Memorandum to the CERN SPSC

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Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches

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1 Introduction

In the late 60's the potentials of liquid noble gases as detection media to realize position sensitive detectors with high spatial resolution was recognized (see *e.g.* [1]). Active R&D eventually led to the possibility of using such media for large and performing calorimeters for particle physics experiments (see *e.g.* [2]). Among the many ideas developed around the use liquid noble gases, the Liquid Argon Time Projection Chamber (LAr TPC), conceived and proposed at CERN by C. Rubbia in 1977 [3], certainly represented one of the most challenging and appealing designs. The technology was proposed as a tool for uniform and high accuracy imaging of massive detector volumes. The operating principle of the LAr TPC was based on the fact that in highly purified LAr ionization tracks could indeed be transported undistorted by a uniform electric field over distances of the order of meters [4]. Imaging is provided by wire planes placed at the end of the drift path, continuously sensing and recording the signals induced by the drifting electrons.

The feasibility of this technology has been further demonstrated by the extensive ICARUS R&D programme, which included studies on small LAr volumes about proof of principle, LAr purification methods, readout schemes and electronics, as well as studies with several prototypes of increasing mass on purification technology, collection of physics events, pattern recognition, long duration tests and readout. The largest of these devices had a mass of 3 tons of LAr [5, 6] and has been continuously operated for more than four years, collecting a large sample of cosmic-ray and gamma-source events. Furthermore, a smaller device with 50 l of LAr [7] was exposed to the CERN neutrino beam, demonstrating the high recognition capability of the technique for neutrino interaction events.

The realization of the 600 ton ICARUS T600 detector culminated with its full test carried out at surface during the summer 2001 [8]. This test demonstrated that the LAr TPC technique can be operated at the kton scale with a drift length of 1.5 m. Data taking of about 30000 cosmic-ray triggers have allowed to test the detector performance in a quantitative way and results have been published in [9, 10, 11, 12, 13].

The success of the fully industrial construction of the T600 module and its excellent performance in the surface test run has further motivated and justified the idea of cloning the detector to reach the 3000 ton mass scale (ICARUS T3000 detector), as required to accomplish astroparticle physics experiments at LNGS [14]. The T3000 certainly represents the largest, practical achievable size by employing a modular approach. On the other hand, modularity was not imposed by the LAr TPC technique but it is an implementation choice motivated by the boundary conditions of the LNGS laboratory and by the requirement to build the detector outside of the underground hall. As a matter of fact, the design of a monolithic magnetized large mass LAr TPC has then been considered [15]. It is based on the extrapolation ("scaling up") of the technique developed by the ICARUS Collaboration, however, embedded in a very large magnet.

Having at our disposal the mature technique developed in the context of the ICARUS programme, physics is today calling for at least two applications at two different mass scales [16]: on the one hand, ultimate nucleon decay searches and high statistics astrophysical and accelerator neutrino experiments will require very large detector masses, of the order of 100 kton. On the other hand, future precision studies of neutrino interactions, calorimetry and near stations for long baseline beam experiments will need detectors with masses in the range of $\sim$ 100 ton.

There is a high degree of interplay and a strong synergy between small and large mass scale apparatuses, the very large detector needing the small one in order to best exploit the measurements with high statistical precision that will be possible with a large mass. We believe that small and very large LAr detectors could play significant roles in a potential future high-intensity neutrino beam facility.

Some activities are in progress along these lines of thoughts and more work will be definitely needed for the future. In particular, we are starting the conceptual design of a 100 kton LAr TPC detector and progressing in the identification of an R&D strategy. We present here a brief overview of our current ideas, activities and plans. We intend to consider all that as the trigger for the creation of a Network of colleagues interested in the further, coherent development of the above ideas, as required to meet the future challenges of neutrino and astroparticle physics.

