

TECHNICAL SCOPE OF WORK

FOR THE 2013 FERMILAB TEST BEAM FACILITY PROGRAM

T-1034

LArIAT: Liquid Argon TPC In A Test beam

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INTRODUCTION

This is a technical scope of work (TSW) between the Fermi National Accelerator Laboratory (Fermilab) and the experimenters of the LArIAT collaboration who have committed to participate in beam tests to be carried out starting during the 2013 Fermilab Test Beam Facility program.

The TSW is intended primarily for the purpose of recording expectations for budget estimates and work allocations for Fermilab, the funding agencies and the participating institutions. It reflects an arrangement that currently is satisfactory to the parties; however, it is recognized and anticipated that changing circumstances of the evolving research program will necessitate revisions. The parties agree to modify this TSW to reflect such required adjustments. Actual contractual obligations will be set forth in separate documents.

This TSW fulfills Article 1 (facilities and scope of work) of the User Agreements signed (or still to be signed) by an authorized representative of each institution collaborating on this experiment.

Precision neutrino physics has entered a new era both with pressing questions to be addressed at short and long baselines, and with increasing interest and development of Liquid Argon Time Projection Chambers (LArTPCs). These open volume liquid argon TPCs drift ionization electrons from passing charged particles to readout wire chamber planes at the edge of the detector. The signals are then combined to form 2D and 3D photo-quality like millimeter scale images of the charged particles tracks and to provide calorimetric measurements of the deposited energy in the detector.

The ICARUS collaboration pioneered this technology in Europe. Interest in LArTPCs in the U.S. has grown recently, starting with the ArgoNeuT LArTPC [1] experiment which has run and is producing physics results [2]. The MicroBooNE experiment [3] is under construction, and LBNE [4] has made a technology choice to use LArTPCs for the far detector design. In addition, there are other ideas to build LArTPCs for neutrino physics including augmenting MicroBooNE's search for sterile neutrinos through electron neutrino appearance, for example with the LAr1 Experiment [5], or ideas to put these detectors on the NuMI beamline [6].

Detailed study of these detectors including the effects of charge recombination along ionization tracks and the features of hadronic and electromagnetic showers on particle identification and calorimetry will greatly improve the ArgoNeuT and MicroBooNE measurements in the near term, and continued short baseline and long baseline oscillation physics beyond this. This memorandum of understanding outlines the plan for the LArIAT calibration test beam program that will operate in the FTBF.

Description of Detector and Tests:

Several phases of the LAr TPC exposure to the FNAL test beam are envisioned. The first phase of the LArIAT program (Phase-1a) will reuse the ArgoNeuT cryostat, the existing TPC and its read-out (warm) electronics, and part of the cryogenics infrastructure for study of tracks slowing down to stop in the TPC; new cold electronics, implemented for a subsequent set of measurements (Phase-1b) with a new TPC detector of finer granularity to be installed in the same cryostat will increase precision on the physics measurements and a subsequent phase

(Phase-2), with a larger LArTPC and cryostat, will add on to the Phase-1 program by containing particle showers in both the transverse and longitudinal directions.

With LArIAT Phase-1 program, the collaboration will study electron recombination in argon and will focus on its impact on particle identification through dE/dx measurements for a variety of different particles. This will include differentiation of electrons from photons, and looking for the particle ID signature of proton decay and n - \bar{n} oscillations. In addition, experience gained from operation in Phase-1 will inform the design for Phase-2.

Calibration is a critical step to understanding the output response of LArTPCs. It is required for a range of energies relevant to future experiments like MicroBooNE, LAr1, and long-baseline LAr detectors. A test beam is the ideal place to perform these studies, providing not only a range of selectable known energies, but also a complete set of selectable types of different particles in both polarities. The test beam also provides a controlled environment in which to tune simulations and to develop tools for particle identification (PID), calorimetry, and event reconstruction without relying solely on simulation.

Calibration can be divided into two main categories: calibration of single tracks and calibration of collective topologies.

The goal of single track calibration is a charge to energy conversion. This requires precise measurements of electron-ion recombination in the argon for a range of energy deposition (dE/dx) and different electric field values (in the ~ 300 - 1000 V/cm range), and at different track-to-electric-field angles. The ideal tool for studying these is pure low energy beams of muons, pions, kaons, and protons that penetrate and slow down to stop in the TPC. These studies can be done with a small volume LArTPC. This part of the calibration program corresponds to Phase-1. Study of e -to- γ initiated shower separation is also a main objective of this Phase-1.

Collective topologies are the second category, where the goal is then a detected energy to incident energy conversion. In this category the goal is to understand the size and features of both electromagnetic and hadronic showers, and to measure the e/π ratio. Larger volume LArTPCs are needed for this, since the showers should be nearly fully contained. This will be addressed in a later addition to this run plan and is a main objective of Phase 2.

LArIAT Phase 1

Precise calorimetry and particle identification are distinctive features of the LArTPC technology. These are entirely based on the measurement of the total amount and of the local density of the electronic charge along the ionization tracks recorded by the wire plane(s) of the TPC.

Charge to Energy conversion

Charged particles slowing down as far as the stopping point inside the LAr volume of the TPC produce tracks with increasing charge density toward the track end as a consequence of the increasing stopping power (energy loss per unit track length, dE/dx) at decreasing kinetic energy according to Bethe-Bloch calculation. Measurements of the dE/dx vs. residual range along the track represent a powerful method for Particle Identification (PID) with LArTPCs.

However, only a fraction of the charge released in LAr via energy deposition in ionization processes survives fast recombination occurring before the opposite charges are spatially separated under the electric field action. This effect is often called charge quenching, and correspondingly the surviving “free charge” (Q_{free}), depends on the local ionization density and on the strength of the electric field applied.

A “calibration function” ($dQ_{\text{free}}/dx \rightarrow dQ_0/dx$) is needed to correctly reconstruct the energy loss per unit track length along the ionization tracks and through this to determine the identity of the incident particle and the total energy deposited. Due to the lack of a fully satisfactory model for the recombination process, the “calibration function” can (only) be phenomenologically determined through data fit with semi-empirical models.

The charge to energy conversion with LArTPC detectors is currently based on these data and fit with the Birks model. Other models have also been suggested, such as the higher order Birks formula with a quadratic dependence on the stopping power, or the box model. However, all these models are considered to be incomplete as some further dependence of dQ_{free}/dx on the specific particle type in addition to dE/dx is expected. In addition, several other effects not included in these models have been found to play a role, like the dependence on the track angle with respect to the drift direction, the dependence on the LAr temperature/density and the effect of delta-rays with different recombination being inseparable from the parent track. The available data does not allow for a conclusive analysis.

The intrinsic relevance of a full characterization of LArTPC technology in terms of particle ID capability and calorimetric energy resolution suggests the need of a new extensive campaign of measurements. A beam test with exposure of an LArTPC to monochromatic pure beams of charged particles of different and unambiguously selected types, with incident energy low enough to produce tracks fully contained in the detector volume, is the ideal venue for this type of investigation where high accuracy and statistical precision are fundamental to achieve an in-depth understanding of the recombination mechanisms in LAr and an optimal way to model their effects. Phase-1 of this proposal is dedicated to this topic: available beams of muons, kaons and

<i>Stop. Ptcl. Type</i>	<i>Dep.En.≡ Inc. kin. En.</i>	<i>Inc. Beam Mom.</i>	<i>dE/dx Interval</i>
μ	205 MeV	290 MeV/c	2.1 ÷ 13 MeV/cm
π	210 MeV	320 MeV/c	2.1 ÷ 14 MeV/cm
K	285 MeV	600 MeV/c	2.8 ÷ 23 MeV/cm
p	380 MeV	940 MeV/c	3.1 ÷ 33 MeV/cm

