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Letter of Intent

ArgonCube: a novel, fully-modular approach for the realization of large-mass liquid argon TPC neutrino detectors

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Abstract

The Liquid Argon Time Projection Chamber is a prime candidate detector for future neutrino oscillation physics experiments, underground neutrino observatories and proton decay searches. A large international project based on this technology is currently being considered at the future LBNF facility in the United States on the very large mass scale of 40 kton. In this document, following the long standing R&D work conducted over the last years in several laboratories in Europe and in the United States, we intend to propose a novel Liquid Argon TPC approach based on a fully-modular, innovative design, the ArgonCube. The related R&D work will proceed along two main directions; one aimed at on the assessment of the proposed modular detector design, the other on the exploitation of new signal readout methods. Such a strategy will provide high performance while being cost-effective and robust at the same time. According to our plans, we will firstly realize a detector prototype hosted in a cryostat that is already available. Then, a larger detector will be constructed and operated in the Neutrino Platform facility at CERN for a complete engineering and physics test program also employing charged particle beams for demonstrating the detection performance.

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Contents

1 Introduction and Physics Case

Neutrino oscillations have been firmly established by experiments conducted in the last two decades with solar, atmospheric, accelerator and reactor neutrinos leading to the determination of the neutrino mass-eigenvalue differences (squared) and of the three angles of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix [1]. We have now entered a new era of further precision studies. Outstanding issues are still to be settled, namely, the possible existence of CP violation in the leptonic sector and the hierarchy of the neutrino mass eigenvalues. In addition, some anomalies seem to give hints for a required extension of the minimal PMNS oscillation scheme by invoking the existence of still undetected sterile neutrinos. These neutrinos would not couple to the other elementary particles but would instead provide an addition to the oscillation mechanism. Altogether, this is a fascinating research field that has so far been the only one to provide signals of new physics beyond the Standard Model of particles and interactions. Several thorough reviews and global analyses of existing data summarize the neutrino oscillation picture (see *e.g.* [2]) and we refer to them for outlining the physics case of this proposal.

In order to achieve the necessary sensitivity in the forthcoming searches and measurements, large samples of events will be required. This condition can only be satisfied by a synergic use of high-flux neutrino beams and very large mass detectors whose technology provides high background discrimination. The oscillation baseline of future experiments will be be either "short" (<1 km) or "long" (>1000 km) according to the neutrino beam energy and to the specific oscillation channel under study. With the goal of discovering a CP violating phase in the PMNS matrix and measuring the mass hierarchy, two projects are presently on the table for the scrutiny of the community: ELBNF at Fermilab [3] (following the recent P5 panel recommendations [5]) and Hyper-Kamiokande in Japan [6]. For both projects new collaborations were recently formed with wide-reaching participation of world community. The first of these two multi-kton mass detectors envisions the use of a large Liquid Argon Time Projection Chamber (LAr TPC), a detection technology also well suited for astroparticle physics topics and sensitive searches for proton decay [7][8], provided a deep underground location is chosen to host the detector. The LAr TPCs are also considered for short baseline experiments, such as those at the Fermilab Short Baseline Neutrino (SBN) program. The latter is aimed at the clarification of the aforementioned "sterile neutrino puzzle", based on the simultaneous running of three LAr TPC detectors placed at three different distances from the source of the Booster Neutrino Beam (BNN) [9][10][11].

Here, we do not elaborate more on the scientific motivations of the current and future neutrino oscillation projects. The main aim of this document is to propose a comprehensive R&D project aimed at a further evolution of LAr TPC technology in view of the next generation of experiments and of their possible upgrades. TPCs are three-dimensional (3D) tracking devices with excellent calorimetric and particle identification capabilities. The passage of charged particles through the TPC inner volume, filled with liquid argon, produces ionization electrons which are drifted towards readout planes (anode) by an electric field obtained by a cathode and field shaping electrodes biased with increasing voltage. The reconstruction of particle tracks is achieved by recording the electric signals generated by the drifted electrons on the readout anode detectors, hence defining the transverse coordinates. The longitudinal space coordinate is obtained from the measurement of the drift time. Long drift distances (necessary for large-size devices or underground neutrino observatories) require extremely pure liquid argon in order to minimize the charge depletion due to the attachment of electrons to impurities having positive electron affinity. Given its high density of 1.4 g/cm^3 and a relatively low cost, liquid argon is well suited for neutrino-physics large-mass TPCs, acting simultaneously as a target and active medium.

Several laboratories worldwide are currently pursuing R&D studies on LAr TPCs and, among them, the signees of this proposal. The U.S. groups are heavily involved in the LBNF/SBN programs at FNAL (*e.g.* MicroBooNE [11] and LAr1ND [9]). These groups have gained experience within the extensive Fermilab effort on LAr TPCs and with the construction of full size experiments. The CERN group has a leading role in the establishment of the CERN Neutrino Platform (CENF) [12] and has extensive technological expertise in cryogenics and detector construction. The AEC-LHEP group of Bern, also involved in the U.S. programs, has conducted in the last years an intense R&D program on specific topics of interest [13][14][15][16], in particular on the achievement of very long drift distances. Before the measurements performed with the large size ArgonTube detector [17][18][19], the longest drift length over which tracks were reconstructed was 1.5 m [20]; now, drift distances exceeding 5 m are routinely reached by employing low noise and low power readout electronics situated in the liquid argon (so called "cold" electronics).

The R&D strategy we propose with this LoI has as main long-term goal the implementation of a novel LAr TPC approach, the ArgonCube. In parallel, we will investigate the feasibility of a signal collection alternative to standard wire readout. This approach is well matched to the requirements of future multi-kiloton neutrino observatories (LBNF), as well as able to offer an effective solution to the upgrade of smaller scale detectors (*e.g.* the SBN infrastructure). The proposed technology builds up on the previously cited experience of the proponents and aims at developing a fully modular detector able to provide a performing, simple, robust and cheap implementation, while suited to rescaled to very large mass of future apparatus. In addition, the full modularity of the detector will allow a "democratic" share of the construction load. The scientific R&D program described in this document will proceed through three consecutive phases. Phase 0, already largely accomplished with the ArgonTube program and with the R&D achievements in the U.S.; Phase 1, aimed at the study of the modular detector configuration and of different readout schemes to be tested with cosmic rays and with modules eventually exposed to CERN SPS charged particle beams; Phase 2, consisting in the realization of the full ArgonCube detector made of 5 full-size modules to be hosted in one suitable cryostat to be installed at CENF and exposed to charged particle beams.

2 LAr TPC Detectors

In the late 60's the potential of liquefied noble gases as detection media to build detectors with high spatial resolution started to be recognized [21]. An active R&D program led to the idea of using such media for large effective calorimeters for particle physics experiments [22]. The LAr TPC conceived by C. Rubbia in 1977 [7] constituted one of the most challenging and appealing detector design, allowing uniform and highly accurate imaging of large detector volumes. The operating principle is based on the fact that in highly purified LAr (*i.e.* virtually without electronegative compounds), ionization tracks can be drifted undistorted by a uniform electric field over distances of the order of meters [23]. Two dimensional imaging can be provided by placing wire planes or other readout devices at the end of the drift path. The third spatial coordinate is provided by the measurement of the drift time.

The feasibility of this technology was demonstrated by the ICARUS R&D program, which included studies on LAr purification methods, readout schemes and electronics, as well as tests with prototypes of increasing mass. The largest of these initial devices had a mass of LAr of 3 ton [24] and collected a large sample of cosmic-ray and gamma-source events. Furthermore, a smaller device with 50 l of LAr [25] was exposed to the CERN WANF neutrino beam, demonstrating for the first time the capability of the technique in detecting neutrino interaction events. The realization of the 600 ton ICARUS T600 detector was followed by its testing carried out on the surface with cosmic rays [26]. These measurements actually demonstrated that the LAr TPC technique can be operated at the kiloton mass scale. The ICARUS detector was then moved to LNGS in the CNGS neutrino beam where it collected samples of neutrino interactions.

The experience of ICARUS motivated several ideas of cloning the detector to increase the active mass [8]. One design of a monolithic magnetized large mass LAr TPC was proposed [27], based on an extrapolation of the technique embedded in a very large magnetic field. Another application envisioned a single cylindrical volume of 70 m diameter and 20 m in height, GLACIER [28], based on a double-phase ionization charge readout. This approach evolved in the LAGUNA and LAGUNA-LBNO [29] proposals with a demonstrator program currently planned at CERN in the framework of the WA105 R&D project [30].

In the United States several projects have started in the last years to build a multi-kiloton scale LAr TPC detector [31]. After successful R&D work the small size ArgoNeuT experiment [32], exposed to low energy ν_μ and $\bar{\nu}_\mu$ in the NuMI beam at Fermilab in 2009-2010 to perform cross section measurements. This was followed by the construction of the 170 ton MicroBooNE detector [11] to measure low energy neutrino argon cross sections and to investigate the low energy excess events previously observed by the MiniBooNE experiment [33]. The detector will start data taking in 2015 and introduces the use of cold electronics, in a first application to larger scale detectors. MicroBooNE will be combined with a new near detector, LAr1ND, and ICARUS T600 as a far detector, to search for sterile neutrinos within the FNAL SBN program [9][10]. A multi-kton detector was also proposed using standard wire readout for the LBNE project [3]. This project featured a long baseline neutrino beam sent from Fermilab to the Sanford Laboratory in South Dakota. Recently, the original LBNE project evolved into the LBNF (Facility) [4] following the recommendations of the P5 panel [5] and incorporating the experience and the contributions from other scientific initiatives. An LoI has been produced and signed by more than 500 collaborators from 145 international institutions [34] and already got approved by the Fermilab as E1062 [35].

With the present LoI, a novel and fully modular approach for the design of large mass LAr TPCs is proposed together with required R&D studies. The idea of such a detector design comes as the natural evolution of the research program conducted over several years with the ArgonTube project at the University of Bern and profit of a series of notable contributions from the other proponent groups. ArgonCube aims at the construction and operation of a series of detectors of increasing dimensions and complexity within a synergic collaboration of various institutions already well engaged in R&D activities on LAr TPC. More collaborators are expected to join with the course of the program.

3 The Concept of the ArgonCube TPC Module

The ultimate goal of the R&D program we outline here is a feasibility study aimed at the achievement of LAr TPC detectors with masses up to several tens of kton. The central idea is to construct and position identical and separate modules in a common bath of liquid argon. Each module featured a relatively short drift length and at a fully independent TPC with its own readout, light detection system, cryogenics, and services. Module walls are made thin to provide transparency to electromagnetic and hadronic showers as well as to neutrino produced primary particles. This detector configuration should also allow for an optimal use of the liquid argon with a relatively large fraction of active volume, as compared to other implementations of the technology. The short drift length will permit less stringent requirement on the liquid argon purity, hence allowing us to concentrate on other R&D subject like *e.g.* development of novel pixel readout schemes.