2 Physics potential with accelerator and astrophysical neutrinos, and matter stability searches

For many years phenomenological studies of the physics potential of future LAr detectors have been conducted encompassing a large physics programme ranging from neutrino physics with artificial beams or astrophysical neutrinos to the search for nucleon decay. Various situations have been studied. For more information we refer to the relevant publications indicated in the following. A detailed review of the physics potential of a LAr 100 kton detector is in preparation [17].

Neutrino Superbeams. The physics potential of the large LAr detector combined with a neutrino Superbeam has been studied in [18, 19]. This kind of measurement advantageously profits from the very good granularity provided by the technique. In particular, the search for $\nu_\mu \to \nu_e$ events is very clean owing to the excellent e/π^0 separation. This was studied in detail in [20].

A systematic study of meson production and neutrino yields was performed in [18] for different incident proton energies and baselines with the aim of optimizing the parameters of a neutrino Superbeam. It is found that to each baseline corresponds an "optimal" proton energy which minimizes the required integrated proton intensity needed to observe a given number of oscillated events. In addition, the neutrino event rate in the relevant region scales approximately linearly with the proton energy. Hence, baselines and proton energies could be adjusted and the performance for neutrino oscillation searches would remain roughly unchanged provided that the product of the proton energy times the number of protons on target remained constant. These considerations were applied to the specific cases of 2.2, 4.4, 20, 50 and 400 GeV protons.

In the above discussions, we implicitly assumed the ability of the LAr TPC to equally well detect accelerator neutrino events from low (~ 100 MeV) to high energy (~ 10 GeV). This is required to allow for the vast range of baseline and energy optimizations and it clearly represents an advantage provided by the unbiased, bubble-chamber like imaging of the technique.

We believe that the optimization of the proton energy (and hence of the baseline) will in practice follow from the overall design and upgrades of the future accelerator complex hosting the beam and might be accomplished in stages according to physics advances and/or to the availability of financial resources. The various neutrino beam optimizations will most likely be performed in accordance with the global physics programme, which could possibly include nuclear, muon, kaon and neutron physics. However, a 100 kton LAr detector would provide a general purpose detector able to exploit all kinds of neutrino Superbeams.

Neutrino Betabeams. The physics potential of the large LAr detector in a Betabeam [21] is presented in [22]. The imaging of the events and the high energy resolution in the LAr TPC make the study of Betabeams very attractive. The possibility to have separately pure ν_e and $\bar{\nu}_e$ beams combined with a massive 100 kton detector would be an ideal configuration to study the neutrino oscillation parameters, in particular the CP-phase.

We tentatively considered the following baselines: $L = 130$ km, 400 km and 950 km with their corresponding neutrino energies [22]. The energy of the neutrinos is determined by the ion γ factor in the storage ring. One finds that the Betabeam optimization requires the longest possible baseline, as long as matter effects are small, in order to benefit from (1) the rise of the neutrino cross-section (this is particularly true for antineutrinos) and (2) the reduction of momentum smearing introduced by the Fermi motion. While the baselines of 130 and 400 km would be nicely accommodated by the CERN SPS maximal energy, the optimal energy of the 950 km baseline will require a machine able to accelerate protons up to ~ 1 TeV.

From the detector side a good $\mu/\pi^{\pm}$ discrimination is important in order to suppress the neutral current background with a charged leading $\pi^{\pm}$. The combination of the information from the imaging (tracking and energy) with the Cerenkov light could provide adequate particle muon/pion separation [44]. Preliminary considerations show that one could separate pions from muons in the kinetic energy range between 100 MeV (threshold) and 850 MeV.

Neutrino Factories. The physics potential of a magnetized large LAr detector combined with a Neutrino Factory [23] has been studied in [24, 25, 26, 27, 28, 29, 30, 31, 32, 33]. General ideas for intermediate and long baseline scenarios have also been discussed in [34, 35].

