SECTION XII

NEW ACCELERATOR CONCEPTS

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THE ROLE OF PLASMAS IN FUTURE ACCELERATORS

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Abstract The Application of plasmas to high-energy accelerators has become an exciting new area of plasma and accelerator research. Plasmas can support ultrahigh electric fields without breaking down and so offer the potential to accelerate particles in a compact device which is meters rather than kilometers long. Besides providing high-gradient acceleration, new roles for plasmas are emerging that are likely to impact accelerator technology in the near future. These include concepts for providing ultra-strong focusing and short scale length bunching of particle beams.

INTRODUCTION

In the decade since T. Tajima and J. M. Dawson first proposed using laser-driven plasma waves to accelerate particles[1], substantial progress has been made on this and other plasma accelerator schemes. Equally as interesting as this plasma accelerator research are the spinoff applications for plasmas in accelerators that it is spawning. While plasma accelerators retain their long-term appeal of providing ultra-high gradient acceleration, new roles for plasmas in accelerators are emerging that are likely to impact accelerators much sooner. These include the use of the ultra-high strength fields available in plasmas for focusing or for longitudinally bunching particle beams. Plasmas have also been proposed as a means of reducing beamstrahlung[2] and as a material for high-current photocathodes. Thus, possible roles for plasmas span the stages of an accelerator from the source to the interaction point. In this paper we review the progress on plasma accelerators and on some of the new roles that plasmas may soon play.

PLASMA ACCELERATORS[3]

What makes plasmas attractive for accelerating particles are the large longitudinal electric fields ($\bar{E} \parallel \bar{k}$) they can support. By accelerator standards, these fields are tremendous—10^3 to 10^4 times those in existing linacs. A simple argument based on Gauss' law gives the order of magnitude of the plasma fields: $E^{MAX} \approx mc\,\omega_p/e \approx \sqrt{n_o\,[\mathrm{cm}^{-3}]}\ \mathrm{V/cm}$. Thus, for plasma densities of order $10^{16}-10^{18}\ \mathrm{cm}^{-3}$, accelerating fields of order 10-100 GV/m are possible. The advent of drivers capable of exciting fields near the E^{MAX} value has recently prompted a more careful examination of the maximum field obtainable in a plasma.[5] Their results indicate that waves can reach amplitudes typically a few times the value given above (before trapping of the background plasma leads to wave collapse).

The Beat Wave Accelerator

The original beat wave accelerator concept[1] is still the most vigorously pursued plasma accelerator scheme in the world today. Experiments are ongoing or recently completed in the U.S., Japan, U.K., Italy, and France. Theoretical and numerical models[6–8] now include the effects of plasma drifts, harmonics, pump rise time, damping, plasma inhomogeneities and self-focusing.

Briefly, the beat wave scheme employs two co-propagating lasers of frequencies ω_o and ω_1 such that their beat frequency $(\omega_o - \omega_1)$ is ω_p. The ponderomotive force (or radiation pressure) associated with the laser envelope then resonantly excites a plasma wave of phase velocity $\frac{\omega}{k} = \frac{\omega_o - \omega_1}{k_o - k_1} = \frac{\Delta\omega}{\Delta k} \approx v_g$, where v_g is the group velocity of laser light in plasma $[v_g \cong c(1 - \omega_p^2/\omega_o^2)^{1/2}]$.

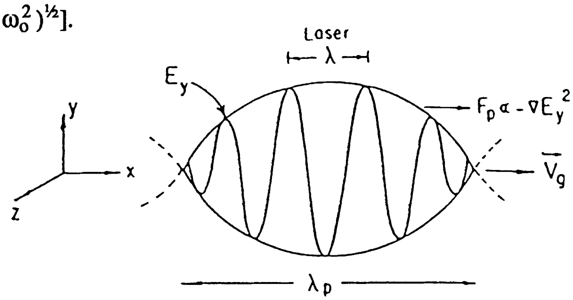
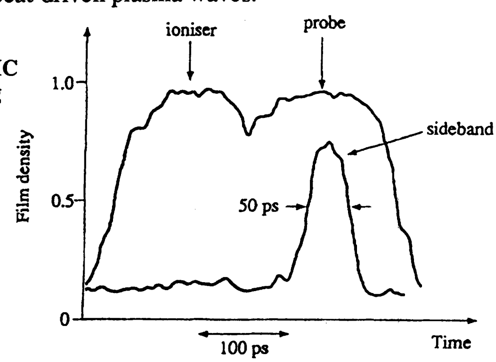


FIGURE 1. Beat wave excitation.

