment to demonstrate energy gain by positrons in a plasma, and to use and accelerate particles that are at energies of interest for high-energy physics. (An existing electron-positron collider at SLAC used beams of particles with energies up to 50 GeV; the 'next linear collider', still at the planning stage, will have beam energies ultimately of 500 GeV.) To achieve this, Blue *et al.*¹ have had to overcome some tough practical problems. For example, the transportation and focusing of the positron pulse in the long plasma chamber is a remarkable achievement. The pulse shows no evidence of instabilities, particularly of the type known as 'hosing' instabilities², which induce transverse oscillations in the tail of the pulse that eventually destroy it. It is also significant that the positrons can propagate in the plasma without being annihilated by their electron antiparticles.

High-gradient acceleration of electrons as well as positrons is necessary for the development of a compact electron-positron plasma collider. In fact, the positron pulse

Figure 2 Beam-driven plasma acceleration. A pulse of positrons (blue line) is fired into a plasma of lithium gas. The positively charged particle pulse attracts the negatively charged electrons in the plasma, drawing them in and creating an electric field in the wake of the pulse (red curve). Initially the longitudinal field dips negative, but then the displaced electrons snap back, overshooting their original positions and driving the longitudinal field to positive values. This strong, oscillating field is termed a 'wake field'. Although particles at the head of the pulse lose energy in setting up the wake field, particles in the tail are accelerated by it.

used by Blue *et al.*¹ could simply be replaced by an electron pulse. The wake field would then arise through a slightly different mechanism: the electron bunch expels all the plasma electrons within its radius (known as 'blow-out'), leaving a channel of positively charged ions or nuclei behind it; again, the oscillating charge density generates a wake field that will accelerate the tail-end of the bunch. Calculations show that the wake fields generated by positrons are weaker than for electrons, but the two would be comparable if, rather than being uniform, the plasma were shaped to form a hollow cylinder³.

Instead of particles, a laser pulse can be used to set up an accelerating wake field in a plasma. In this case, the radiation pressure of the laser pushes the plasma electrons out of its path, creating oscillations in its wake.

Ageing

Microarraying mortality

David Gems and Joshua J. McElwee

Understanding how we grow old is a long-sought goal. A new large-scale study of gene expression in worms allows us to glimpse the complex biochemistry of lifespan.

The past decade has seen dramatic developments in studies of the genetics of ageing and longevity, mostly involving model organisms such as the nematode worm *Caenorhabditis elegans*, baker's yeast, fruitflies and mice¹. This has created considerable optimism that an

Previous experiments⁴ on plasma wake fields driven by terawatt lasers have shown that particles injected into the wake field gain about 200 MeV of energy, but the acceleration has only been sustained over millimetre distances; Blue and colleagues' beam-driven acceleration is sustained over more than a metre.

Perhaps the first incarnation of the plasma wake-field accelerator will be within a conventional accelerator as a 'plasma afterburner'⁵. By introducing 10-m plasma sections into a linear collider that is many kilometres long, wake-field acceleration could be used to double the energy of conventionally accelerated particles. But wake-field acceleration comes at the price of decelerating the head of the particle bunch. To counteract this, plasma lenses are included in the design, between the afterburner and the collision point. Such lenses focus the particles into a tighter bunch, far more strongly than do the conventional magnetic variety⁶. The tighter the bunches are focused, the more likely are particles in opposing bunches to collide when they meet, so the rate of collisions is not degraded by inclusion of the afterburner.

The work presented by Blue *et al.*¹ marks the most significant progress so far in the field of advanced accelerator research. It is likely to have an impact on many fields, as compact accelerators are developed for wider applications, such as in medicine. And the impact on the way particle physics is done in this century will no doubt be profound.

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Plasma-Wakefield Acceleration of an Intense Positron Beam

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Plasma wakefields are both excited and probed by propagating an intense 28.5 GeV positron beam through a 1.4 m long lithium plasma. The main body of the beam loses energy in exciting this wakefield while positrons in the back of the same beam can be accelerated by the same wakefield as it changes sign. The scaling of energy loss with plasma density as well as the energy gain seen at the highest plasma density is in excellent agreement with simulations.

