Proposal to Measure the Efficiency of Electron Charge Sign Determination up to 10 GeV in a Magnetized Liquid Argon Detector (μLANNDD)

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Abstract

The recent dramatic success of the ICARUS 300-ton liquid-argon time-projection-chamber prototype [1] indicates that it is timely to review the possibilities for large-scale application of this technology for accelerator-based neutrino physics, neutrino astrophysics, and proton decay [2, 4, 3, 5]. A full exploration of the MNS neutrino mixing matrix (and extensions if sterile neutrinos exist) should be possible if the large mixing angle MSW solution to the solar neutrino problem, presently favored by the data [6], is confirmed by future measurements. A large detector for this purpose should be able to distinguish the charge of the lepton into which the neutrino converts, for which the detector should be immersed in a magnetic field.

The most promising option for a large detector that can distinguish the charge of an electron is magnetized liquid argon [7, 8]. However, all studies to date of liquid argon detectors suitable for neutrino physics [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] have been in zero magnetic field. We propose to study two key issues with a liquid argon detector of size $0.7 \times 0.7 \times 3.0$ m^3, sufficient to contain an electromagnetic shower, placed in a 120D36 magnet in the AGS A3 beamline:

1. Verification that a liquid argon detector can be operated with the electric field perpendicular to the magnetic field (unlike gas-phase time projection chambers that must be operated with $\mathbf{E}$ parallel to $\mathbf{B}$).
2. Verification that the electron charge can be determined up to several GeV by analysis of electromagnetic showers.

We request 15 shifts of slow beam time in the A3 line, with the A target in place to provide 0° secondary beams of 1-10 GeV. There should be an interval of at least one week after the first 10 shifts during which the detector would be reconfigured to have $\mathbf{E} \parallel \mathbf{B}$.

1 Concept of a Large Magnetized Liquid Argon Detector

The proponents' interest in a large detector for neutrino physics arises from our involvement in studies for high performance neutrino factories based on muon storage rings [21], and for neutrino superbeams from pion decay [22, 23]. A new accelerator-based neutrino physics program must provide significant contrast to the program developing in Japan in association with the JHF [24]. The Japanese detector is the 50-kton (22-kton fiducial volume) water Čerenkov detector, SuperKamiokande, presently operating with no magnetic field, with a possible upgrade to a 1-Mton detector in the future.

A superior detector must offer greater information about the neutrino interactions, particularly the sign of the leptons into which the neutrino converts, which implies that it must be immersed in a magnetic field. A water Čerenkov detector with PMT readout is not very compatible with magnetic analysis. A magnetized-iron sampling calorimeter can analyze the momentum of final state muons, but has little ability to analyze the momentum of electrons. Among devices that could be scaled to very large volumes, a magnetized liquid argon detector is the only one that can analyze electron charge (up to a few GeV), and provides the most detailed tracking information for neutrino interactions.

An overall concept of a large magnetized liquid argon detector is shown in Fig. 1. The LANNDD (Liquid Argon Neutrino and Nucleon Decay Detector) [2, 8] is a time projection chamber, meaning that electrons ionized by charged particles from a neutrino (or other) interaction are drifted by an electric field to an x-y readout plane that is sampled in time to provide the z coordinate of pattern of ionization via knowledge of the drift velocity of ionization electrons. Anticipating the possibility that neutrino beams are eventually sent to it from more than one accelerator, the magnetic field is vertical so the trajectories of secondary particles are generally orthogonal to the magnetic field.

1.1 Operation with $\mathbf{E} \perp \mathbf{B}$

To keep the readout channel count reasonably small ($\approx 200,000$), a pixel readout is not used, but rather arrays of wires at 0° and 90° to the vertical detect direct and induced signals from drifting electrons. The mechanics of the very large wire planes are somewhat easier if the planes are vertical, as shown in Fig. 1, which implies that the drift electric field is horizontal, *i.e.*, perpendicular to the magnetic field.

