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A Plasma Lens for a Linear Collider Final Focus*

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Abstract

High density relativistic beams propagating in a plasma are affected by fields induced by plasma motion. We consider the possible use of a plasma cell very close to the interaction point of a linear collider where the self-pinch induced in the relativistic beams can be used to increase the luminosity of colliding beams. We describe the benefits of this self-pinch, as well as some engineering details on the production of the required plasma.

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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[2,3,4] can be used to accelerate and focus particles. The effects on trailing beams and self focussing can be strong and nonlinear. This paper discusses a short focal length lens which uses linear electrostatic plasma oscillations to produce self pinching.[5] The dynamics of this focussing are similar to pinching produced by currents in plasmas[6] and pinching by other beams (in disruptions).[7] As an example, we consider a final focus system for the Stanford Linear Collider, considering methods of plasma production, vacuum system and backgrounds, and show how the luminosity could be increased using this system.

PLASMA WAKE FIELDS

The longitudinal and transverse wake fields produced by a beam bunch propagating along the z axis in a plasma have been described by Chen.[1,8] If the bunch is described by the relation

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

with $z = s - ct$, s and z being the position in a fixed and moving coordinate systems respectively. The wake fields can be obtained from the equations

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

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

where the potential $(A_z - \phi)$ 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,

$$G(z) = k_p \int_z^{\infty} dz' g(z') \mathrm{Sin}\, k_p(z' - z)$$

$$F(r) = k_p^2 \int_o^r r'dr' f(r')\, I_o(k_p r')\, K_o(k_p r)$$

$$+ k_p^2 \int_r^{\infty} r'dr' f(r')\, I_o(k_p r)\, K_o(k_p r')$$

where I_o and K_o are the Bessel functions.

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 $k_p = 2\pi/\lambda_p$ and 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 $\lambda_p/2\pi$. Ripple in the potential due to plasma oscillations is of the order $(\lambda p/2b)^2$ for a bunch of length b.

For linear colliders the beam bunches produced have radii measured in microns and lengths on the order of mm. The constraint that the plasma oscillation be linear requires that the plasma density be greater than the beam density which determines the maximum value of λ_p. For this application we consider the case

$$a < \lambda_p/2\pi \ll b$$

with a and b referring to the gaussian width and length. In this geometry, plasma electrons move radially to neutralize the electric field of the beams, moving towards positron bunches and away from electron bunches. A large radial electrostatic field which can be obtained from Gauses Law is thus produced in the plasma. This field can then act back on the beam. The effect is always focussing since the beam is attracted to the induced charge required to neutralized it. In this special case where plasma electrons move radially, one can consider the plasma as neutralizing the electrostatic repulsion between fast moving beam particles, so that the magnetic self forces pinch the beam. In general, however, magnetic fields from plasma currents cannot be neglected.

At the high plasma densities required by linear colliders, plasma collisional effects can become significant. The primary result of collisions would be to damp plasma oscillations and plasma wakes, however focussing, which results from induced charges, should not be affected if the collision frequency ν_{ei} is less than the plasma frequency $2\pi\omega_p$.

The fields produced by a gaussian beam are shown in Fig. 1 for a gaussian beam of 5 micron width and a plasma density of $10^{17}/cm^3$ giving a plasma wavelength of 107 microns. The focussing force rises approximately linearly with radius out to about one σ and then goes slowly to zero. The focussing effect of such a lens is shown in Fig. 2. There are a number of important differences between a plasma lens used in this way and a quadrupole, one being that the plasma lens, because it depends on self induced fields is always focussing in both planes simultaneously, whereas a quadrupoles focus in one plane and defocus in the other. Another difference is that the plasma lens is linear only near the center of the beam and the focussing force decreases with radius for most beam profiles. This and other aberrations (described below) ultimately limit this type of plasma lens to applications where comparatively large aberrations can be tolerated.

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 seems to be as a short focal

length lens to be used 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.

The final focus quads at SLC are presently designed to reduce a beam from 1000 μm to about 1.6 μm. The addition of a plasma lens about 2 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.) In order to evaluate the usefulness of this concept we have attempted to consider the constraints on a complete system.

Since plasma lens performance is ultimately limited by aberrations, optimizing the luminisity gain implies comparitively short focal lengths. The length of the plasma, however, also rises for short focal lengths, producing increased beam gas event rates. An additional constraint considered was the ability to discriminate between tracks originating at the interaction point and those originating in the plasma lenses, which seems to require a few centimeters between the lenses and the IP.