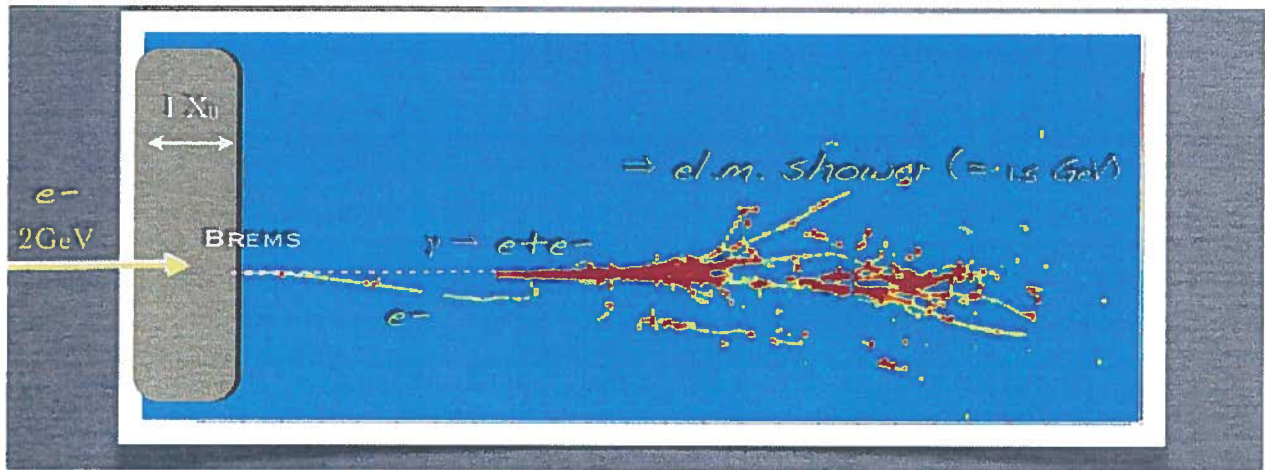
protons allow collection of data at high statistics for a range of stopping powers, from the MIP mean-value ($dE/dx_{\text{mip}} \cong 2.1 \text{ MeV/cm}$) with muons/pions, up to about 30 MeV/cm with protons ($\sim 15 \times dE/dx_{\text{mip}}$), see table below:

Study of e-to- γ initiated shower separation

The efficient separation of signal e- and background- induced EM showers and a resulting low residual event contamination is a feature of the LArTPC that is of fundamental importance for the physics goals of present and future generation neutrino programs. So far this problem has only been studied using detailed and extensive Monte-Carlo simulations, and a direct

We assume a contained-track max length (for a stopping particle in LAr) of $\ell_{\text{max}} = 80 \text{ cm} \leq \text{LArTPC longitudinal dimension (e.g., 90 cm in ArgoNeuT TPC)}$. For different charged particles (column 1), shown here are the corresponding deposited energies (column 2) (equiv. to incident kinetic energy of the particles), incident beam momenta (column 3), and interval of (mean) dE/dx values along the track (column 4).

confirmation from experimental measurements has never been performed. This topic can be included in Phase-1 of this program (using a small volume LArTPC) since it is mainly the initial part of the shower that is relevant for separation algorithms (because the γ converts to an (e^+e^-) pair producing double ionization in the first portion of the track at the shower start). For such a study we need to produce a high-energy "photon beam." This can be achieved by e-bremsstrahlung of few GeV beam electrons in a $1-X_0$ pre-shower added in front of the TPC. Monte-Carlo simulations show it is possible to obtain high energy photons (200MeV) in this manner and that they are often sufficiently separated from the originating electron. A preliminary estimate suggests that it is possible to obtain measurable photons for $\cong 10 - 20\%$ of electron beam events.



REFERENCES

- [1] ArgoNeuT Collaboration (B.T. Fleming et al.), T962: ArgoNeuT (Argon Neutrino Test) A Liquid Argon TPC in the NuMI Beam, <http://t962.fnal.gov>, arXiv:1205.6747 [physics.ind-det]
- [2] ArgoNeuT Collaboration (C. Anderson et al.), First measurements of inclusive muon neutrino charged current differential cross sections on argon, Phys Rev Lett 108, 161802 (2012)
- [3] MicroBooNE Collaboration (H. Chen et al.), Proposal for a New Experiment Using the Booster and NuMI Neutrino Beamlines: MicroBooNE, FERMILAB-PROPOSAL-0974
- [4] LBNE Collaboration (T. Akiri et. al.), The 2010 Interim Report of the Long-Baseline Neutrino Experiment Collaboration Physics Working Groups, arXiv:1110.6249
- [5] LAr1 Collaboration (B. Fleming et al.),
http://www.fnal.gov/directorate/program_planning/June2012Public/P-1030LAR1_LoI_Submission_May23_2012.pdf
- [6] GLADE Collaboration (J. Thomas et al.)
http://www.fnal.gov/directorate/program_planning/June2012Public/P-1029_GLADE_LOI.pdf

PERSONNEL AND INSTITUTIONS:

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	Alan Hahn		Faculty	LBNE
	Douglas Jensen		Faculty	NuMI/NuMI+/NOvA
	Michael Kirby		Faculty	MicroBooNE
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II. EXPERIMENTAL AREA, BEAMS AND SCHEDULE CONSIDERATIONS:

2.1 LOCATION

- 2.1.1 The Phase-1 beam test with the LArIAT/ArgoNeuT detector will take place in MCenter, specifically in the MC7 area - upstream location, next to the roll-up door, where the ceiling above is higher than the rest (upstream and downstream) of the beam enclosure. In the drawings in Appendix I, the front, top, and side views of the experimental area are shown with details of the positioning of the detector (ArgoNeuT detector with the current cooling/filtering system on its top side) and of the tertiary beam (target+collimator, the two bending magnets and the series of beam monitor detectors). The tertiary beam is assumed to be the exact setup as was used in T-977: MINERvA Test Beam Calibration. The axis of the tertiary beam will be aligned with the longitudinal axis of the TPC. The total height of the detector, as currently depicted in the drawing, exceeds the available height of the experimental area in MC7. However modifications of the stand below the detector and the new cooling/filtering system on top will be made to fit the vertical size of the available area.
- 2.1.2 Storage space available for a period of 4 months before beam operation start-up, in a nearby location is necessary, approximately 30 m² (about 300 ft²), for subsystems pre-assembly and storage of equipment not in use (spare filters, cryogenic lines, etc.). Access to this area should be, if possible, restricted to members of the LArIAT collaboration.
- 2.1.3 Counting Room for operating the detector is necessary, with a delimited space (20 m²) with dedicated phone-line, Wi-Fi, fast network connection and UPS system. The UPS will service 2 computers (DAQ start/stop and on-line data analysis), and the slow control system which will monitor, control, and record the parameters and functions of the cryogenic system. The power requirements for these devices will be quantified at a later date, once the system is finalized, but the required power is expected to be low for these devices. Detector DAQ operation, on-line beam monitoring and setting (magnet current) and cryogenics slow-control (cryocooler and recirculation pump) monitoring/operation will be performed from the Counting Room, mainly through web access restricted to shifters and on-call experts of the LArIAT Collaboration. In case the Counting Room is shared with other users, the space allocated for the LArIAT test beam operations must be delimited and the use of computers and UPS restricted to the members of the collaboration.

2.2 BEAM

2.2.1 BEAM TYPES AND INTENSITIES

The use of MCenter secondary beam is required for low momenta tertiary beam extraction from a dedicated *Cu-Target ⊕ Collimator(16°) ⊕ Bending Magnet* System. The tertiary beam components are assumed to be the same (or equivalent) components used by T-997: MINERvA Test Beam Calibration, transported and suitably repositioned in MC7 by FTBF personnel.

A 4-second spill duration, arriving every one minute, is taken as reference for the secondary beam line. The secondary beam is assumed to be available 24 hours per day (1440 spills per day), unless otherwise specified or communicated by the FTBF Coordinator.

Secondary Beam

Energy Range : 8 - 32 GeV/c
 Particles: pions (π^+ , π^-)
 Intensity: 10k – 300k particles/spill
 Beam spot size: $\approx 1 \times 1 \text{ cm}^2$

Control and operation of the secondary beam is under AD responsibility and specific settings (intensity and beam polarity) agreed by communication with the AD Main Control Room.

Tertiary Beam

Momentum Range : 0.2 - 1.0 GeV/c
 [assuming min momentum of secondary pion beam, 8 GeV/c]
 Beam spot size \equiv Beam Window Aperture¹: $\varnothing=10 \text{ cm}$ (80 cm^2)
 Beam Spot Particles/Intensity² [assuming max intensity of secondary pion beam]
 π^\pm ($\geq 10/\text{spill}$)
 p^+ , μ^\pm , e^\pm ($\geq 1/\text{spill}$)
 K^\pm ($\geq 0.1/\text{spill}$)
 anti-p (very few)
 Trigger purity (% of particles of Type-X in the beam): $\geq 95 \%$
 Momentum resolution: $\delta p/p \leq 5\%$

Control and operation of the *tertiary beam* is under responsibility of the LArIAT Collaboration.

