The Development of Plasma Lenses for Linear Colliders*

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Introduction

The plasma lens, first proposed by Chen[1], can in principle raise the luminosity of a linear collider with minimal interaction with the accelerator systems, nevertheless the short focal length lens[2] design does interact strongly with the design of the particle detector at the interaction point. We have thus considered a number options for using the lens and have begun to test plasma focusing experimentally.

This paper briefly reviews constraints on use of the lens and its proposed operating modes, and then describes tests of a prototype valve/nozzle system and experimental tests of focusing.

Optics

Plasma lenses can be used in either the overdense or underdense mode, depending of the ratio of the density of the plasma to the beam. In the overdense mode the focusing is produced by induced charge density which is equal to the beam density. In the underdense mode, which works only for electron focusing, the induced charge density is limited to the positive ion density.[3] The lenses can be used asymmetrically or symmetrically for e^+ and e^-.[4] Since e^+ focusing cannot be done in an underdense mode, it is important to determine the minimum density required to focus positrons.[5]

Constraints on Optics

Two general constraints govern the use of plasma lenses in colliders: the aberrations associated with the focusing process require that the focal length must be short, but short focal lengths involve dense beams and plasmas and contribute to backgrounds. The constraint on focal length for the SLC beams can be derived from the size of the aberration σ_a, produced from a beam of size $\sigma_L = fx'$, and, from $\sigma_a = \sigma_L(\Delta K/K)$, is given by

$$f \quad \leq \quad (\sigma_a/x')(K/\Delta K) \sim 1.3mm(K/\Delta K),$$

where K is the focusing strength of the lens, $x' = \epsilon/\sigma$ is the divergence of the beam at the focus in terms of the emittance and the focused beam size, and σ_a is assumed to be about 0.2 times the design spotsize of $\sim 1.8\mu$. Even if the plasma lens itself is aberration free, beam jitter in position, and, to a lesser extent, in shape, will cause the focused spot to follow the initial density of the beam, and perturb the focusing by $(K/\Delta K) \sim \sigma/\delta\sigma_{jitter}$. Estimates of the jitter of the SLC beams are in the range 0.02 - 0.1 σ_L, thus constraining the focal lengths to less than about 7 cm.

Backgrounds can be estimated from the expression

$$R_{BG} = N_e n_N \sigma_{eN} t,$$

where $N_e n_N \sigma_{eN}$ and t are the number of beam particles, density of target nuclei, cross section for inelastic scattering and target thickness. The plasma density is assumed to be a trigaussian whose density is a function of the transverse and longitudinal bunch dimensions at the lens, σ_L and σ_z, and the ratio of plasma density to beam density, $m = n_p/n_b$. Using the expression for focusing strength, defined above, the rate for background events from the plasma is then

$$R_{BG} \quad = \quad mN_e\sigma_{eN}/2\pi r_e f,$$

which varies like m/f. Thus the focal length should be maximized within the constraints imposed by jitter and aberrations. Reducing the plasma density requires thicker plasmas, and does not reduce the background. The parameters of a useful plasma lens are then constrained to the approximate range f = 2 - 6 cm, with $n_p = mn_b \sim 10^{16}$ cm^{-3} and $t \sim 2$ cm.

Using this information, the parameters of the nozzle required to produce the gas can be set. The density of the jet and the neutral pressure in the region of the IP, which determine backgrounds, are a function of the gas injected on each pulse, which are in turn a function of the flow rate and pulse length from the valve. In order to examinenozzle behavior we have constructed and studied a piezo electric valve with a short pulse length.

Valve/Nozzle Tests

Since the lens hardware must be within a few centimeters of the IP, its size and mass must be minimized. Previous use of piezoelectric valves has centered around a disk shaped crystal but these devices tend to be big, slower than required, and poorly sealing due to the low force that can be exerted by the crystal. In order to solve these problems we decided to use a piezocrystal stack translator which had a high resonant frequency and large mechanical loading capacity. The Physik Instrumente P245.50 was chosen because of its comparatively high resonant frequency (9 kHz) and large travel (85 μm)[6]. The design of the valve is shown in Fig 1a. The sealing surface is a thin slice of viton, cemented to the end of the piston. The piston itself is a thin walled stainless steel tube 5 cm long. The nozzle used was patterned after that of Auerbach and McDiarmid [7], in order to make

*This work supported in part by the U. S. Department of Energy, Division of High Energy Physics, Contract NO W-31-109-ENG-38.

