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LASER STEERING OF PARTICLE BEAMS: REFRACTION AND REFLECTION OF PARTICLE BEAMS

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Abstract. The co-propagation of an intense particle beam with an ionizing laser beam in a working gas/plasma is considered. When the axes of the laser and particle beam are not aligned, then asymmetric plasma lensing results in a net dipole field acting on the particle beam. The particle beam can be steered or bent (as well as focused) by steering the laser. An analogy is made between the bending of the particle beam by collective effects at a plasma boundary and the refraction or reflection of light at an interface. This mechanism of particle steering may be of interest in applications for which permanent magnets are inconvenient or a fast turn on is required. 3-D particle-in-cell simulations and relevance to a recent experiment are discussed.

Introduction

When an intense particle beam is combined with a laser beam in a plasma, a variety of interesting physical effects can occur. One well known and particularly robust example is the focusing of the particle beam by the so called plasma lens. Plasma lenses can produce extreme focusing strengths -- as high as giga-Gauss/cm. If the axis of the lens and the particle beam were to be 'misaligned', then the plasma lens would be asymmetric, and correspondingly high dipole fields could be produced. The particle beam could be steered or bent (as well as focused). In this paper we describe how this effect could be used so that a laser in a working gas would steer a particle beam. Such a process may be of interest in applications for which permanent magnets are either too heavy, too slow to turn on or not strong enough to be practical. Aside from practical applications, the mechanism is of fundamental interest as a new class of physical behavior -- that of reflection and refraction of particles beams by an inhomogenous medium. In this case, the medium is a dilute plasma created by a laser.

In the next section we develop a physical model for the deflection of a beam at a plasma boundary. In the following section 2-D and 3-D particle-in-cell simulations are presented. In the final section, we will consider the possible reflection of a 30 GeV particle beam off of a millimeter of low density plasma gas. This possibility is remarkable given that such beams easily penetrate centimeters of solid metal.

Physical Models

Before describing the asymmetric laser steering of a particle beam, we briefly review the physical mechanism of the familiar symmetric case of plasma lensing [1]. In an underdense plasma lens, the head of an intense particle beam (beam density n_b higher than the plasma density n_o) displaces the plasma electrons in its path, creating a positive ion channel that focuses the remainder of the beam. The size of the focusing force is easily estimated from Gauss' law for a cylinder of positive charge density n_o:

$$F = 2\pi n_o e^2 r \tag{1}$$

In engineering units, we can see that this focusing field can be quite large, equivalent to quadrupole magnets of strength 300 MG/cm at a plasma density of 10^{17} cm^{-3}. This is the parameter regime of a current plasma lens experiment (E-150) at the Stanford Linear Accelerator Center.

In the event that the plasma has a gradient in density perpendicular to the beam, the ion channel focusing of the beam will become asymmetric and there will be a net deflection as well as focusing of the beam (Fig. 1). This could be realized experimentally by using a laser to ionize a working gas, and steering the laser to be at an angle to the beam. This is the basis of the laser steering scheme we consider.

To estimate the order of magnitude of this deflection, consider the extreme case of the beam near the edge of a sharp plasma boundary (Fig. 2) of density n_o. The beam of radius r_b and density n_b has a positive ion charge column on one side of radius $r_c=\alpha(n_b/n_o)^{1/2}r_b$, where α is 1 for long beams and 2 for beams of order of the plasma wavelength long[2]; at the edge of the column is a layer of electrons with a total charge equal and opposite to that in the ion column; and on the other side of the beam there is no charge. The nearby positive charge will attract the beam toward the center of the plasma. The electric field at the beam is easily estimated for this picture from Coulomb's law, yielding

$$F = -eE = 2n_o e^2 r_c \tag{2}$$

Multiplying this force by the time that the beam is within a channel radius of the edge gives the impulse on the beam. The time spent near the edges is $2r_c/c\cos\phi$, where ϕ is the angle between the beam and plasma boundary. Dividing by the particles' parallel momentum γmc gives a scaling law for the deflection angle θ:

$$\theta = \frac{8\alpha N r_e}{\pi\sqrt{2\pi}\gamma\sigma_z \sin\phi} \tag{3}$$

where $N/\sqrt{2\pi}\sigma_z$ is the charge per unit length of the beam and r_e is the classical electron radius. Note that the dependence on plasma density has cancelled out because higher density, although giving a stronger deflection force, gives a narrower channel and hence a shorter time for the impulse.