2.2.2 BEAM SHARING

The use of the tertiary (low momentum) beam is reserved for the LArIAT Collaboration. However, the target/collimator can (temporarily) roll out of the secondary beam line, allowing the use of the secondary beam to other users downstream of the MC7 area. Sharing of the secondary beam for tertiary beam extraction and for downstream users' application should be agreed over a 4-6 month planning basis.

2.2.3 RUNNING TIME

This MoU establishes that the proposed LArIAT test experiment will be running at MCenter (MC7) for a period of at least two years, after beam operation start-up in 2013.

¹ The *tertiary beam spot size* is assumed to be the size of the beam window [$\varnothing=10 \text{ cm}$ (80 cm^2)], at the center of the front flange of the cryostat (where the amount of material upstream of the TPC active volume, along the beam line, is minimized).

² The *tertiary beam intensity* is defined as the number of particles per spill that intersect the area of the "beam window" and determined by the size of a (a set of) trigger(s) counter to be positioned in front of the detector.

During the stay in MC7, at least three long periods of data-taking are foreseen, each 3 to 6 months in duration, corresponding to Phase-1a (3 + 6 months) and Phase-1b (6 months) of the LArIAT experimental test proposed here. An interruption (3 months) is expected between Phase-1a and Phase-1b, as a major modification of the detector layout (change of TPC structure and read-out electronics) will take place.

During the run periods, data acquisition in beam trigger mode will be organized on a periodic basis (e.g. 2-4 weeks), with intermediate periods (1-2 weeks) of cosmic ray trigger mode and/or detector maintenance.

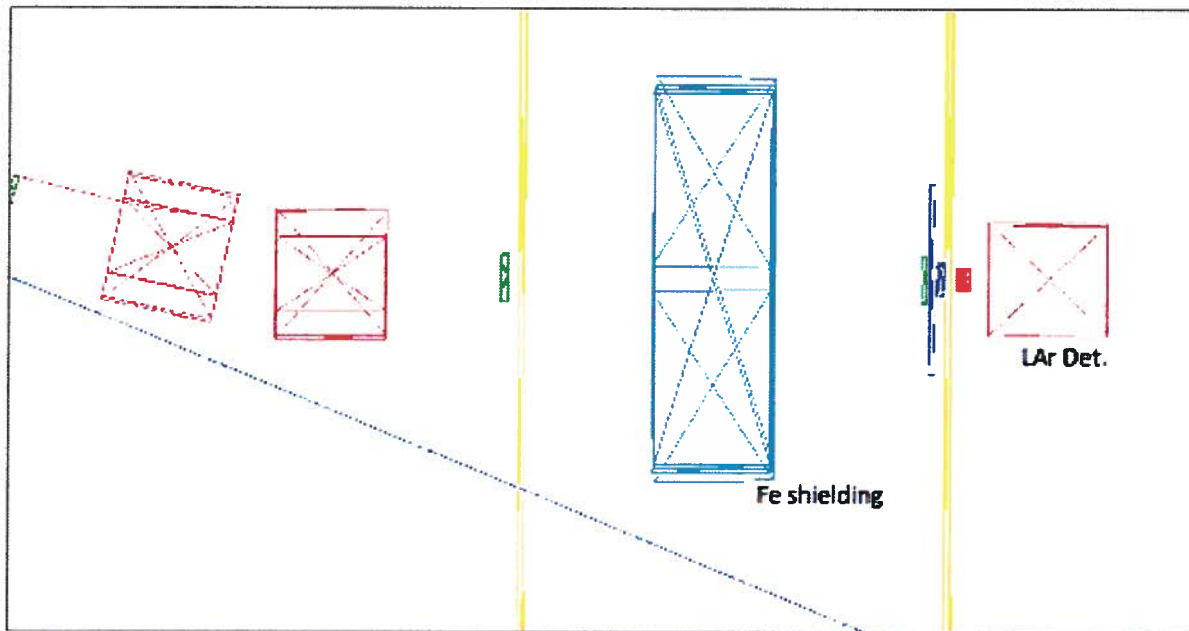
During the data acquisition periods, 2 consecutive shifts (8 hrs each) from h:08:00 to h:24:00 are envisioned, interleaved with a LAr purification cycle and maintenance overnight (from h:00:00 to 08:00). Data acquisition will be extended to three shifts per day when specifically required (e.g., acquisition of kaons or anti-protons, where the tertiary beam rate is expected to be low).

2.3 EXPERIMENTAL CONDITIONS

2.3.1 AREA INFRASTRUCTURE

Tertiary Beamline:

- A. Power supplies: The location (or re-location) of the power supplies for the tertiary beam magnets will be specified by the AD Power Supply group. (Remote) control of the current settings should be made available in the Counting Room.
- B. Four tracking chambers are to be used in the beam-line, provided by FTBF, to define and monitor the beam spot. The MWPCs should have 1mm wire pitch, 128 wires per plane, and two planes per chamber (X and Y).
- C. A set of TOF counters (PMTs at each end of the counter 1 upstream, crossed pair downstream) same (or equivalent) to those used by T-977: MINERvA Test Beam Calibration, should be provided by FTBF for particle selection in the beam.
- D. Trigger counters of appropriate size will be made by members of the T-1034 collaboration.
- E. High beam purity is required after Particle Id tagging by TOF counters. For electrons, the experimenters request the implementation of a (new) Cherenkov counter. Other devices for beam particle tagging may also be provided by the Collaboration.
- F. Helium tubes available at FTBF may be needed in MC7 in the tertiary beam.
- G. *Tertiary Beam – downstream shielding:* Fe shielding to reduce the punch-through through the basic collimator can be made of stacked Fe blocks, set at a small angle to define the collimator. Details to be determined: e.g. 500 mm/1000 mm along the beam direction, 100 mm vertical gap on axis with the beam window - see figure.



Layout of the Tertiary beam extracted from the MCenter Secondary Beam

The Experimental Setup:

The experimental setup for Phase-1 discussed here largely capitalizes on the availability of the existing hardware from the ArgoNeuT experiment operated in the NuMI beam in 2009-10.

The LArIAT setup consists of two main elements: the main cryostat housing the active TPC detector (both from ArgoNeuT), and a new cryogenic system for argon cooling and purification forming a closed-loop around the cryostat. Read-out electronics for the TPC are fully available from the ArgoNeuT run on the NuMI beam, but these require some improvements in DAQ rate in order to be suitable for test beam running. The collaboration is actively working on these, and the upgraded read-out will be ready before beam startup. There are also a number of ancillary devices (vacuum pumps, cryocooler and its He compressor, chillers, HV and LV supplies, crates for the read-out electronics boards, etc., connected to the main elements) available for reuse in the LArIAT setup.

The main cryostat is a vacuum insulated dewar for ultra-pure liquid argon containment (see table below for its main geometrical parameters), in which is mounted the active detector, i.e. a Time Projection Chamber with its field-shaping system. The anode of the TPC, opposite the cathode at one side of the detector volume, consists of two active planes of parallel wires (240+240 wires in total) with different orientations. The TPC is operated at uniform electric field between cathode and anode. Feed-throughs on an exit flange on top of the cryostat provide the electrical connection of the wires to the (outside - warm) read-out electronics. A front-end integrating preamplifier, followed by high- and low-pass filters, for each wire of the TPC make up the analog readout electronics. Wire signals are digitized by fast ADC and recorded at each beam

trigger. Behind the wire planes an array of cryogenic PMTs provide read-out of the scintillation light signal in argon (this is a new detector component).

The cryogenic system is a closed-loop for the cooling/recirculation and purification of the liquid argon volume of the main cryostat. Cooling is provided either by a Liquid Nitrogen condenser or by a cryocooler unit mounted above the cryostat. Any of these devices is used to re-condense boil-off vapor from the liquid volume. Purification is achieved by directing the re-condensed liquid into a filter that removes electronegative impurities. A cryogenic pump forces the liquid through the filter and back into the cryostat.