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 2 cm focal length with a 50 GeV beam can be calculated from the relation

$$t = 1 / K f \approx 0.2\ \mathrm{cm}.$$

The plasma density required is determined by two constraints: 1) the plasma density must be higher than the beam density, so the plasma oscillations will be approximately linear, 2) 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. 3.

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 above, and ΔK are due to aberrations discussed below. 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

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

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 thus 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.

Aberrations

Optical aberrations in plasma lenses are due to a number of causes. Aberrations are minimized if the bunch density is a constant in r and z, however real bunches are more likely to approach gaussians. The primary aberrations for gaussian beam shapes are: 1) the beam shapes decrease in focussing strength seen at large radius (Fig. 1), and 2) the variation in

focussing strength along the length of the beam bunch caused by the density variation. Chromatic aberration would also be present, however the small momentum variation of the SLC beam ($\Delta p/p < 1\%$) would produce a negligable perturbation on these primary effects. The variation in focussing due to effects associated with the plasma wavelength can be made negligable by suitable choice of λ_p.

Additional aberration, due to beam density fluctuations could also be present. We assume that the bunch profiles and bunch-to-bunch repeatability are determined by the properties of the damping rings and are essentially constant. This is, however, unlikely to be the case. Variations in the transverse position as a function of longitudinal position in the bunch could also occur due to transverse modes in the accelerator structure. One would expect that position fluctuations within the bunch could be significant and difficult to reduce, since operation for maximum luminosity may require beam bunches near the beam break-up limits. Dipole modes, in which the tail of the bunch is displaced relative to the head, could significantly degrade focussing. Effects which alter the bunch shapes could perturb focussing, however it is difficult to evaluate these effects or to speculate about how these aberrations could be reduced.

Gross deviations in the bunch shape from gaussian profiles will also affect the focussing and can be evaluated. A parabolic distributions, for example produce the radial potential and focussing forces shown in Fig. 4 where the normalizations are the same as for Fig. 1. The focussing strength at small radii is related to the beam density as $r \to 0$, and equal for the two cases, although the magnitude of the potential and large radius behavior are quite different.

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.[8] The luminosity enhancement factor H(D)

is roughly proportional to $1 + 2D^2$ 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 gain from using a plasma lens is

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

where $H_\ell(D_\ell)$ is the luminosity enhancement factor with the lens. 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, assuming half of the beam is poorly focussed by the plasma lens thus missing final disruption (Table 1).

The luminosity gain thus described results from a two-step beam compression process, the first step using the plasma lens and the second step using the disruption. Both processes proceed by similar mechanisms and should be ultimately limited by knowledge of initial beam profiles and aberrations. Since the magnitude of these uncertainties is presently unknown, the percentage errors on the lumonisity gain are large.

Plasma Production

We have assumed that a plasma could be produced using a system shown in Fig 5. 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 could then be ionized by means of 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 transverse dimensions) to satisfy the present requirements using optics which was kept two meters from the plasma location.[9] The Neodymium glass laser produced 20 J of light with a 0.5 μm wavelength from a frequency doubler and focussing system.

We have considered the use of zirconium-aluminum Non Evaporable Getter (NEG) 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. The amount of H_2 that can be held by these pumps is about 100 torr ℓ/g and thicknesses of 0.2 mm can be applied, thus since the density is 2.5 g/cm^3, a 10 cm by 10 cm area would be able to hold 500 torr ℓ/side.[10] Assuming a gas load of 10^{-2} torr ℓ/sec, regeneration would be required every 12 hrs. Cryopumping would also be an alternative.

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 actual level of beam gas triggers is highly experiment dependent. In order to make estimates of this rate we have used information from the High Resolution Spectrometer which operated at PEP until 1986.[11] Raw triggers on the HRS occurred at a rate of ~ 10^2 Hz and these consisted of beam gas and cosmic triggers. Minimal analysis of these triggers was done online to produce an event rate for reconstructable tracks of about 1 Hz, and subsequent analysis of these events showed that beam gas event rates in this sample were about 10^{-2} Hz. Scaling the rate of beam gas events to the plasma lens in the SLC can be done using the following relation