Equation (3) gives the deflection angle of a beam incident at angle ϕ. Alternatively, if $\theta \sim \phi$, then we obtain an estimate for the angle of total internal reflection:

$$\theta_i = \sqrt{\frac{8\alpha N r_e}{\pi\sqrt{2\pi}\gamma\sigma_z}} \tag{4}$$

Particle-in-cell simulations

To test the simple analytic model above, we perform fully self-consistent, electromagnetic particle-in-cell simulations in two and three dimensions. Three-dimensional simulations are needed because in 2-d slab geometry, the beam is infinite in the plane out of the page in Fig.2. In this case, the transverse space charge forces tend to be independent of the distance from the space charge as in an infinite parallel plate capacitor. Thus the blown out electrons' field in Fig.2 tends to cancel the ions field, reducing the inward deflection considerably over what it would be for 3-d round beams.

The physical and simulation parameters for the simulations are given in the tables in Fig. 3. The code used is OSIRIS and is described in Ref. 3. The size of the bunch and width of the plasma were chosen to be similar to the case of the E-157 plasma wakefield accelerator experiment at SLAC. However, the energy of the beam and length of the plasma are appropriately reduced in scale to shorten the simulation time. The beam energy is 17.5 MeV rather than 30 GeV, and the plasma is taken to have a sharp boundary. Full scale simulations of the meter long plasma in the E-157 experiment are currently in process.

Fig. 4 shows snapshots of the real space (y vs. z) of the plasma in a 2-D simulation (using the code WAVE). Note the asymmetric blowout of plasma electrons. Fig. 5 shows results of a 3-D simulation. Phase space snapshots of the beam, p_y vs. z and p_y vs. p_z after exiting the plasma are shown. These are similar to the images one would expect in real y-z space after drifting downstream a long distance toward the detector of an experiment. The head of the beam is seen to propagate in its original direction while the tail of the beam is kicked back toward the plasma. Note that once blowout occurs, the remainder of the beam has the same deflection angle. This results in a characteristic splitting of the beam downstream into two as seen in the figure. Qualitatively similar deflection and splitting has been observed experimentally during the laser alignment procedure for the E-157 experiment.

Quantitatively, the deflection momentum imparted to the tail of the beam was .9mc or a deflection angle of θ=26 mrad. The incident angle was ϕ=61mrad. For comparison, for the parameters of the simulation Eq. (3) predicts θ=23 mrad. More work is planned to further test this scaling law and the scaling law for internal reflection (Eq. 4); however, Eq. (3) appears to be of the right order of magnitude.

Discussion

In this work we have analyzed an idealized case of a sharp plasma/vacuum boundary. In any real experiment there will naturally be a non-zero scale length to the boundary. We expect the arguments presented here to be valid so long as this scale length is short compared to the blowout radius r_c. Note that the scale length may still be quite large compared to the beam radius.

The results of this preliminary study suggest that it is possible to refract or even reflect a particle beam from a dilute plasma gas. For example, for the parameters of a recent experiment[4] at the Stanford Linear Accelerator Center with a 30 GeV beam ($N=2\text{x}10^{10}$, σ_z=.63mm, $\gamma=6\text{x}10^4$), Eq. (4) predicts total internal reflection for an incident angle of 2 mrad. Remarkably, for a 30 GeV beam, the collective effects of a plasma one million times less dense than air appear to be strong enough to "bounce" the beam off.