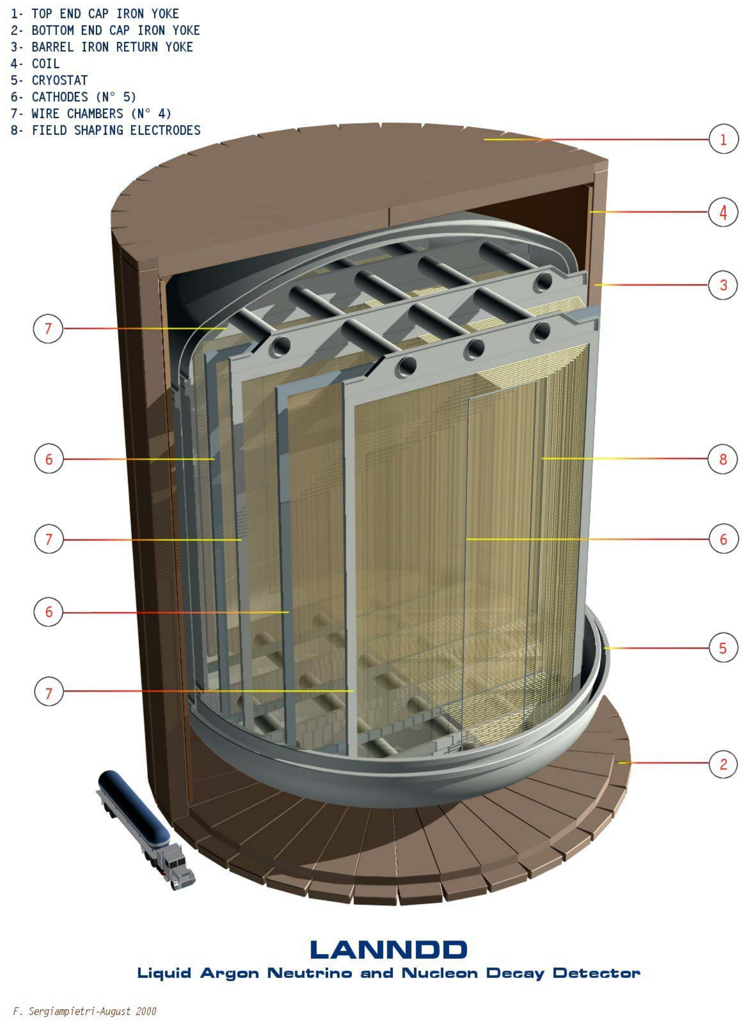

Figure 1: Concept of a 70-kton Liquid Argon Neutrino and Nucleon Decay Detector (LANNDD) [2, 8].

Furthermore, when using crossed-wire planes for the readout rather than pads, pattern recognition is considerably easier if the electron drift is perpendicular, rather than parallel, to the magnetic field. Then, electrons from different regions of a track generally arrive at the readout plane at different times, and the problem of "ghost hits" is reduced [8].

All time projection chambers operated in a magnetic field to date have used a gas as the ionization medium, and have had the electric field parallel to the magnetic field. There are two reasons for this, neither of which holds for a liquid medium. First, to obtain good momentum measurements in a gas, the electron diffusion in the bend plane must be suppressed, which requires $\mathbf{E} \parallel \mathbf{B}$. But diffusion is so greatly suppressed in a liquid that good spatial resolution is maintained over large drift distances even in zero magnetic field, as shown in Fig. 2 from [1]. Second, the relatively high drift velocity of ionization electrons in a gas would result in a large "Lorentz angle" of drift relative to the electric field lines, and hence a compressed track pattern in one readout coordinate. But the electron drift velocity in a