This detector, the ArgonCube, is expected to be suitable for the next generation of neutrino observatories, possibly coupled to a long baseline neutrino beam. However, the relatively large number of novel technical solutions, mainly on the full modularity and on the readout schemes, dictates the necessity of a graded implementation strategy, by increasing step-by-step the prototype size and progressively addressing all the various design challenges.

3.1 Modular TPC Design

The proposed TPC design is based on a module with dimensions of 2 × 2 m^2 and a length of up to 10 m encased into a rectangular box with electrically transparent ∼1 cm thick walls made of fiberglass. Fig. 1 shows a schematic drawing of the basic module. The walls can be made thin thanks to the fact that individual modules do not have to hold a liquid hydrostatic pressure higher than a few tens of millibar at any time. The inner pressure is always compensated by the outer one as the level in the inner volume vill be kept equal to the external bath. This allows bringing the amount of inactive material to the level of a few percent of the total detector-target mass.

The top of the TPC box is equipped with a stainless steel flange hosting all connections required for TPC operation: high voltage (HV) and readout feedthroughs, cryogenic lines, valve control rods, connections for the light collection system, quartz feedthrough for the laser calibration system and the cryocooler head. The top flange operates at a temperatures not lower than 280 K. For this reason, its hermetic attachment to the fiberglass box becomes relatively easy. The edge of the top flange is designed in such a way that it can be fixed to the neighbor module's flange or to the outer volume flange and sealed with an indium wire, as sketched in Fig. 2.

The drift field cage is made of a number of field-shaping loops electrically biased via a resistive divider. Loops are made of copper strips produced by standard copper-on-fiberglass Printed Circuit Board (PCB) technology. The strips are deposited on the inner surface of the module walls and are isolated by an additional thin layer of fiberglass. The cathode and the readout planes are attached at the two sides of the resistive chain. The TPC features a double-drift volume configuration with an aluminum cathode at the center of the chamber biased to -100 kV and two mirrored drift volumes on either side. It is worth stressing that the designed drift length rather conservative for LAr TPC (1-2 meters). To avoid the formation of insulating aluminum oxide layers that would prevent the neutralization of positive argon ions and lead to accumulation of space charge, the aluminum can be plated with chromium or gold. Two readout planes placed at ground potential are located on the fiberglass box walls. The back of each plane with respect to the drift volume is equipped with cryogenic electronic boards providing charge amplification and possibly digitization and zero-suppression logic to reduce the data flow to the DAQ system.

In order to detect the scintillation light from liquid argon a scheme with two planar light guide is being considered. These light guides are made of polystyrene and coated with wave length shifter (Tetraphenyl butadiene (TPB) in polystyrene matrix) in order to recover the UV light from its maximum emission at 128 nm. A pair of silicon photomultipliers (SiPM) is mounted at the top of each light guide and the readout signals are then routed out of the module.

3.2 Charge Readout and R/O Electronics

The standard method for reading out the ionization charge in a LAr TPC relies on the use of consecutive planes of sensing wires to measure two of the three space coordinates. This method was used for ICARUS and MicroBooNE, and was also adopted as a baseline configuration for LBNE. Although the concept is proven and gained considerable interest in the community, it has an intrinsic limitation in resolving ambiguities, which result in making the event reconstruction difficult in some cases. In addition, the construction and mounting of wire planes poses some constraints and is considerably expensive. Therefore, a non-projective readout would have advantages.

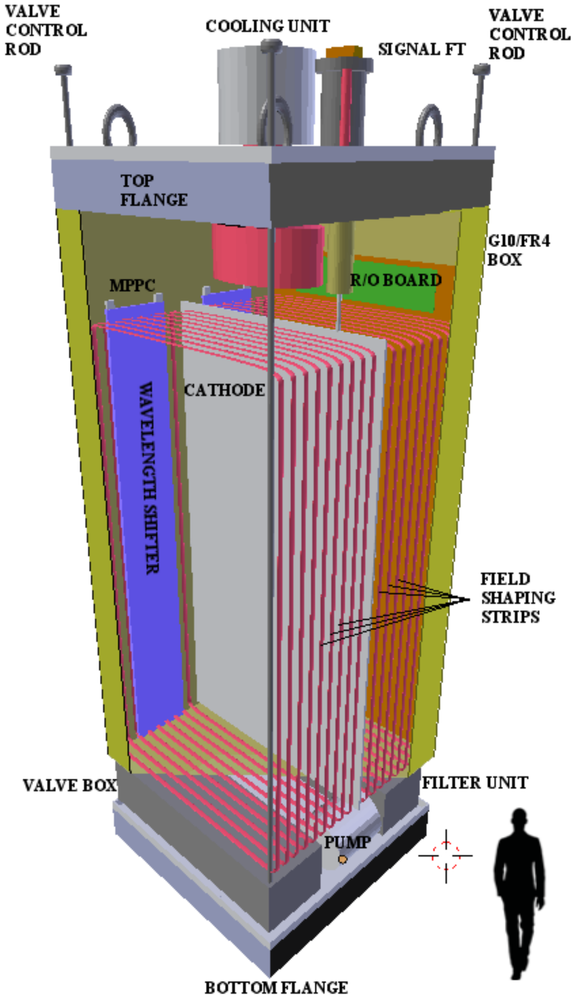


Figure 1: Schematic design of the ArgonCube basic module.

As with many other detectors, a single readout electrode segmented into pixels/pads of a size comparable to the wire spacing in the standard approach the most compelling option we see today. The number of pixels for equal spatial resolution will be two or three orders of magnitude higher than the number of sense wires, with a corresponding increase of the number of signal channels, data rates and power dissipation. This would make such a solution untenable except for small detectors. We propose a readout scheme that allows to reduce these issues to a reasonably low level. Multi-prong R&D effort will be an iterative process with multiple phases of prototypes including cosmic rays and charged particle test beams, as well as data analysis to reach the optimum solution and the best configurations.

Charge Readout Schemes

At this stage, three options are being considered for the geometrical arrangement of the charge readout pattern.

The first option utilizes solid circular pads (VIAs) as pixels. The signal from each pixel is routed to a multi-channel ASIC mounted on the back side where it is amplified, digitized and connected to a digital data bus multiplexing circuit (Fig. 3). The circuit's function is to digitize and multiplex data from the region of interest (ROI) to a reduced number of digital readout lines. The region of interest is defined by the induction signal from the grid copper pattern between pixels and covering a 8 × 8 pixel regions (for clarity only 4 × 4 pixel group is shown in Fig. 3). The induction signal is also used to switch the ASIC from low-power standby mode to a readout mode for a time needed to digitize and send out data for the particular ROI. A multi-level ROI logic can be implemented with more than one of such induction patterns [36]. This scheme enables fully pixelized, unambiguous charge-coordinate readout at the cost of a higher complexity of the electronic circuit on the cold readout PCB boards. The effects of heat dissipation from

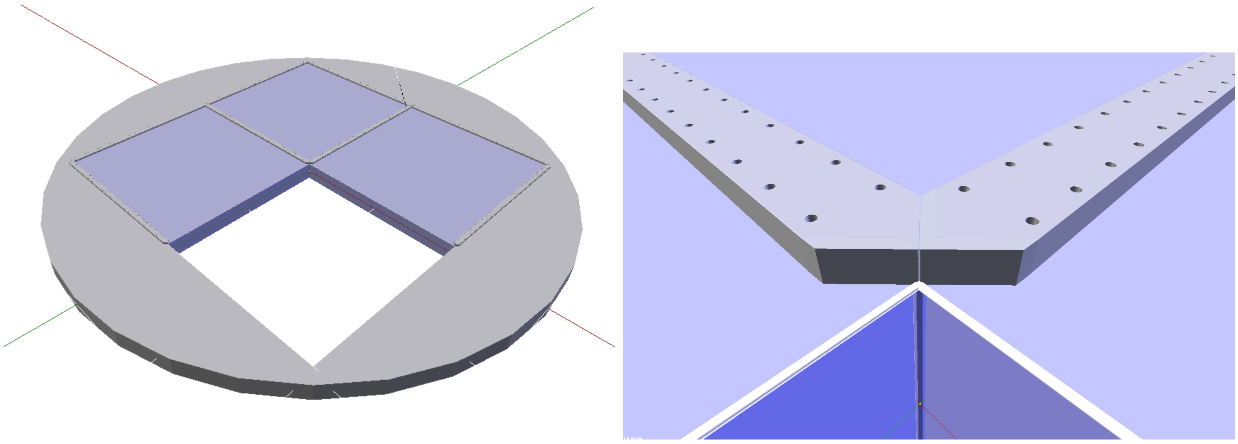


Figure 2: Design of the cryostat top flange and of the sealing scheme. Left: view of the 4-module detector top flange with one module extracted. Right: details of the sealing structure.

the entire readout plane (bubbles, convection) have to be investigated in details.

In the second option, a charge readout pixel configuration is made of two separate copper patterns (Fig.4, left) providing equal sharing of the collected charge. The two copper patterns are respectively connected to the two orthogonal readout projections. This scheme provides readout of both X and Y projections of the charge spot in charge collection mode simplifying the subsequent 3D reconstruction. The signal from each line is amplified by a cryogenic pre-amplifier IC mounted on the back side of the PCB and fed to the top edge of the readout plane. Optionally, an inclined U-coordinate can be added in order to resolve projection ambiguities. The number of pixels connected to each line is optimized to reduce the capacitance, on one hand, and the number of ICs, on the other.

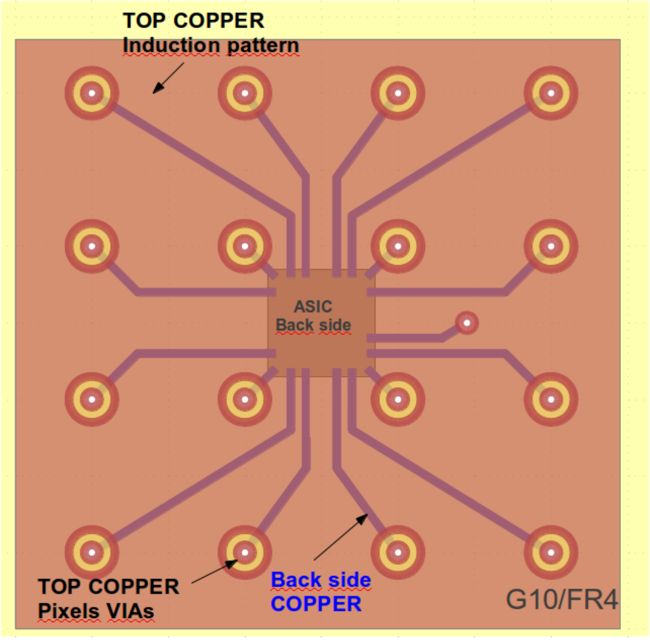


Figure 3: Charge readout scheme with the induction pattern over the ROI and the processing ASIC at the back side of the PCB.