The work suggests that practical applications such as steering a particle beam with lasers rather than magnets may be possible. For such an application it will probably be necessary to use a second laser or particle beam (which may be of much lower energy) to pre-form the ion channel and deflect the entire following particle beam. Other interesting effects of combined laser and particle beams suggest themselves. One is the corollary case of using a particle beam to steer a laser. By overlapping the two beams in a plasma, the plasma and particle beam act as an optical fiber to guide the laser[5]. If a magnet is then used to steer the particle beam, the laser can follow. In this sense, this is the bending of light by a magnetic field.

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References

1. P. Chen, Part. Accel. **20**, 171 (1987); J.J. Su, T. Katsouleas and J. M. Dawson, Phys. Rev. A 41, 3321 (1990).
2. S. Lee et al., submitted to Phys. Plasmas (1999); M. Lampe et al., Phys. Fluids B **5**, 1888 (1993); N. Barov et al., Phys. Rev. Lett. 80, 81 (1998).
3. R. Hemker et al., Proc. PAC 99, p. 3672, IEEE Catalog No. CH36366 (1999).
4. R. Assmann et al., Proc. PAC 99, p. 330, IEEE Catalog No. CH36366 (1999).
5. G. Shvets, private communication.

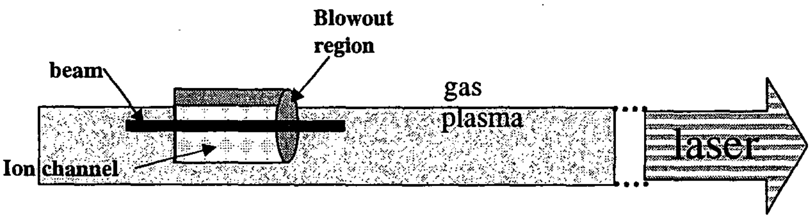


Figure 1. Schematic of laser steering concept.

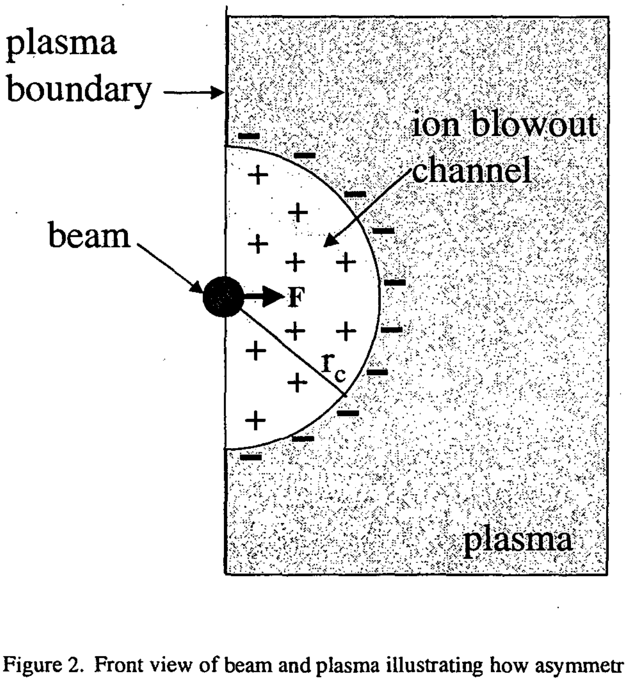
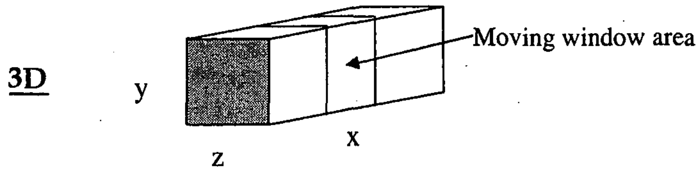


Figure 2. Front view of beam and plasma illustrating how asymmetric blowout creates a net deflection force.