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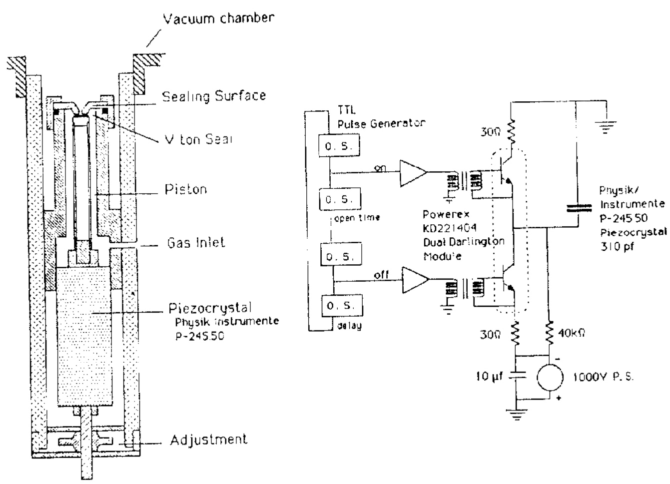

Figure 1: a) Components (not to scale) of the Valve/Nozzle assembly, and b) the power supply

comparisons between the two valve designs. An additional nozzle was constructed in order to look at the dependence of the gas flow pattern on the nozzle shape.

The primary technical problem associated with the design of this valve is that the crystal is capable of larger pushing forces (1000 N) than pulling forces (300 N) and must expand when negative voltage is applied. When the power supply is turned on or off, the seating of the valve must be readjusted mechanically using the adjustment screw.

The power supply used to pulse the crystal used adjustable monostable oscillators to control high power transistors. Since the capacitance of the translator is large, high speed operation requires high currents and high voltages. The power supply is shown in Fig 1a. The top transistor shunts the piezocrystal, connecting the translator to ground and opening the valve. The bottom transistor connects the crystal to the -HV, closing the valve. When the transistors are not firing, the piezocrystal is held at -HV thru a 40 kΩ resistor. The power Darlingtons require high base currents to switch both on and off. The piezocrystal functions both a speaker (creating vibrations from electrical signals) and a microphone (producing electrical signals from mechanical oscillations), and has a tendency to ring.

A standard Bayard-Alpert ion gauge head is used to monitor gas pressure, with the signal from the collector being fed directly into the input of the oscilloscope. In order to increase the frequency response of the IG, the length of the cable was minimized (to about 1 m) and the load resistor was reduced to 47 kΩ, giving a time constant of τ = RC = 6 μs with the 120 pf capacitance of the cable and scope. The signal at the IG is then the convolution of the valve transmission profile, the time of flight distribution due to the spread of molecular speeds and the and the resolution of the ion gauge itself. The resulting gas pulses, Fig 2b, seem to accurately reflect the voltage profile on the crystal, Fig 2c, although faster resolution might be possible. The profiles for the different nozzles show similar rise times but different fall times.

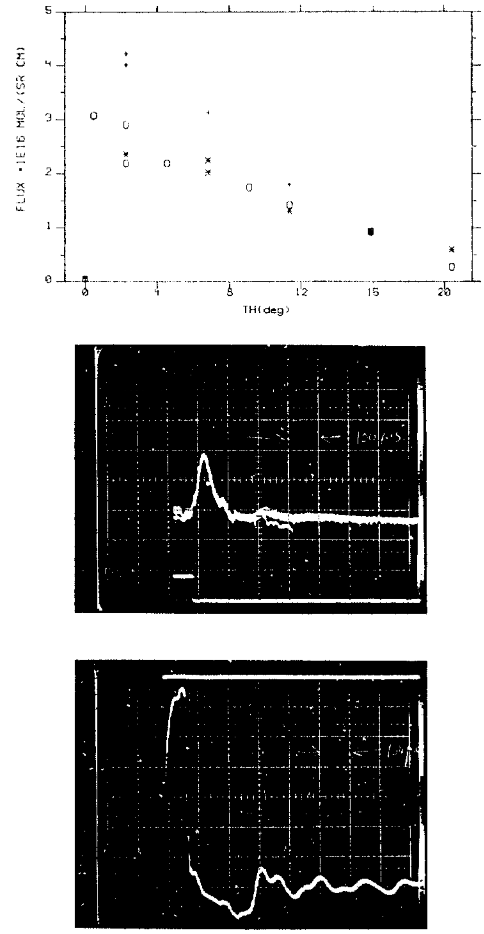

Figure 2: a) angular distributions, b) pulse lengths from the valve which are produced from a voltage pulse shown in c).

