Collective Refraction of a Beam of Electrons at a Plasma-Gas Interface

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In a recent *Brief Comment*, the results of an experiment to measure the refraction of a particle beam were reported [P. Muggli, et al., Nature 453, May 3, 2001]. The refraction takes place at a passive interface between a plasma and a gas. Here the full paper on which that Comment is based is presented. A theoretical model extends the results presented previously [T. Katsouleas et al., Nucl. Inst. Meth. Phys. Res. A **455**, 161 (2000)]. The effective Snell's law is shown to be non-linear and the transients at the head of the beam are described. 3D particle-in-cell simulations are performed for parameters corresponding to the experiment. Finally the experiment to measure the refraction and also internal reflection at the Stanford Linear Accelerator Center is described.

The refraction of light at an interface is as familiar as rainbows and "bent" pencils in a glass of water. The refraction of charged particles at an interface between two media on the other hand is not commonly considered. Take for example the case of a 30 GeV electron incident on water. The refraction takes the form of a small amount of random scattering [1,2] – an rms scattering angle of 20 micro-radians after one millimeter. In this letter we report the collective refraction of a 30 GeV beam of electrons at a plasma/gas interface that is orders of magnitude larger than would be expected from single electron considerations and that is unidirectional. Although the density of plasma nuclei is ten million times less than that of the water example above, the collective response of the plasma produces a deflection of the electron beam of the order of one milliradian. The electron beam exiting the plasma is bent away from the normal to the interface in analogy with light exiting from a higher index medium.

To understand the physical picture of this collective refraction mechanism, consider the geometry shown in Fig. 1. A dense beam of electrons is incident from the plasma side on a planar boundary between a medium of ionized plasma gas and un-ionized gas. For simplicity we neglect the small effect of Coulomb scattering by the gas and treat the boundary as between plasma and vacuum. We consider the case of dense beams or underdense plasmas such that the beam's density n_b is greater than the plasma density n_o. While the beam is fully in the plasma, the space charge at the head of the beam repels the plasma electrons out to a radius r_c[3]. The remaining plasma ions constitute a positive charge channel through which the latter part of the beam travels. The ions provide a net focusing force on the beam [4]. When the beam nears the plasma boundary, the ion channel becomes asymmetric producing a deflecting force in addition to the focusing force. This asymmetric plasma lensing gives rise to the bending of the beam path at the interface. The bending of the beam by the collective effect of the (passive) medium at the boundary is the particle analog to refraction of photons at a dielectric boundary [5].

To estimate the order of magnitude of this deflection, consider the simple case of the beam at the edge of a sharp plasma boundary (Fig. 1b) 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 [3] and approximately 2 for beams of length on the order of the plasma wavelength [6] (due to a resonant overshoot of the expelled electrons). For beams shorter than the plasma wavelength (λ_p) there is not enough time for the channel to reach its full extent and α can be shown to scale as $\frac{4}{\pi}\frac{\sigma_z}{c/\omega_p}$, where σ_z is the Gaussian bunch length and c/ω_p is the plasma skin depth ($=\lambda_p/2\pi$ $=c/\sqrt{4\pi n_o e^2/m}$). 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 [7]. 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 applied to a cylinder with the cross-section [8] shown in Fig. 1b, yielding

$$F=-eE=2n_o e^2 r_c \qquad (1)$$

The impulse on the beam is found by multiplying this force by the time that the beam is within a channel radius of the edge. The time spent near the edges is $2r_c/c \sin\phi$, 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 valid for ϕ greater than θ:

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

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 for long beams compared to the plasma skin depth (or equivalently, high plasma densities) such that α is constant, the dependence of θ on plasma density cancels out. This is because higher density, although giving a stronger deflection force, gives a narrower channel and hence a shorter time for the impulse.

We note that the impulse approximation used in obtaining Eq. (2) breaks down at small incident angles ϕ such that the deflection θ is on the order of ϕ. In this case, the beam can be internally reflected. From the simulations, when ϕ is less than θ above, the beam is deflected just enough to skim along the interface. That is

$$\theta \sim \phi \tag{3}$$

for small angles ϕ.

The simple analytic model above was tested with the electron beam from the Stanford Linear Accelerator Center (SLAC) linac at the Final Focus Test Facility. The experimental setup has been described in Ref. [9]. The plasma was created by photoionization of a column of lithium vapor by an ArF laser (193nm). The plasma density was $1\text{-}2\times10^{14}$ cm^{-3} with a cross section of approximately 2.5 mm $\times$ 2.1 mm and length of 1.4 m. The beam consisted of 1.9×10^{10} electrons at 28.5 GeV in a Gaussian bunch of length σ_z=.7mm and spot size $\sigma_x\sim\sigma_y\sim$40 μm. The electron beam traversed a thin glass pellicle located 57 cm before the plasma, and overlapped with the ionizing laser beam that reflected off the same pellicle. The angle between the electron bunch initial trajectory and the laser beam ϕ (in Eq. 2) was remotely adjusted using the pellicle tip-tilt angle, and was monitored by measuring the deflection of a reference HeNe laser. The electron beam propagated over a distance of about 12 m after the plasma and its shape and transverse position at that location were measured using a Cerenkov radiator (1mm thick aerogel) and an imaging system. The transverse position was also monitored independently at several other locations downstream of the plasma, including by a beam position monitor located from the plasma exit 4.3m. Sample results are shown in Figs. 2 and 3.