The third scheme is a modification of the second one. In this case, one features a lower strip capacitance due to the reduced surface of the copper pattern. However, one has to utilize non-standard PCB manufacturing technology that involves the deposition and etching of copper-coated Kapton layers on top of the PCB (Fig. 4, right).

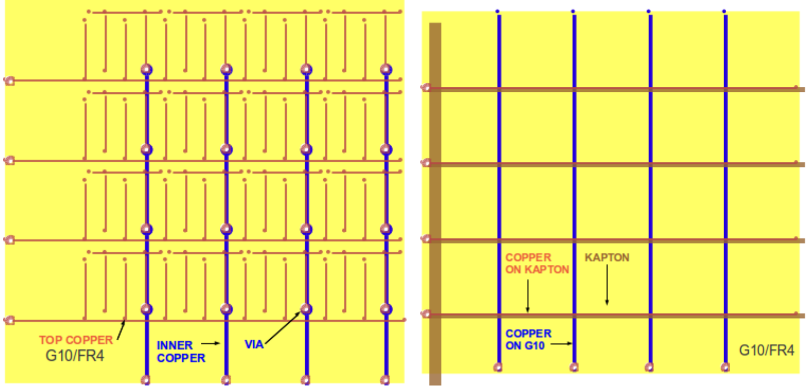


Figure 4: Charge readout schemes with separate copper patterns. Left: X-Y projection readout with standard PCB technology pattern; right: low capacitance X-Y projection readout pattern with Kapton-on-PCB technology;

Readout Electronics

Readout options 2 and 3 assume the use of the cryogenic charge-sensitive preamplifier ASICs LARASIC4 [38] designed by the BNL group, which has many years of experience in these circuits with several successful implementations. An example readout system based on these ICs is shown in Fig. 5. The IC has 16 readout channels, each including a charge amplifier, a 5^{th} order Gaussian filter and a buffer output stage. Gain and timing parameters for each individual channel are programmed by an external control module via a 1.8 V LVCMOS digital synchronous serial link. The gain G can take any of the following values: 4.7, 7.8, 14 or 25 mV/fC, while the peaking time τ can be chosen to be 0.5, 1.0, 2.0 or 3.0 μs. The trans-impedance of the preamplifier at G=25 mV/fC and τ= 3 μs is equal to 120 mV/nA. The equivalent noise charge with a detector capacitance of C_{det}=1 pF is about 400 electrons. Implemented in the 20 cm long ArgonTube detector wires (C_{det}=7-10 pF) it reached an electron equivalent noise value of 525 electrons. Such performance allows detecting a track from a crossing minimum ionizing particle (MIP) with a S/N ratio exceeding 16 (see ArgonTube performance, Section 5.1) and to have a charge detection threshold of about 1000 electrons with a S/N=2. The thermal power dissipation of one ASIC is lower than 10 mW per channel.

In the scheme where the readout is performed by wire planes, the number of readout channels is 1660 for a detector module with an anode surface of 1.0 × 2.0 m^2 and a wire pitch of 3 mm , hence requiring 104 LARASIC4 ICs per anode plane. The total amount of ICs per module is then 208. The total dissipated power of such a system is still lower than 16 W.

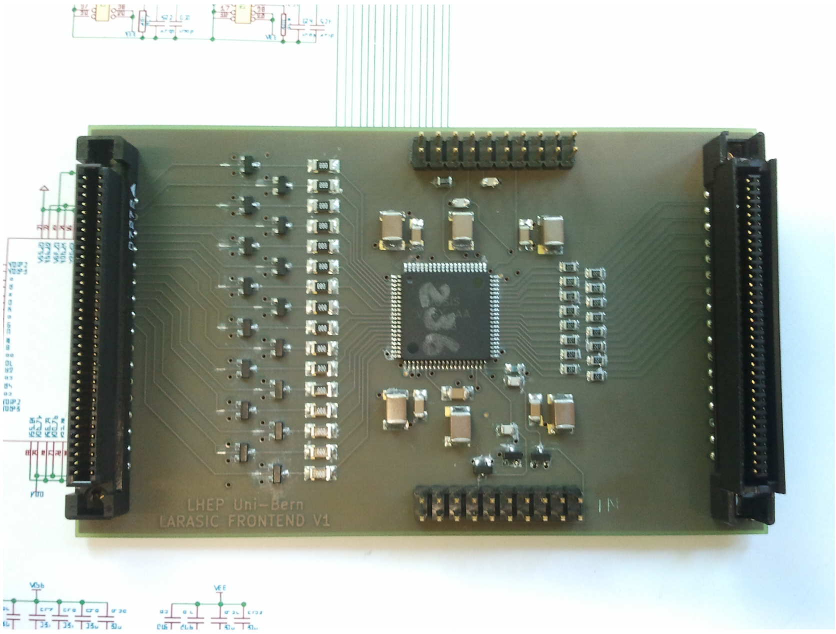
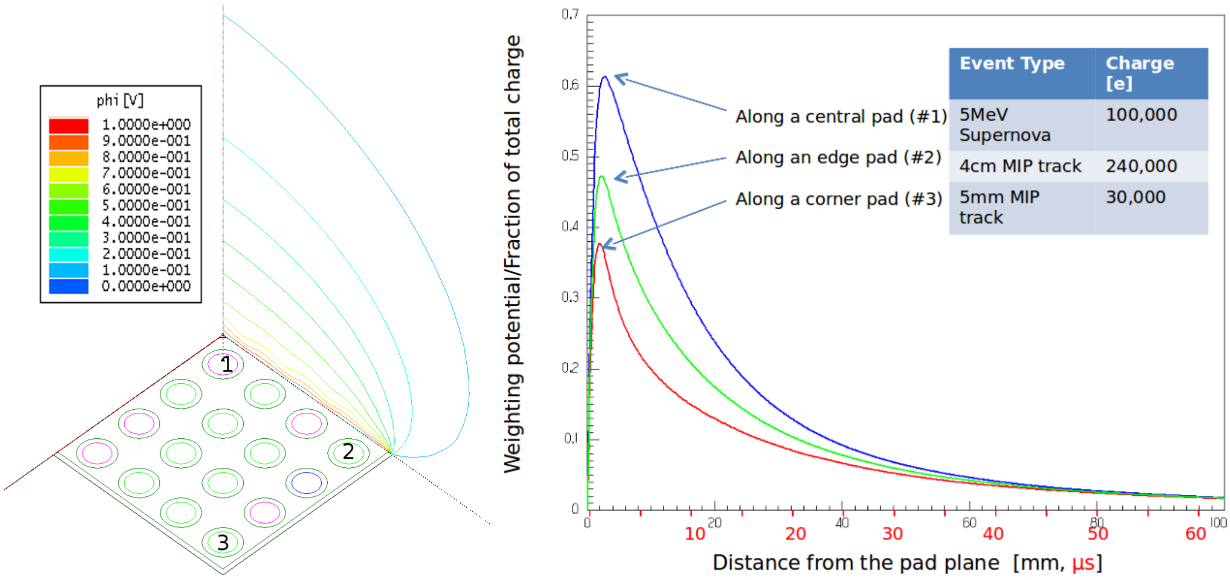


Figure 5: Implementation of a charge readout board based on the LARASIC4 cryogenic preamplifier IC as used for the ArgonTube detector.

Despite its simplicity and low cost, charge readouts for options 2 and 3 have a number of drawbacks. Readout of charge projections may result in reconstruction ambiguities for complex events with high track multiplicity. Additionally, the capacitance of the readout wires increases with their length, leading to a corresponding increase of the equivalent noise charge and hence, of the charge detection threshold. Therefore, it is very desirable to implement a readout scheme in a pixelized arrangement rather than having projections only. A pixelized readout configuration would eliminate projection ambiguities and limit C_{det} to a typical pixel capacitance (order of a few pF). However, the difficulty of such an approach is given by the large number of channels to be readout. In order to drastically reduce this number, a suitable grouping of pixels can be attempted together with a smart zero suppression before and after digitization. Such a scheme is the essence of the readout option 1.

This scheme would allow to process and read out only those pixels belonging to the ROI where the track charge is localized. The ROI triggering is made from the signal induced to the copper pattern surrounding the charge collection pads. This signal is used to ”wake up” the ASIC from the low-power standby mode with only induction channels activated to a full readout mode. This approach allows to drastically reduce the average power dissipation of the readout electronics. The signal induced on the ROI induction pattern can be estimated by using finite element analysis (FEA) simulations. In Fig. 6 the geometry used for the simulation is shown on the left, and the induced signal as a fraction of the total charge is presented on the right. The ASIC must be able to process all of the 64 pads in case of full occupancy within a time window of 1 μs. This, however, is a rare case for most of the expected neutrino events. In the majority of the cases, the amount of data will be limited and therefore not exhibiting such a problem.



Event Type	Charge [e]
5MeV Supernova	100,000
4cm MIP track	240,000
5mm MIP track	30,000

Figure 6: FEA-based simulation of the induced signal for ROI wake-up in the readout scheme 1.

In addition to that, for some applications, an external trigger (beam, scintillation light) can be used to switch the R/O system from standby to full power operation mode. The primary issues to be investigated for this scheme are: switched power operation with a minimal transient time; readout schemes for high data rates and volumes; low-power ASIC design; interconnections and power distribution over large readout electrode (multi-layer PCB) surfaces.

The general aspects that have to be studied for the proposed program to be successful are: how serious the reconstruction ambiguity issue is, and what pros and cons of an intermediate solution utilizing readout options 2 and 3 are.

The number of 3 × 3 mm^2 pixels for a module with an anode surface of 2.0 m^2 is of the order of 100000, while the number of digital readout lines fed via the top flange to the DAQ can be as low as 1000. In such a way, one has similar requirements for the engineering of the cryostat top flange as for the readout options 2 and 3.

3.3 High Voltage and Calibration

The HV potential is fed into the inner TPC volume by a dedicated feedthrough. Its inner conductor tube is directly attached to the aluminum cathode plane, providing its mechanical support from the top side. This HV system is based on the design presented in [37]. This publication reports, in particular, on the observation of flash-overs across the feedthrough dielectric for voltages even below 100 kV. Subsequent studies showed that this problem can be solved by raising the level of the liquid argon to ∼50 cm above the lower end of the ground shielding. This configuration eventually allowed the successful operation of the ArgonTube feedthrough up to 130 kV without the detection of breakdowns. In summary, we are not anticipating any show-stopper or the need for a specific R&D work on this subject.