After initial filling, liquid argon circulates through the closed loop without exhalation in atmosphere. No LAr refills are expected during detector operation. At the end of the run (Phase-1a and Phase-1b) the cryostat will be emptied either through an exhaust pipe in open air, outside the experimental area or through the filling pipe system (in the opposite direction) in case temporary recovery of the liquid argon volume is made possible (or considered convenient).

1. The LArIAT cryogenic system with respect to the system adopted during the ArgoNeuT run in the NuMI tunnel must provide a much higher recirculation speed (increased LAr flow rate) and fit in the available height at MC7. Details of this modification are reported in the next section. Redesign of the argon recirculation/cooling system is under active development now, and details for power requirements will be specified here at a later date when the system details have been finalized.

The main specifications for the original ArgoNeuT cryostat and cryogenics system are summarized in the Table below. As mentioned above, some of these details may be changed later when the cryogenic recirculation system design is finalized.

Liquid Argon volume (mass)	550 liters (0.77 t)
Inner Vessel Dimensions	$\phi=30''$, $l=130$ cm
Outer Vessel Dimensions	$\phi=42''$, $l=163$ cm
Insulation	Vacuum Jacket (10^{-4} mbar) with SuperInsulation
Total Heat Load	< 100 W

The total weight of the cryostat (when filled with LAr) is approximately 1.6 t (about 3500 lbs).

In the case that the original ArgoNeuT system may be reused, the (main) ancillary devices made available by the Collaboration to operate the system (cryostat/detector and cryogenics) are:

2. Three vacuum pump units for the vacuum jackets (cryostat and cryogenic loop)
3. A cryocooler (300 W cold power) and its He-compressor unit [220/230 VAC, 3 Phase, 60 Hertz - 7.5kW @ 60Hz]. A HV power supply (20 kV) and some LV power supplies for the TPC and the PMTs.
4. A standard rack with VME crates (for the digital readout boards) and a custom rack for the analog boards (positioned on top of the cryostat).
5. UV lamp for purity monitor

All these devices will be located in MC7, in the area near the main cryostat.

2.3.2 FACILITY INFRASTRUCTURES

The ancillary devices (to be made available by FTBF) to operate the system (cryostat/detector and cryogenics) are:

1. If the original ArgoNeuT recirculation system is used, a chiller for water cooling the cryo-cooler (see point 2 above) is needed [Minimum flow 2.1 GPM (8 LPM) @ 80°F (27°C) maximum temperature] - or any equivalent system available at MC7 (e.g., centralized water cooling distribution system). (Details to be defined at a later date, depending on the final configuration of the cooling/purification system.)
2. UPS (2-3 hours capacity) of adequate power for the cryo-cooling system, for the chiller, for the recirculation pump, and for the vacuum pumps. Estimated total power of 30 kVA (~25 kW). (More precise power estimate to be defined at a later date, depending on the final configuration of the cooling/purification system.)
3. Gigabit Ethernet connection for remote control of operations (detector, cryogenics, slow-control) from the DAQ to the Counting Room and to more permanent storage. After DAQ upgrades are completed, this will be more fully specified with average and peak bandwidth requirements.
4. Off-line data storage 30 TB disk space (BlueArc storage disks for ready access and also ENSTORE tape for permanent storage).
5. Air Conditioning for operation at stable temperature (acceptable variations within 10°F around a set point of 70°F)
6. Rack of pressurized N₂ bottles for a gas system (electro-pneumatic valves)
7. Tracking and Triggering systems: A trigger signal formed by the beam spill signal and PID counters (TOF, Cherenkov for electrons, finger-scintillators, tracking chambers) in coincidence logic is expected to be provided. This trigger signal will be used in coincidence with the detector external and internal trigger system (scintillator paddles in x-y geometry and internal PMTs for detection of the prompt scintillation component in LAr). The upgraded chamber read-out system is assumed to be available. The list of counters and beam monitoring chambers corresponds to those in use in the tertiary beam at MTest, and includes an additional Cherenkov counter for electrons (to be made at FNAL as the Lab's contribution to this specific experiment).
8. Again, in the case that the original ArgoNeuT recirculation/cooling system is used, necessary electrical power (220/230 VAC, 3 Phase, 60 Hertz) is: for the cryo-cooling system (in case of use of the cryocooler, it requires installation of a dedicated plug and switch, made available from the LArIAT Collaboration) and for the chiller. Standard 120 VAC (60 Hz) plugs for the cryogenic pump, for the vacuum pumps, for the electronics racks and any other device in use. Once the recirculation system design has been finalized, this specification will be updated.
9. Low-noise ground connection ("quiet" power) for all the equipment.

10. A rotating platform situated beneath the detector on its stand would allow measurements at different incident beam angles [e.g., choice of incident angles from 0° to 45°]. The details of the rotation device will be defined, depending on the final configuration of the cooling/purification system and will be provided by the T-1034 collaboration. The option to place the detector stand on rails in order to allow translation of the detector into the secondary beamline is also desired. These configuration options will be considered more fully and defined further at a later date.

11. Work space around the detector is necessary, about 15 m (along the beam line,) x 8 m (the full width of the MCenter tunnel) as indicated by the light-blue area in the figure labeled “Top View of the MCenter beam line” in Appendix I.

12. The area dedicated to the experiment must be delimited with a plastic curtain (wide, transparent vertical strips) or similar to limit access to the experimental area and maintain a reasonably clean environment (from dust spreading), during installation and detector assembly. The curtain might be removed if necessary during operation, or when cryogenics are present, as determined by ESH&Q. Access to this area should be restricted to individuals directly involved with the installation. This can be done with a Restricted Access List given to the MCR.

During data taking, normally no access to the experimental area is foreseen. Remote control for the cooling system and for the LAr forced purification system (cryo-pump operation) is established by control panels in the Counting Room. Overnight operations (beam-off) for detector maintenance should be defined and agreed with FTBF.

2.3.3 DETECTOR MODIFICATIONS

The present FTBF shut-down period is intended to be dedicated to the refurbishment of the experimental area (MC7) for LAr detector(s) operation, to detector installation and assembly, and to sub-component tests and detector commissioning (LAr filling and initial purification cycles).

Hardware innovations and modifications are required to convert part of the existing ArgoNeuT detector layout for the LArIAT Phase-1 experimental program at FTBF. Necessary funds are mainly provided by University Groups (from DOE and NSF grants or other sources). Engineering/technical manpower/labor are agreed here to be provided by FNAL PPD together with a financial contribution for specific parts (cryogenics) of the system.

The main hardware modifications to the existing set-up are:

1. *New Argon purification system.* The skid is composed of a forced recirculation network with vacuum-jacketed and super-insulated transfer lines, a long shaft centrifugal pump for cryogenic applications and an in-line filter for impurity removal.
2. *“Beam window”.* The amount of material upstream of the TPC active volume, along the beam line, must be minimized for operation in a charged particle beam. A “beam window” at the center of the front flange can be made by a series of two coaxial small diameter apertures (4”) in the inner and outer vessel, blanked with a special, thin (0.1 mm) Titanium flanged window (developed and produced at FNAL for use in Cherenkov counters) and by an excluder (vacuum can) inside the cryostat.

3. *Scintillation Light readout system.* This will provide an internal fast signal for trigger formation in coincidence with the external signal from the beam counters. The skid is composed by an array of two HQE PMTs (for cryo-applications), a mechanical support for the PMTs, cryogenic feed-throughs, read-out electronics and voltage supply. The array is deployed in LAr and mounted onto the inner side-port of the cryostat, behind the wire planes of the TPC.

Cost sharing among the Institutions of the LArIAT Collaboration and FNAL as well as manpower sharing (man*weeks of technicians and engineers) are reported in Tables 1 and 2 of Appendix II.