To compare to the experiments as well as to provide further insight into the physical mechanisms involved in the refraction we performed fully self-consistent, electromagnetic particle-in-cell simulations in three dimensions [10]. Fig. 2c shows a snapshot of the real space of the beam and plasma electron density (blue) from a simulation. The head of the beam has emerged undeflected from the plasma at this time, but the tail portion has been deflected toward the plasma and is near the plasma boundary. This results in a characteristic splitting of the beam downstream into two as seen in Figs. 2b and 2d.

The apparent break-up of the beam into bunchlets can be understood in the following way. There is a focusing force from the plasma that increases from head to tail as the plasma responds to the beam [6]. The head is not focused, but as the plasma responds, the ion column forms producing focusing, and the first waist that forms has separated the head from the next bunchlet. This bunchlet is separated from the remainder of the beam by another waist. Note that once plasma blowout occurs, the remainder of the beam has the same focusing and deflection angle.

Figure 3 is a plot of beam deflection (θ) measured with the beam position monitor versus angle between the laser and the beam (ϕ). The solid curve is the prediction from the impulse model. For incident angles ϕ less than 1.3 mrad, the beam appears to be internally reflected in agreement with Eqs. (2) and (3).

The simulations and experimental results presented here show that it is possible to refract or even reflect a particle beam from a dilute plasma gas. Remarkably, for a 28.5 GeV beam, the collective effects of a plasma are strong enough to "bounce" the beam off of an interface one million times less dense than air. It is possible to ascribe to the plasma an effective index of refraction and corresponding Snell’s law for this collective phenomenon. However, the refractive index is angle-dependent and intrinsically nonlinear, and we leave it for a future paper.

The refraction and total internal reflection of light obviously have many significant applications such as the guiding of light pulses in optical fibers. It is interesting to contemplate the possibility of a similar use of internal reflection of particles to guide electricity in “vapor wires” that are rapidly created or reconfigured by shining laser beams through a gas. One can imagine fast optical kickers replacing magnetic kickers or even compact magnetless storage rings. For such applications it will probably be necessary to use an auxiliary laser or particle beam (which may be of much lower energy) to pre-form the ion channel and deflect all of a trailing particle beam. As an example, consider a gas that is ionized to a density of 10^{16} cm^{-3} by a laser that propagates at an angle of a few milliradians to the path of a focused electron beam. For beam parameters typical of SLAC, the deflection force (Eq. 2) is equivalent to a 50 kG dipole magnet, and the turn-on time is approximately ω_p^{-1} = 200 femtoseconds.

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Fig. 1. Schematic of refraction mechanism: a) side view and b) front view of beam and plasma illustrating how asymmetric blowout creates a net deflection force.

