Transverse Focussing using Plasma Wake Fields*

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Dense particle beams travelling in plasmas can produce very high electric and magnetic fields, and these fields, described by Chen[1] and others[2,3] can be used to accelerate and focus particles. The effects on trailing beams and self focussing can be strong and nonlinear. This paper discusses two aspects of self pinching beams: 1) the production of beams which do not self pinch, and 2) a short focal length plasma lens which uses self pinching to reduce beam sizes at the interaction point of a linear collider.

As an example, we consider a final focus system for the Stanford Linear Collider, considering plasma production, vacuum system and backgrounds, and show how the luminosity could be increased using this system. We also discuss experimental tests of the plasma lens concept.

PLASMA WAKE FIELDS

The longitudinal and transverse wake fields produced by a beam bunch propagating along the z axis in a plasma has been described by Chen.[1] If the bunch is described by the relation

$$\rho(r,z) = \rho_0 \, f(r) \, g(z),$$

the wake fields can be obtained from the equations

$$W_{\parallel} = \delta_z(A_z - \phi)$$

$$W_{\perp} = \delta_r(A_z - \phi) \quad ,$$

where the potential $(A-\phi)$ is determined from the equation

$$A_z - \phi = \frac{\pm 4\pi e\rho}{k_p^2} G(z) \, F(r) \quad ,$$

where the longitudinal and transverse effects have been factorized. The expressions G(z) and F(r) are obtained from the integrals of Greens functions over the volume of the bunch. The focussing potential produced by a bunch is thus determined by the profile of the bunch and the plasma density, which determines the plasma wavenumber $k_p = 2\pi/\lambda_p$ or wavelength. The scale length for plasma effects is determined by the plasma wavelength

$$\lambda_p[\mathrm{cm}] = 1.054 \sqrt{10^{13}/n_e[/\mathrm{cm}^3]}$$

The volume over which the potential is significant is determined by whichever is larger: the beam dimensions or the $\lambda p/2\pi$. In the limit where f(r) and g(z) are slowly varying functions over dimensions of a plasma wavelength, the focussing potential approaches the driving beam profiles and the focussing force, which is the derivative of the potential, becomes proportional to the derivative of the beam profile. Ripple due to plasma effects is of the order $(\lambda p/2\ell)^2$, for a bunch of length 2ℓ.

BEAMS WHICH RESIST SELF PINCHING

Although self pinching can be highly desirable, the development of plasma accelerators may require beams which can propagate for long distances in plasmas without external focussing or self pinching. These beams can, in principle, be produced by controlling the phase space density of the beam.[4]

Self-pinching of the particle beam occurs when the phase space density of the beam is altered by propagation through the system. This pinching can be eliminated if the phase space distribution of the beam is matched to the focussing system. The desired phase space distribution can be found by 1) calculating the focussing potential for an arbitrary beam profile using the relations described above, 2) tracking rays of different initial x through the potential, Fig. 1, 3) integrating over x' to find the radial profiles produced by these rays, and 4) constructing the initial, arbitrary beam profile from the contributions of individual rays with different initial x.

A SELF PINCH FINAL FOCUS LENS

We have considered a number of possible applications for a plasma lens using self pinching, including the first element in a positron or antiproton production system, however the most obvious use for plasma lenses would be as the final focussing element in a linear collider. For this application the plasma lens must provide very high focussing gradients, however additional constraints include compatibility with experiments, ability to cope with disrupted beam leaving the interaction point, and compatibility with other elements in the beam lines. Since the focussing force is a self pinch, both e^+ and e^- are focussed.

While a plasma lens will be very strong, its aberrations will limit the maximum compression (initial/focussed size) of the beam which goes through it, according to the relation

$$\sigma_i/\sigma^*_{ab} = K/\Delta K,$$

where K is the focussing strength of the lens, evaluated below. The variation in focussing strength results from particles of different momenta, different radial or longitudinal position and fluctuations in the properties of the plasma. An additional contribution to the beam size comes from the beam emittance and lens geometry. Using β_i and β^* as the beta at the lens and final focus one can write

$$\sigma_i/\sigma^*_\varepsilon = \sqrt{\beta_i/\beta^*} = \sqrt{1 + (\ell/\beta^*)^2} \quad ,$$

where ℓ is the distance between the lens and focus. The ultimate beam size is then approximated by

$$\sigma^* = \sqrt{(\sigma^*_\varepsilon)^2 + (\sigma^*_{ab})^2} \; .$$

While the compression of the beam size is limited, the plasma lens can be operated close to the focus of a normal optical system, so that all the beam compression can be utilized to raise the beam density and luminosity.