The most recent beat wave experiments have demonstrated wave accelerating fields of order GeV/m over a centimeter length[9] at UCLA and 300 MeV/m at RAL/Imperial College.[10] Both experiments showed evidence of plasma instabilities predicted to compete with the beat wave process for weak laser pumps (laser amplitudes $eE_o/m\omega_o c$ were each less than .03 in these experiments). Experiments are now proceeding toward the demonstration of controlled acceleration of injected particles in the beat-driven plasma waves.

FIGURE 2. Time history of RAL/IC beat wave experiment. An ionizing laser was used to produce a plasma with homogeneity better than 99%. The sideboard on the probe laser indicates scattering from a plasma wave of amplitude 300 MeV/m.



The Laser Wakefield Accelerator

One of the exciting developments in the plasma accelerator field this year is the development (at LLNL and Osaka) of laser technology capable of generating large amplitude plasma wakes with a single short laser pulse.[4] This idea of a laser wakefield accelerator[1,13,14] is similar to the beat excitation in Fig. 1 but with a single beat packet. This retains many of the advantages of the BWA without the need for a finely tuned resonant density.

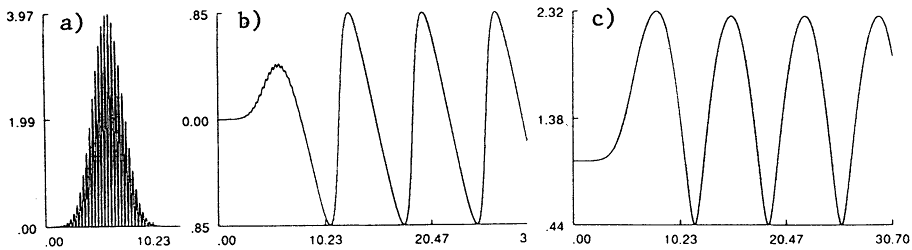


FIGURE 3. Non-linear laser wakefield solutions showing (a) laser pulse intensity $(eE_o/m\omega_oc)^2$, (b) plasma wakefield $(eE/m\omega_pc)$ and (c) wake potential $(e\phi/mc^2+1)$ vs. $\omega_p(t-z/c)$. Parameters are similar to a proposed experiment with the LLNL 10 TW laser.

Numerical solutions of the cold 1-D plasma fluid equations are shown above for a Gaussian laser pulse of fullwidth at half maximum $\approx \pi/\omega_p$ and amplitude $v_{osc}/c \equiv eE_o/m\omega_oc = 2$. From the numerical solutions we have found that the wake amplitude scales as[15]

$$eE/m\omega_p c \sim \frac{1}{2}(v_{osc}/c).$$

The particle acceleration length is the shorter of the particle dephasing length, the laser diffraction length, and the laser pump depletion length. For relativistic pumps ($v_{osc}/c > 1$) the laser group velocity and hence the wake phase velocity are very close to c, so particle dephasing is not a limiting factor.[15] The laser diffraction length ($\sim\pi\sigma^2/\lambda_{laser}$, σ is spot size) can be overcome in principal by optical guiding (caused by the refractive index change in the laser channel due to relativistic mass increase of electrons oscillating in the laser field) for powers exceeding $\sim 20\,\dfrac{\omega_o^2}{\omega_p^2}$ GW. The pump depletion length scales as $(\omega_o^2/\omega_p^2)c/\omega_p$. Applying these scaling laws to the parameters of the planned 10 TW lasers gives the preliminary accelerator parameters below.