$$R_{\text{Beam gas,(SLC)}} = \frac{(N\ f\ p\ \Delta\ l\ \langle A\rangle)_{SLC}}{(N\ f\ p\ \Delta\ l\ \langle A\rangle)_{PEP}}\ R_{\text{Beam Gas (PEP)}}$$

$$= \frac{(5.10^{10} \times 100\ \text{Hz} \times 1\ \text{torr} \times 0.4\ \text{cm} \times 1)}{(3.10^{12} \times 0.14\ \text{MHz} \times 5.10^{-9}\ \text{torr} \times 50\ \text{cm} \times 6)}\ R_{\text{Beam Gas, PEP}}$$

$$\approx 3\ R_{\text{Beam Gas PEP}}$$

where N, f, p, Δl and $\langle A \rangle$ are the e^-/pulse, frequency, gas pressure, length, and average nucleon number associated with gas in SLC and PEP.[12] This argument gives a minimum rate of reconstructable beam gas events on the order of a one Hz. (Table 1) Note that the beam gas rate is roughly proportional to the luminosity gain. Single tracks, which could contaminate reconstruction, would occur at a higher rate. Since the HRS was primarily concerned with large angle phenomena, the tracks within 8° of the beam direction were not recorded.

The angular distributions of tracks produced in beam gas interactions should be similar to that measured by Hand et al., for muon deep inelastic scattering,[13] and cross sections for the relevant reactions have been summarized by Bjorken.

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 beam jitter at the focus 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. It seems possible that additional effort at vibration isolation and noise reduction could mitigate this problem somewhat.

Jitter in the SLC beams due to the accelerator systems, damping rings, kickers etc. can, in principle, be corrected as proposed by Stiening,[15] by measuring the position errors of the beams as they enter the arcs and sending the corrections across to kickers incorporated with the final focus systems. Jitter due to motion of the arcs and final quads should not change appreciably.

Compatability with Beam line optics and disruptions

A working plasma lens could 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.[16]

The plasma lens operates in a similar way to a normal disruption, described by Hollebeek,[8] where the disruption parameter has been defined as

$$D = \sigma_z/f$$

for paraxial rays. For focal lengths of the order of 1-3 cm and σ_z about 1 mm, the effective disruption parameter of the lens system is about 0.03-0.1. This is much less than the beam-beam disruption which would take place at the interaction point (D = 1-2). Synchrotron radiation effects are thus negligable with respect to those produced in the final disruption.

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 lens on the downstream side of the interaction point, it too should be focussed.[15] 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[18] 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 high power laser. Extension of plasma lens focussing to higher energy colliders is also being considered.

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Table 1 Luminosity Gain and Beam Gas Rates

$\frac{\Delta K}{K}$	β_1, cm		Focal Length 0.5 cm	1 cm	2 cm	
0.04	9μ	Gain =	42	14	2	
	25μ		36	22	8	
	49μ		21	18	11	
0.08	9μ		21	10	2	
	25μ		10	9	4	
	49μ		4	4	3	
		Beam Gas Rate =	2.6	1.3	0.6	Hz

Beam gas rates are scaled from background rates of 0.1 Hz for the HRS at PEP.[11]

FIGURE CAPTIONS

Fig. 1 Radial dependence of the beam profile, the potential function $(A_z - \phi)$, and the radial focussing force F_r for a gaussian profile with $\sigma = 5\ \mu$.

Fig. 2 Phase space for particles being focussed by a plasma lens.

Fig. 3 Beam density as a function of the distance from the interaction point without a plasma lens.

Fig. 4 Beam profile, potential and focussing force for a parabolic beam profile. Normalizations are equal to those in Fig. 1.

Fig. 5 Details of the plasma lens system, showing the gas jet and ionization system for plasma production, and pumping incorporated in the vacuum pipe.

Fig. 1.