EXAMPLE: A PLASMA LENS FOR THE SLC FINAL FOCUS

The final focus quads at SLC are presently designed to reduce a beam from 1000 μm to about 1 μm. The addition of a plasma lens 2 - 4 cm from the final focus, would provide additional focussing which would reduce the beam from a few microns in radius to a fraction of a μm. Note that beams of both polarities are focussed by the self pinch.

The focussing strength of a self pinch calculated by Chen[1] for parabolic bunches of width a and length b is given by

$$K = 4Nr_e/\gamma a^2 b \approx 2\ \mathrm{cm}^{-2}$$

for SLC parameters, assuming a slightly defocussed beam: E = 50 GeV, a = 5 μm, b = 1000 μm, r_e is the electron radius, N = 5 10^{10} e/bunch. The thickness of a lens capable of producing a 4 cm focal length can be calculated from the relation

$$t = 1 / K f \approx 0.1\ \mathrm{cm}.$$

The plasma density required is determined by two constraints: the plasma density must be higher than the beam density so the plasma oscillations will be approximately linear, and the plasma wavelength must be shorter than the bunch length to insure that the focussing force varies smoothly with the bunch length. Both constraints are satisfied if the plasma density is 10^{17} to 10^{18}, corresponding to a complete ionization of a gas at 1 - 10 torr, Fig. 2.

A number of concerns have been examined in the context of the SLC.

Luminosity gain

The gain in luminosity produced by the lens can be obtained from the ratio of the luminosity,

$$L = \frac{N^2 f H(D)}{4\pi\sigma^2},$$

with and without the plasma lens. Here N f and D are the beam population, frequency and disruption parameters. The luminosity enhancement factor H(D) is roughly proportional to D^2 if the disruption parameter is small, and a constant, 6, if it is large. The disruption parameter is defined by

$$D = \frac{r_e \sigma_z N}{\gamma\sigma^{*2}}.$$

Thus the luminosity enhancement

$$L_\ell/L = (\sigma^*/\sigma^*_\ell)^2\ H(D_\ell)/H(D) \propto (\sigma^*/\sigma^*_\ell)^6$$

for small improvements in beam size in the region where the luminosity enhancement factor is rapidly changing. Rough calculations have shown that a plasma lens might improve the luminosity as much as a factor of 10-100, depending on the focal length, lens aberrations and beam parameters.

Plasma Production

We have assumed that a plasma could be produced using a system shown in Fig 3. Hydrogen gas, with a pressure of a few torr would be injected into the vacuum pipe a few cm from the interaction point by means of a pulsed jet. The gas would then be ionized using multiphoton ionization using a laser. Recent experiments at Rutherford have been able to produce plasmas with essentially 100% ionization over a large enough volume (400 μm diameter) to satisfy the present requirements.[5] These plasmas have been produced using optics which was kept two meters from the plasma location. The Neodymium glass laser produces 20 J of light with a 1 μm wavelength into a frequency frequency doubler and focussing system. Power supply modifications would be required to operate this system at the SLC rep rate.

We have considered the use of zirconium-aluminum Non Evaporable Getter material as a pump to remove the leftover gas. This material would line the vacuum pipe to provide the maximum pumping capacity in the immediate region of the IP. Baffles, perhaps coated with getter material could further control the vacuum environment. The NEG material is highly resistant to radiation and pumps about 1 l/sec per cm^2.

Backgrounds

In the proposed operating mode, the beam of high energy electrons must pass through a plasma whose density is greater than that of the beam. Although the probability of electromagnetic interactions is small since the target contains only about 10^{-7} radiation lengths of material, it is necessary to consider background from hard collisions with protons and electrons essentially at rest in the plasma.

The signal to background ratio can be evaluated by comparing with existing experiments at PEP, with the following assumptions. The annihilation cross section for e+e- goes like $1/E^2$ at high energies, however SLC would be expected to operate where the W and Z produced enhancements of roughly 3000 in the cross section. Beam gas scattering should decrease somewhat at higher energies. The event rate for these collisions would go like 1/E to a mild increase with E depending on whether the trigger was sensitive to a fixed fraction of the beam energy or a fixed energy in the hadron system. The e^+e^- annihilation rate is sensitive to beam size and going from PEP (400 * 60 μm) to the SLC (1 * 1 μm, or smaller) parameters will further enhance the event rates by factors of $2.4 \cdot 10^4$, or more. In addition it may be possible to consider modifications to the trigger system which would help to discriminate against events where all tracks went forward or backward, which would be the signature of a beam gas event. The pressure in the PEP vacuum chamber was in the range of 10^{-9} torr over a sensitive length of about 50 cm. The high pressure region of the plasma lens, however, is only required to be a few millimeters long. Significant increases in the signal/background from that seen in PEP might also be tolerable in some experiments.