The calibration of the detector consists of three main tasks: charge readout calibration, charge lifetime measurement and drift field calibration. The first is performed by the LARASIC4 built-in calibration capacitor (200 fF). A test pulse fed through this capacitor injects a constant charge to the preamplifier input, allowing to measure the circuit gain and quantify its response. The second and third tasks are more complex due to the relatively high rate of ionization by cosmic radiation for a detector located at Earth's surface and not shielded by a substantial overburden. While electrons from such ionization are quickly swept from the drift region towards the anode, the argon positive ions have a drift velocity $\sim 10^5$ times lower. Their drift time in a 0.5 m long gap is in the range of seconds. The equilibrium distribution of this space charge may introduce a noticeable parasitic electric field that can reach 10% of the nominal drift field. In the proposed ArgonCube geometry the expected disturbance due to this field is at least 10 times lower. However, accurate measurements of the drift field map will allow to decouple its effect from the Multiple Coulomb Scattering (MCS) of the detected particles, and, therefore, enhance the momentum resolution at higher momentum from MCS analysis.

We finally intend to calibrate the electric field map and to measure the ionization charge lifetime by using straight tracks produced in liquid argon by multi-photon absorption of the $\lambda = 266$ nm radiation from a high-power pulsed UV laser, as already performed for the ArgonTube detector [17] and implemented for the MicroBooNE experiment [11]. An optical feedthrough allowing to route the laser beam into the drift region will be used in a design similar to that of ArgonTube. A portable laser unit is placed on the top of the module where calibration is needed and provides a steerable beam directed downwards and covering most of the TPC inner volume. Tracks with uniform yield are then readout by the DAQ system and reconstructed. The information on the detected charge is used to derive the charge attenuation along the drift and measure the charge lifetime. The deviation of the detected track from a straight line is used to derive the parasitic electric field due to the accumulated space charge or to field non-uniformities generated in the detector construction and assembly.

4 R&D Strategy

The main purpose of this LoI is to establish a complete R&D program, which will serve the purpose of demonstrating the feasibility of the ArgonCube concept and of the proposed technological solutions in view of larger size demonstrator. This program can be thought of as separated into 3 phases:

(i) Phase 0 is the predecessor of all this work and is based on the experience gained by the Bern group with the construction and operation of the ArgonTube detector, by BNL with the realization of the cold electronics and by all the U.S. groups with the constructions of MicroBooNE and ArgoNeuT. Several of the results previously obtained will translate directly to this new R&D program. This work and selected results related to the ArgonTube detector construction and operation are described in Section 5.

(ii) Phase 1 deals with the construction of a number of TPC prototype modules, and with the development of the related signal readout schemes. The main purpose of these detectors will be to prove the feasibility of the ArgonCube concept. In this phase, the different readout techniques will be scrutinized and the basic technological choices will be made, both for the charge readout and the light collection. Several different TPC modules with external dimensions of $0.67 \times 0.67 \times 1.8$ m^3 will be built. The module extraction-insertion procedures will be tested together with the argon flow management. The prototypes will be first exposed to cosmic rays in Bern utilizing an existing cryostat. After that the modules and the cryostat will be moved to CERN to be tested in a charged particle SPS beam. This work is described in Section 6.

(iii) Phase 2: Once the mechanical concept and the principles of the detector design have been validated, a larger prototype will be constructed and characterized as a full demonstrator of the proposed technique. The main goal will be to prove the successful modular approach, and to assess the technical performance and competitiveness of the technology, as well as the scalability towards a massive neutrino detector. This large size prototype (∼180 ton of liquid argon) will be integrated at CERN and exposed to beams at the CENF infrastructure. We expect our program to profit from the new cryogenics, DAQ, and slow control infrastructure that will become available. This work is described in Section 7.

5 Phase 0: Experience Gained with the ArgonTube Project

Several R&D activities have been conducted by the groups authors of this LoI in the last years. In particular, some of them were finalized to the realization and operation of neutrino detectors eventually built such as ArgoNeuT [32] or MicroBooNE. In addition, a specific development work around the basic properties of the LAr TPC technology was carried out at AEC-LHEP Bern. This activity allowed setting the bases for the proposal of the ArgonCube concept outlined in this document. As we will see, most of the technical achievements will directly be applied to the ArgonCube design allowing to simplify and speed up the following R&D work.

Since 2007 the *Grosslabor* laboratory in Bern has been hosting detector prototypes related to work on LAr TPCs. The laboratory is fully instrumented with cryogenics infrastructure and also hosts a facility for the regeneration of copper-based oxygen-trapping filters required for the purification of the liquid argon to an ultra-pure state. Fig.7 depicts the Bern Grosslabor with the ArgonTube pit.

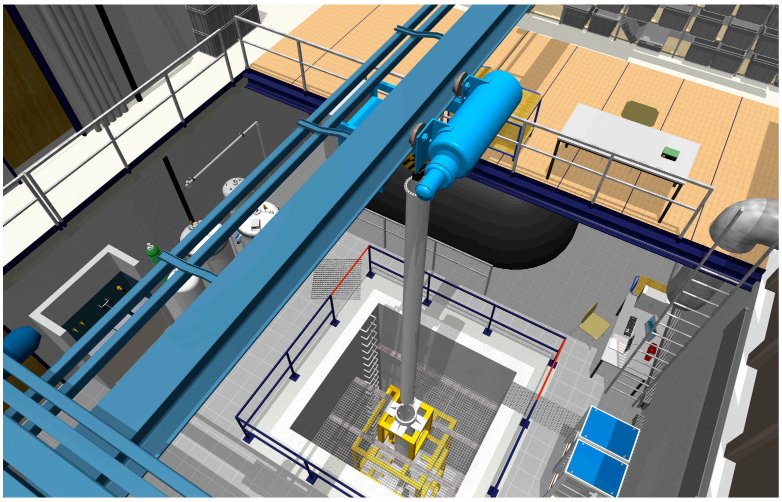


Figure 7: Artist view of the Grosslabor in Bern and of the ArgonTube pit.

In order to gain knowledge on LAr TPCs, extensive tests were carried out in Bern on prototypes of increasing size and complexity. The first TPC built has been the so called micro-chamber. Details of it can be found in [13][15]. This detector allowed for specific studies on ionization signals produced by Compton electrons and alpha-particles when the chamber volume was filled with different mixtures of liquid argon and liquid nitrogen [13][15]. The second detector has been a medium-size TPC with 20 l of active volume, meant as a precursor of the ArgonTube [14][16], which allowed to develop the purification/recirculation system for LAr, preamplifiers and DAQ, the UV laser system to measure the purity of LAr and testing individual detector components. Moreover, the detector was extensively used to perform the first studies of UV-laser ionization of liquid argon and to measure the cross section of the process, as well as recombination properties of argon ions and electrons and the charge life time. The Bern R&D work culminated with the design, realization and operation of the ArgonTube detector as a tool to experimentally assess the feasibility of very long drift in LAr TPCs. In the following, we outline the main features of the ArgonTube and its performance, mostly in the light of the proposal of the ArgonCube detector.

5.1 The ArgonTube Experience

The ArgonTube consists of a chamber 5 m long in the drift direction and 40 cm in diameter hosted in a vacuum-insulated cryostat with an inner (5.6 m long and 50 cm diameter) and an outer vessel, vacuum insulated by 50 layers of super-insulation to minimize the heat input from thermal radiation (Fig. 9, left). Both the inner and outer volumes are filled with liquid argon, with the latter volume acting as a cryogenic bath to keep the inner volume cold and to reduce LAr boiling. The heat input into the outer volume is compensated by the boiling of the argon. The whole structure is hanging on four pillars of PAI fixed to the top flange.

The electric field has a design value of 1 kV/cm, obtained with a potential difference between two consecutive rings of 4 kV, which results in a potential of 500 kV at the cathode at 5 m distance from the readout wire planes placed on top of the tube. The field is established by metal shaping rings. In order to minimize the weight of the field-shaping rings and to increase the drift volume, a race-track shape with a

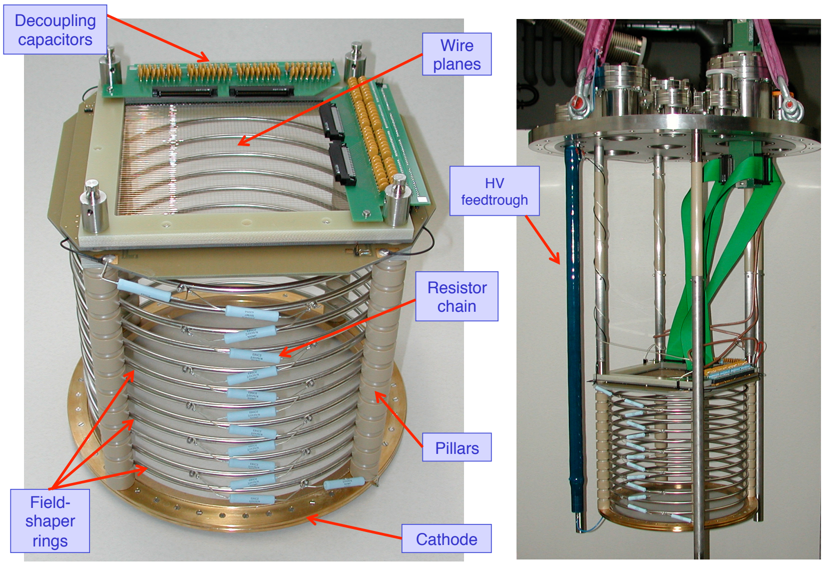


Figure 8: The medium-size LAr TPC in Bern.

thickness of 1.6 cm, a height of 3.4 cm and an inner radius of 8 mm was chosen. The optimal pitch for placing the field-shaping rings is 4 cm with a 5 mm space between the rings. This results in 125 rings mounted in a column to build up the field cage, each of them having an outer diameter of 40 cm (Fig. 9, right).

Given the difficulty to feed a voltage as high as 500 kV into the liquid argon without provoking discharges, a voltage multiplier based on a Greinacher circuit (also known as Cockcroft-Walton) was developed and realized. An AC charging voltage is applied to the circuit in which the voltage is rectified and multiplied by a factor depending on the number of stages. With a 4 cm distance between rings and an input AC voltage of 2 kV (4 kV peak-to-peak) one could reach a field intensity of 1 kV/cm.