The 10 TW laser will enable the demonstration of high-gradient wakefield acceleration (e.g., 7 MeV over .5 mm) and laser self-focusing in separate experiments. The development

TABLE I Laser Wakefield Design Examples

	10 TW	PetaWatt
pulse length	.25 ps	1 ps
v_{osc}/c	2	11
plasma density	6×10^{16} cm^{-3}	4×10^{16} cm^{-3}
Gradient (eE)	15 GeV/m	20-80 GeV/m
Max. energy gain	7 MeV†	150 GeV††
	† laser diffraction limited	†† pump depletion limited

of a petawatt laser suggests the potential for combining the two effects in a laser wakefield accelerator exceeding 100 GeV in 5 meters. These results are based on 1-D scaling laws. A great deal more work is required before the ramifications of non-linear effects are understood in 2-D, but the incentives are clearly great for pursuing this research.

<u>Particle-Driven Wakefield Accelerator</u>

The particle-beam driven wakefield accelerator uses the space charge of a particle beam rather than the ponderomotive force of a laser to create a wake of plasma oscillation.[16–18] The appeal of this scheme is the potential to boost the energy of an accelerator a factor of ten or more by adding a short section of plasma at the end.

Recent progress on wakefield accelerators has been sparked by two phases of successful experiments at ANL in Illinois (see J. Simpson, these proceedings). The first experiments verified linear theory. In the second experiments last year the density of the driving beam was increased and non-linear wakes were excited. A plasma wake amplitude of 5 MeV/m was inferred from the energy gain of test particles. This is close to the linear theory prediction (after taking into account the beam's self-pinching). However, the measured waveform was significantly steepened suggestive of a wave amplitude nearly an order of magnitude larger.

To understand the experimental results, we performed a 2-D PIC simulation with the parameters[19] of one of the operating points of the ANL experiment (below). In the simulation, the driving beam self-pinched in the plasma by a factor of 3 in radius, in agreement with the predictions of the ANL group. This produced a peak beam density on axis of about 50% of the background plasma density, large enough to account for the non-linear steepening of the wake. However, the electric field of the plasma wave responds in some sense to the average charge density over a radius equal to the plasma skin depth c/ω_p. This average density is only about 5% of n_0 as was the normalized wake amplitude (~ 7 MeV/m), in reasonable agreement with the test particle results of the experiment.

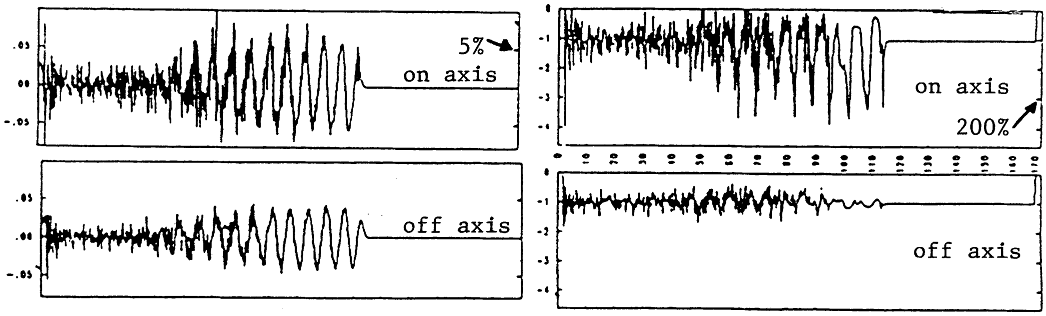


FIGURE 4. Simulation of plasma wake field (left) and plasma density response in the ANL experiment on axis and at $R = .2\, c/\omega_p = .4$mm.

The successes of the ANL experiments are encouraging for a next stage of wakefield accelerator demonstration. With high-current and possibly shaped beams from photocathode technology it is now possible to design a 20-100 MeV acceleration experiment that could address a number of important questions for an eventual high-energy device.[19]

PLASMA LENSES

Although the present concepts for using plasma lenses at the final focus of colliders evolved fairly recently[20] from work on the plasma wakefield accelerator, the use of plasmas for focusing particles dates as far back as 1947 and the Gabor lens. In the Gabor lens, a magnetic mirror traps an electron cloud. The space charge of the cloud then provides the focusing for positively charged beams. A second plasma lens concept dating back to the mid 1960's employs the azimuthal magnetic field of a current-carrying plasma to focus beams.[21] This type of lens is of interest for focusing or collecting low-current beams such as beams of anti-protons en route to the anti-proton accumulator. The remainder of this section is devoted, however, to the concept of a self-pinch plasma lens, appropriate for the final focus of a collider.