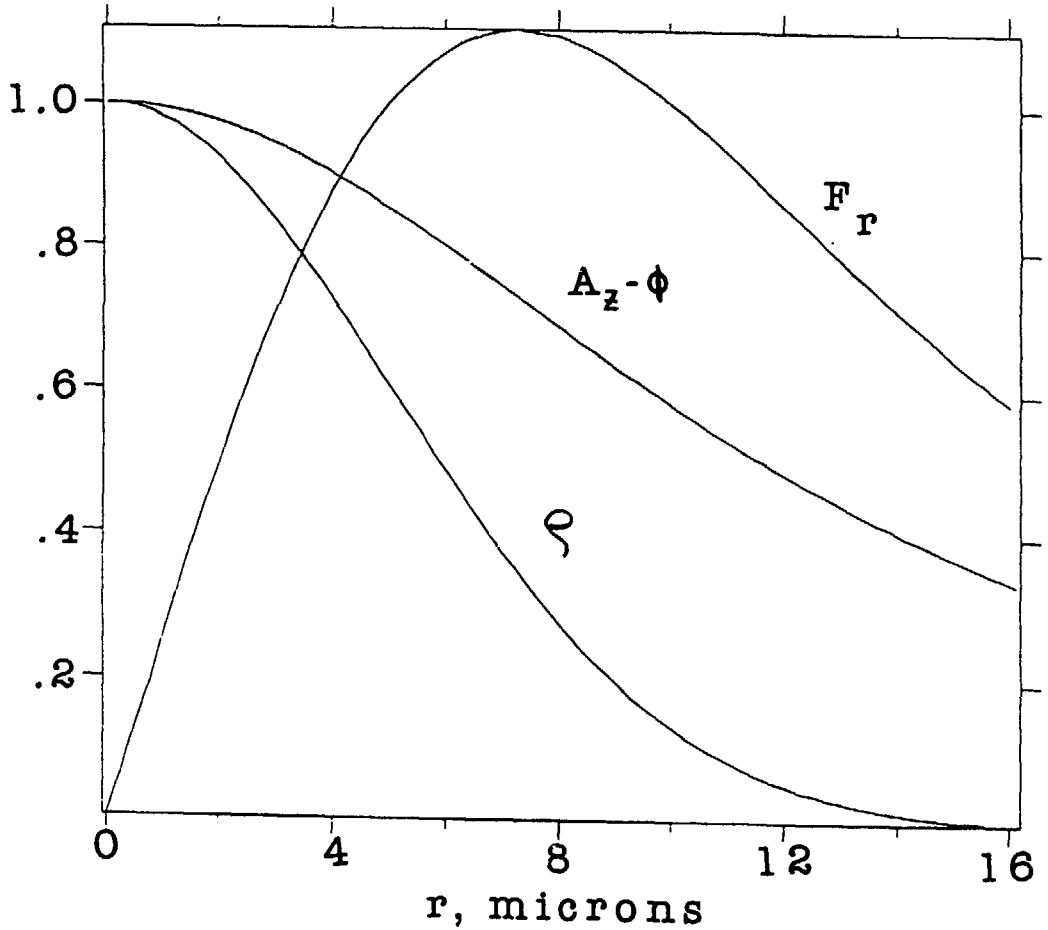


Fig. 2

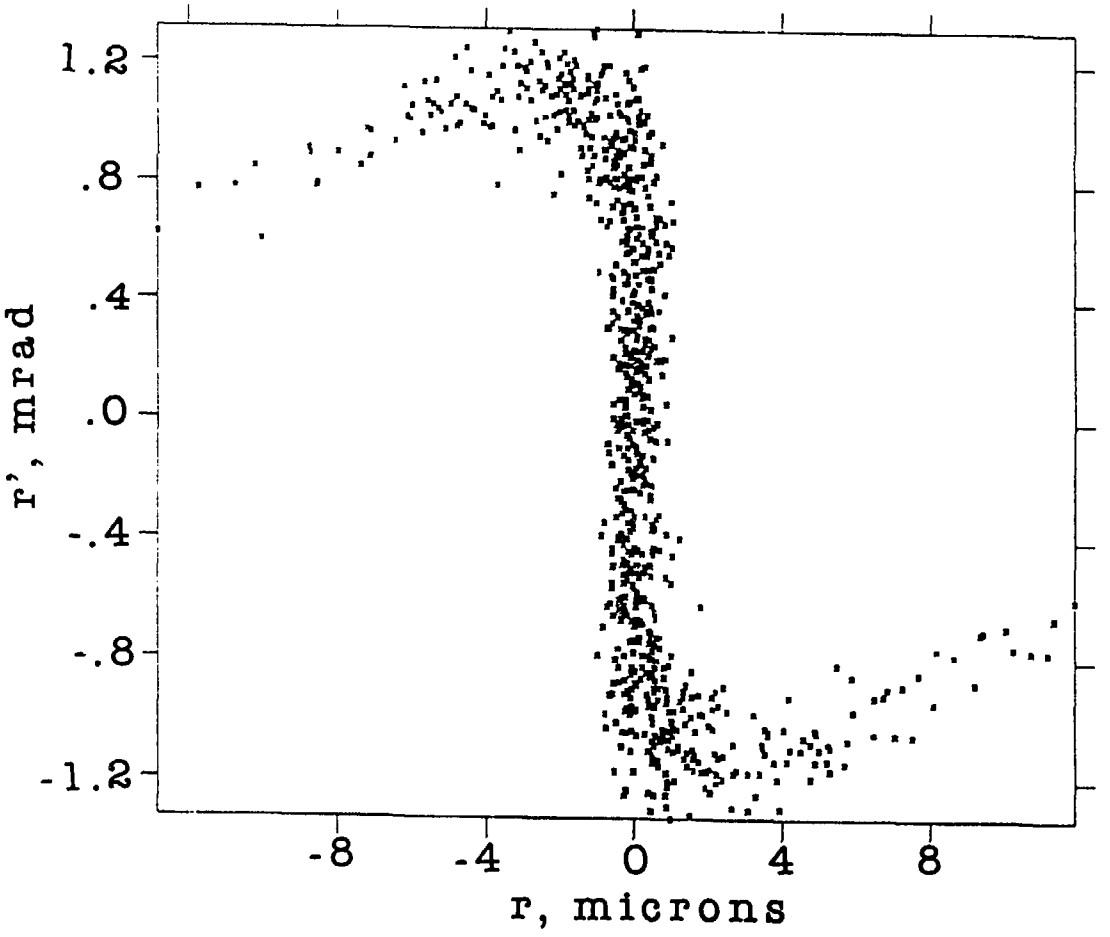


Fig. 3.