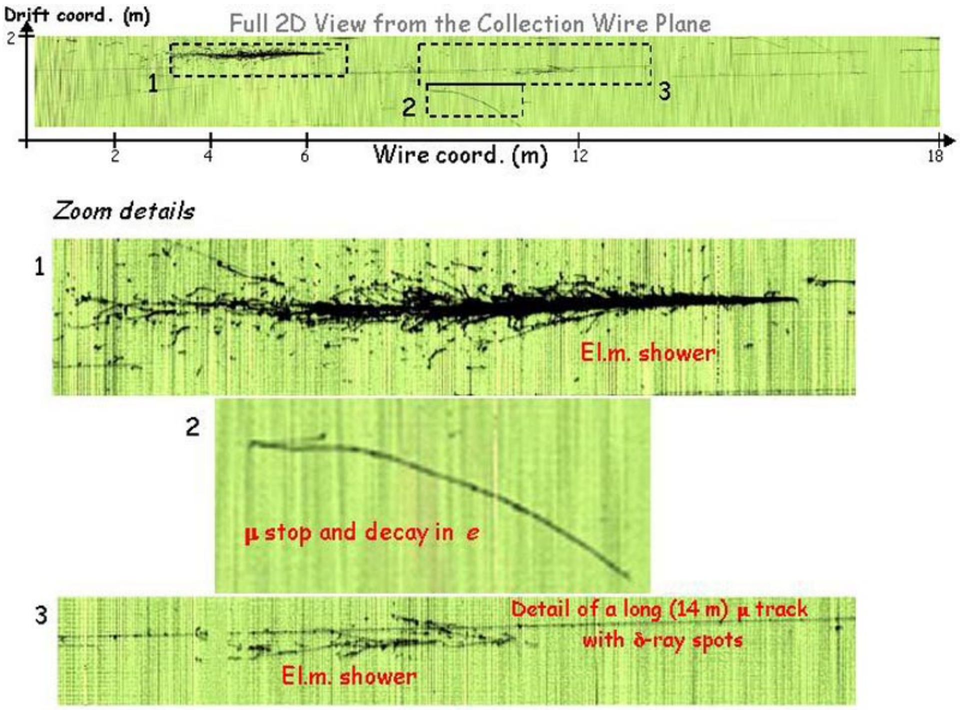

Figure 2: An event from the recent cosmic-ray test run of ICARUS [1], showing excellent track resolution over long drift distances in zero magnetic field.

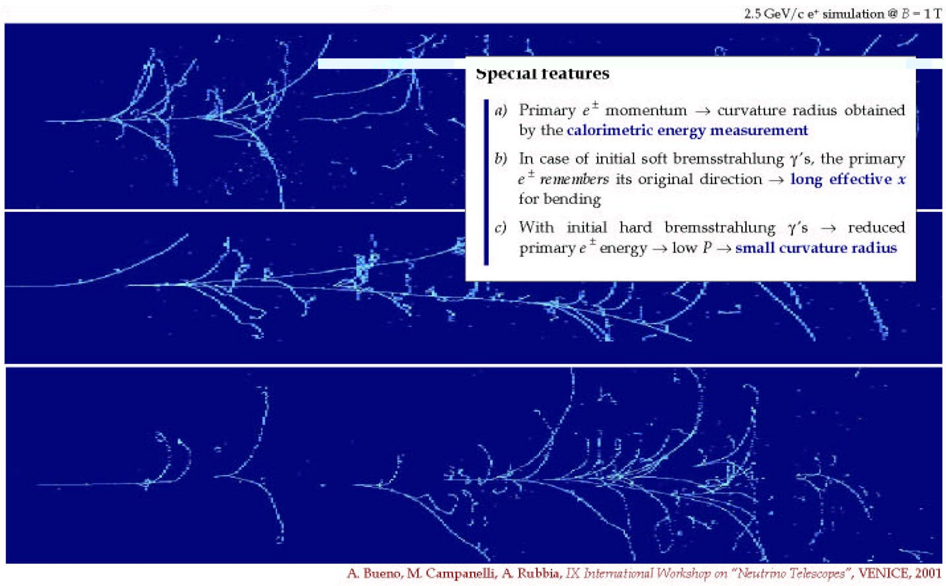

Figure 3: Simulations of electromagnetic showers of 2.5 GeV electrons in liquid argon with a 1-T transverse magnetic field [22].

liquid is low enough that the Lorentz angle effect should be negligible.

Nonetheless, in view of the novelty of operating a time projection chamber with $\mathbf{E} \perp \mathbf{B}$, we propose to study this.

1.2 Determination of the Sign of the Electron Charge

One of the greatest advantages of a magnetized liquid argon detector is its ability to determine the sign of an electron up to a few GeV, by detailed analysis of its electromagnetic shower for which the radiation length is 14 cm. Measurement of the curvature of the electron trajectory before, and after, the first bremsstrahlung provide the signature of the electron charge, as illustrated in Fig. 3.