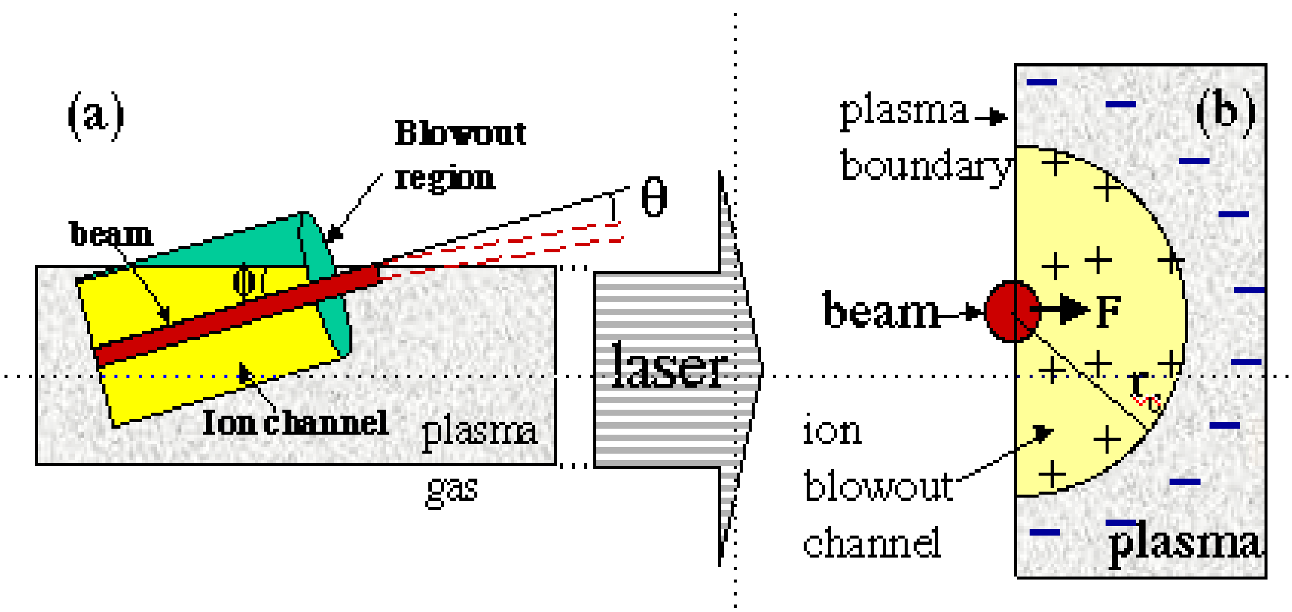

Fig. 2. Images of the electron beam showing refraction of a portion of the beam: a) Cerenkov image without the plasma (i.e., laser off). b) Cerenkov image with the laser on at an angle ϕ of

1mrad to the beam. Cross- hairs show the undeflected beam location. This shows a characteristic splitting of the beam into two in qualitative agreement with the simulation shown below it. c) PIC simulation of electron beam, side view with plasma shown (blue). The inward motion of the plasma electrons is visible as a depression in the blue plasma surface behind the beam. d) PIC simulation, head on view corresponding to (b). The code used was OSIRIS and is described in Ref. [10]. The simulation parameters were chosen to be similar to be similar to the experiment; namely a 30 GeV beam with $2x10^{10}$ electrons in a bi-Gaussian distribution (spot size σ_r=70μm, bunch length σ_z=0.63 mm) incident on a plasma of density $2x10^{14}$ cm^{-3}. In the simulation, the beam propagated through approximately 80 cm of plasma before encountering a sharp plasma/vacuum boundary at an incident angle of 0.9 mrad in the x-z plane. The model consisted of $2x10^7$ particles on a 160x120x88 grid representing a 2.9mmx2.2mmx6.5mm section of plasma (x,y,z) moving with the beam (z-direction).