Two readout (anode) planes are mounted on top of the TPC. Each plane is made of 64 Be-Cu alloy wires, 125 μm in diameter, with a 3 mm pitch and 20 cm length, yielding a readout surface of 20 × 20 cm^2. Drifting electrons induce a signal on the first plane and are then collected by the second plane. In the final experimental configuration, the charge signals were fed to cold preamplifiers realized by the BNL group [38] able to work immersed in the liquid argon. The front-end electronics is directly mounted on the wires, close to the source of the signals. In this way, one can also avoid the use of long cables between wires and preamplifiers, hence reducing the noise from pick-ups on the way and from the cable capacitance. In addition, operating at 87 K the CMOS technology features low thermal noise, high gain and speed.

The wire signals are then brought to CAEN V1729 ADCs with a sampling period of 1.01 μs and an acquisition time window of 8274 μs. A PMT system is used to detect the prompt scintillation light in liquid argon. This defines the starting time for the charge drift and also provides a trigger for the data acquisition. Since a large fraction of the scintillation light of liquid argon lies in the UV spectrum, the PMTs are coated with a layer of TPB serving as a wavelength shifter to blue light.

The liquid argon is filled through cryogenic oxygen-trapping filters based on activated copper powder. To further increase the argon purity and to compensate for possible outgassing of detector components in the warm phase, the inner volume is equipped with two cryogenic pumps that circulate the liquid through two additional filters. A bellow pump driven by pressurized nitrogen gas completes the system and provides a recirculation speed of 300 l/min of liquid with minimal electromagnetic interference to the TPC readout system and very limited heat input. Before filling the detector with liquid argon, the inner vessel is evacuated to minimize the amount of residual impurities. Typically, a pressure of about 5 × 10^{-5} mbar is reached. The inner volume is kept at an overpressure of 0.1 bar with respect to atmospheric pressure, while the outer volume is open to the atmosphere. After filling the liquid argon is recirculated through the oxygen-trapping filters with a recirculation speed of 120 l of liquid per hour. The purification lasts for about 24 hours to let the argon reaching the design level of impurities (0.1 ppb) before the high voltage is ramped up. Drift field values above 240 V/cm resulted in electric breakdowns at about 1.2 kV of input AC voltage, which corresponds to 150 kV at the cathode. This issue was first addressed in a related publication [37] and recently solved, as reported in [39] and discussed above.

An ArgonTube event gallery is shown in Fig.10 with cosmic ray induced events collected with the cold electronics readout. The vertical axis corresponds to the readout plane coordinate in centimeters (3 mm wire pitch) and the horizontal axis describes the drift time in microseconds or equivalently the drift distance

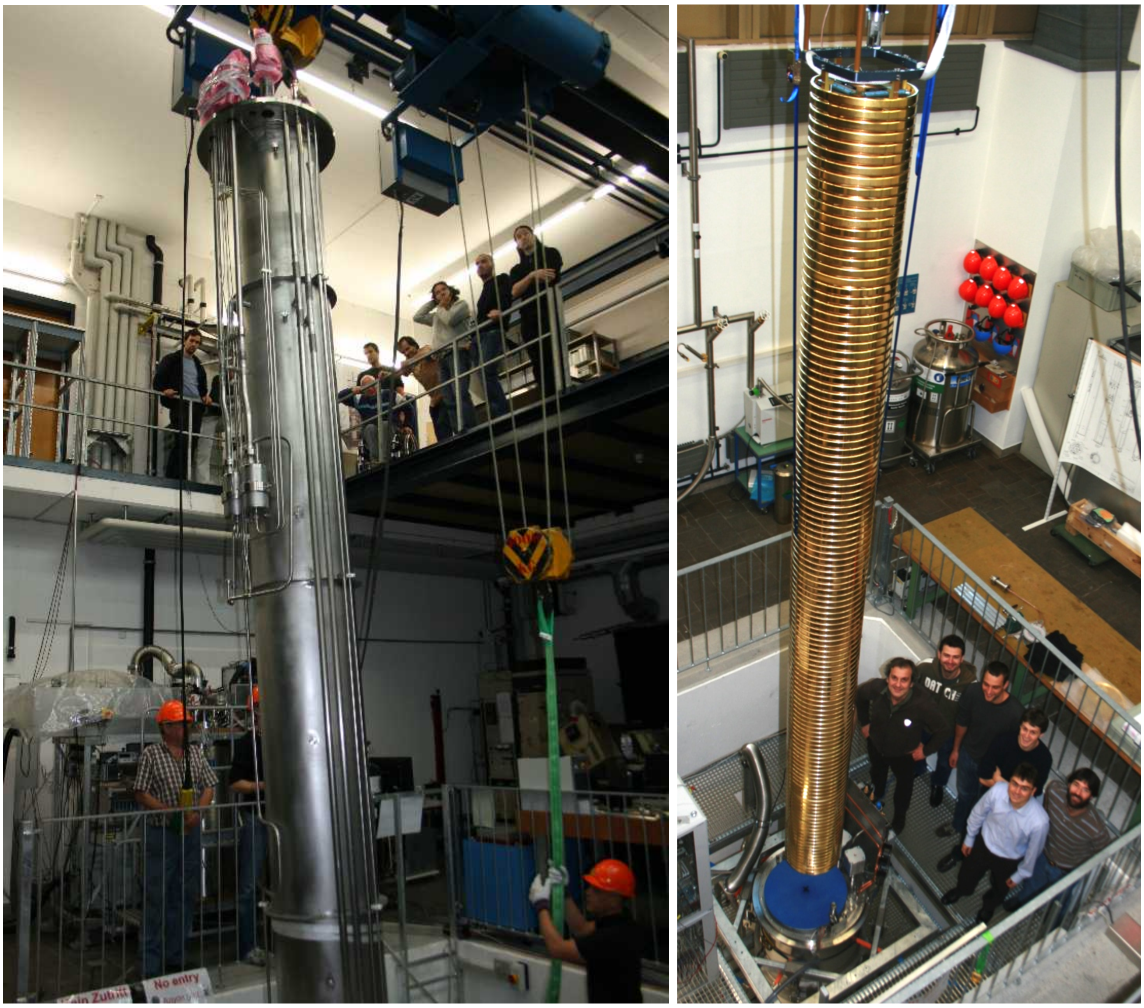


Figure 9: The ArgonTube LAr TPC in the Bern laboratory. Left: inner vessel installation in the vacuum-insulated cryostat; right: the field cage formed by a set of metal rings.

in centimeters. The displays are therefore turned by 90 degrees compared to the detector orientation in the laboratory. Also the aspect ratio is compressed in time (distance). The results unambiguously indicate the excellent performance of the cold electronics developed at BNL, corresponding to a S/N ratio for MIPs of 16. This is illustrated in Fig.11 where two similar events taken respectively with conventional and cold electronics are shown.

In Fig.12 we also show an event induced by the UV-laser beam in the ArgonTube. The beam enters from the side and goes to the cathode where a cloud of electrons is produced due to photoelectric effect on the gold-plated cathode surface. 100 laser tracks are superimposed in the Figure to obtain a better signal to noise ratio. Therefore, the 5 m drift is much more visible compared to single cosmic ray events. Assuming a homogeneous drift field, the end of the track from the photoelectric emission at the cathode is found to be at 5.4 m instead of 5.0 m.

Finally, the liquid argon purity in the ArgonTube was measured by using long inclined cosmic muon and laser beam tracks by analyzing the exponential decay of the charge signal versus the drift time. The collected charge as a function of the drift time along a muon track allows to infer the charge lifetime. Values of about 2.0 ms were obtained, in agreement with what derived by studying laser induced events [17], although with a smaller measurement uncertainty (Fig.13). As we will see in the following, most of the technological solutions we studied and developed for the ArgonTube will be directly applied to the design and prototype realization of the ArgonCube modules. This allows us speeding up detector construction time and execution of the whole R&D project.

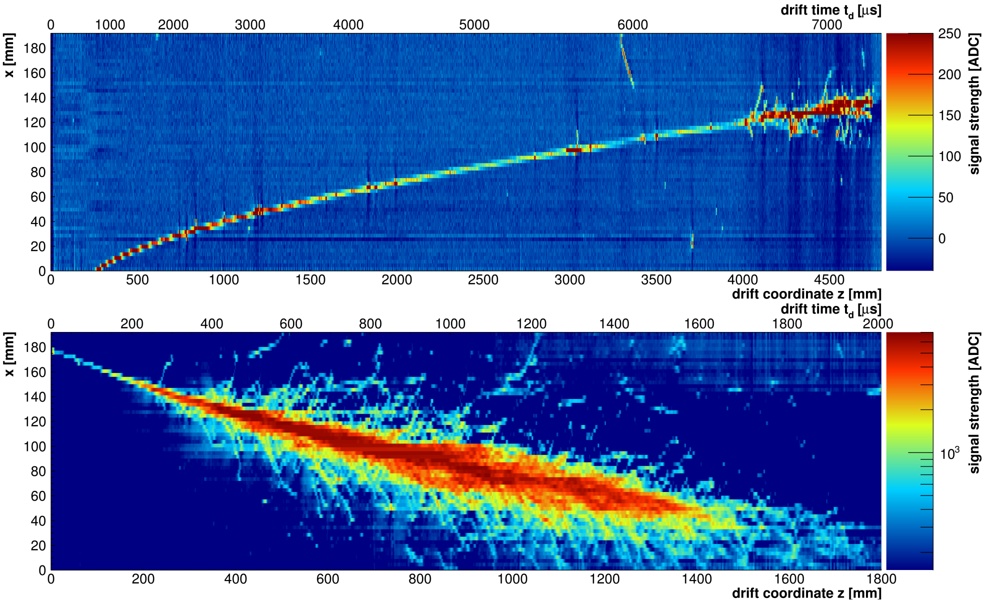


Figure 10: Display of ArgonTube events readout with the cold electronics.

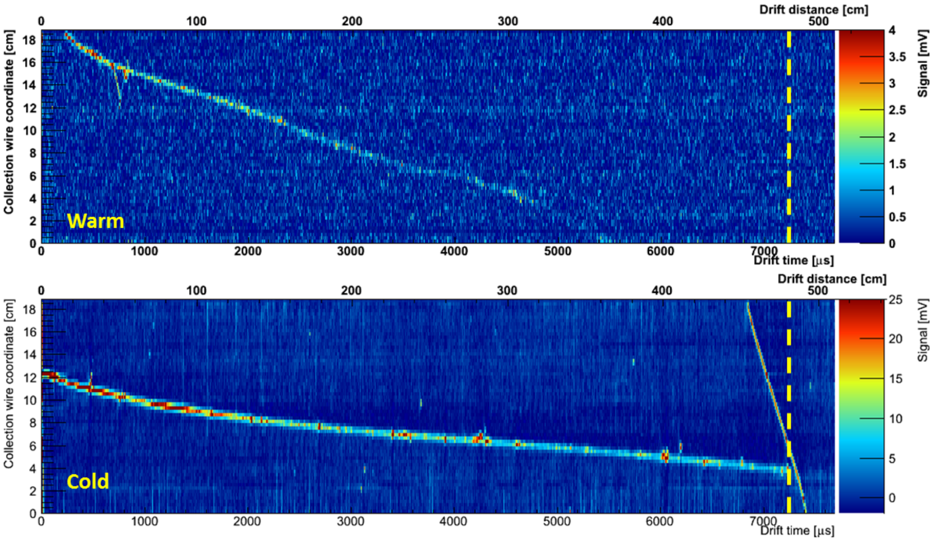


Figure 11: Comparison of cosmic muon tracks readout with warm and cold electronics, respectively. The dashed line shows the position of the cathode located at 4.76 m from the readout planes.