In [27] it was concluded that in order to fully address the oscillation processes at a Neutrino Factory, the ideal detector should be capable of identifying and measuring all three charged lepton flavors produced in charged current interactions and of measuring their charges to discriminate the incoming neutrino helicity. Embedding the volume of Argon inside a magnetic field would not alter the imaging properties of the detector and the measurement of the bending of charged hadrons or penetrating muons would allow a precise measurement of the momentum and a determination of their charge.

For long penetrating tracks like muons, a field of 0.1 T allows to discriminate with $> 3\sigma$ the charge for tracks longer than 4 m. This corresponds to a muon momentum threshold of 800 MeV. Hence, performance is excellent even at very low momenta. Unlike muons or hadrons, the early showering of electrons makes their charge identification difficult. The track length usable for charge discrimination is limited to a few radiation lengths after which the shower makes the recognition of the parent electron more difficult. From full simulations one found that the determination of the charge of electrons in the energy range between 1 and 5 GeV is feasible with good purity, provided the field has a strength in the range of 1 T. Preliminary estimates show that these electrons exhibit an average curvature sufficient to have electron charge discrimination better than 1% with an efficiency of 20%.

From quantitative analyses of neutrino oscillation scenarios one can conclude [27] that in many cases the discovery sensitivities and the measurements of the oscillation parameters are dominated by the ability to measure the muon charge. However, there are cases where identification of electron and tau samples significantly contribute. Kinematical searches for τ appearance in the context of very long baseline experiments have been discussed in [29]. One could then make a unique measurement of the $\nu_e \to \nu_\tau$ transition performing a stringent unitarity test of the lepton mixing matrix.

Apart from being able to measure very precisely the magnitude of all the elements of the mixing matrix, the more challenging and most interesting goal of the Neutrino Factory will be the search for effects related to the phase of the mixing matrix. This complex phase will alter the neutrino flavor oscillation probabilities and will most strikingly introduce a difference of transition probabilities between neutrinos and antineutrinos (the so called CP-violation effects, however affected by matter effects), and between time-reversed transitions (the so called T-violation effects unaffected by matter effects).

As shown in [25], the ability to measure electron and muon charges is the only way to address T-violation, since it implies the comparison between the appearance of ν_μ ($\bar{\nu}_\mu$) and $\bar{\nu}_e$ (ν_e) in a beam of stored μ^+ (μ^-) decays as a function of the neutrino energy. A magnetized LAr detector would be unique in this respect.

Astrophysical neutrinos. The astrophysical neutrino physics programme is naturally very rich for a 100 kton LAr observatory. One expects about 10000 atmospheric neutrino events per year and about 100 ν_τ charged current events per year from ν_μ oscillations. These events are characterized by the excellent imaging capabilities intrinsic to the LAr TPC and will provide an unbiased sample of atmospheric neutrinos with an unprecedented quality and resolution. This will allow for improved measurements of atmospheric events, compared to existing or planned studies based on Cerenkov ring detection.

Solar neutrinos provide about 324000 events per year with electron recoil energy above $\sim$5 MeV, whose energy will be measured with high accuracy (the threshold depends on the actual radioactive background conditions at the underground site). This will provide the possibility to make precision measurements of the solar neutrino flux and to study possible short and long term variations, for example, related to the solar cycles.

The physics that can be performed via the observation of a core collapse supernova has been discussed in [36, 37, 38]. A galactic SN-II explosion at 10 kpc yields about 20000 events. Sensitivity to extragalactic supernovae (*e.g.* in Andromeda) should be possible. Relic SN neutrino fluxes can also be addressed. A characteristic feature of the LAr TPC is the accessibility to several independent detection channels (elastic scattering off electrons, charged neutrino and antineutrino, and neutral currents on Argon nuclei) which have different sensitivities to electron-neutrino, anti-electron-neutrino and other neutrino flavors (muon and tau (anti)neutrinos). The study of all neutrino flavors from supernova explosion would be performed in great detail by a LAr detector, in an appreciably better way when compared to water Cerenkov detectors, which are mainly focusing on the $\bar{\nu}_e$ flavor. A high sensitivity to ν_es is fundamental to study the shock breakout, namely, the neutrino burst from the core collapse, preceding the cooling phase [37]. In addition, the sensivitiy to all flavors during the cooling phase allows to over-constrain the supernova and the flavor mixing parameters and, to some extent, disentangle neutrino from supernova physics [36].