2.3.4 FACILITY MODIFICATIONS

In addition to the modifications of the detector layout described above, some external independent systems are agreed here to be realized as parts of the LAr permanent facility at FTBF:

1. *LAr Filling Station.* The station includes a vacuum-jacketed and super-insulated transfer line from an external LAr storage (either a permanent LAr storage dewar - 1500 lt or more, or a temporary storage - truck Swap Body or array of 220 lt “ranger” transportable dewars) and an in-line filter for the initial filling and purification. This can be designed to allow for detector emptying and LAr recovery/recycle use.
2. *Filter Activation/Regeneration system.* Filters in the recirculation loop need to be activated at their first use, and regenerated when reaching saturation, by a flow of hot inert gas containing 2-4% Hydrogen. The system is composed of an array of Ar-H₂ gas mixture pressurized bottles, a piping system with valves and heaters to wrap the filter cartridge. The activation/regeneration system requires automated operation control and data recording.
3. *LN₂ Storage Dewar* (min. 3000 lt) OR a LN₂ transfer line from the main FTBF building (LN₂ network from the large FNAL LN₂ storage) to carry liquid Nitrogen into MC7 - useful as source of cryogenic power for the LArIAT cooling system.
4. *Venting system and ODH sensors* (outputs of the relief valves mounted on the main cryostat and recirculation loop are grouped together by a common piping system and then conveyed outside the experimental hall in open atmosphere).

Cost sharing among the Institutions of the LArIAT Collaboration and FNAL as well as manpower sharing (man*weeks of technicians and engineers) are reported in Tables 1 and 2 of Appendix II.

A summary of costs for detector modifications and for facility modifications is reported in Section V.

2.3.5 ELECTRONICS NEEDS

For the LArIAT experimental program at FTBF, the existing TPC will be used equipped with the available warm electronics from ArgoNeuT. The readout electronics are structured as a multi-channel waveform recorder that continuously stores charge information collected by each sense wire during the drift of ionization electrons inside the TPC. The readout chain is composed of a series of three main stages (and corresponding electronic cards/boards): (1) bias voltage distribution (and decoupling), (2) preamplifier and filter/shaping, and (3) ADC, circular memory buffer, and digitizer. The readout electronics for TPC are derived (front-end boards) or borrowed (digitizers) from D-Zero Run-II electronics. The preamp stage (dual FET integrating charge to voltage preamplifier) and the narrow gaussian shaping/filter stage on single boards are at room temperature ("warm electronics"), enclosed in a double RF-shielded cage mounted on the outside of the cryostat. This read-out chain was reconfigured and optimized for the ArgoNeuT neutrino run on the NuMI beam in 2010.

The full readout and DAQ system from the ArgoNeuT run in the NuMI beam is available for the proposed beam test at FTBF.

2.4 SCHEDULE

The beam request (secondary beam line at MCenter) is for two years of beam time, starting from beam operation start-up (reliable data-taking beam expected around August 2013).

The detector components will be partially pre-assembled elsewhere and transported and assembled in MC7 starting in March 2013.

The area at MC7 is accessible at the current time.

III. RESPONSIBILITIES BY INSTITUTION – NON-FERMILAB

3.1 YALE U:

Cryostat Modifications, PMT read-out and daq integration, mc simulation and Off-line software Development

3.2 MICHIGAN STATE U.:

TPC read-out and Daq Electronics, Signal FeedThrough

3.3 U. OF TEXAS AUSTIN:

External Trigger and beam/Veto Counters

3.4 U. MINNESOTA DULUTH:

Tertiary Beam Configuration, Optimization, and Reconstruction

3.5 U. CINCINNATI:

Tertiary Beam Installation, Beam PID Counters

3.6 U. OF CHICAGO:

(Ext. and Int.) Detectors Synchronization

3.7 WILLIAM & MARY:

Beam Trigger

3.8 SYRACUSE U.:

TPC detector

3.9 IMPERIAL COLLEGE LONDON (UK):

On-line and Off-line Software

3.10 UNIVERSITY COLLEGE LONDON (UK):

On-line and Off-line Software

3.11 U. OF MANCHESTER (UK):

MC Simulations and off-line software

3.12 U. OF L'AQUILA (ITALY):

Scintillation Light Read-out (PMTs and optical System)

For Fermilab collaboration members see Section 4.5

Items to be assigned:

- TPC HV system (HV feed-through, HV supply for TPC cathode, Bias voltage (wire-planes), LV supply and FT)
- Slow-Control (P, T, LAr Levels, Cooling System On/Off & Monitoring, LAr Recirculation Pump On/Off & Monitoring)
- Detector Calibration: LAr purity monitoring (with automated cosmic ray DAQ and with purity monitor)

IV. RESPONSIBILITIES BY INSTITUTION – FERMILAB

4.1 FERMILAB ACCELERATOR DIVISION:

- 4.1.1 Use of MCenter beamline as outlined in Section II.
- 4.1.2 Maintenance of all existing standard beam line elements (SWICs, loss monitors, etc) instrumentation, controls, clock distribution, and power supplies.
- 4.1.3 Scalers and beam counter readouts will be made available via ACNET to the MCenter control room.
- 4.1.4 Reasonable access to the equipment in the MC7 area of the MCenter beamline.
- 4.1.5 Connection to beam console and remote logging (ACNET) should be made available.
- 4.1.6 The test beam energy and beam line elements will be under the control of the AD Operations Department Main Control Room (MCR). [0.5 persons per week]
- 4.1.7 Position and focus of the beam on the experimental devices under test will be under control of MCR. Control of tertiary devices that provide these functions may be delegated to the experimenters as long as it does not violate the Shielding Assessment or provide potential for significant equipment damage.
- 4.1.8 The integrated effect of running this and other SY120 beams will not reduce the neutrino flux by more than an amount set by the office of Program Planning, with the details of scheduling to be worked out between the experimenters and the Office of Program Planning.

4.2 FERMILAB PARTICLE PHYSICS DIVISION:

- 4.2.1 The test-beam efforts in this TSW will make use of the Fermilab Test Beam Facility. Requirements for the beam and user facilities are given in Section II. The Fermilab Particle Physics Division will be responsible for coordinating overall activities in the MCenter beam-line, including use of the user beam-line controls, readout of the beam-line detectors, and FTBF computers. [1.0 persons per week]
- 4.2.2 FTBF will be responsible for relocating the components of the Tertiary beam line into the MC7 area into the configuration specified in Section II for use by LArIAT.
- 4.2.3 Engineering and technical manpower will be provided by FNAL PPD together with financial support, for Design, Modifications and Installation of specific cryogenics parts of the experimental layout (New Recirculation System, Filling Station, Filter Activation/Regeneration, Beam Window-Ti Flange) The number of person-weeks is dependent on the final decision of the cryogenic recirculation/purification system (whether it is designed/built by FNAL engineers, or contracted out to an external company. Once the decision is finalized, this will be specified more fully.
- 4.2.4 Conduct a NEPA review of the experiment.
- 4.2.5 Provide day-to-day ESH&Q support/oversight/review of work and documents as necessary.
- 4.2.6 Provide safety training as necessary, with assistance from the ESH&Q Section.
- 4.2.7 Update/create ITNA's for users on the experiment.

- 4.2.8 Initiate the ESH&Q Operational Readiness Clearance Review and any other required safety reviews.
- 4.2.9 Conduct an ODH assessment. (The venting system and ODH sensors for the cryogenic system must be reviewed and approved by ESH&Q before operation of the system.)

4.3 FERMILAB COMPUTING SECTOR

- 4.3.1 Internet access should be continuously available in the counting house.
- 4.3.2 See Appendix II for summary of PREP equipment pool needs.
- 4.3.3 Off-line data storage ~~30~~ ^{5TB} TB disk space (BlueArc storage disks for ready access and also ENSTORE tape for permanent storage).

4.4 FERMILAB ESH&Q SECTION

- 4.4.1 Assistance with safety reviews.
- 4.4.2 Provide safety training, with assistance from PPD, as necessary for experimenters.

4.5 FERMILAB COLLABORATION MEMBERS

- Cryogenic System (Cooling and Purification)
- Filling Operation
- Filter Activation/Regeneration
- Off-line software development
- Shift Organization

SCD agrees to 5TB of Bluearc to start and will decide on how much and what flavor of disk as we get experience

R.R.
3/8/13

V. SUMMARY OF COSTS

Source of Funds [\$K]	Materials & Services	Labor Technicians + Engineers (person-weeks)
Particle Physics Division	\$200k ^c	90
Accelerator Division	\$0k	26 ^d
Scientific Computing Division	\$12k ^e	0
ESH&Q Section	\$10k ^f	0
Totals Fermilab	\$ 222 K	116
Totals Non-Fermilab	\$ 150 K (US Groups) \$ 23 K (non US Groups)	9 (Ext. Company) 6 (non US Mech. WS)

^c M&S and Labor from FNAL/PPD are preliminary estimates for:

- DESIGN, FABRICATION AND INSTALLATION of the COOLING/RECIRCULATION/PURIFICATION system
- LAR FILLING STATION.