The actual level of signal/background will be beam and trigger dependent, however beam gas rates should be ~ 1 Hz, which might be tolerable for many experiments at SLC. The extension of this technology to higher energies, however, may be difficult, as the thickness of the plasma lens increases with energy to compensate for the beam momentum, and the cross section for annihilation will drop rapidly beyond the W / Z region.

Jitter

Since the beam passing through the plasma lens undergoes a self pinch, the beam spot will get smaller without the corresponding decrease in the uncorrectable beam jitter that takes place in fixed quadrupoles. This seems unavoidable. The level of jitter that might be expected in a carefully optimized system in not known, however. Order of magnitude estimates that the jitter could be of the order of

1/10 of the beam dimensions imply that reducing the focal spot would significantly enhance jitter problems, however it is not clear that additional effort at vibration isolation and noise reduction could not mitigate these problems.

Comments

The plasma lens would significantly alter the constraints and parameters of the linear collider system. The effects on the final focus and beam optics are generally favorable, as aberrations are reduced along with the focal length. In addition, the short focal length lens may significantly reduce the requirements on the beam optics leading to it, permitting a simpler/shorter beam line system with large momentum acceptance.[6]

A variety of other effects such as synchrotron radiation in the plasma lens, effects on the beam beam disruption, inhomogenieties and end effects in the plasma have not been studied in detail.

Since the plasma wavelength is shorter than the beam bunch, the plasma should adiabatically return to something like its initial state after the beam bunch goes through. Thus when the disrupted beam coming from the interaction point enters the plasma it too should be focussed. This is highly desirable since disrupted beam hitting the first solid focussing element would constitute a significant background in detectors and a source of damage to the quad itself.

CONCLUSIONS

Plasma wake field focussing effects can produce very high gradient lenses. The most interesting application for these lenses is for focussing systems in a linear collider such as SLC and a detailed study of this system is now underway. Proof of principle experiments will be done soon in the ANL/UCLA/UW advanced accelerator test facility using plasmas of 10^{13} - 10^{14}cm^{-3}, and development of a system more suited to linear colliders with densities of 10^{17}-10^{18}, is being proposed. This system would use a gas puff jet system in conjunction with a Nd glass laser. Extension of plasma lens focussing to higher energy colliders is also being considered.

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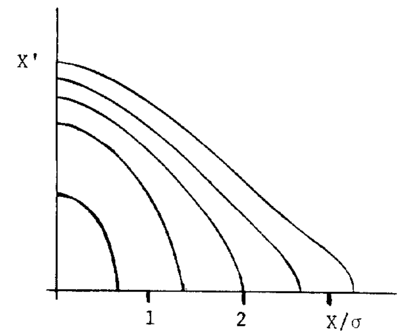

Fig. 1. Tracking particles Through a Plasma Wake Field Potential

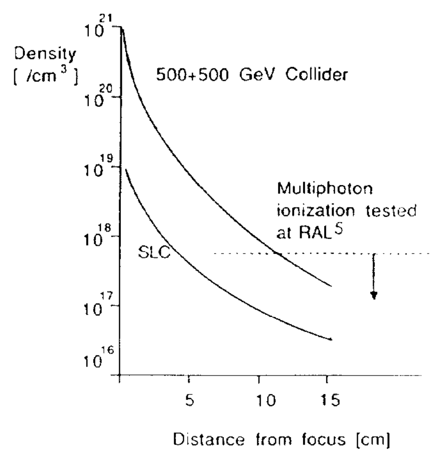

Fig. 2. Beam and Plasma Densities

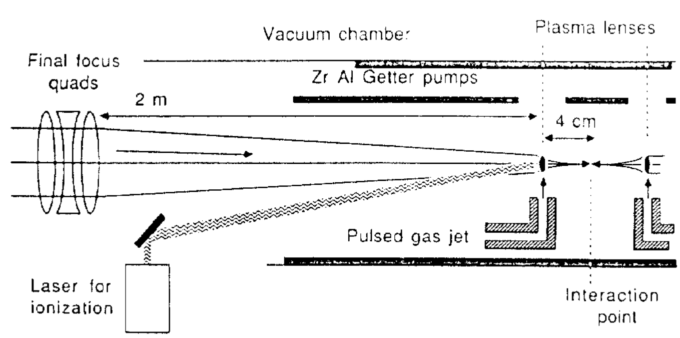

Fig. 3. A Plasma Lens in a Linear Collider