The basic mechanism of self-pinching in a plasma has been experimentally verified in both the overdense ($n_o > n_b$) and underdense ($n_o < n_b$) plasma regimes— the overdense regime in the ANL wakefield experiments and the underdense regime in so-called IFR (ion focused regime) experiments.[22] The mechanism is as follows. When an electron beam enters a plasma, the plasma electrons respond to the excess charge by shifting away from the beam particles. The remaining plasma ions partially (underdense) or completely (overdense lens) neutralize the space-charge force within the beam. For positron beams the charge neutralization is similar but is due to the plasma electrons shifting in the opposite direction. While the plasma is very effective at shielding the beam's space charge, it is less effective at shielding its current (if the beam radius is small compared to c/ω_p). Thus the beam experiences almost the full effect of its self-generated azimuthal magnetic field. From Ampere's law this is $B_\theta = 2\pi n_b e r$

for a uniform beam density n_b, where $\beta = v/c \approx 1$. This gives a net radial force

$$F_r \approx 2\pi n e^2 r \qquad \text{or} \qquad F_r/r \approx 3\times10^{-9} n_b \quad \text{Gauss/cm}$$

where n is in cm^{-3} and is the beam density in the overdense regime and the plasma density in the underdense regime. For beam parameters similar to those required for future TeV colliders (F_r/r can be of order 10^8 G/cm) and exceed by four orders of magnitude the equivalent focusing strength of conventional quadrupole magnets.

The simple physical argument given above based on plasma shielding of space charges neglects some important effects such as electron inertia, return currents, and the radial dependence of n. All of these are included quantitatively by a plasma wakefield analysis. The physical model is in good quantitative agreement with the wakefield analysis under the following conditions on the beam's scale length and radius:

$$l_b \gg c/\omega_p \gg r_b$$

where c/ω_p is the plasma skin depth ($\sim 5\times10^5\, n_o^{-1/2}$ [cm]), and r_b is the beam radius. The first inequality assures that the beam density rises slowly enough that the plasma electrons respond essentially adiabatically to maintain charge neutrality (i.e., without overshooting and oscillating). The second inequality assures that the plasma return current (which flows in a cylinder a few skin depths in radius) flows mainly outside of the beam and so does not reduce the focusing force within the beam.

Wakefield Description and Simulations

A formal wakefield analysis has been used to fully characterize the focusing strength[20] and spherical and longitudinal aberrations[23,24] in the overdense plasma regime. Sample results for the focusing force F_r vs. r, the spherical aberrations $\Delta K/K$ ($K \equiv F_r/r\gamma mc^2$) vs. Gaussian beam width σ_r and focusing force vs. axial position z (illustrating longitudinal aberrations) are shown in Fig. 5. Clearly, Gaussian beams in overdense plasma lenses have large aberrations—

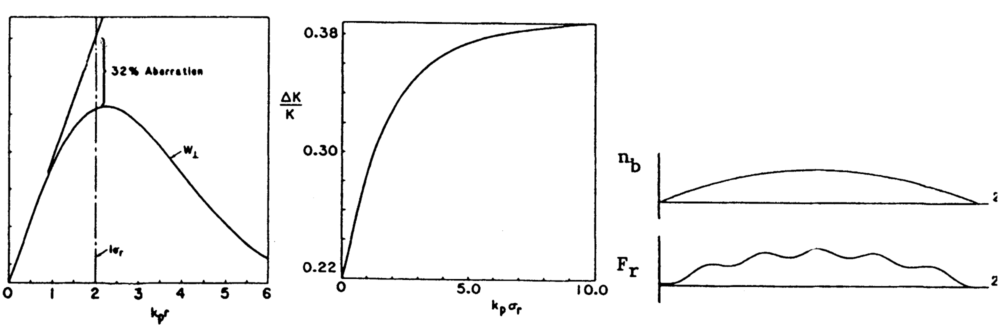


FIGURE 5. Analytic results characterizing overdense plasma lenses.

typically 25% unless steps are taken to make beam density more uniform in r. Spherical aberrations limit the spot size reduction (σ_o/σ^*) to a factor $(\Delta K/K)^{-1} \approx 4$, so overdense lenses must be placed very near to the final focus of the conventional optics.