Matter stability. Last but not least, the physics of the nucleon decay has been addressed in [39, 40]. Direct evidence for GUT and baryon number violation represents one of the outstanding goals of particle physics. Nucleon decay searches require a very good knowledge of the backgrounds induced by atmospheric neutrinos. Precise understanding of the neutrino physics is therefore a fundamental component for ultimate proton decay experiments.

A target of 100 kton = 6×10^{34} nucleons yields a sensitivity for protons of $\tau_p/Br > 10^{34}$ years × T(yr)× ϵ at the 90% C.L. in the absence of background. This means that lifetimes in the range of 10^{35} years can be reached within 10 years of operation. Channels like $p \to \nu K$ have been shown to be indeed essentially background free. A study of the background due to cosmic-rays can be found in [41].

Although the envisioned detector has a mass of 100 kton, its physics programme effectively competes with a 1 Megaton water Cerenkov [42] owing to better event reconstruction capabilities provided by the LAr technique [43]. A 100 kton LAr TPC would represent one of the most advanced massive underground detectors built so far [43].

3 Conceptual design of a 100 kton liquid Argon TPC

In this Section we summarize conceptual design ideas for a 100 kton LAr TPC [44]. Although the LAr TPC technology has been demonstrated to be mature and the basic R&D studies have been completed by the ICARUS Collaboration, the possibility to construct and operate a very large LAr TPC can be considered a very complex technical task. Here we describe some issues that to our mind indicate that a 100 kton detector might be technically feasible, economically affordable and able to be safely operated.

A single LAr volume is the most attractive solution from the point of view of construction, operation and cryogenics and is to be favored over the modular approach. It appears that the maximum size of the single unit is limited by the requirement to locate the detector in an underground cavern [45].