6 Phase 1: Realization of a Mini-ArgonCube as a Technology Demonstrator

Prior to the realization of the ArgonCube detector to be installed at the CENF facility at CERN, Phase 1 of the proposed program will consist in building and operating a prototype detector known as "Mini-ArgonCube". The detector will consist of four TPC module units hosted into an existing cryostat in Bern, shown in Fig. 14. The dimensions of this vacuum-isolated cryostat are ∼2.2 m diameter and ∼2.8 m in depth, making a nearly 6 m^3 total volume. The cryostat will host four modules with somehow reduced dimensions of $0.67 \times 0.67 \times 1.8$ m^3 each. This configuration allows for testing the mechanical design, detector read out schemes and cryogenic systems. Having four TPCs deployed at one time in the cryostat will allow studying the extraction and insertion procedure necessary for the modular design as well as the evaluation of the physics performance of various TPC solutions. Each module will have different design features, electronic readout and light collection system. This configuration will allow for side-by-side comparison of the design during operation. Furthermore, we will have a practical and pragmatic share of the construction load among the various collaborating institutions. Mini-ArgonCube will be first exposed to cosmic rays in Bern and then to a dedicated charged test beams at the CERN SPS with momentum ranging from 0.5 to 20 GeV/c.

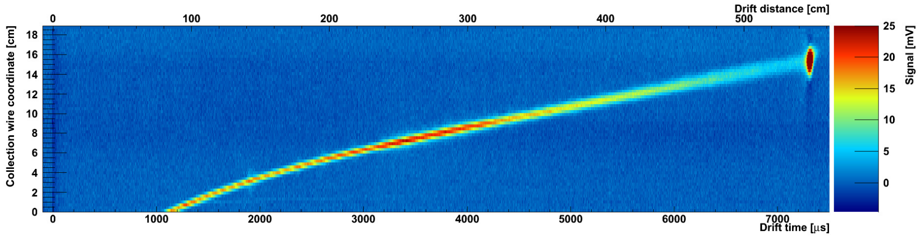


Figure 12: Display of ArgonTube events induced by UV laser beams.

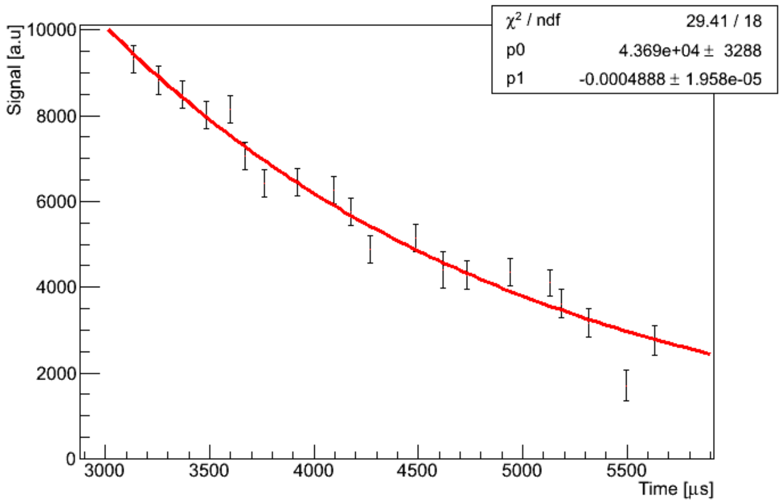


Figure 13: Charge attenuation of 100 laser tracks versus drift time with ArgonTube. The charge lifetime is found to be 2.05 ± 0.08 ms.

The next section describes the common design features of all four modules and the different charge and light readout systems to be studied with individual module design.

6.1 Common Mini-ArgonCube Module Design

The Mini-ArgonCube modules are essentially a down-scaled version of the nominal modules. The readout planes are 0.67 m wide and 1 m high. The remaining 0.8 m of the module length are occupied by the feedthroughs in the top flange and by the recirculation system in the bottom part. The side walls of the modules are made of fiberglass while the flanges on top and bottom are made of stainless steel. In order to address the various engineering challenges, all modules will be fully equipped in the same way as for the final design.

One of the goals of the Mini-ArgonCube prototype is to test the insertion and extraction of individual modules and the sealing process with indium wires incorporated in the gaps between the top flanges of adjacent modules. These procedures are described in detail in Section 7 for the full size demonstrator. The design of the top flange of the cryostat is shown in Fig. 2. It is the same as for the full size demonstrator just down-scaled to fit the smaller module size.

The basic design of the modules follows the final design outlined in Section 3 and shown in Fig. 1. The TPC is divided into two parts by a vertical aluminum cathode plate placed in the middle of the module, which is directly connected to the HV feedthrough. The latter will be built according to the design that has already been successfully operated at a voltage of 100 kV for the ArgonTube. However, due to the reduced size of the modules, the cathode will be at a lower potential compared to the nominal design. The field-shaping loops are made of copper strips produced employing copper-on-fiberglass PCB technology. They are interconnected by a resistive divider.

On the top flange, two feedthroughs are placed for HV and signal cables as well as an exhaust used upon insertion and extraction of the module. Each module is individually cooled by a dedicated unit in the top flange. The intermediate space between the TPC and the bottom flange houses a Barber-Nichols pump for recirculating the liquid argon through oxygen filters located at the same place. Recirculation is controlled by valves operated by using control rods reaching up to the top flange. The valves can be switched between filling the module through the filters, recirculating internally through the filters, and draining directly to the

Figure 14: Cryostat that will host the for Mini-ArgonCube detector in Bern.

outer volume.

To measure the purity of the liquid argon and to determine the corrections to the electric field, a UV laser system to produce straight tracks in the TPC in different directions will be used, as described earlier. The field correction will be done separately for each module. The laser enters the module through a quartz glass feedthrough in the top flange extending a few cm into the field-cage. The head containing the mirror that deflects the laser at the desired angle is a modified version of one used for the ArgonTube and the MicroBooNE experiment [11]. To keep the costs at a reasonable level, only one laser will be used for all four modules.

6.2 Charge and Light Readouts

In the following we describe the various readout configurations implemented in at least four separate modules, that will be tested for the Mini-ArgonCube. These designs represent the starting R&D steps for towards the final design for an ArgonCube module to be used in Phase 2.

i) Standard Wire & PMT TPC

As a baseline and reference configuration, one Mini-ArgonCube module will employ the standard three-plane wire readout attached to cold mother boards operating LARASIC4 chips. For an anode surface of 0.67×1 m^2, 3 mm spacing and pitch of the wire planes will result in $\geq$1000 channels to be readout. Utilizing conventional wire readout for a single module will allow for side-by-side comparisons with other modules employing alternative readout methods in a similar environment.

The light detection system for this module will have PMTs with surfaces coated by TPB placed near the anode frame, looking down from the top flange. These PMTs will penetrate through the field cage and provide a trigger for the readout.

ii) PCB Readout Planes with Scintillating Paddles

A second module will utilize PCB readout planes as described in Section 3.2. The charge readout pixel is formed by two separate copper patterns (Fig.4, left), providing equal sharing of the collected charge. One of the patterns is connected to the X-line and the other one to the Y-line. The signal from each line is amplified by a cryogenic preamplifier IC mounted at the back side of the PCB and fed to the top edge of the readout plane. The exact configuration and number of pixels will be defined at a later stage. This unit will provide a testbed for new methods for zero suppression at the digital level as well as for further studies for 3D reconstruction techniques.

The light readout for this module will employ two planar light guides made of polystyrene and coated by TPB. Two 25 cm wide light guides with SiPM will be used. The number, spacing, and thickness of the paddles will be optimized before construction.

iii) Pixel Readout and Scintillating Paddles with Wavelength Shifting Fibers

The remaining two Mini-ArgonCube modules will allow testing different aspects of the pixel readout scheme and light readout methods by using scintillating paddles with wavelength shifting fibers. The first (pixel) readout scheme, as described in Section 3.2 will make use of a pixelized readout configuration with a smart zero suppression after digitization. This scheme will have the readout surface instrumented with pixels and readout by LARASIC4+ADC+ALTERA for digital zero suppression, for a total of ∼60000 pixels, digitized and multiplexed to ∼200 digital lines. As previously mentioned, such a readout configuration will allow to get rid of ambiguities in high track multiplicity events and limit C_{det} to a pixel capacitance of the order of a few pF.

As previously described in Section 3.2, solid circular pads (VIAs) will be used as pixels in this readout scheme. The signal from each pixel is routed to the multi-channel ASIC mounted at the back side where it is amplified and connected to a digitizing and multiplexing circuit. The circuit function is to multiplex pixels from the region of interest to a reduced number of readout lines. The multiplexer addressing is performed by low-voltage (1.8 V) uni-polar logic signals fed to the plane from the external DAQ control system. The region of interest is defined by the induction signal from the grid copper pattern in-between pixels and covering 8×8 pixel regions. This scheme enables fully pixelized unambiguous charge-coordinate readout at the cost of complexity of the electronic circuit on the cold readout PCB board.

In the pixel approach, the design concept is based on the use of an induction electrode signal as trigger, a power switching mode to read out detector signals with the goal of controlling the overall power consumption of huge number of pad readout into a reasonable and realizable limit. The geometry of induction electrode co-planar with the pixels, and cold electronic have to be designed in order to sense the ionization charge approaching the readout electrode in time for the cold electronics to wake up. Therefore, the following features on the readout electronics have to be fulfilled: (1) switched power operation with minimal transient times; (2) a readout scheme for high data rates and volumes; (3) low power design; and (4) interconnections and power distribution over large readout electrode areas. The effects of heat dissipation from the entire readout plane have to be investigated. The use of beam based or scintillation light signals as an external trigger to wake up the electronics will be studied as well.

Some devices for pixel readout being developed in Bern are shown in Fig. 15. Here a small TPC with 5 cm drift distance was equipped with a simple pixel anode, with each pixel measuring 3×3 mm^2 area and readout by using customized LARASIC4 chips.