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High-gradient acceleration of both positrons and electrons is a prerequisite condition to the successful development of a plasma-based e^+e^- linear collider. Such an accelerator employs the longitudinal electric field of a relativistically propagating wakefield in a plasma to accelerate charged particles [1–3]. In proof-of-principle experiments, laser-driven plasma wakefields have been shown to accelerate electrons at gradients that are significantly greater than those employed in current radio-frequency accelerators [4–7]. In this Letter we show for the first time that a beam of positrons can drive and be used to probe the longitudinal electric field component of the plasma wakefield. When a 28.5 GeV, 2.4 ps long positron beam at the Stanford Linear Accelerator Center (SLAC) containing 1.2×10^{10} particles propagates through a lithium plasma of electron density $1.8 \times 10^{14} \text{ cm}^{-3}$, the main body of the beam is decelerated at a rate of approximately 49 MeV/m, while a beam slice containing 5×10^8 positrons in the back of the same bunch gains energy at an average rate of $\sim 56 \text{ MeV/m}$ over 1.4 m. These results are critical to the development of future plasma-based linear colliders.

When an ultrarelativistic, highly focused ($\sigma_r \ll c/\omega_p$) positron beam enters an underdense plasma ($n_b > n_p$), the in-vacuum balance between the beam's space-charge defocusing field and self-magnetic focusing field is modified by the highly mobile plasma electrons that are pulled in neutralizing the excess space charge of the positron beam. Here σ_r , c , ω_p , n_b , and n_p are the beam radius, speed of light, plasma frequency, beam density, and plasma density, respectively. The degree of neutralization depends not only on the plasma density but also on the longitudinal position along the positron bunch. This in turn leads to a longitudinal and transverse nonuniform focusing force that nevertheless can focus the beam [8,9]. While the focusing of the positron beam by the transverse fields has been experimentally demonstrated, there has not been a systematic investigation of the longitudinal component of the wakefield induced by the positron beam

in a plasma. As plasma electrons from various radii arrive on the axis of the beam at various times and overshoot, they create a wakefield structure that has complex longitudinal and transverse electric field components [10]. In this experiment, a single positron bunch is used to both excite and probe the longitudinal electric field component of the plasma wakefield with picosecond resolution by diagnosing the energy change of different longitudinal slices of the drive beam itself. If the rms bunch length σ_z is approximately $\pi c/\omega_p$, then the bulk of the positrons do work in pulling in the plasma electrons and therefore lose energy to the wakefield. However, there are a significant number of particles in the latter half of the beam where the wakefield has changed sign and are therefore accelerated. For instance, Fig. 1 shows the plasma wakefield (red curve) induced by a 28.5 GeV positron beam with $\sigma_z/c = 2.4 \text{ ps}$, containing 1.2×10^{10} positrons (dashed blue curve) in a $1.8 \times 10^{14} \text{ cm}^{-3}$ plasma obtained using the 3D, particle-in-cell (PIC) code OSIRIS [11]. The bunch is moving from right to left with the head, or front of the beam, located $\sim 7 \text{ ps}$ ahead of the centroid, and the tail, or back of the bunch, located $\sim 7 \text{ ps}$ behind the centroid. The simulation parameters consisted of grid sizes $\Delta x = \Delta y = \Delta z = 50 \text{ } \mu\text{m}$, eight plasma particles per cell, 12 beam particles per cell, and a moving simulation window of $3.2 \text{ cm} \times 3.2 \text{ cm} \times 6.4 \text{ cm}$ in x , y , and z , respectively. The E_z field was averaged over $0 \leq r \leq \sigma_r$ in the simulation grid. Near the beam center (centroid), the peak decelerating field E_z^- is approximately 50 MV/m, whereas the peak accelerating field E_z^+ located 3 ps after the centroid is approximately 64 MV/m. With such a field structure, the beam energy is transferred from a large number of particles in the core of the bunch to a fewer number of particles in the back of the same bunch. The wakefield thus acts like a transformer with a ratio E_z^+/E_z^- of ~ 1.3 . Figure 2 shows the predicted change in beam energy vs position in the beam after propagating through 1.4 m of $1.8 \times 10^{14} \text{ cm}^{-3}$ plasma obtained from the same 3D PIC simulation used to generate the fields of

FIG. 1 (color). Longitudinal electric field (solid red curve) excited in a plasma by a positron beam which is moving right to left in the figure (dashed blue curve). The field is averaged over one σ_z . A peak decelerating field of 50 MV/m occurs 1 ps ahead of the centroid and a peak accelerating field of 64 MV/m occurs 3 ps behind the centroid.

