Plasma Lens for a US Based Super Neutrino Beam*

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Abstract. The plasma lens concept is examined as an alternative to focusing horns and solenoids for a neutrino beam facility. The concept is based on a combined high-current lens/target configuration. Current is fed at an electrode located downstream from the beginning of the target where pion capturing is needed. The current is carried by plasma outside the target. A second plasma lens section, with an additional current feed, follows the target. The plasma is immersed in a solenoidal magnetic field to facilitate its current profile shaping to optimize pion capture. Simulations of the not yet fully optimized configuration yielded a 25% higher neutrino flux at a detector situated at 3 km from the target than the horn system for the entire enegry spectrum and a factor of 2.47 higher flux for neutrinos with energy larger than 3 GeV. A major advantage of plasma lenses is in background reduction. In anti-neutrino operation, neutrino background is reduced by a factor of close to 3 for the whole spectrum, and for and for energy larger than 3 GeV; neutrino background is reduced by a factor of 3.6. Plasma lens advantages are due to: larger axial currents, high signal purity: minimal neutrino background in anti-neutrino runs. Additionally the lens medium consists of plasma, consequently, particle absorption and scattering is negligible. Withstanding high mechanical and thermal stresses in a plasma is not an issue.

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INTRODUCTION

In many areas of research involving charged particle beams, various methods of magnetic focusing have been employed to enhance the flux of charged particles from a divergent source such as a production target,[1] or to confine ions emerging from the cross-over region of an ion diode to betatron oscillation for propagation to a small target a few meters away.[2] The method of choice for focusing of high energy charged particles, produced in nanosecond to microsecond bursts, that need to be transported for a distance of a meter or more has been the use of azimuthal magnetic fields that pull the particles radially inward as a consequence of the Lorentz force. Large currents that are oriented along the desired flight path of the charged projectiles usually generate strong azimuthal magnetic fields. Therefore, devices with large axial current can be utilized as lenses.

Lithium lenses [3,4] and horns [1,5] have been used in high energy physics research, while various spark, and Z channels were developed for fusion experiments.[2,6,7,8] Spark, Z channels, Z-pinches shall be referred to as plasma lenses, even though in high energy physics research this term was used for lithium lenses and lenses where lithium was replaced by high pressure gases.

Although some features vary from experiment to experiment, there are a number of common requirements including lenses for the neutrino experiments: very large axial electrical currents must be generated and sustained. The lens medium should have the lowest density possible to minimize pion absorption and scattering. The lens must endure high mechanical and thermal stresses caused by pulsing high currents and EM fields, and must survive prolonged exposure to radiation. The lens should minimize neutrino background during anti-neutrino beam runs (signal purity). A cost-effective, power-efficient lens is desirable.

For generating powerful neutrino beams, high-energy pions must be captured and maintained as a beam until they decay. Description and comparison of the various lenses, with focus on a plasma lens is presented in this paper.

LENS OPTIONS

Interest in this type of charged particle focusing is varied and many applications require customized lens configuration. The lens choice in this paper, however, is done based on applicability to neutrino generation.

Horns

A horn system is a hollow coaxial structure of conductors through which large currents flow.[1,5] Requirements on the inner horns are extremely demanding: very large thermal and mechanical stresses are generated during pulsed operation. Yet they must be thin to minimize particle losses, thus limiting the current that can be carried. Additionally, horns do not capture pions with velocities that are at very small angles to target axis.

Spark (or Z) channels

Spark (or Z) channels are plasma transport channels, characterized by large currents (100s of kA), which have been developed to transport (and focus) intense beams of light ions over distances of up to 5 meters.[8] Channel radii from 1 cm to over 10 cm were reported (larger radii are easy to generate; radii below 1 cm are next to impossible).[8,9] Pulse lengths of 10s of nsec at a repetition rate of 500 Hz - 1 kHz have been generated, as well as 3 μsec long pulses at lower repetition rates.

These channels consist of two biased annular plates (or rings) placed in a vacuum chamber. The vacuum chamber is usually filled to a pressure of a few Torr to as high as 40 Torr with a gas. After an appropriate bias (10s of kV) is applied a spark or a laser pulse initiates a discharge that heats the gas. A large variety of these channels have been made, and an even larger variety is possible.[9] Another feature of these channels, which adds to their versatility, is the ease with which the direction of the discharge current can be changed.

Z-Pinches.

A Z pinch involves a sudden compression of low-density plasma by means of a large discharge current that lasts for a few microseconds. It bears some superficial similarity to a spark channel in that a discharge is formed between two end plates, but their plasma properties different, since the Z-pinch fill pressure is below a milli-Torr. In a series of experiments with magnetized Z pinches, 2 MA, 250 μsec were reached for a length of 0.8 meters.[10] Present day Z-pinch research involves discharge currents of 10 MA over a few centimeters.[11]

NOVEL PION CAPTURE LENS

Presently, a horn system is being considered for pion capture in the Super Neutrino beam. The first focusing lens is a 250 kA horn with an inner (outer) radius of 0.8 cm (8 cm) surrounding the 6-mm radius, 80 cm long carbon target.[12] A lithium lens is not an attractive alternative to a horn system since the radius of a lithium lens is 1 cm or smaller,[13] and the magnetic field at a distance of about 10 cm from its axis, which is most important for focusing, is an order of magnitude lower than at the lens radius. As an alternative to a horn, magnetized Z-pinches are being considered (can be flared) here.