In designing a plasma lens one must consider the limitation on spot size reduction due to beam emittance as well as aberrations. To lowest order this is[24]

$$\frac{\sigma^*}{\sigma_o} \geq \frac{2\varepsilon_N}{\sigma_o}\frac{n_o}{n}\left[\frac{1}{k_p l}\right]\left[\frac{1}{k_p\sigma_o}\right] \sim \frac{\varepsilon_N}{l\sigma_o^2}\left[\frac{5\times10^{11}\ \mathrm{cm}^{-3}}{n}\right]$$

where $\varepsilon_N = \gamma_\varepsilon$ is the normalized emittance in cm-rad, $k_p \equiv \omega_p/c$, n is n_b (overdense) or n_o (underdense regime) and all lengths are in cm in the last expression.

The aberrations can be reduced by an order of magnitude or more for electrons without beam shaping simply by passing to the underdense plasma regime ($n_o < n_b$).[25] In this case nearly all the plasma electrons are blown out of the beam path leaving a net focusing force due to the remaining ions. Since the ions are homogeneous, the focusing force is very linear in r. From the spot size reduction observed in self-consistent PIC simulations using the code ISIS, we infer that the aberrations in the underdense lens are less than 3%.

In the figure below we show a simulation of identical electron (right) and positron beams focused by identical underdense plasma lenses and finally colliding at the center. The focusing of the positron beam in the underdense regime is not as aberration-free as that of the electron beam; however, the net luminosity enhancement is still large (~ 44) due to the strong pinching disruption of the e^+ beam by the magnetic field of the more tightly focused e^- beam.

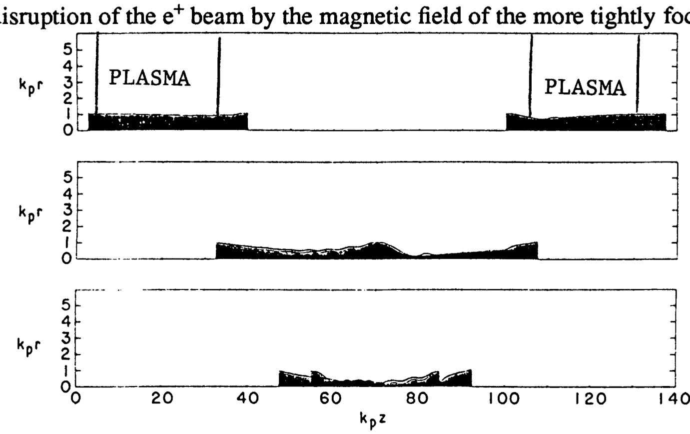


FIGURE 6. 2-D PIC simulation of $e^+ e^-$ focusing by plasma lenses and disruption.

<u>Disruption</u>

The plasma lenses in the above simulation enhanced the luminosity of the collision in two ways. First, by pinching the beams, the lenses increased the "bare" luminosity of the collision by a factor of 23 (for detailed parameters see Ref. 24). Second, by pinching the beams, the lenses increased the beams' disruption parameters D ($=N^2 e^2 \sigma_z / \gamma mc^2 \sigma^{*2}$) from .4 to about 4. This brought the beams from a regime of negligible disruption enhancement ($H_D \sim 1.2$) to a regime where significant disruption occurred ($H_D \sim 2$) giving an overall luminosity enhancement of 44.

The disruption of colliding beams is increasingly important in collider designs beyond SLC, with or without plasma lenses. The collective interaction of these charged particles is an interesting and challenging area of plasma physics research (see W. B. Mori et al., in these proceedings). Thus, the roles for plasma physicists in accelerator research are likely to grow even faster than are the roles for plasmas in accelerators.