The COOLING/RECIRCULATION/PURIFICATION system is presently assumed to be suitably designed and sized for operation with LArIAT-Phase-1 (ArgoNeuT cryostat) and successively re-used with a larger cryostat for LArIAT-Phase-2.

M&S and Labor from US Groups (Non-FERMILAB) are current estimates for:

- CRYOSTAT MODIFICATIONS (Yale U.) required to use the ArgoNeuT detector (formerly used on v beam) on a charged particle beam ("Beam Window", Side ports modification for Scintillation Light read-out, LAr outlet for LAr recirculation)
- TRIGGER SYSTEM for Beam operation (W&M Coll.)
- TPC structure modifications (Syracuse U.)

[request for funds submitted to DoE, through FOA-000733 solicitation]

M&S and Labor from NON-US Groups (L'Aquila U. - IT) are for:

- Scintillation Light Optical System and Read-out system (HQE PMTs). General Considerations

^d This is a generic estimate based on 0.5 persons/week for operation and maintenance of the beam line elements. Realistically, we expect this to be closer to 0 persons/week.

^e We have estimated this as follows: 30TB BlueArc (\$9000), 20TB permanent (tape) storage (\$2000), 4-core virtual machine (\$1000)

^f This is a very generic estimate (including ODH fan, piping for venting, and ODH sensors and alarms). We don't yet know what will be required.

VI. GENERAL CONSIDERATIONS

- 6.1 The responsibilities of the Spokespersons and the procedures to be followed by experimenters are found in the Fermilab publication "Procedures for Researchers": (<http://www.fnal.gov/directorate/PFX/PFX.pdf>). The Spokespersons agrees to those responsibilities and to ensure that the experimenters all follow the described procedures.
- 6.2 To carry out the experiment a number of Environmental, Safety and Health (ESH&Q) reviews are necessary. This includes creating an Operational Readiness Clearance document in conjunction with the standing Particle Physics Division committee. The Spokespersons will follow those procedures in a timely manner, as well as any other requirements put forth by the Division's Safety Officer.
- 6.3 The Spokespersons will ensure at least one person is present at the Fermilab Test Beam Facility whenever beam is delivered and that this person is knowledgeable about the experiment's hazards.
- 6.4 All regulations concerning radioactive sources will be followed. No radioactive sources will be carried onto the site or moved without the approval of the Fermilab ESH&Q section.
- 6.5 All items in the Fermilab Policy on Computing will be followed by the experimenters. (<http://computing.fnal.gov/cd/policy/cpolicy.pdf>).
- 6.6 The Spokespersons will undertake to ensure that no PREP or computing equipment be transferred from the experiment to another use except with the approval of and through the mechanism provided by the Scientific Computing Division management. The Spokespersons also undertake to ensure no modifications of PREP equipment take place without the knowledge and written consent of the Scientific Computing Division management.
- 6.7 The experimenters will be responsible for maintaining both the electronics and the computing hardware supplied by them for the experiment. Fermilab will be responsible for repair and maintenance of the Fermilab-supplied electronics listed in Appendix II. Any items for which the experiment requests that Fermilab performs maintenance and repair should appear explicitly in this agreement.

At the completion of the experiment:

- 6.8 The Spokespersons are responsible for the return of all PREP equipment, computing equipment and non-PREP data acquisition electronics. If the return is not completed after a period of one year after the end of running the Spokespersons will be required to furnish, in writing, an explanation for any non-return.
- 6.9 The experimenters agree to remove their experimental equipment as the Laboratory requests them to. They agree to remove it expeditiously and in compliance with all ESH&Q requirements, including those related to transportation. All the expenses and personnel for the removal will be borne by the experimenters unless removal requires facilities and personnel not able to be supplied by them, such a rigging, crane operation, etc.
- 6.10 The experimenters will assist Fermilab with the disposition of any articles left in the offices they occupied.
- 6.11 An experimenter will be available to report on the test beam effort at a Fermilab All Experimenters' Meeting.

SIGNATURES:

A handwritten signature in blue ink, appearing to read "Flavio Cavanna", is shown on a light blue rectangular background.

2 / 28 / 2013

Flavio Cavanna (Yale U. / L'Aquila U.), Experiment Spokesperson

A handwritten signature in black ink, appearing to read "Jennifer Raaf", is shown on a light blue rectangular background.

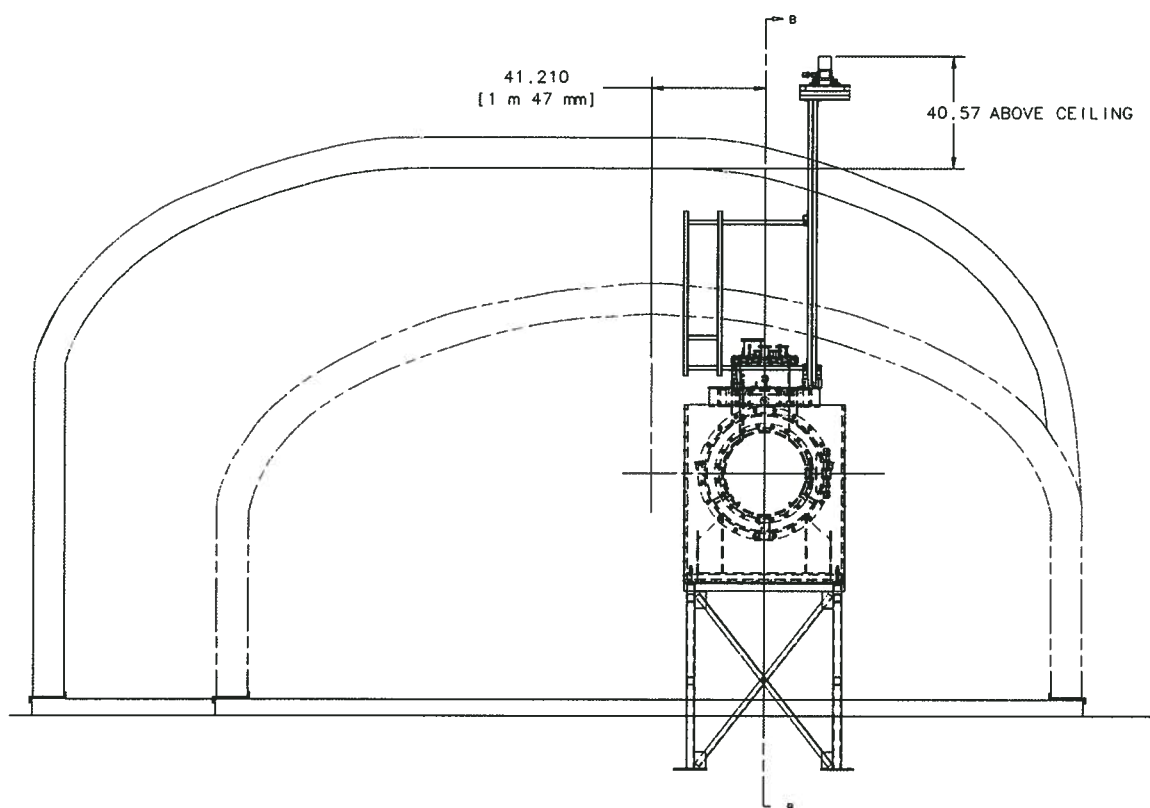
2 / 28 / 2013

Jennifer Raaf (FNAL), Experiment Spokesperson

APPENDIX I: MC7 AREA LAYOUT

Top View and Cross Section view of MC7 with indication of the expected location of the ArgoNeuT detector and of the components of the Tertiary Beam (Target/Collimator + 2 Magnets and beam monitor detectors). Also indicated (light blue area) in the Top View the extension of the area dedicated to the LArTPC test beam (about $15 \times 8 \text{ m}^2$). In the CrossSection View indication of the modifications required to fit within the available height of the experimental hall.