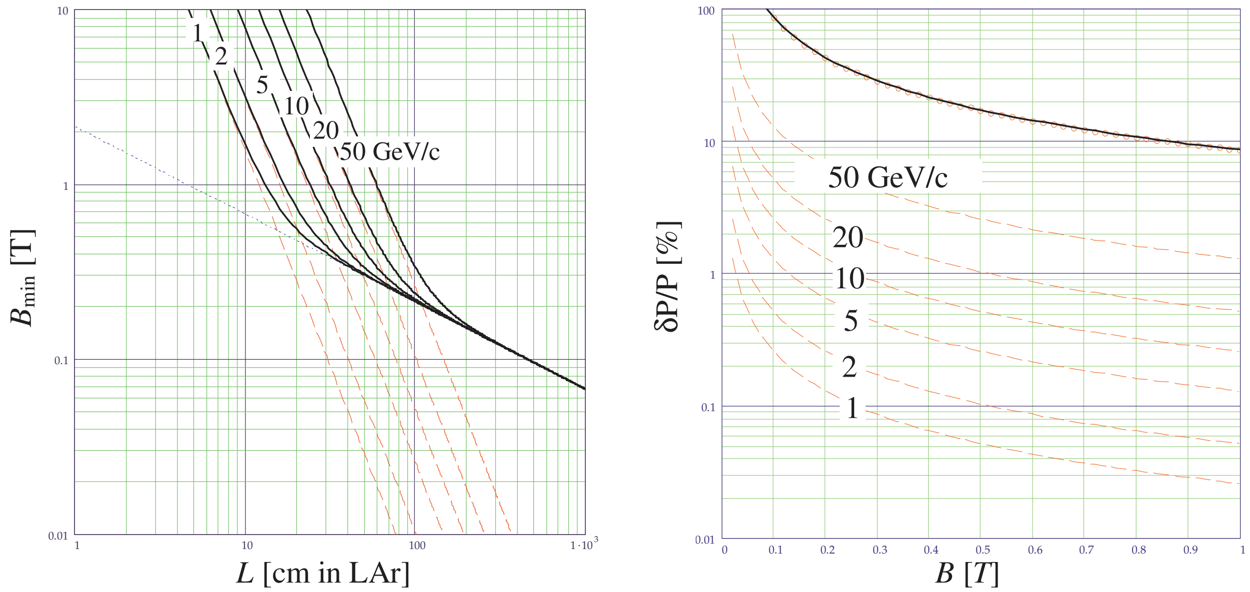

Figure 4: a) Minimum magnetic field *vs.* track length required to discriminate between positive and negative curvatures at 3-σ. Dashed curves: contribution of the detector resolution at momenta 1, 2, 5, 10, 20 and 50 GeV/c. Dotted curve: contribution of the multiple scattering in the range 1-50 GeV/c. Solid thick curves: combined contribution of detector resolution and multiple scattering in the range 1-50 GeV/c. b) Momentum resolution *vs.* magnetic field for muons crossing 20 X_0 in liquid Argon. Dashed curves: contribution of the detector resolution at momenta 1, 2, 5, 10, 20 and 50 GeV/c. Circles: contribution of the multiple scattering independent of momentum. Solid thick curve: combined contribution of detector resolution and multiple scattering in the range 1-50 GeV/c.

For charge sign discrimination, the magnetic bending should be stronger than the multiple scattering and distinguishable against the detector resolution. In both cases, we have to discriminate between positive and negative curvatures. Figure 4a shows the minimum magnetic field required to perform this discrimination at 3-σ. This figure indicates that: a) for muons with track lengths over one meter and $B \geq 0.2$ T, charge sign discrimination is feasible even at momenta greater than 50 GeV/c; b) for electrons, assuming $2X_0$ analyzable track length, an average 3-d detector pixel of $(3.4 \text{ mm})^3$, and $B = 1$ T, charge-sign discrimination is possible for momenta up to 7.7 GeV/c at 3-σ.

Momentum determination through the measurement of the curvature in a magnetic field is a valuable tool for analysis of charge-current neutrino interaction events, especially when the final-state muons exit the active detector volume. Figure 4b shows that for tracks of 3 m length, the momentum resolution is 20% at 0.5 T and 10% at 1 T.