Figure 1 is a display of a plasma lens and target configuration. Figure 1a is the 3-D embodiment, while 1b is a schematic of the configuration. Part of the plasma straddles the target. Current is fed at an electrode located near the beginning of the target where pion capturing is needed. An additional current feed, at the end of the target facilitates higher (or different) current in the downstream part of plasma lens. The plasma lens is immersed in a solenoid magnetic field to facilitate its current profile shaping.

Neutrino yield simulations for the above lens were performed for a 28 GeV proton beam on the carbon target. The range of simulated plasma outer radii was 3-12 cm for the section straddling the target, while 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 remained 3 cm larger than R_out1. In Figure 1, the plasma is shown in pink. The carbon target (6 mm radius, 80 cm long[12]) is shown in gray.

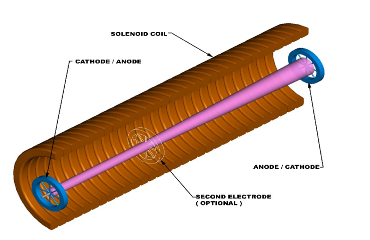

FIGURE 1a. Lens/target embodiment.

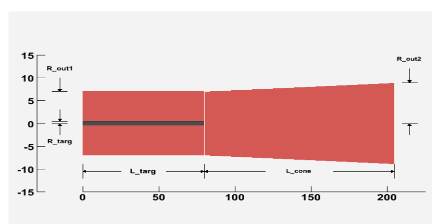

FIGURE 1b. Schematic of the plasma lens and target. Dimensions are given in cm.

The plasma current was chosen to be the same throughout the lens in all simulations. But, it is possible to flow different current in different sections of the lens, hence, the optional electrode in Figure 1a. The second lens that is positioned downstream from the first lens is unchanged from the original BNL design.

Results of 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_outer1 and plasma current values as well as the horn[12] shown in a dashed line. Figure 2a shows whole neutrino spectrum while 2b shows the spectrum for E_ν>3 GeV. Figure 3 shows the ratio of background neutrino flux to anti-neutrino flux for anti-neutrino running. Similarly Figure 3a shows the whole spectrum and 3b shows only the spectrum for E_ν>3 GeV.

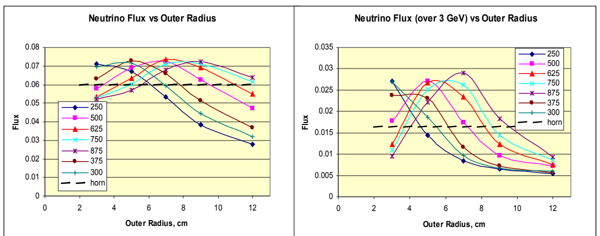

FIGURE 2. Neutrino flux vs. lens current and radius for whole energy spectrum (a), for greater than 3 GeV neutrinos (b).

The optimal overall neutrino flux is for plasma lens currents of 375 and 625 kA and outer radii of 5 and 7 cm respectively, while high-energy (> 3GeV) neutrinos have optimal flux at currents of 250, 300, and 625 for outer radii of 3,5, and 7 cm respectively.

Comparing these neutrino fluxes to those obtained with a horn as the first pion focusing lens reveal a 25% overall neutrino 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, (Fig. 3) are impressive: a factor of 3 for the whole neutrino spectrum and 3.6 for E_ν>3 GeV.

Optimal background reduction occurs for plasma lens radii of 3 – 7 cm, for almost any current.

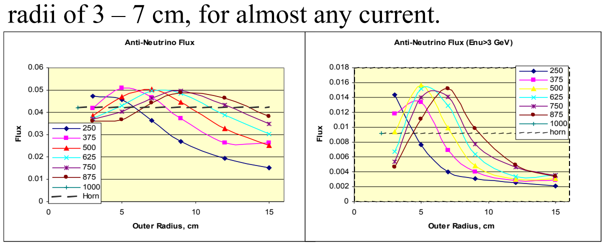

FIGURE 3. Neutrino to anti-neutrino ratio for whole neutrino spectrum (a); for neutrinos with energy larger than 3 GeV (b).

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 a Fermilab ν beam. The 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 120 GeV proton beam on target. Comparable gains (of 35% for the whole spectrum and a factor of 1.8 for E_ν>3 GeV) can be seen in Figure 4.

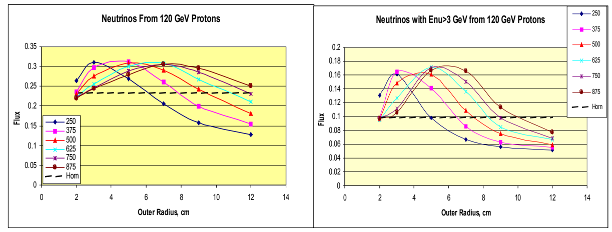

FIGURE 4. The neutrino flux from 120 GeV incident protons vs. lens current and radius for (a) the whole energy spectrum and for (b) E_ν>3 GeV.

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