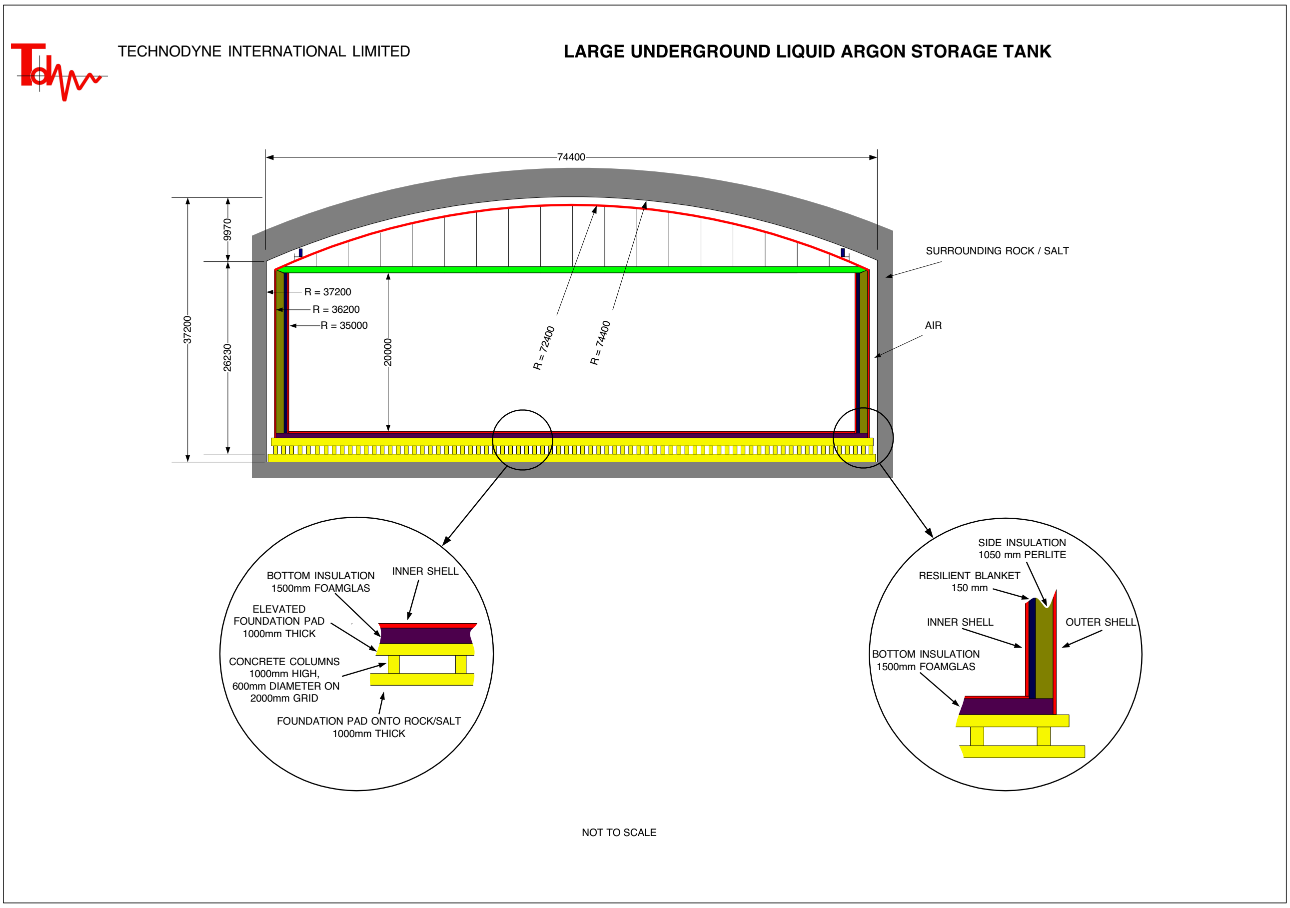

Figure 1: Conceptual design of a 100 kton liquid Argon cryogenic tanker developed by Technodyne International Limited [47].

The basic design features of the detector can be summarized as follows:

1. **Single 100 kton "boiling" cryogenic tanker** at atmospheric pressure for a stable and safe equilibrium condition (temperature is constant while Argon is boiling). The evaporation rate is small (less than 10^{-3} of the total volume per day given by the very favorable area to volume ratio) and is compensated by corresponding refilling of the evaporated Argon volume.

2. **Charge imaging, scintillation and Cerenkov light readout** for a complete (redundant) event reconstruction. This represents a clear advantage over large mass, alternative detectors operating with only one of these readout modes. The physics benefit of the complementary charge, scintillation and Cerenkov readout are being assessed [17].

3. **Charge amplification to allow for very long drift paths**. The detector is running in bi-phase mode. In order to allow for drift lengths as long as ~ 20 m, which provides an economical way to increase the volume of the detector with a constant number of channels,

charge attenuation will occur along the drift due to attachment to the remnant impurities present in the LAr. We intend to compensate this effect with charge amplification near the anodes located in the gas phase.

4. **Absence of magnetic field**, although this possibility might be considered at a later stage. R&D studies for charge imaging in a magnetic field are on-going and results are expected soon [46]. Physics studies [26] indicate that a magnetic field is really only necessary when the detector is coupled to a Neutrino Factory and can be avoided in the context of Superbeams and Betabeams.

The cryogenic features of the proposed design are based on the industrial know-how in the storage of liquefied natural gases (LNG, $T \simeq 110$ K at 1 bar), which developed quite dramatically in the last decades, driven by the petrochemical and space rocket industries. LNG are used when volume is an issue, in particular, for storage. The technical problems associated to the design of large cryogenic tankers, their construction and safe operation have already been addressed and engineering problems have been solved by the petrochemical industry. The current state-of-the-art contemplates cryogenic tankers of 200000 m^3 and their number in the world is estimated to be $\sim$ 2000 with volumes larger than 30000 m^3 with the vast majority built during the last 40 years.