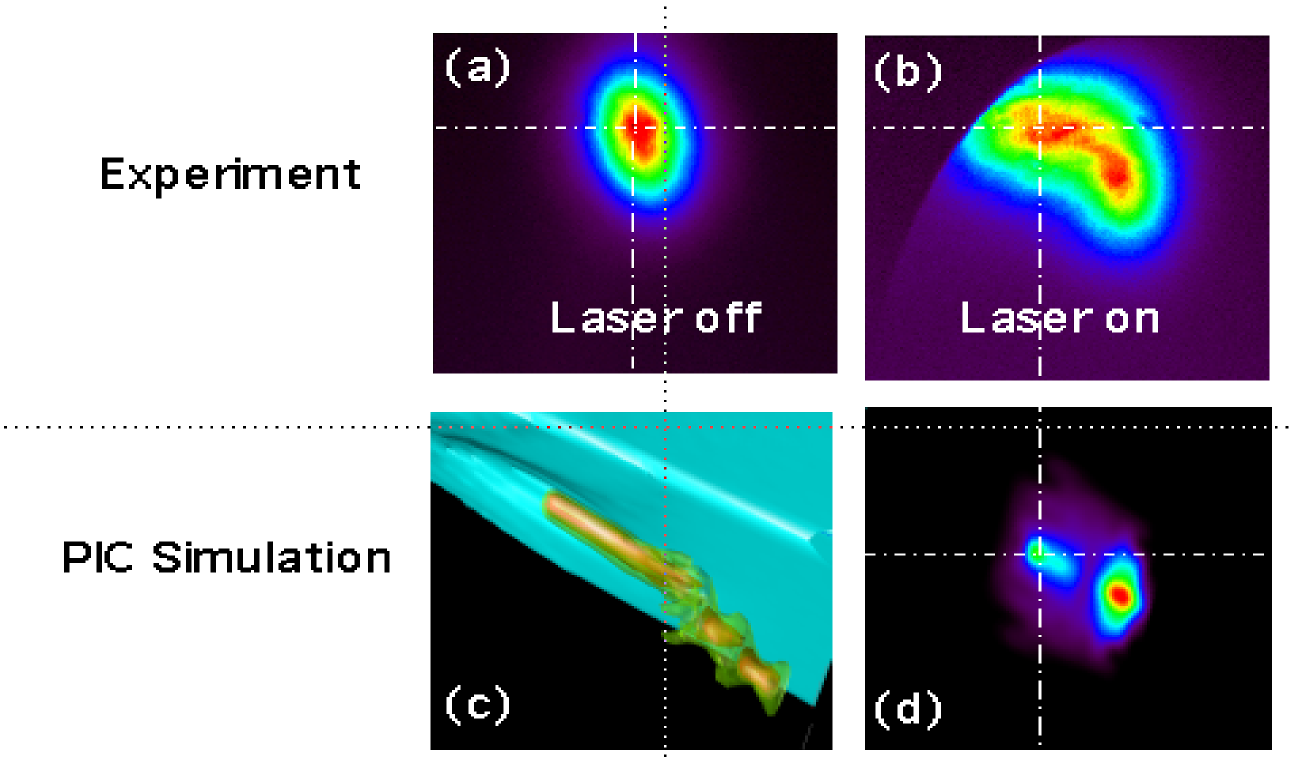

Fig. 3. Experimentally measured electron beam deflection θ as a function of angle between laser and e-beam (i.e., angle of incidence ϕ). Solid curve is the impulse model from Eqs. (2) and (3) with α=1.4 for the bunch length and plasma density corresponding to this run (0.7 mm and $1x10^{14}$ cm^{-3}, respectively). Since the beam deflection measured by the beam position monitor is a weighted

average over the entire beam, it is less than one would obtain for the peak deflection of the tail portion of the beam. To compare to the data, the impulse model has been scaled by an overall factor (0.17). Note that the critical angle for total internal reflection (the cusp in the figure) is independent of the choice of scaling factor.

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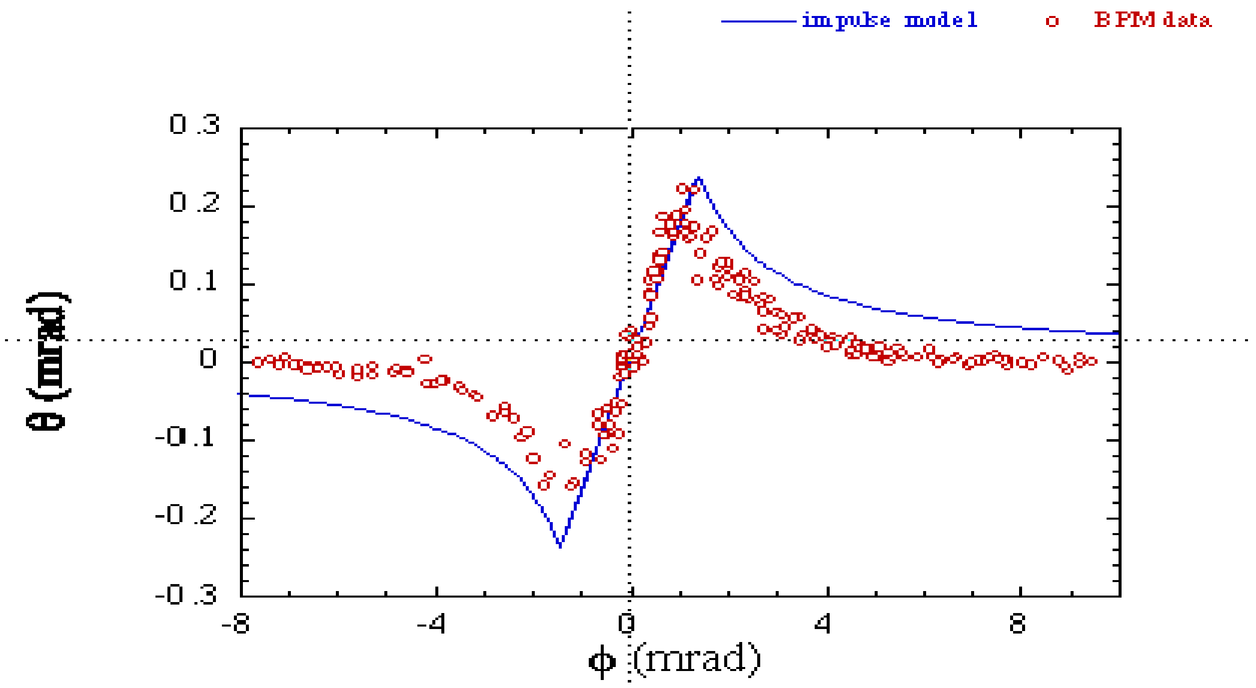

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[7] When the beam center is near the boundary but still inside the plasma, some plasma electrons (the ones above the beam axis) are expelled from the plasma. These electrons are attracted back to the ion column after the passage of the beam. Once the beam crosses the boundary, all plasma electrons ahead of the beam will be blown inward, and the simple physical description in the text applies.

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