In contrast to the long-term view of research on plasma accelerators, plasma lenses could impact accelerator technology in the very near future. Although detailed experiments are needed to fully characterize plasma lenses, it is clear that some enhancement of the SLC's luminosity could be obtained by inserting thin (~ 1 cm) plasma slabs near the IP (see Ref. 24 for a design example). Presently, there is concern that scattering of synchrotron photons (from the final quads) by the plasma electrons may swamp detectors;[26] however, the effort and risk associated with masking the photons and installing the lenses may be worth taking once the immediate round of Z_o experiments concludes.

OTHER ROLES

Plasma Bunchers

Many designs for next generation linear colliders specify fewer particles and much shorter bunches (e.g., 15-50μ [27]) than the present generation SLC collider. Furthermore, many FEL applications require short bunches to generate sub-picosecond light pulses. Plasma waves are naturally suited to producing kylstron-type bunching of a longer bunch into bunches on the scale of tens of microns. This is illustrated in the self-consistent particle simulation below.

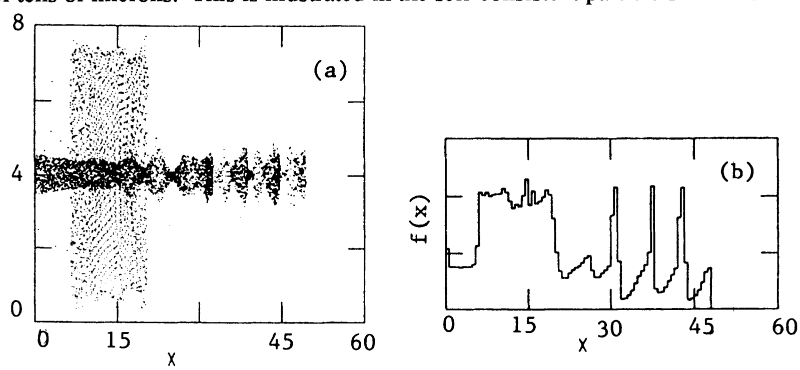


FIGURE 7. Electron beam send into a plasma slab supporting a plasma wave (a) real space of beam and plasma, (b) x-distribution of particles.

The scale of the bunching can be determined by choosing the plasma density. For densities in the range of 10^{16}–10^{18} cm^{-3}, the plasma wavelength is 300–30 μ and the scale of the bunches is 80μ–8 μ.

Plasma Compensation[2]

As collider parameters evolve toward shorter narrower bunches and higher energies, the problem of beamstrahlung radiation losses of the colliding beams increases. D. Whitham, A. Sessler and S. Yu of LBL have proposed a means of reducing the beamstrahlung loss by colliding the beams in a dense plasma background. In the regime opposite to that of a plasma lens (i.e., $\sigma^* \gg c/\omega_p$), the plasma provides a return current that reduces the azimuthal magnetic field and hence the synchrotron losses. We have performed a PIC simulation of this process and observe a reduction in the magnetic field as predicted by the LBL group. However, this concept would require extremely dense plasmas ($> 10^{20}$ cm^{-3}) and creative detector designs to discriminate against background noise contributed by beam-plasma events.

Plasma Cathode/Injector

Intense lasers impinging on solid targets produce high-density plasmas (10^{19-21} cm^{-3}). The number of electrons available from a $(10\mu)^3$ volume is more than 10^{10} and could make a cathode of minute dimensions. While a small cathode is desirable for generating a low emittance beam, it needs to be seen whether or not the huge thermal energy of such a plasma would defeat the scheme.

CONCLUSION

Significant progress has been made on plasma-based accelerator concepts in the last decade and the last year. Wakefield experiments have demonstrated test particle acceleration and beat wave experiments have demonstrated the highest accelerating fields of any novel accelerator technique to date. With the recent developments in short-pulse high-power lasers, the prospects are good for more exciting results in the coming year. The progress on plasma accelerators and the development of new ideas such as plasma lenses make it likely that plasmas will play an increasing role in future accelerator technology.

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