Each of the two TPC modules will use planar light guides with the addition of wavelength shifting fibers as a potential readout method. The addition of the fibers yields higher light yield and sensitivity compared to the signal from the scintillation light. The location and geometric pattern of the wavelength shifting fibers is left as an option to be explored during the building and testing of various light readout systems.

Following the successful construction and installation of the Mini-ArgonCube prototype in Bern, the detector will operate for several months taking cosmic ray data and certifying long term operation. During this time, the extraction and insertion of TPC modules will take place, exercising the procedure and addressing the functionality of the system to perform repairs.

By using these data as taken by different TPC readout designs will build the ground for the decision of the options for the Phase 2 detector. After the cosmic ray run, the modules and cryostat will be moved to CERN to be exposed to the charged SPS test beams. This test beam run will allow the full characterizing of the different module performance by exploiting beams of known particle type and momenta.

7 Phase 2: Full Size ArgonCube Demonstrator

A full size ArgonCube demonstrator will be installed at the CENF, in the extension of the EHN1 experimental hall [41] for a comprehensive R&D program meant to demonstrate the feasibility of the proposed modular approach, optimize readout and cryogenic technologies and evaluate the physics performance also exploiting charged particle beams, on a scale larger than Mini-ArgonCube.

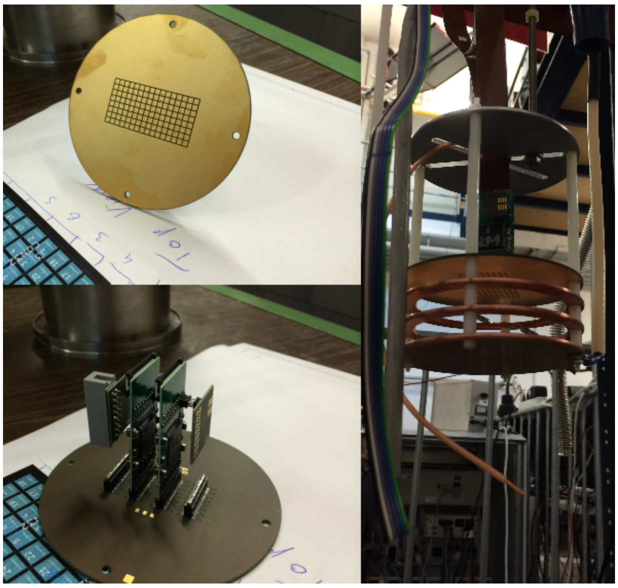


Figure 15: Devices used in Bern to study the feasibility of readout scheme.

The final ArgonCube demonstrator with three $2 \times 2 \times 5$ m^3 size modules and two $1 \times 2 \times 5$ m^3 modules will be installed in the facility after the first phase of the R&D program with the Mini-ArgonCube device is concluded. This detector will feature the techniques developed, tested and optimized with the previous prototypes. ArgonCube will be used to study several parameters, such as the overall geometric efficiency, the calorimetric capabilities (by means of charged particle beams), the effect of the modular structure on the reconstruction efficiency as a function of the energy, and the evaluation of the accuracy in the momentum reconstruction and particle identification of leptons and hadrons in the momentum range from 0.5 to 10-20 GeV/c.

Each module will reflect the findings obtained within Phase 1, in particular for the charge readout and the light detection. The module overall layout is the one described in Section 3. Fig.16 shows a schematic design of the full ArgonCube detector. One can see the four independent modules hosted in the cryostat and one module being extracted.

The exact layout of this setup (number of modules and lateral dimensions) has still to be optimized by simulation studies. On the one hand, the idea is to experience the exact features of a 2×2 m^2 module, but at the same time to test electromagnetic shower energy sharing properties when several modules are involved. Therefore, all possibilities are still open. One possible solution could be to have three modules in the front row where the two external ones are smaller in lateral dimensions.

The choice of the cryostat to host the full size ArgonCube modules is under evaluation. We consider the possibility to share time with a cryostat that might become available at the CENF platform to test the future LBNF modules [42].

The technical details of module readout, geometry and layout, as well the design of the main cryostat will become more evident once the Phase 1 R&D begins to deliver the first results with cosmic rays. Our proposal is therefore to come at that moment with a detailed technical proposal ready to be presented to the SPSC for approval. In the meantime, detailed simulation work, structural engineering modeling, cryogenics design and the construction of a full size mock-up will take place and all findings related to the Phase 1 will be integrated.

7.1 Detector Installation and Operation

The technique by which modules are inserted and removed from the cryostat volume is of great relevance and, to some extent, a key feature of this project. The modular approach allows both servicing of the TPC and upgrades detector as time goes on.

The first step is to prepare the large ArgonCube cryostat to be able to receive the TPC modules. The constraints and the complexity of the modules are less critical than for other envisioned approaches [30] [42]. This is due to the fact that the outside volume of liquid argon has no specific purity requirements. Since the pure liquid is confined and handled inside individual modules, the requirements to the outer cryostat are greatly simplified. The main liquid argon bath equalizes the hydrostatic pressure at the modules boundaries and maintains a constant liquid temperature. Mechanically, the cryostat must be equipped with a flange

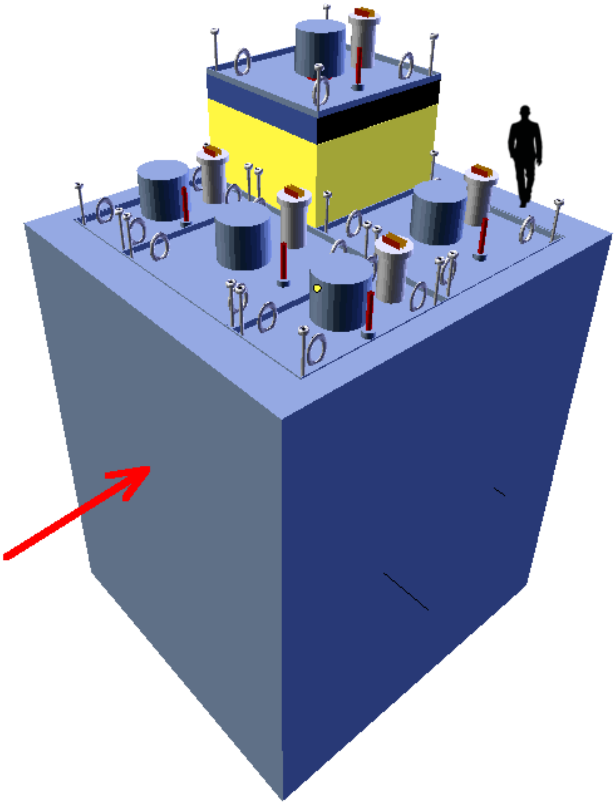


Figure 16: Schematic view of the ArgonCube detector. The 5 modules are visible, with one of them is partly extracted. The beam direction is indicated by the red arrow.

capable to handle individual modules. In particular, this is important during the insertion and removal process of the modules. In the following, we describe the sequence of operations to insert and bring into operation any individual modules.

The first TPC module with its fully equipped top flange is initially lowered into the outer volume to its nominal position at one of the corners. The top flange is fixed to the vessel's top flange by a 3 mm diameter indium wire that serves as a vacuum seal. Next, the positions of the other modules are closed by dummy placeholder "bottom" flanges, sealed one by one in the same way. After this operation the top surface is closed. Then, the warm test of vacuum tightness of the whole vessel can be performed using a helium leak checker, according to the maximum tolerable leak rate that is defined a priori.

The readout electronics is then connected via a low-signal flange connector. The charge readout is tested with a test-pulser and test capacitors for each channel of the preamplifier ICs. Next, the first module is connected via its filter to the outer bath, being filled with liquid argon through the line corresponding to one of the dummy flanges. The cryocooler of the inserted module is set to stabilize the internal pressure at the atmospheric level. The gas produced by evaporation during the cooling-down of the vessel and the module structure is vented via an exhaust valve of the module and by that on the top frame flange. The argon level is monitored via a level meter of the outer volume and visually thanks to an optical feedthrough of the inserted module. Once the cooling-down is completed and the argon level in both outer and inner volumes reaches the nominal value ($\sim$10 cm above the field-liner structure), the filling flux is slowed down to keep the liquid level constant in the outer bath.

At this stage the drift field can be applied to the TPC and the first cosmic muon tracks depending on the purity of the outer volume argon, can be detected. In order to reach the nominal argon purity the valve box is switched to decouple the inner volume from the outer one. The recirculation pumps are turned on and the liquid argon starts to be purified through the oxygen-trapping filters. A portable UV laser unit is then placed on top of the TPC and ionization tracks from the laser can be detected, as well. The process of purification is monitored by the observation of charge attenuation from the laser-induced tracks, or, alternatively, from those of high-energy cosmic muons. Once the purity level reaches the asymptotic value of 0.1 ppb of oxygen-equivalent concentration, a first test of the cryocooler performance and stability against breakdowns can be conducted. The drift field uniformity can be measured with laser tracks, as described above. The verification of the module fiducial volume is conducted at this stage, as well.

While the second TPC module is inserted, the already commissioned module stays in operation and the purity is continuously monitored to quantify the income of oxygen from ambient air. The second module is placed on top of its corresponding dummy flange and is attached with the fixation poles. The top seal of the flange is then removed and the outer liquid volume is exposed to ambient atmosphere through a narrow gap around the flange. A slight overpressure in the outer volume is kept to ensure a positive gas argon flux from inside the volume to the atmosphere. This flux should mitigate potential risks of contamination from the ambient air to the argon. The valve box is set in order to connect the module to the outer bath and, together with the dummy flange at the bottom, it is slowly lowered into the bath with a speed of 1 mm/s. This allows the module structure to cool down without excessive thermal stresses. The whole insertion procedure lasts less than one hour. The evaporated argon, as before, is vented out via an exhaust valve of the module itself and of the one mounted on the vessel top frame flange. During the insertion the level of liquid inside the module is 20-30 cm lower than in the outside volume. The buoyancy of the corresponding volume limits the insertion speed, hence providing additional safety limit for the cooling rate. Once the module reaches its nominal position, the top flange is sealed with an indium wire and the module can be turned on following the same procedure, as for the first module. Insertion and commissioning of the following modules is performed in a similar way, while continuously monitoring the liquid purity in the modules already in operation.

For the extraction of modules, the liquid recirculation is turned off and the first module valve box is set to drain the liquid directly to the outside volume. The top flange indium seals are removed and the module is lifted up with a speed such to allow the liquid draining from the inner volume with a level difference inside-to-outside not larger than 10-20 cm (5 to 10 minutes). The bottom flange reaches the top level position and the gap around is temporarily sealed with indium. This operation is repeated when the flange temperature is equalized with the nominal top flange temperature (slightly below room temperature). During the whole procedure the purity of liquid argon in the other three modules is continuously monitored. After warming up, the module can be detached from its dummy flange and moved away for inspection. The re-insertion procedure does not differ from the initial insertion sequence described above.