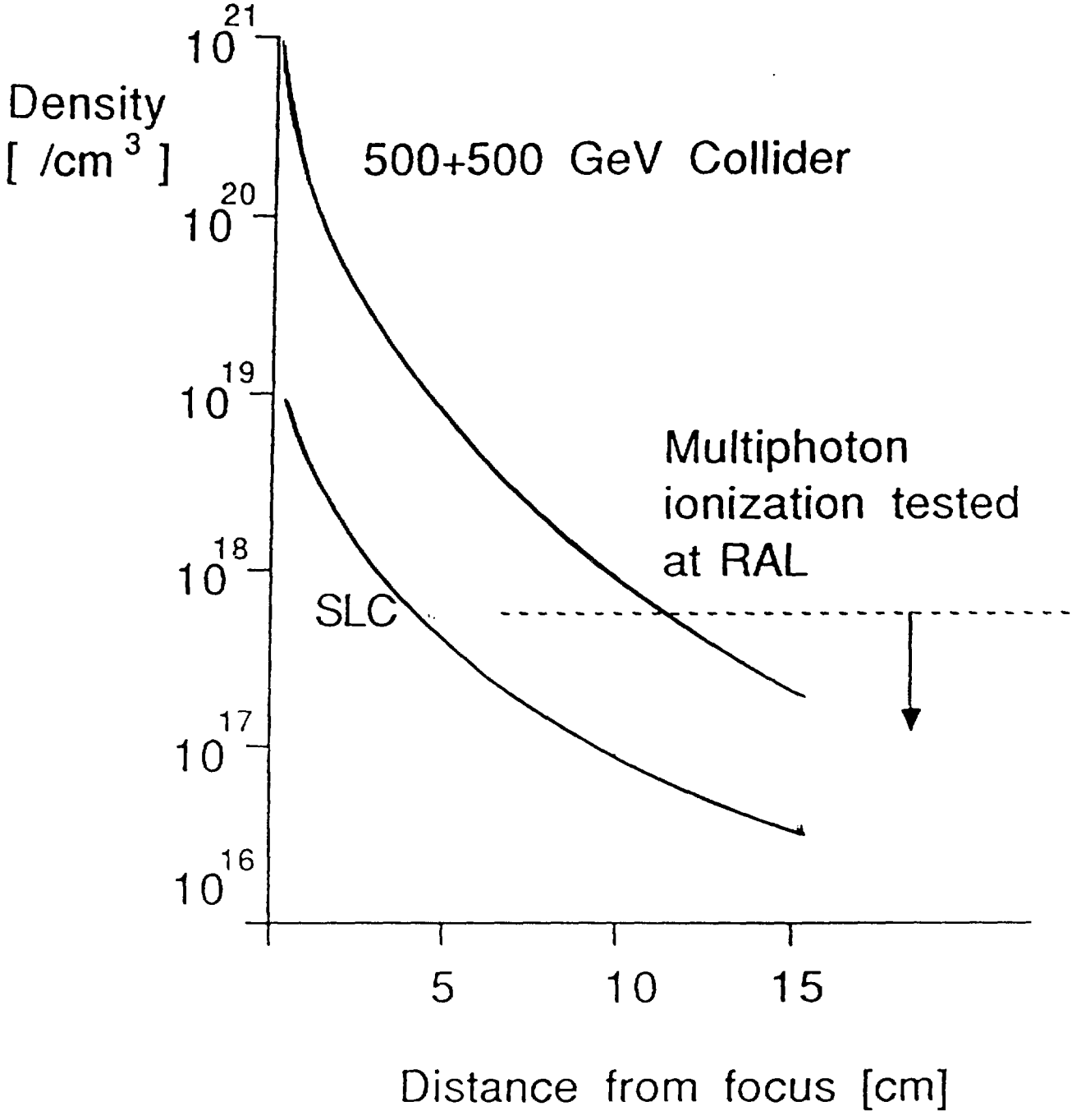

Density
[/cm 3]
10 21
10 20
10 19
10 18
10 17
10 16
500+500 GeV Collider
Multiphoton
ionization tested
at RAL
SLC
5
10
15
Distance from focus [cm]

Fig. 4.