Simulation system parameters

total size of grid :	64x100x100
cell sizes:	.15x.1x.1 c/ω_p
particles per cell :	plasma: 4, beam: 8
total # of particles :	~1 million
timestep :	.04 ω_p^{-1}

Physical parameters

Size of plasma :	4cm long x 4mm
Plasma density:	2×10^{14} cm^{-3}
Beam length (FW) :	1.7mm
Beam radius (FW) :	180 μm
Beam density:	1×10^{14} cm^{-3}
Beam γ :	35

Figure 3. Computational and physical parameters and geometry of the scaled simulations.

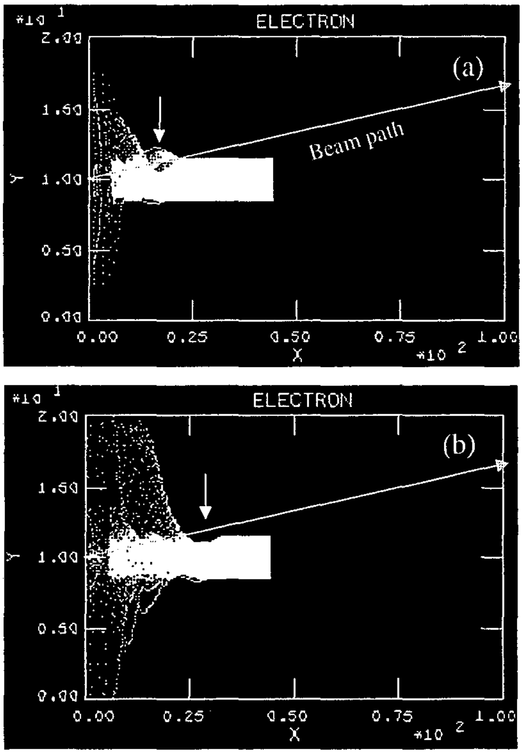


Figure 4. 2-D PIC simulation of real space y vs. x of the plasma electrons showing asymmetric blowout. As shown by the arrows, the beam is inside the plasma in (a) and outside in (b). Axes are in units of c/ω_p.

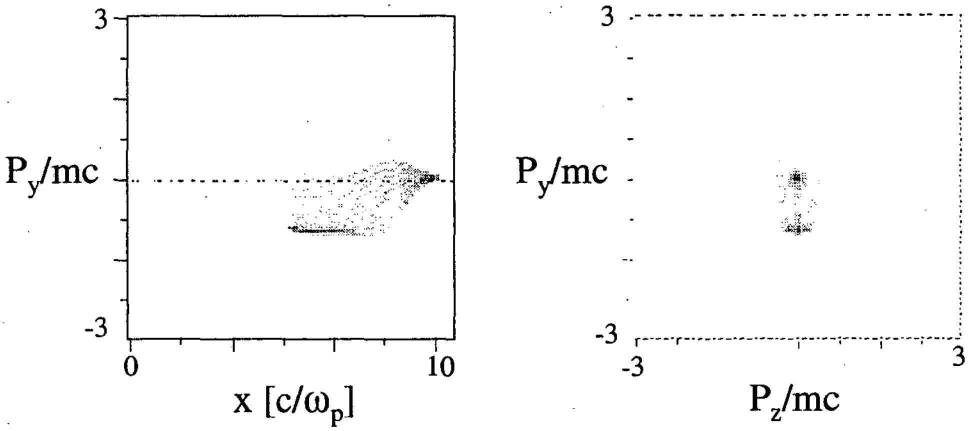


Figure 5. Phase space images of the beam after exiting the plasma in a 3-D PIC simulation: (a) p_y/mc vs. $\omega_p x/c$ and p_y/mc vs. p_z/mc. The dotted line shows the original beam path direction (i.e., the figure is rotated with respect to Fig. 4.)

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