Concerning safety issues, we note that during the last 60 years there have been only two spontaneous ruptures of large refrigerated tanks (in 1944 and 1977). In the first, the cause was attributed to brittle fracture due to the steel used and the second was due to a failure of a weld that had been repaired following a leak the previous year. Large ships transporting volumes up to 145000 m^3 of LNG often cross the oceans. Nowadays severe leaks of liquid are simply discounted as a mode of failure.

Most LNG tankers are of double-wall construction with efficient but non-vacuum insulation between the walls. Large tankers are of low aspect ratio (height to width) and cylindrical in design with a domed roof. Storage pressures in these tankers are very low.

We have appointed the Technodyne International Limited, UK [47], which has expertise in the design of LNG tankers, to initiate a feasibility study in order to understand and clarify the issues related to the operation of a large underground LAr detector. Commercial tankers are located on the surface and hence, for our application, although of reasonable size, one must face the additional constraint of the the detector being located underground. Initial results indicate that *the extrapolation from LNG to liquid Argon is rather straight-forward.* A conceptual design is shown in Figure 1. The full report of this study, including the tank design, cavern and process considerations (initial fill, re-liquefaction of boil-off, purification), safety issues and cost estimate will be available soon.

Having in mind the above considerations, a schematic layout of the inner detector is shown in Figure 2. The detector is characterized by the large fiducial volume of LAr included in a large tanker, with external dimensions of approximately 40 m in height and 70 m in diameter. A cathode located at the bottom of the inner tanker volume creates a drift electric field of the order of 1 kV/cm over a distance of about 20 m. In this field configuration ionization electrons are moving upwards while ions are going downward. The electric field is delimited on the sides

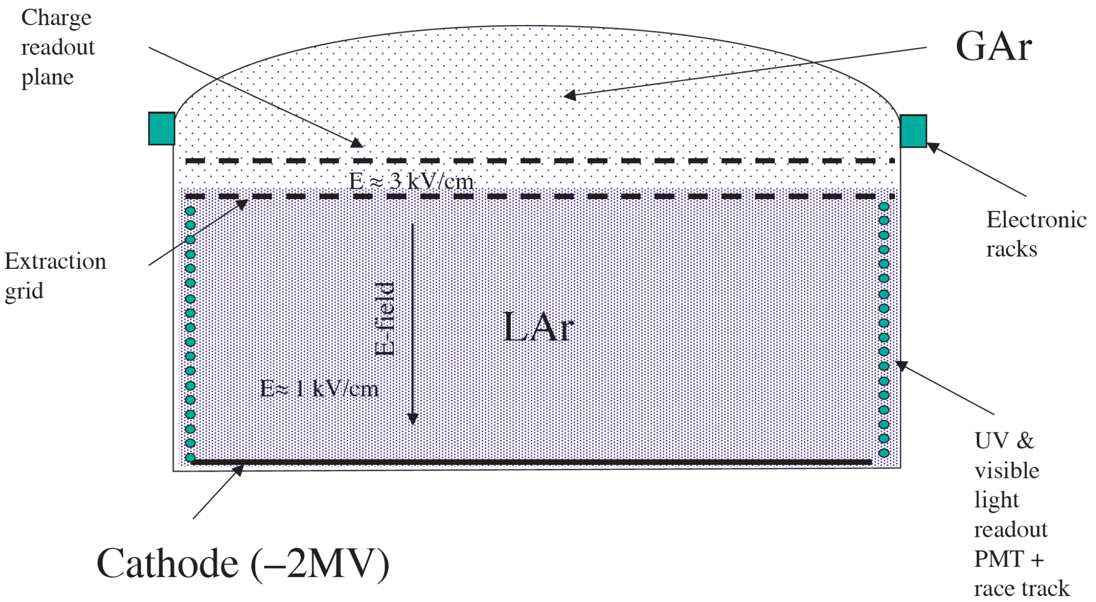

Figure 2: Schematic layout of a 100 kton liquid Argon detector. The race track is composed of a set of field shaping electrodes.

of the tanker by a series of ring electrodes (race-tracks) placed at the appropriate potential by a voltage divider.