2 The μ-LANNDD Proposal

In view of electromagnetic shower fluctuations, it is important to verify the efficiency of the electron charge determination as a function of electron energy in actual experimental conditions. For this, a liquid argon detector some $60 \times 60 \times 280$ cm^3 with vertical drift over 60 cm, sketched in Figs. 5, 6 and 7, will be placed in the AGS A3 beamline inside a 120D36 magnet with 1-T horizontal field, as sketched in Fig. 8.

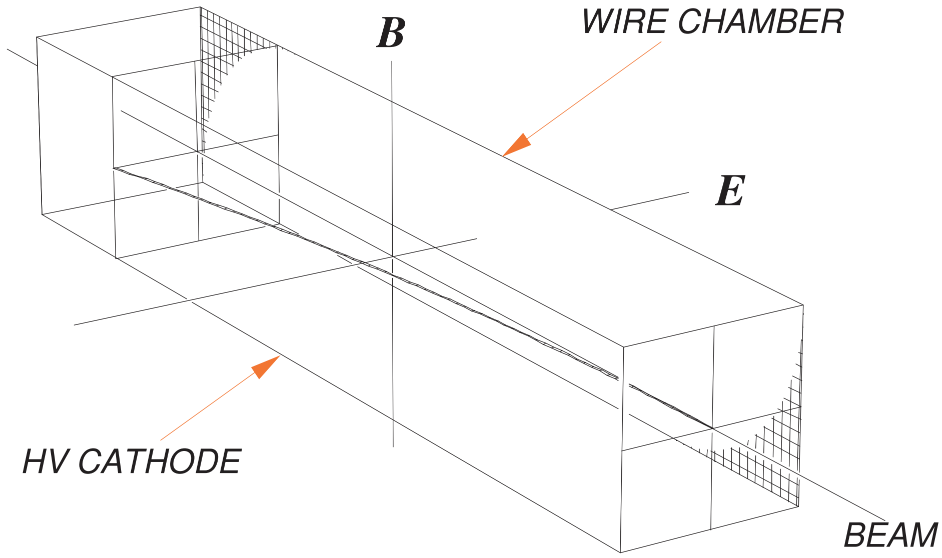

Figure 5: Geometry of the μ-LANNDD detector being proposed to study the efficiency of electron charge determination in a magnetized liquid argon detector. At the AGS, the magnetic field would be horizontal, and the electric field would be vertical.

The A3 beamline will be operated with a secondary target of copper, or preferably beryllium or carbon. Secondary charged particles are collected at 0°, while the primary beam is pitched into a dump. The electron component of the beam varies from about 30% at 1 GeV to about 3 % at 10 GeV, as shown in Fig. 9. Data can be collected at a rate of about 100 Hz per beam spill, so a run of one hour will provide ample statistics at any one setting of beam energy and magnetic field. We will collect data at 10 beam energies, 1-10 GeV,

