PLASMA LENS FOR MUON AND NEUTRINO BEAMS*

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Abstract

The plasma lens is examined as an alternate to focusing horns and solenoids for use in a neutrino or muon beam facility. The plasma lens concept is based on a combined high-energy lens/target configuration. The current is fed at electrodes located upstream and downstream from the target where pion capturing is needed. The current flows primarily in the plasma, which has a lower resistivity than the target. A second plasma lens section, with an additional current feed, follows the target to provide shaping of the plasma for optimum focusing. The plasma lens is immersed in an additional solenoid magnetic field to facilitate the plasma stability. The geometry of the plasma is shaped to provide optimal pion capture. Simulations of this plasma lens system have shown a 25% higher neutrino production than the horn system. Plasma lenses have the additional advantage of negligible pion absorption and scattering by the lens material and reduced neutrino contamination during anti-neutrino running. Results of particle simulations using plasma lens will be presented.

INTRODUCTION

Many methods have been employed to provide magnetic focusing to enhance the charge particle flux from a divergent source such as a production target. The most effective of these devices use azimuthal magnet fields that pull the particles radially inward as a consequence of the Lorentz force. These devices require large longitudinal currents to generate the strong azimuthal fields. Lithium lenses and horns have been used to focus secondary particles for high energy physics applications while spark and Z channels were developed for fusion experiments. Spark, Z channels, and Z-pinches shall be referred to as plasma lenses, even though in high energy physics applications this term is also used for lithium lenses where lithium was replaced by high pressure gases.

In this paper we shall largely consider the use of a plasma lens for capturing secondary pions to produce a high intensity neutrino beam. Although some features vary from experiment to experiment, there are a number of common requirements for using lenses for a neutrino beam:

1. Very large axial electrical currents must be generated and maintained.
2. The magnetic fields generated should capture the largest number of pions.
3. The lens medium should have the lowest density possible to minimize pion absorption and scattering.
4. The lens must endure high mechanical and thermal stresses caused by pulsing high currents and electromagnetic fields.
5. The lens must survive prolonged exposure to radiation.
6. The lens should be cost-effective and power-efficient.

For generating large neutrino beams, high-energy pions must be captured and maintained as a beam until they decay.

LENS OPTIONS

The lens choice for pion capture is based on the applicability to the generation of a neutrino beam. A horn is widely employed as a focusing lens for this application. A horn is a hollow coaxial structure of conductors through which large currents flow such as to produce an azimuthal field. The device is pulsed which produces large thermal and mechanical stresses, however the conducting walls of the horn must be thin to minimize particle losses. The alternative capture system that is being proposed in this paper is a plasma lens based on a Z-pinch. A Z-pinch involves a sudden compression of low-density plasma by means of a large discharge current that lasts for a few microseconds. The Z-pinch fill pressure is less than a milli-torr. In a series of experiments with magnetized Z pinches, 2 MA, 250 μs were reach for a plasma length of 0.8 m [1]. Present day Z-pinch research involves discharge currents of 10 MA over few centimeters.[2]

NOVEL PION CAPTURE LENS

We described a comparison of a horn pion capture system to a similar plasma lens system for a super-neutrino beam. That study looked at a 28 GeV proton beam that would have been used for a neutrino beam from BNL to the DUSEL laboratory in South Dakota [3]. The horn system consists of two magnetic lens separated by eight meters. The first focusing lens is a 250 kA horn with an inner (outer) radius of 0.8 cm (8 cm) surrounding a 6-mm radius, 80 cm long carbon target. As an alternative to the horn, a plasma lens based on a magnetized Z-pinch is being considered.

Figure 1 is a display of a lens-target configuration. Figure 1a is the 3-D embodiment, while figure 1b is a schematic of the configuration. Part of the plasma straddles the target. Current is fed at an electrode near the

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beginning of the target and collected at another electrode downstream of the target as shown in the figure. An additional electrode position at the end of the target is used to shape the target and permits different current in the target and downstream part of the plasma lens. The plasma lens is immersed in a solenoid magnetic field to stabilize the plasma.

Neutrino yield simulations for the above lens were performed for a 28 GeV proton beam on a carbon target. The study used a 180 m decay channel and is compared to a horn with the BNL geometry. The plasma lens cases were simulated with different outer radii in the range of 3-12 cm for the section straddling the target, while the range outer radii of the flared section end was 5-15 cm. Basically the outer radius of the straight plasma lens section, R_out1 and the end of the flared section R_out2 were varied by the same amount, but R_out2 was 3 cm larger than R_out1. In figure 1, the plasma is shown in pink, while the carbon target, which is 6 mm in radius and 80 cm in length, is shown in grey. The plasma current was chosen to be the same throughout the lens in all simulations, although it is possible to flow different currents in the two sections with the optional electrode shown in figure 1a. A second lens that is positioned downstream from the first lens was of the BNL horn design for both scenarios.