The tanker contains both liquid and gas Argon phases at equilibrium. Since purity is a concern for very long drifts of 20 m, we assume that the inner detector could be operated in bi-phase mode: drift electrons produced in the liquid phase are extracted from the liquid into the gas phase with the help of a suitable electric field and then amplified near the anodes. In order to amplify the extracted charge one can consider various options: amplification near thin readout wires, GEM [48] or LEM [49]. Studies that we are presently conducting show that gain factors of 100-1000 are achievable in pure Argon [50]. Amplification operates in proportional mode. Since the readout is limited to the top of the detector, it is practical to route cables out from the top of the dewar where electronics crates can be located around the dewar outer edges.

After a drift of 20 m at 1 kV/cm, the electron cloud diffusion reaches approximately a size of 3 mm, which corresponds to the envisaged readout pitch. Therefore, 20 m practically corresponds to the longest conceivable drift path. As mentioned above, drifting over such distances will be possible allowing for some charge attenuation due to attachment to impurities. If one assumes that the operating electron lifetime is at least $\tau \simeq 2$ ms (this is the value obtained in ICARUS T600 detector during the technical run [12] and better values of up to 10 ms were reached on smaller prototypes during longer runs), one then expects an attenuation of a factor ~ 150 over the distance of 20 m. This loss will be compensated by the proportional gain at the anodes. We remind that the expected attenuation factor (compensated by the amplification) will not introduce any detection inefficiency, given the value of ~ 6000 ionization electrons per millimeter produced along a minimum ionizing track in LAr.

In addition to charge readout, we envision to locate PMTs around the inner surface of the tanker. Scintillation and Cerenkov light can be readout essentially independently. LAr is a very good scintillator with about 50000 γ/MeV (at zero electric field). However, this light is essentially distributed around a line at $\lambda = 128$ nm and, therefore, a PMT wavelength shifter (WLS) coating is required. Cerenkov light from penetrating muon tracks has been successfully detected in a LAr TPC [11]; this much weaker radiation (about 700 γ/MeV between 160 nm and 600 nm for an ultrarelativistic muon) can be separately identified with PMTs without WLS coating, since their efficiency for the DUV light will be very small.

In summary, about 1000 immersed phototubes with WLS would be used to identify the isotropic and bright scintillation light, while about 27000 8"PMTs without WLS would provide a 20% coverage of the surface of the detector for the Cerenkov light. These latter should have single photoelectron counting capabilities.

We stress that the above detector layout has to be considered as a preliminary conceptual design, with the aim of driving the required, future developments. There is obviously room for new ideas and several alternative options are envisageable.

4 Ongoing studies and initial R&D strategy

We have started a few studies with the aim of identifiying the main issues of the future systematic R&D and optimization activities. Work is being presently conducted on:

1. **The study of suitable charge extraction, amplification and imaging devices.**

   We are continuing an R&D study to further optimize the technique for charge extraction, amplification and imaging. We are seeking a solution which yields gains between 100 and 1000 in pure Argon, which is electrically and mechanically stable, and easy to be mass produced. Independent studies in the context of an R&D work for Dark Matter detection have given encouraging results [50]. The quality and resolution of imaging after extraction and amplification has to be fully demonstrated.

2. **The understanding of charge collection under high pressure as expected for events occurring at the bottom of the large cryogenic tanker.**

   We are constructing a prototype chamber which will be pressurized to 3-4 bar to simulate the hydrostatic pressure present at the bottom of a future 100 kton tanker. We intend to check that the drift properties of electrons are not affected at these pressures.