Fig. 1. The beam is traveling from right to left with the head and tail marking the front and back of the beam, respectively. The color-mapped intensity at each point in the graph is proportional to the number of beam particles within a $\Delta\text{energy} \times \Delta\text{time}$ grid point. The peak energy loss of the beam is about 64 MeV, whereas the “slice” of the bunch located $\sim 1.7\sigma_z$ behind the peak energy loss location (i.e., the slice at 3 ps) has gained approximately 80 MeV. The maximum energy gain and loss seen in the

FIG. 2 (color). 3D particle-in-cell simulation of a positron beam in a plasma. The image depicts the phase space of the beam after it has traversed 1.4 m of plasma. Beam parameters in the simulation were identical to experimental parameters. The simulation predicts an energy loss of 64 MeV and an energy gain of 79 MeV.

OSIRIS simulations are consistent with the transformer ratio inferred from the plot of the longitudinal field of Fig. 1 demonstrating that once established, the longitudinal fields do not significantly evolve as the beam propagates through the plasma.

The experiment took place in the Final Focus Test Beam facility at the SLAC. A 28.5 GeV positron beam with $N = 1.2 \times 10^{10}$ particles (~ 1.9 nC) in a $\sigma_z = 0.73$ mm long bunch was focused at the plasma entrance with a spot size of $\sigma_r = 40$ μm . The beam’s charge was measured using current monitors before and after the plasma, the incoming spot size was measured by imaging the optical transition radiation emitted by the positron beam passing through a 37 μm thick titanium foil onto a charge coupled device (CCD) camera [12], and the incoming beam energy before entering the plasma was monitored using a beam position monitor in a dispersive section of the beam line upstream of the plasma. The plasma source [13] consisted of an ionized lithium vapor (ionization potential = 5.4 eV) in a heat pipe oven which had a neutral gas density of $N_g = 2 \times 10^{15} \text{ cm}^{-3}$ over a length of 1.4 m. The plasma was created via single photon ionization of lithium atoms using a pulse from a 193 nm (photon energy = 6.4 eV) argon fluoride excimer laser. The plasma density was varied between $0\text{--}2 \times 10^{14} \text{ cm}^{-3}$ by varying the laser pulse energy. The laser pulse energy was measured before and after the lithium vapor column on every shot, and therefore the plasma density was known for every shot.

Upon exiting the plasma, the positron beam was imaged with a magnetic imaging spectrometer with a magnification of 3 in both the horizontal and vertical planes onto a 1 mm thick aerogel Cherenkov radiator located 25 m away [1]. The magnetic dispersion of 291 MeV/mm at the Cherenkov radiator spread the beam out in the vertical plane, so that by measuring the vertical position of different longitudinal slices of the beam at the Cherenkov plane, the beam energy distribution could be determined. Since the vertical displacement at the aerogel induced by the energy changes of the beam in the plasma was on the order of the beam’s spot size, time resolution of the beam was necessary to separate the energy changes of the beam’s various longitudinal slices. The Cherenkov radiation was imaged onto both a CCD camera for a time-integrated energy diagnostic and onto the slit of a streak camera with 1 ps temporal resolution for time-resolved measurements. The time-integrated energy diagnostic was used to monitor the positron beam’s transverse shape and to determine which portion of the beam was sampled by the streak camera slit. The Cherenkov radiation which was sent to the streak camera was first split into two paths with a beam splitter. One arm was passed through a 90° rotator and a time delay before it was recombined with the other arm to produce two orthogonal images (y vs t and x vs t) on the streak camera. The vertical streak camera image (y vs t) thus measured the

temporal energy variation of the positron beam while the horizontal streak camera image (x vs t) measured the transverse (dispersion-free) dynamics.