A number of ancillary devices (listed in Sec. II.3.1-4) will also be located in this area, near the

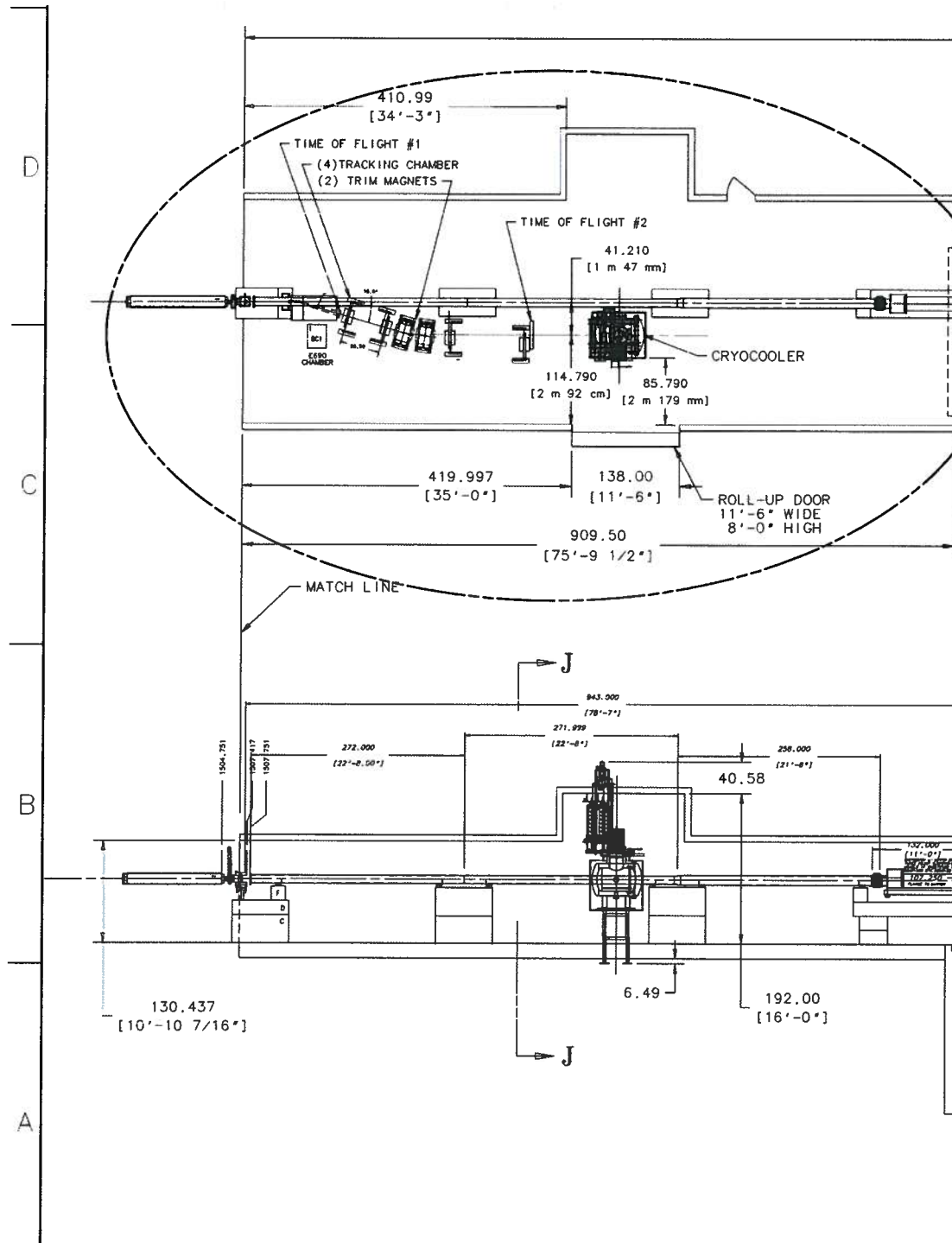


SECTION J-J
SCALE: 1/8
(CRYOCOOLER)

detector, not reported in these drawings.

View along beamline showing short- and tall-section ceiling heights with existing ArgoNeuT design (including stand below and cryogenics piping above). The cryogenics/recirculation system will be redesigned to fit in the taller-ceiling section of the MCenter beamline, and the stand will be modified.