The flux of argon during normal operation of the detector, as well as during insertion-extraction, is controlled by a valve box placed under the bottom of the fibreglass case of each module, which is in the outer "dirty" argon volume. The scheme of flux switching is shown in Fig 17. The valves can be configured in one of three modes:

(i) Connecting the inner and the outer volumes through a filling oxygen trap located near the valve box (valves VF1 and VF2 are opened). In this configuration the argon flows from the outer volume into the module during its insertion to the detector via a purifier, similar to that used for the ArgonTube detector. This allows bringing the impurity concentration in the inner liquid down to the level of 1 ppb.

(ii) Connecting the inner volume both to the recirculation pump and to the second oxygen trap (valves VR1 and VR2 are opened). This configuration is used during normal detector operation, allowing to further purify the argon down to the level of 0.1 ppb. The recirculation pump, a Barber-Nichols turbine, provides 300 l/s argon flow for extended time.

(iii) Connecting the inner volume directly to the outer one (valve VD is opened). This scheme is used during module extraction in order to drain the liquid from the inner to the outer volume.

A Sumitomo helium cryocooler mounted on the top flange provides heat sink from the liquid bulk to the outside of the module, keeping the liquid at the required temperature. The power of the cooling head is linearly regulated such that the pressure inside the module is at the level of 1050 mbar. This allows to maintain the liquid in the active volume below its boiling point. Such measure helps preventing accidental sparks due to gas bubbles formed in the high field region of the device.

Under the valve box and the recirculating system another flange is mounted ending the module from below. This flange is a replica of the top one in the outer edge but without any openings. The bottom flange is fixed to the bottom of the fibreglass case by four detachable poles. When the module is extracted from the outer bath up to the height where the bottom flange takes the place of the top flange, it is fixed to the neighbor flanges and sealed with the same technique. The mounting poles are then removed and the TPC module detached from the bottom flange. The module can be transported to the test/reparation site after this operation, after its warm-up and drying of any condensed water and ice.

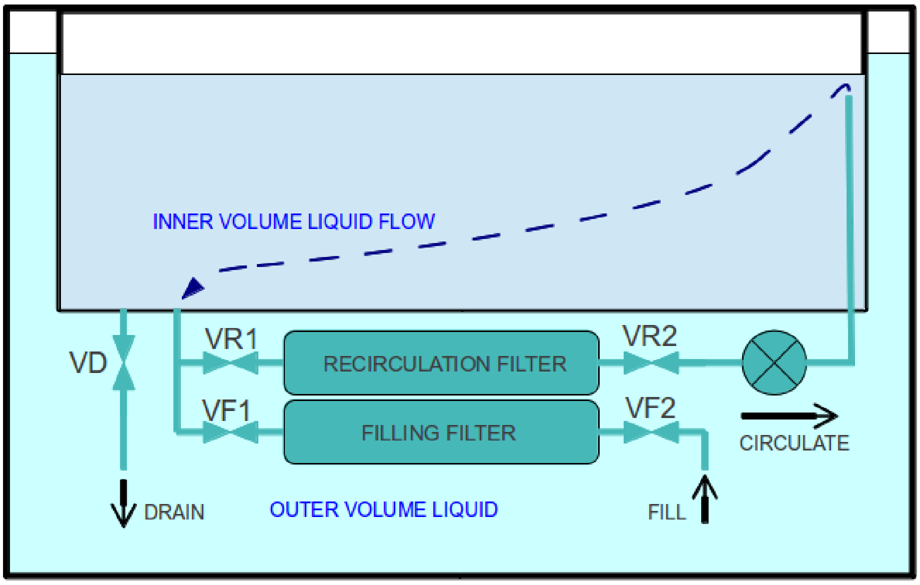


Figure 17: Liquid argon flow diagram. Module insertion: VF1 and VF2 are opened to let argon flow into the inner volume through the filling filter. Module extraction: VD opened to drain liquid from inner volume to outer. Normal operation: VR1 and VR2 are opened, recirculation pump is providing argon purification through circulation filter.

8 Cost, Planning and Milestones

8.1 Project Milestones

The R&D part of this project is clearly defined in 2 phases. The first one serves in the final definition of the detector layout and characteristics of the demonstrator to be built for of Phase 2.

Phase 1

Phase 1 will start soon after the presentation of the LoI to the SPSC Committee and its hopefully positive reception and encouragement to proceed further with a proposal.

- May 2015: mechanical definition of the mini module layout with detailed design of all services (field shapers, feedthroughs, internal services and top/bottom flanges) and cryogenic components.
- September 2015: small-scale pre-prototypes of the charge readout and light collection ready for tests and assessment.
- April 2016: first mini-module constructed and ready for cosmic-ray exposure in Bern.
- July 2016: all mini-modules constructed and ready for cosmic-ray exposure.
- November 2016: Phase 1 cryostat equipped with mini modules arrives at CERN to be installed on an SPS North Area beam line for further beam tests.

Phase 2

Once the first results from cosmic-ray exposure of Phase 1 will become available, a detailed technical proposal for Phase 2 will be prepared and presented to the SPSC. If approved, the construction of the demonstrator will start.

- July 2016: Detailed technical proposal presented to the CERN SPSC for approval.
- June 2017: first full module ready at CERN in a dedicated clean room.
- October 2017: insertion of all modules into the cryostat.
- April 2018: if the results will be positive as expected, a TDR could be submitted for a large detector at LBNF or for a possible upgrade of the SBN detector complex.

8.2 Cost and Planning

We expect collecting further interest from several more institutions wordwide. However, the costs of Phase 1 are kept to the minimum and will be mostly covered by existing hardware and infrastructure (cryostat, cryogenics, ...). The investments for Phase 1 will mainly go to the charge readout and the related electronics, but here again we count on using the same hardware that is already planned for the short baseline program at FNAL and for the LBNF module tests (in particular for the electronics, developed at BNL). We think that new hardware costs will remain at the level of 200-300 KCHF to be shared within the collaboration by running R&D grants.

The main costs will relate to the necessary manpower, but here again we will count on the interest of existing collaborators. The costs will mainly cover students and young graduate positions in the various institutions, while technicians and engineer manpower is already available at various institutions.

For Phase 2 the situation is different. For cryostat and cryogenics we count on the possibility to use and share with other groups the cryostat and cryogenics facility that CERN is providing as part of the Neutrino Platform project at CERN. For the material costs we count on dedicated grants obtained by the various groups in their respective countries and a shared support by the CERN group. This should be formalized by MoUs between CERN and the collaborating institutions.

We think that the material costs should not exceed 1 MCHF and the direct additional manpower costs will not exceed 4 FTEs, excluding the technician labor already available in most of the partner laboratories.

For the entire duration of the project we will organize as a scientific collaboration (CERN style) with an Executive Body and Collaboration Board capable to guide the collaboration through the various phases.

9 Conclusions and Outlook

The largest LAr TPC operated to date is the T600 detector of the ICARUS collaboration at the LNGS underground laboratory, filled with 600 ton of liquid argon (476 ton fiducial mass). The next largest LAr TPC physics experiment is MicroBooNE, with a total liquid argon mass of 170 ton. The MicroBooNE TPC has a single drift volume with a width of 2.5 m, 2.5 m height and 10 m length resulting in 89 ton of active target mass. For the future, the recent U.S. P5 report [5] states that a future large long baseline neutrino oscillation experiment has as main scientific goal a mean sensitivity to CP violation larger than 3σ over more than 75% of the range of possible values of the unknown CP violating phase δ_{CP}. By current estimates, this corresponds to an exposure of 600 kt×MW×y assuming systematic uncertainties of 1% and 5% for signal and background, respectively. With a wide band neutrino beam produced by a proton beam of 1.2 MW, this implies a far detector with a fiducial mass of larger than 40 kiloton of liquid argon and a suitable near detector.

For the far detector, this is 84 times larger than ICARUS. The direct scaling of the current approaches might not be sufficient, as many elements of the detector cannot be sized this much larger. More importantly, the risks of failure will have to be carefully assessed as many malfunctions would not directly scale and extrapolating to such a large factor is very difficult. As an example, one difficulty is the application of a sufficiently high drift field. The longest drift distance reached to date is that of ArgonTube, as described earlier in Section 5. This performance does not come without a layer of complexity that needs to be addressed.

Our proposed R&D directly addresses the scalability of the LAr TPC technology. It also takes into account the challenges related to the application of very high voltages and the maintenance of extreme purities to ensure long drift lengths. As shown in Sections 6 and 7, we propose to use TPCs with a relatively short drift distance which have been proven to work very reliably with minimal operational risks. The modular design ensures the scalability of the design to very large active masses. In a very simplistic view, an array of 25 × 25 times the MicroBooNE detector would exceed the P5 recommendations in term of active mass.

We would also like to note that the P5 further recommends to "*select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab*". As an intermediate detector towards a large mass observatory of the order of 50 kton, we could very well imagine upgrading the detectors at the Fermilab short baseline significantly. A LAr TPC of the order of a kton or more could be realized in time to be beneficial to the program.

We further stress the fact that the ArgonCube modular design has advantages in terms of collaboration building. Collaborators can take responsibility for a number of modules and claim them as deliverable as we plan to be already at the level of Phase 1 and Phase 2. Very positive feed-back from participating (or potential new) collaborators has been received in this respect.

Finally, the timescale until a very large underground observatory materializes will extend well into the next decade. Therefore, we believe that one has to plan for the possibility of incorporating new developments in the LAr TPC technology for the realization of such a momentous project. Several choices in the design of the current LAr TPCs, and also for future large mass observatories date back to the first prototypes. On the other hand, novel ideas are being tested and developed and rapid progress is being made, *e.g.* for cold readout electronics. There is therefore a great potential for several elements of the LAr TPC technology that would contributing in a large observatory better, decrease its cost and make it more robust.

With this LoI we propose a two stage R&D program aimed at a new implementation of the LAr TPC technique, the ArgonCube, exploiting a fully modular detector design and the availability of novel signal readout schemes. The proposed technology builds up on the large experience gathered so far by the collaborating institutions. The ArgonCube technological choices will provide a performing, simple, robust and cheap implementation, largely based on well established achievements. In addition, the modularity of the detector construction will allow for a democratic share of the construction load, likely favoring interest and the future involvement of new collaborators. In a first phase, we plan to construct a feasibility study that should prove the viability of the proposed modular layout, based on relatively short drift lengths and the new approaches to charge readout. Detector modules will be built and take data, at first, using cosmic ray muons and later on by exposure to CERN test beams. In a second step, a full size demonstrator based on the technologies certified in Phase 1 will be constructed and operated at the CERN Neutrino Platform.

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