Measurements of the throughput of the valve were made by pulsing it into a (valved off) 40 l test chamber for 100 pulses, subtracting the pressure obtained without pulsing and dividing by the measured FWHM open time for the valve. The result, 7 torr l/sec, seems to be comparable with other, somewhat slower valves.

Jitter in the gas density produced from the valve is undesirable since fluctuations in density cause fluctuations in focusing strength, which contribute to the upper limit to the allowed focal length. These considerations thus set a lower limit to the background from beam gas events. Initial tests of the valve showed small fluctuations in gas signal so that five pulses produced negligible widening of the detected signal. As other nozzles were inserted and tested, the random fluctuations increased to about ±10%, evidently due to the degradation of the viton sealing surface.

Angular distributions were made by moving the ion gauge head, which was located 12 cm from the nozzle, perpendicular to the direction of the gas flow. The angular range that could be scanned was ±20° and there were no obstructions within 70° of the valve centerline. The angular distributions produced for three shapes of nozzle, Fig 2a, show little dependence on the shape of the nozzle. The units

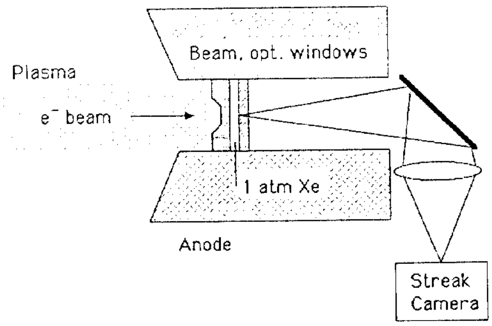

Figure 3: A test of plasma focusing at Argonne

chosen for flux are useful since they permit easy calculation of densities at various distances from the nozzle.

Tests of Focusing

Strong indirect evidence for plasma focusing has recently been seen in plasma wake field acceleration measurements at the Argonne Advanced Accelerator Test Facility (AATF)[8].

An experiment to directly measure the focusing effect at the Argonne facility is presently underway and is now producing preliminary results. This experiment places a small (2 mm thick, 10 mm dia) Cherenkov cell within the anode of the hollow cathode arc plasma cell and images the light from cell directly on the slit of a streak camera, producing time resolved images of the bunch. The 0.5 mm thick beam window of the cell is a slot about 1 cm by 0.5 mm and the edges of the window are tapered to allow for the maximum heat removal. Multiple scattering in the window is negligable and the taper is shallow enough to prevent scattering beam into the part of the cell seen by the streak camera. The device is shown in Fig 3.

In order to examine the physics of plasma focusing for high density beams, we a proposing an experiment which would a Back Lighted Thrytron (BLT) plasma to focus a beam from the ANL-CHM linac. The linac beam would be focused to a size of 100 - 200μ using a pulsed solenoid. The BLT is a stable high current plasma source that runs in a superdense glow mode. By controlling the external circuit it is possible to get pusle lengths from about 100ns to over 10μsec.[9] Beam profiles can be measured using a water Cherenkov counter and transmitting this image to a streak camera.

An experiment to look at plasma focusing at SLAC under conditions similar to those at the SLC IP is also being proposed. Measurement of the beam size and profiles is difficult when the beam dimensions are less than 1 μ, however a techniqne has been proposed which looks at the width of the penumbra of the collimator located downstream of the focus, and preliminary estimates are that this system potentially has a resolution, limited by ground vibrations, of a few nm.[10]

Conclusions

The limitations of plasma focusing are imposed primarily by aberrations, of which jitter may be the dominant one, and backgrounds. These constraints require plasma lens focal lengths in the range of a few cm, and plasma densities of $\sim 10^{16}$ cm^3. A pulsed valve/nozzle has been constructed which produces very short (70μsec) gas pulses with the required density. Experimental study of focusing is proceeding. Indirect evidence of pinching has been seen in longitudinal wakefield measurements, direct measurements are now underway and yielding preliminary results, and more thorough measurements have been proposed at Argonne and SLAC.

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