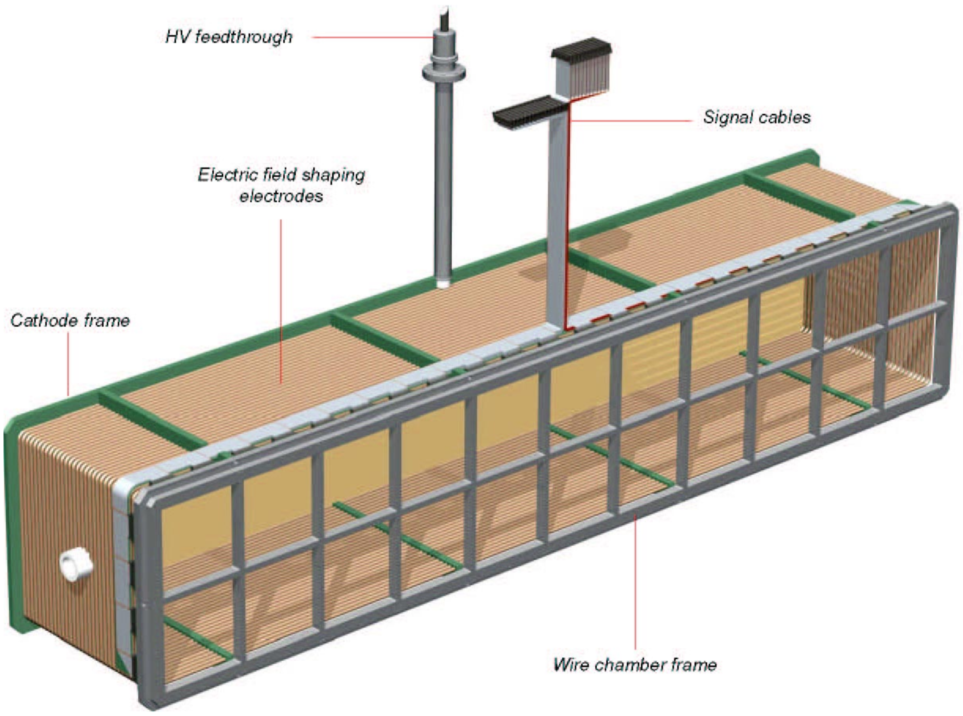

Figure 6: Sketch of the μ-LANNDD detector.

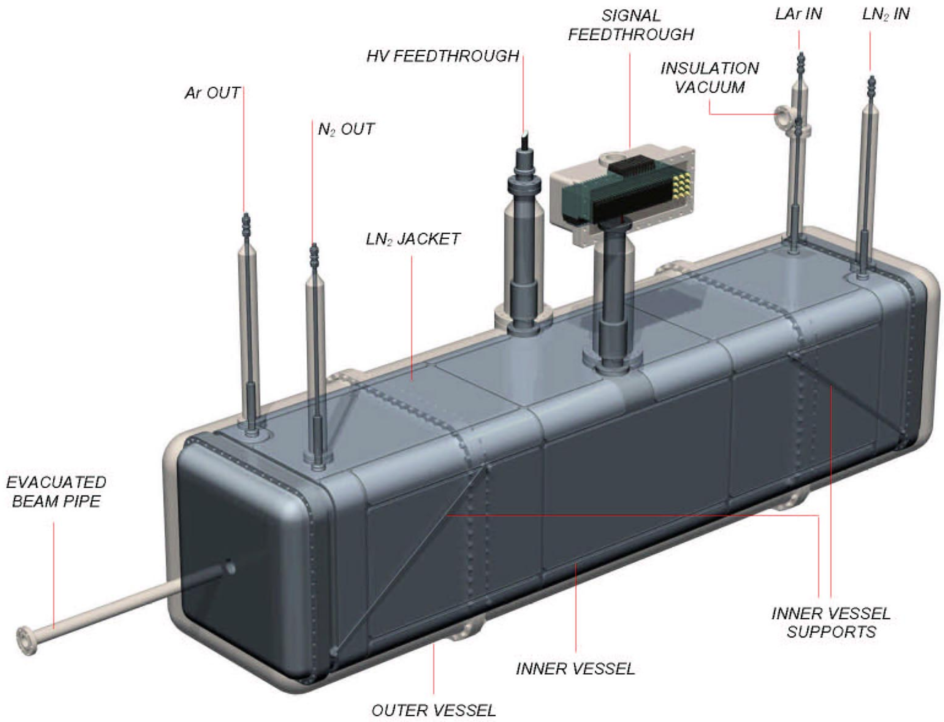

Figure 7: Sketch of the μ-LANNDD detector cryostat.