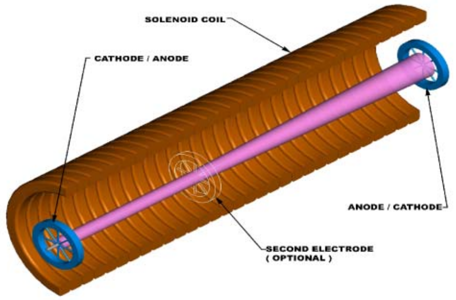

Figure 1a: 3d sketch of lens-target embodiment

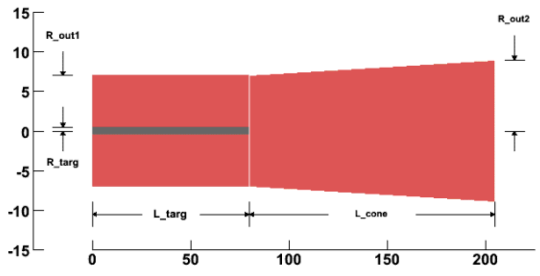

Figure 1b: Schematic of the plasma lens and target. Dimensions are in *cm*.

Results of the simulations are shown in figures 2 and 3. Displayed in figure 2 is the neutrino flux at 3 km from the target in neutrinos per m^2 per proton on target for various R_out1 and plasma current values as well as the horn shown in a dash line. Figure 2a shows the whole neutrino spectrum, while figure 2b shows the spectrum for $E_\nu>3$ GeV. Similar results were seen for the anti-neutrino spectrum. It is interesting to look at the neutrino background flux in the anti-neutrino beam. Figure 3 shows the ratio of background neutrino flux to anti-neutrino flux for anti-neutrino running. Figure 3a shows the plots for the whole spectrum and figure 3b shows only the spectrum with $E_\nu>3$ GeV.

The optimal overall neutrino flux occurs for the plasma lens current of 375 and 625 kA for outer radii of 5 and 7 cm respectively, while high-energy (that part of the spectrum with $E_\nu>3$ GeV) neutrinos have optimal flux at currents of 250, 300, and 625 kA for outer radii of 3,5, and 7 cm respectively.

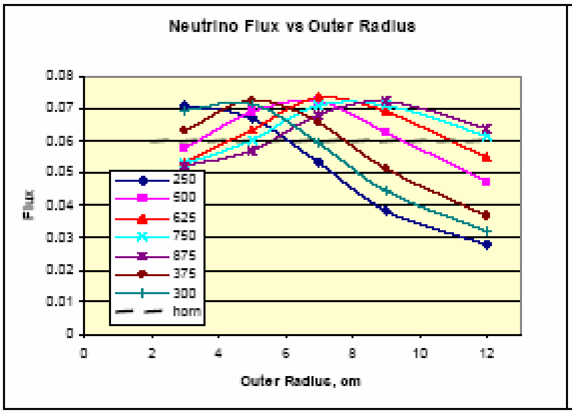

Figure 2a: Neutrino flux vs. lens current and radius for whole energy spectrum from a 28 GeV incident proton beam.

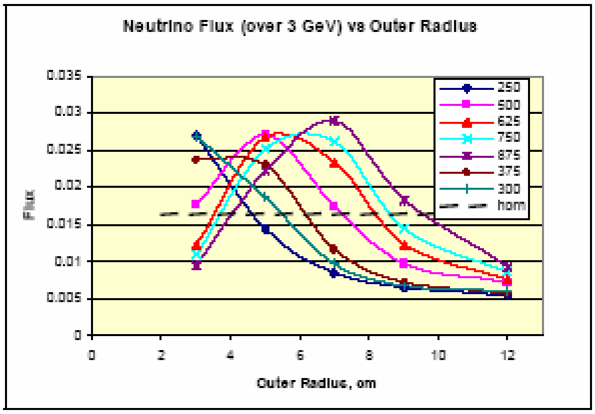

Figure 2b: Neutrino flux vs. lens current and radius for spectrum with $E_\nu>3$ GeV from a 28 GeV incident proton beam.

Comparing these neutrino fluxes to those obtained with horn as the first focusing lens reveals a 25% overall neutrino flux gain in using a plasma lens. Results are more dramatic for high-energy neutrinos where the gain is a factor of 2.47.

For neutrino background reduction during anti-neutrino runs, the results shown in figure 3 are impressive for currents greater than 375 kA and outer radius less than 7 cm.