TSW for T-1034: LArIAT

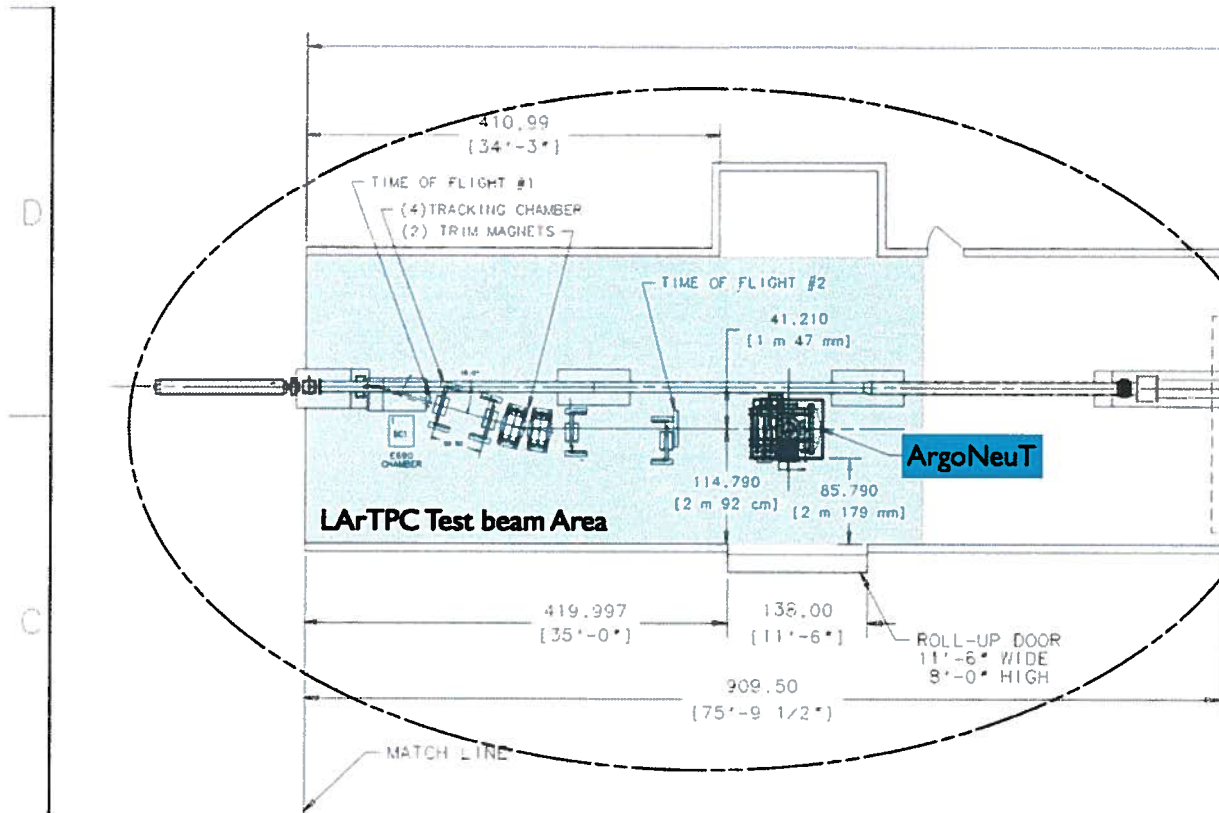


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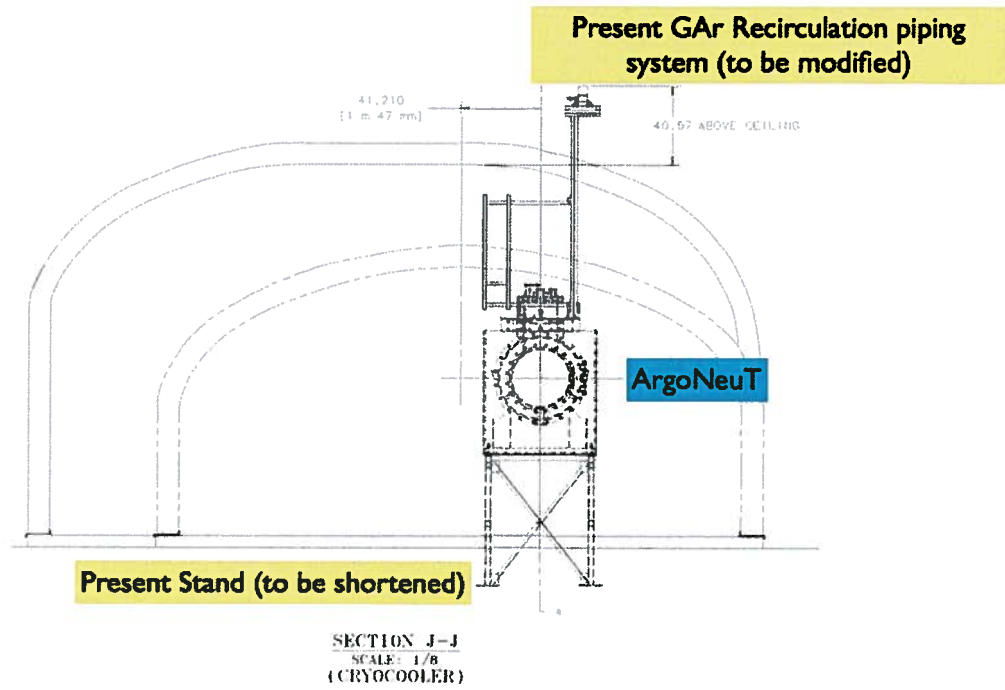
TSW for T-1034: LArIAT

Top view and side view of (pre-modification) ArgoNeuT in MCenter beamline with tertiary beam components shown exactly as situated in MTest during MINERvA calibration test.

Top View of MC7 at M-Central



CrossSection View of MC7 at M-Central



APPENDIX II: EQUIPMENT NEEDS**PROVIDED BY EXPERIMENTERS:**

<i>Equipment</i>	<i>Type/Model</i>	<i>owned by</i>
LAr cryostat	PHPK Tech.	<i>Yale</i>
TPC Detector (2 active planes, 240 wires each)	(custom)	<i>Syracuse</i>
Cryocooler	CRYOMECH AL300	<i>Yale</i>
Chiller	NESLAB HX300	FNAL
Slow-Control (P, T, LAr Levels, Cryocooler Operation)	-	FNAL
Turbo+Primary Vacuum Pump system	Pfeiffer	<i>Yale</i>
Two Primary Vacuum Pump	Varian TriScroll 300	<i>Yale</i>
HV pwr supply (125 kV)	GLASSMAN	FNAL
LV pwr supply	LeCroy 1440	FNAL
R/O electronics: Bias Voltage Distribution Card Preamplifier and Filter Card Digitizer Module	(custom) 20 units (x 24 chs. each) 30 units (x 16 chs. each) 15 units (x 32 chs. each)	<i>Michigan State U.</i>
DAQ computer (for TPC)	-	<i>Yale</i>
2 PMT (HQE for cyo-applic.) -Scint.Light R/O	Hamamatsu	<i>U. of L'Aquila</i>
Trigger System Instrumentation (TDC, QDC and logic module)	-	<i>W&M</i>
UV lamp for purity monitor	Hamamatsu	<i>Yale</i>
gas (N2) system	-	FNAL

Equipment Pool and PPD items needed for Fermilab test beam, on the first day of setup.

PREP EQUIPMENT POOL:**Quantity Description**

- 1 GLASSMAN HV power supply (125 kV) - already available from ArgoNeuT
- 2 LeCroy 1440 LV power supply - already available from ArgoNeuT

PPD FTBF:**Quantity Description**

- 1 set of ToF scint. counters [with HV supply and read-out electronics]
- 1 set of (2) Prop. Wire Chambers [with HV supply and read-out electronics]
- 1 set of (2) He Tubes

APPENDIX III: - HAZARD IDENTIFICATION CHECKLIST

Items for which there is anticipated need have been checked. See next page for detailed descriptions of categories.

Flammable Gases or Liquids		Other Gas Emissions		Hazardous Chemicals		Other Hazardous /Toxic Materials
Type:		Type:			Cyanide plating materials	List hazardous/toxic materials planned for use in a beam line or an experimental enclosure:
Flow rate:		Flow rate:			Hydrofluoric Acid	
Capacity:		Capacity:			Methane	
Radioactive Sources		Target Materials				photographic developers
	Permanent Installation		Beryllium (Be)			PolyChlorinatedBiphenyls
	Temporary Use		Lithium (Li)			Scintillation Oil
Type:			Mercury (Hg)			TEA
Strength:			Lead (Pb)			TMAE
Lasers			Tungsten (W)			Other: Activated Water?
	Permanent installation		Uranium (U)			
	Temporary installation		Other:	Nuclear Materials		
	Calibration	Electrical Equipment		Name:		
	Alignment	X	Cryo/Electrical devices	Weight:		
Type:			Capacitor Banks	Mechanical Structures		
Wattage:		X	High Voltage (50V)		Lifting Devices	
MFR Class:			Exposed Equipment over 50 V		Motion Controllers	
			Non-commercial/Non-PREP	X	Scaffolding/Elevated Platforms	
			Modified Commercial/PREP		Other:	
Vacuum Vessels		Pressure Vessels		Cryogenics		
Inside Diameter:		Inside Diameter:	30"	X	Cryocooler	
Operating Pressure:		Operating Pressure:	1.2 bar (abs)	X	Condenser + PhaseSeparator	
Window Material:		Window Material:	St.Steel	X	Cryogenic Pump	
Window Thickness:		Window Thickness:	3/16" (4.8 mm)	X	LAr Cryostat	

OTHER GAS EMISSION**Greenhouse Gasses** (Need to be tracked and reported to DOE)

- ☐ Carbon Dioxide, including CO₂ mixes such as Ar/CO₂
☐ Methane
☐ Nitrous Oxide
☐ Sulfur Hexafluoride
☐ Hydro fluorocarbons
☐ Per fluorocarbons
☐ Nitrogen Trifluoride

NUCLEAR MATERIALS**Reportable Elements and Isotopes / Weight Units / Rounding**

Name of Material	MT Code	Reporting Weight Unit Report to Nearest Whole Unit	Element Weight	Isotope Weight	Isotope Weight %
Depleted Uranium	10	Whole Kg	Total U	U-235	U-235
Enriched Uranium	20	Whole Gm	Total U	U-235	U-235
Plutonium-242 ¹	40	Whole Gm	Total Pu	Pu-242	Pu-242
Americium-241 ²	44	Whole Gm	Total Am	Am-241	—
Americium-243 ²	45	Whole Gm	Total Am	Am-243	—
Curium	46	Whole Gm	Total Cm	Cm-246	—
Californium	48	Whole Microgram	—	Cf-252	—
Plutonium	50	Whole Gm	Total Pu	Pu-239+Pu-241	Pu-240
Enriched Lithium	60	Whole Kg	Total Li	Li-6	Li-6
Uranium-233	70	Whole Gm	Total U	U-233	U-232 (ppm)
Normal Uranium	81	Whole Kg	Total U	—	—
Neptunium-237	82	Whole Gm	Total Np	—	—
Plutonium-238 ³	83	Gm to tenth	Total Pu	Pu-238	Pu-238
Deuterium ⁴	86	Kg to tenth	D ₂ O	D ₂	
Tritium ⁵	87	Gm to hundredth	Total H-3	—	—
Thorium	88	Whole Kg	Total Th	—	—
Uranium in Cascades ⁶	89	Whole Gm	Total U	U-235	U-235

¹ Report as Pu-242 if the contained Pu-242 is 20 percent or greater of total plutonium by weight; otherwise, report as Pu 239-241.

² Americium and Neptunium-237 contained in plutonium as part of the natural in-growth process are not required to be accounted for or reported until separated from the plutonium.

³ Report as Pu-238 if the contained Pu-238 is 10 percent or greater of total plutonium by weight; otherwise, report as plutonium Pu 239-241.

⁴ For deuterium in the form of heavy water, both the element and isotope weight fields should be used; otherwise, report isotope weight only.

⁵ Tritium contained in water (H₂O or D₂O) used as a moderator in a nuclear reactor is not an accountable material.

⁶ Uranium in cascades is treated as enriched uranium and should be reported as material type 89.