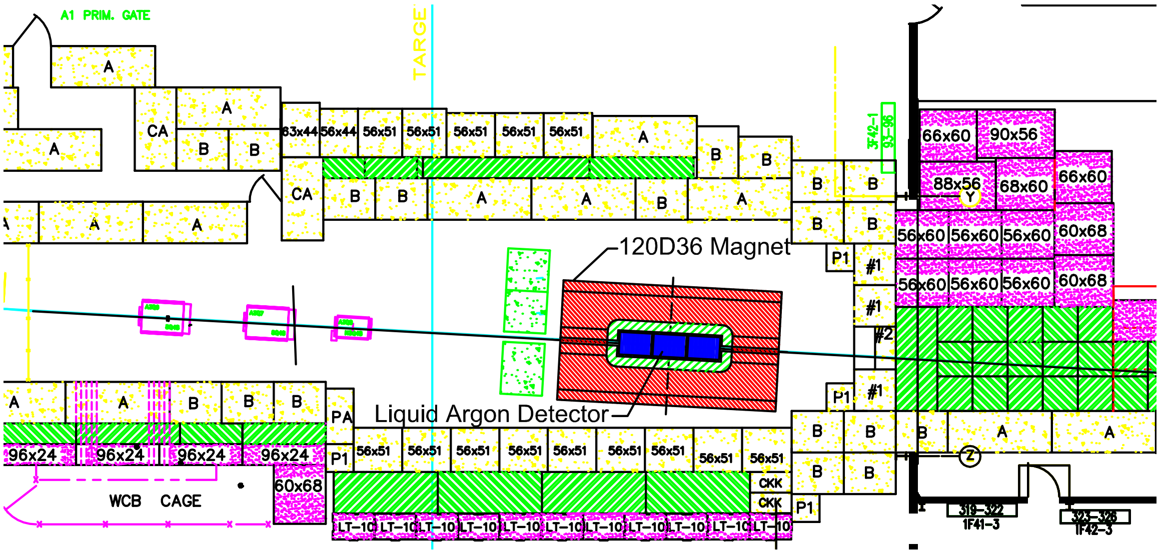

Figure 8: Sketch of the μ-LANNDD detector located inside a 120D36 magnet in the AGS A3 beamline.

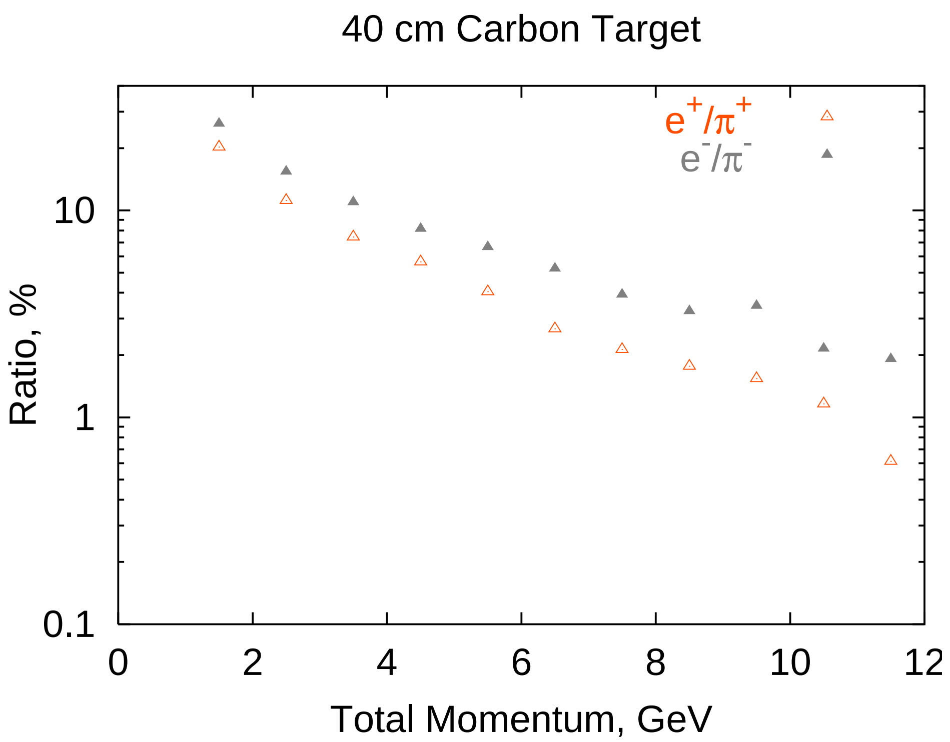

Figure 9: MARS simulation of the ratio of electrons to pions produced at 0° in a 40-cm-long carbon target in a 24-GeV proton beam.

and four magnetic field strengths, 0.25-1 T, for a total of 40 hours with $\mathbf{E} \perp \mathbf{B}$. Then the detector will be brought to room temperature, reconfigured with $\mathbf{E} \parallel \mathbf{B}$, recooled to liquid argon temperature, and a second set of 40 hours of data collected.

An initial estimate of detector construction costs is $200k [25], with another $200k required to reconfigure the 120D36 magnet, with power, in the A3 beamline [26].

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