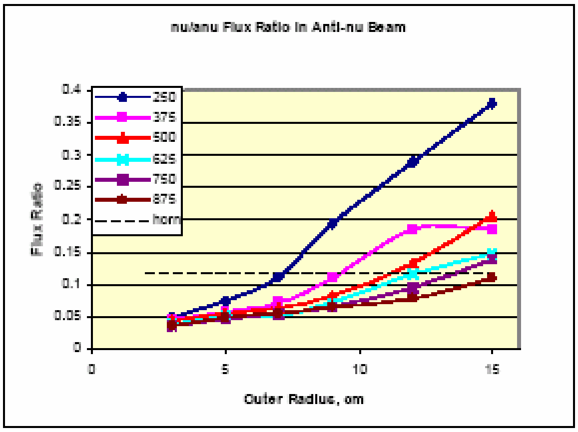

Figure 3a: Neutrino to anti-neutrino ratio for the whole anti-neutrino spectrum for a 28 GeV incident proton beam

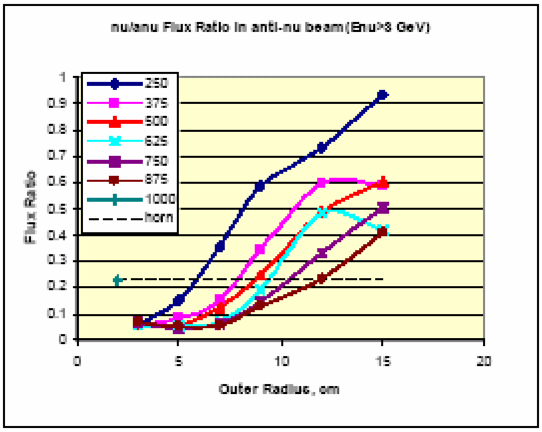

Figure 3b: Neutrino to anti-neutrino ratio for $E_{\nu}>3$ GeV for a 28 GeV incident proton beam.

A similar study was performed for a neutrino beam created with 120 GeV initial protons to investigate the practicality of using a plasma lens for the Fermilab NuMi beam line. This study used only a 180 m decay channel and is compared to the BNL horn geometry with the higher energy protons. Figure 4 shows the neutrino spectrum that would be seen with the incident 120 GeV proton beam. Comparable gains of 35% for the whole energy spectrum and a factor of 1.8 for the spectrum with $E_{\nu}>3$ GeV can be seen in figure 4.

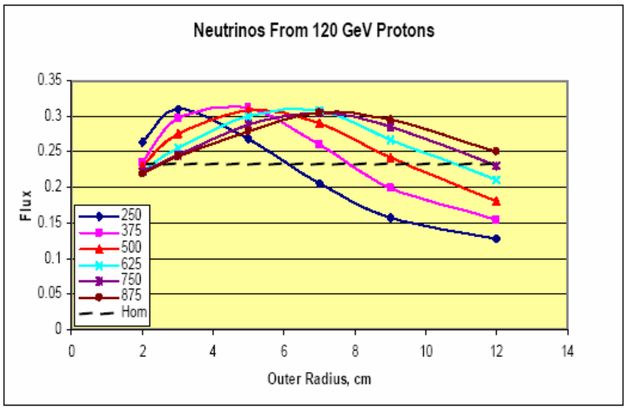

Figure 4a: Neutrino flux vs. lens current and radius for whole energy spectrum from a 120 GeV incident proton beam.

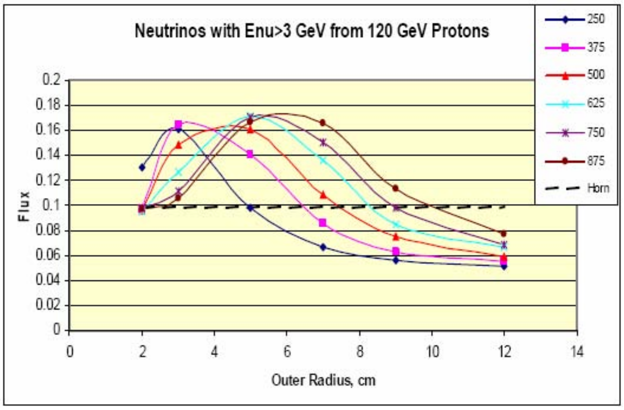

Figure 4b: Neutrino flux vs. lens current and radius for spectrum with $E_{\nu}>3$ GeV from a 120 GeV incident proton beam.

ACKNOWLEDGEMENT

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REFERNCES

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[2] Work by McDaniel, D. Cook, private communication, 1994; Rahman, Wessel, and Rostoker, PRL 74, 714 (1995)

[3] AGS Super Neutrino Beam Facility: Accelerator and Target System Design. BNL-71228 (2003).