A primary indicator that the positron beam is driving, and thus transferring energy to, a plasma wakefield is the observation of energy loss. Energy loss measurements over a wide range of plasma densities are presented in Fig. 3 (blue circles). Figure 3 also shows the energy loss predictions from 3D PIC simulations (red triangles). The energy loss of the beam was measured after the plasma by dividing the entire energy-dispersed streak camera image into 1 ps slices, fitting a Gaussian profile to the data of each slice and tracking the relative position of each Gaussian's mean. The plasma density was varied between 0 – $2 \times 10^{14} \text{ cm}^{-3}$ over a series of 200 shots. The ionizing laser was not fired every fourth shot to provide a baseline measurement of incoming beam parameters and to provide the data for zero plasma density. The measured mean positions were binned by plasma density, and the peak energy loss was calculated for each density by subtracting the mean of the incoming beam energy from the mean of the slice which lost the greatest energy after the plasma. The vertical error bars represent the standard deviation of the mean for each density bin. As can be seen in Fig. 3, simulations predict and experimental data confirm that the beam loses energy in the plasma. The energy loss gradually increases with increasing plasma density with a maximum measured energy loss of $68 \pm 8 \text{ MeV}$ at a plasma density of $1.8 \times 10^{14} \text{ cm}^{-3}$. This is in good agreement with 3D OSIRIS simulations which predicted a peak energy loss of 64 MeV at the same plasma density.

FIG. 3 (color). Energy loss of the positron beam's centroid after propagating through 1.4 m of plasma. The energy loss of the centroid increases with increasing plasma density. The red triangles are the 3D PIC simulation predictions of peak energy loss. The blue circles are the experimentally measured energy losses at different plasma densities. At a density of $1.8 \times 10^{14} \text{ cm}^{-3}$, the energy loss is $68 \pm 8 \text{ MeV}$.

Since the plasma wakefield is an energy transformer, the energy loss data strongly suggest that the particles in the beam's tail should gain energy in this experiment. As opposed to the energy loss of the beam, which can be measured at plasma densities as low as $3 \times 10^{13} \text{ cm}^{-3}$, the energy gain of the "tail particles" can be observed only for densities greater than $\sim 1.5 \times 10^{14} \text{ cm}^{-3}$. For densities less than $1.5 \times 10^{14} \text{ cm}^{-3}$, the plasma wakefield wavelength (see Fig. 1) is too long for the wake to accelerate enough beam charge to be measured with the limited dynamic range of the streak camera. Figure 4 shows the relative energy of each time slice along the bunch of the positron beam when the plasma is off (blue triangles) and when the plasma is turned on (red squares) with a density of $1.8 \times 10^{14} \text{ cm}^{-3}$. The vertical error bars represent the standard deviation of the mean for each temporal bin. Temporal resolution of the beam was possible only between the -4 ps slice and the 5 ps slice due to the signal-to-noise ratio in the streak camera. Therefore, the first and last slices measured on the streak camera are not the true head and tail of the beam. Rather, they represent slices which lie $\sim 2\sigma_z$ before and after the centroid. Since the change in energy is important, not the absolute energy, energy changes were measured with respect to the -4 ps plasma off slice. The plasma off case shows that the beam has a head-to-tail energy chirp of $\sim 20 \text{ MeV}$. With the plasma on, energy loss is observed for the bulk of the beam out to about σ_z behind the centroid. The positrons behind this point have gained energy. The data show that $\sim 5 \times 10^8$ positrons in a 1 ps slice $1.6\sigma_z$ after the centroid were accelerated by $79 \pm 15 \text{ MeV}$ in 1.4 m ($\sim 56 \text{ MeV/m}$ gradient). These results are in

FIG. 4 (color). Time slice analysis of the energy dynamics within a single positron bunch. The plasma off (blue triangles) shows a slight head-tail energy chirp of $\sim 20 \text{ MeV}$. When the plasma is on (red squares), the front half of the beam loses energy driving the plasma wave, while the back half of the beam is accelerated by the plasma wave. The black line is the charge distribution within the bunch

good agreement with 3D PIC simulations which predicted a peak energy gain of 78 MeV. The maximum energy loss in the simulations occurred at about -1.5 ps, whereas in the experiment the 0 ps slice (i.e., the beam's center slice) shows the greatest loss. This is thought to be due to small differences between the actual beam current profile and the fitted Gaussian current profile that was used in the simulations and also due to space-charge broadening effects in the streak camera.