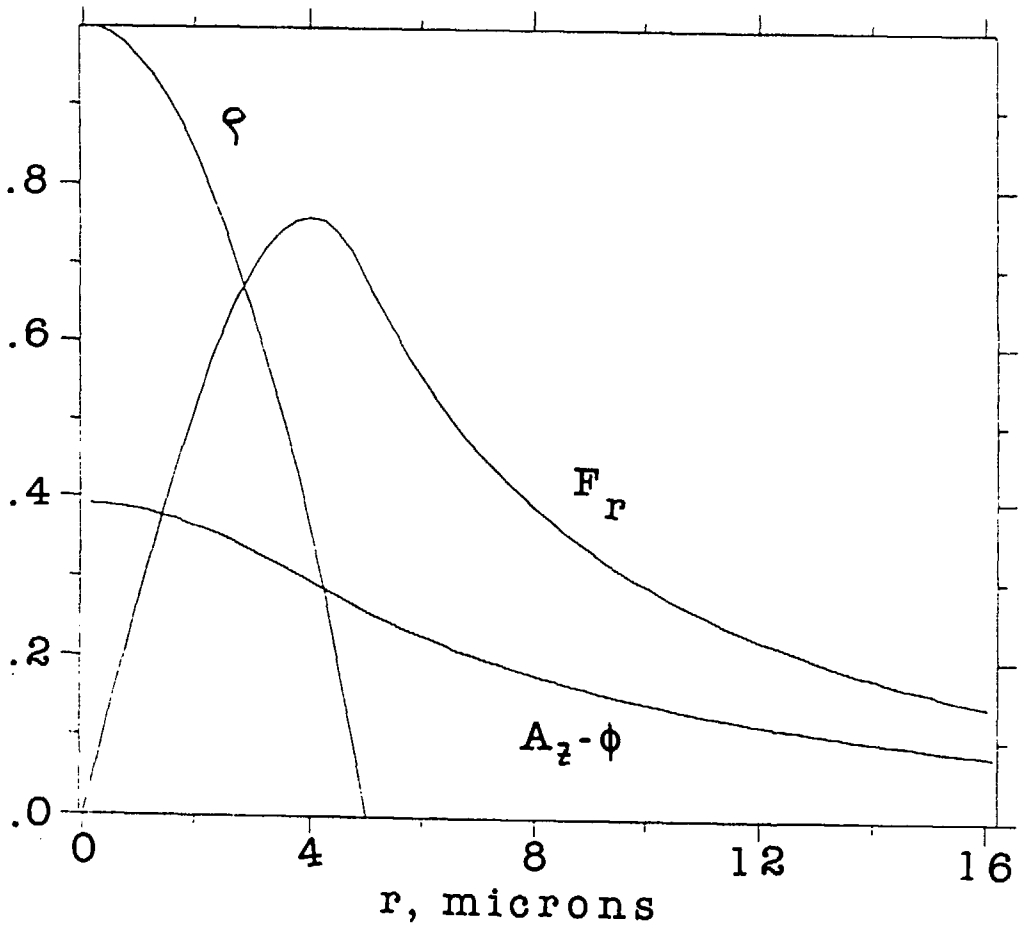
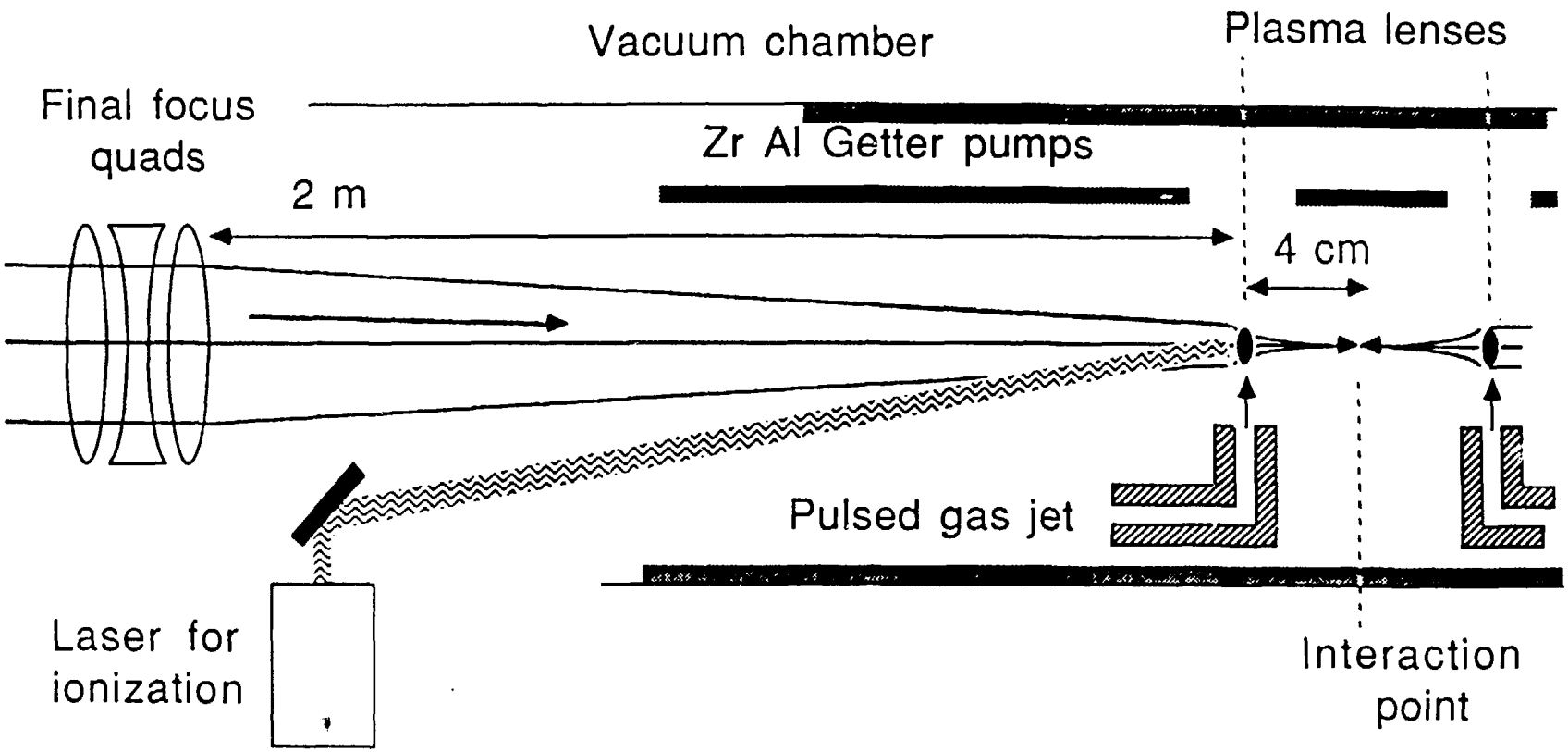


Fig. 5.


Vacuum chamber
Plasma lenses
Final focus quads
Zr Al Getter pumps
2 m
4 cm
Pulsed gas jet
Laser for ionization
Interaction point