3. **The realization of a 5 m long detector column.**

   We are constructing a column-like dewar 6 m long and 40 cm in diameter which will contain a 5 m long prototype LAr detector. The device will be operated with a reduced electric field value in order to simulate very long drift distances of up to about 20 m. Charge attenuation and amplification will be studied in detail together with the adoption of possible novel technological solutions. In particular, several options are being studied for both the HV field shaping electrodes and for the readout devices.

4. **The study of LAr TPC prototypes immersed in a magnetic field.**

   An R&D programme to investigate a LAr drift chamber in a magnetic field was started in 2001. The goal is to study the drift properties of free electrons in LAr in the presence of a magnetic field and to prove that the detection capabilities are not affected. In particular, tests are planned on: the basic imaging properties; the traversing and stopping muons bending; the charge discrimination; the measurement of the Lorentz angle ($\alpha \sim 30$ mrad @ E=500 V/cm and B=0.5 T).

5. **The further development of the industrial design of a large volume tanker able to operate underground.**

   The project initiated with Technodyne International UK should be considered as a first "feasibility" study, meant to select the main issues that will need to be further understood and to to promptly identify possible "show-stoppers". The report will include the tank design, cavern and process considerations (initial fill, re-liquefaction of boil-off, purification), safety issues and cost estimate. If encouraging results are found we expect to continue this study by a more elaborated and detailed industrial design of the large underground tanker also including the details of the detector instrumentation. The cost of the full device located underground has already been preliminarily estimated. At this stage an underground large mass LAr detector appears to be a technically feasible, safe and cost effective option.

6. **The study of logistics, infrastructure and safety issues related to underground sites.**

   We are making preliminary investigations with two "generic" geographical configurations: (i) a tunnel-access underground laboratory such as for example the Gran Sasso [51] or the planned Frejus laboratories [52], (ii) a vertical mine-type-access underground laboratory [53]. Early considerations show that such sites correspond to interesting complementary options. Concerning the provision of LAr, a dedicated, possibly not underground but nearby, air-liquefaction plant is foreseen. Technodyne International has started investigating the technical requirements and feasibility of such a facility.

5 Outlook

Given the extremely appealing physics potential of a large mass liquid Argon astroparticle observatory, nucleon decay and neutrino detector, we warmly invite the community to a deep reflection concerning the feasibility of a next generation 100 kton LAr TPC.

The detector discussed here largely profits of the outstanding experience gathered so far in the study of liquid noble gas detectors, and in particular of the successful development of massive liquid Argon TPCs (see [3], [8] and references therein). The main design features include the possibility of a bi-phase operation with charge amplification for long drift distances, an imaging plus scintillation plus (possibly) Cerenkov readout for improved physics performance, and a very large boiling industrial cryostat (LNG technology). A feasibility study was initiated with Technodyne International UK to investigate the possibilities of constructing a large liquid Argon underground storage tank. The full report of this study, including the tank design, cavern and process considerations (initial fill, re-liquefaction of boil-off, purification), safety issues and cost estimate will be available soon.

The detector offers the widest output for accelerator and astroparticle physics. Coupled to future Superbeams, Betabeams or Neutrino Factories it could greatly improve our understanding of the mixing matrix in the lepton sector with the goal of measuring the CP-phase, and in parallel it would allow to conduct astroparticle experiments of unprecedented sensitivity.

International sites with suitable underground depths and infrastructure for potentially locating such detector should be reviewed and compared, by optimizing the expected physics performance against the parameters of the beam facility.

In order to start up a complete programme of investigations along these lines of thoughts, we intend to promote the creation of an International Network of colleagues and institutions interested in contributing to the development of these ideas, which, if successful, could lead to a submission of Expressions of Interest at a later stage in time.

If CERN will decide to proceed with a high-intensity neutrino facility, we believe that the realization of a 100 kton LAr detector exploiting these beams could greatly benefit from a strong CERN involvement at the level of the engineering, cryogenics, infrastructure, test beams, and safety aspects, with CERN playing the role of logistic center of gravity of the whole project.

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