In addition to the measurements in the energy-dispersive plane, the dispersion-free plane was analyzed to measure transverse dynamics of the beam's tail. One concern for energy gain measurements was that the beam's tail might have undergone transverse oscillations or hosing-type (two stream) instabilities [14] and that these oscillations would cause vertical deflections which would appear to be energy gain on our diagnostics. Our measurements of the transverse dynamics in the dispersion-free plane show no evidence of "hosing" in our data [15], thus confirming that the measurements of energy gain and loss were due to energy changes imparted on the beam by the plasma.

In summary, this Letter demonstrates the first acceleration of positrons by a plasma wakefield. Excellent agreement was found between the experimental results and those from 3D PIC simulations for both energy gain and loss. Energy loss of the centroid was found to increase with increasing plasma density up to a value of ≈ 68 MeV at a plasma density of $1.8 \times 10^{14} \text{ cm}^{-3}$. At this density, energy gain of positrons in a plasma of 79 MeV was measured. The acceleration gradient of 56 MeV/m measured in this proof-of-principal experiment can be increased to the GeV/m level in future experiments by a combination of an increase in the drive beam charge, a decrease in the drive beam pulse width (with a corresponding increase in the plasma density), and by employing a plasma channel rather than a uniform plasma [10]. Furthermore, in a real application of such a plasma wakefield accelerator, the drive positron bunch will be followed by an optimally placed trailing witness

bunch with a sufficient current to both realize high-gradient acceleration and a reasonable beam load and narrow energy spread. These scalings have been explored through PIC simulations [16]. These results and future experiments will be the basis of work to design a plasma-based linear collider which will utilize either multiple plasma wakefield accelerator sections [17] or an extremely high-gradient single stage plasma wakefield "afterburner" at the end of an existing linac to double the energy of the electron and positron beams [18].

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The new hot rods of the physics world

Physics in Action: February 2003

From zero to 200 MeV in less than a millimetre in a wake-field accelerator

Particle accelerators are the largest pieces of equipment that physicists have to help them unravel nature's secrets. Take the 27 km circumference of the Large Hadron Collider under construction at CERN in Geneva or the 3 km linear accelerator at the Stanford Linear

Accelerator Center in the US. These machines accelerate particles to energies above 10^{10} eV and then collide them to explore fundamental questions in high-energy physics.

However, as successful as they are in tackling problems such as the origin of mass and the asymmetry between matter and antimatter, accelerators cannot keep achieving higher and higher energies. Most accelerators use radio-frequency waves confined in metallic cavities to give particles a "kick" in energy each time they pass through the cavity. However, the acceleration gradients that these machines can achieve are limited, and the only way to reach higher energies is to build bigger accelerators with more cavities.

Wake-field accelerators

However, an exciting alternative method of acceleration is making great strides towards the next energy regime. The "laser wake field" accelerator relies on exploiting the radiation pressure of an intense laser pulse to displace the electrons in a plasma, leaving a large electric field in its wake ([figure 1](#)). Now Viktor Malka of the Ecole Polytechnique in France and

colleagues from the CEA/DAM laboratory in Bruyères-le-Châtel, the University of Bordeaux and Imperial College in the UK have demonstrated that electrons can be rapidly accelerated by surfing such a wake (V Malka *et al.* 2002 *Science* **298** 1596).

Their results show that an electron at rest can be accelerated to an energy of 200 MeV in a distance of just 1 mm. This is a terrestrial particle-acceleration record, although similar plasma-acceleration processes may occur with even greater ferocity in the astrophysical plasmas that surround supernovae and black holes. At rates like this, the current high-energy frontier could be reached in an accelerator only one metre long!

But there is a catch. In addition to reaching high energies, the accelerator must also produce a beam of high quality if it is to be of use in physics applications. This means that the beam must be well collimated, it must contain a large number of particles and all the particles must have the same (or almost the same) energy. There is still a long way to go to realize all these requirements in a working accelerator, but Malka and co-workers have made a significant step towards achieving two of them. They have accessed a new physical regime of the laser-wake-field accelerator, which has resulted in both the highest energy from such a scheme to date and an improvement in the collimation of the beam. The higher-energy particles were found to emerge in a narrow cone of less than 5° and corresponded to a transverse beam quality that is better than that of a typical conventional linear accelerator.

Surfing the wake

Plasmas make promising particle accelerators because they can support electric fields that are greater than several hundred gigavolts per metre. This is achieved by exciting relativistic plasma waves (space-charge oscillations, which depend on the density of the plasma) with a high-intensity laser.

There are different types of plasma-based accelerator. In a basic laser-wake-field accelerator, a pulse of photons that is shorter than the plasma wavelength excites a wake, much like the wake produced by a boat ([figure 2 top](#)). This is the simple, or resonant, laser-wake-field regime, which is characterized by clean wakes and its relative freedom from instabilities due to the shortness of the pulse.

This regime, however, has been difficult to access experimentally. As a result, most of the experimental work to date has focused on the longer-pulse regimes. These are the "beat wave" regime in which two lasers beat at the frequency of the plasma wave ([figure 2 middle](#)), and the "self-modulated" regime in which a long laser pulse becomes modulated

at the plasma frequency due to an instability of the laser in the plasma ([figure 2 bottom](#)).

The latter regimes have been successfully employed by groups from the University of California at Los Angeles, the Naval Research Laboratory, the University of Michigan and the Lawrence Livermore National Laboratory – all in the US – and the Rutherford Appleton Laboratory in the UK to accelerate electrons to roughly 100 MeV.

The high-energy frontier

Simple laser-wake-field acceleration has been out of reach until now due to the laser requirements. The pulse must be short enough to "fit" into half a plasma wavelength but must carry enough energy to drive the oscillating plasma electrons to relativistic speeds. These electrons need to be fast enough so that some of them catch the wake and become trapped and accelerated, like white water cascading down the face of an ocean wave. Using advances in short-pulse power made possible by chirped-pulse-amplification technology, the French group was able to generate a pulse with 1 J of laser energy in 30 fs (30 TW of peak power).

However, even this was not quite short enough to fit into the 10 fs half-wave period of the high-density plasma. Instead, the researchers relied on the plasma itself to reshape and effectively shorten the laser pulse. Several mechanisms contribute to this but the simplest to understand is perhaps the one that arises from the difference in group velocity between the head and the tail of the laser pulse in its own wake. The head travels in the plasma and moves at less than the speed of light, while the tail travels in a plasma depression and so moves at roughly the speed of light in a vacuum. Like a collapsible boat travelling in a water depression, the tail catches up with the head ([figure 1](#)). Malka and co-workers refer to this as the "forced" laser-wake-field regime.

As exciting as these results are, they are really just the tip of the iceberg of what laser-wake-field accelerators can do. Malka and co-workers point out a number of exciting applications for their ultrashort (100 fs) bursts of collimated electrons, including the production of short, bright X-ray pulses for biology and crystallography. Researchers around the world are hotly pursuing ideas for extending the interaction length and energy reach of wake-field accelerators, as well as improving other aspects of the beam quality.

Energies of 10^9 eV cannot be far away and represent another big step towards the high-energy frontier, and beyond.

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Plasma Wakefields Accelerate Positrons

An experiment conducted at SLAC features a number of firsts: the first time positrons have been accelerated by the plasma wakefield method (see [PNU #385](#) for background information); the first time wakefield acceleration has been achieved with meter-size plasmas (previous efforts have taken place in 10 cm cells); and the first to operate under realistic accelerator conditions (in this case a 30-GeV beam of positrons). In this UCLA/SLAC/USC collaboration, positron bursts are sent into a 1.4-meter-long chamber filled with a lithium plasma. The first two-thirds of the burst sets up powerful electric fields in the plasma which then serve to accelerate the trailing one-third of the burst to higher energy. The boosted positrons increased their energy by about 80 MeV over a length of 1.4 m, for an acceleration gradient of about 50 MeV/m. This is comparable to the best acceleration that can be accomplished with conventional RF techniques in which electrons or positrons are taken up to higher energies by soaking up radio energy coupled into the beam pipe. But the wakefield researchers expect that the gradient can be enhanced a hundredfold to 5 GeV/m if the size of the beam pulses can be shrunk by a factor of 10. According to Chan Joshi of UCLA (contact [Chan Joshi](#), 310-825-7279) the wakefield approach may not be fully mature by the time the next electron-positron collider is built, but its benefit could be tested by installing two plasma accelerator sections, one for positrons and one for electrons, just before the interaction point for some final energy boosting in an existing collider. (Blue et al., [Physical Review Letters](#), upcoming article)

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