

Conceptual design of a scalable multi-kton superconducting magnetized liquid Argon TPC

A. Ereditato^a and A. Rubbia^b

^aIstituto Nazionale di Fisica Nucleare, INFN Sezione di Napoli, Napoli, Italy

^bInstitut für Teilchenphysik, ETHZ, CH-8093 Zürich, Switzerland

We discuss the possibility of new generation neutrino and astroparticle physics experiments exploiting a superconducting magnetized liquid Argon Time Projection Chamber (LAr TPC). The possibility to complement the features of the LAr TPC with those provided by a magnetic field has been considered in the past and has been shown to open new physics opportunities, in particular in the context of a neutrino factory. The experimental operation of a magnetized 10 lt LAr TPC prototype has been recently demonstrated. From basic proof of principle, the main challenge to be addressed is the possibility to magnetize a very large volume of Argon, corresponding to 10 kton or more, for future neutrino physics applications. In this paper we present one such conceptual design.

1. Introduction

The liquid Argon Time Projection Chamber was proposed [1] as a tool for uniform and high accuracy imaging of massive detector volumes. The chamber is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances of the order of meters. Imaging is provided by wire planes at the end of the drift path, continuously recording the signals induced. T_0 is provided by the prompt scintillation light.

The main technological challenges are summarized elsewhere [2] and include techniques of Argon purification, operation of wire chambers in cryogenic liquid and without charge amplification, low-noise analog electronics, continuous wave-form recording and digital signal processing. The extensive ICARUS R&D program dealt with studies on small LAr volumes, LAr purification methods, readout schemes and electronics, as well as studies with several prototypes of increasing mass on purification technology, collection and analysis of physics events, long duration tests and readout [3–5]. The test of a 300 ton module carried out at surface [2] has demonstrated that the technique can be operated at large mass scale with a drift length of 1.5 m. Data taking with cosmic-ray events assessed the detec-

tor performance in a quantitative way (see references in [2]), in view of its installation at the LNGS.

The possibility to complement the features of the LAr TPC with those provided by a magnetic field has been considered in the past [6,7] and would open new possibilities: (a) charge discrimination, (b) momentum measurement of particles escaping the detector (*e.g.* high energy muons), (c) very precise kinematics, since the measurement precision is limited by multiple scattering (*e.g.* $\Delta p/p \approx 4\%$ for a track length of $L=12$ m and a field of $B=1$ T). The orientation of the magnetic field can be chosen such that the bending direction is in the direction of the drift where the best spatial resolution is achieved. This is possible since the Lorentz angle is small [8,9]. However, this is not mandatory and the B-field could also be parallel to the drift field.

The presence of magnetic field is certainly beneficial for the application in the context of the neutrino factory, depending on the actual field strength [7]: (1) a low field, *e.g.* $B=0.1$ T, for the measurement of the muon charge (CP-violation); (2) a strong field, *e.g.* $B=1$ T for the measurement of the muon/electron charges (T-violation). For a practical application, however, the mass of the detector will have to be very large, in the mul-

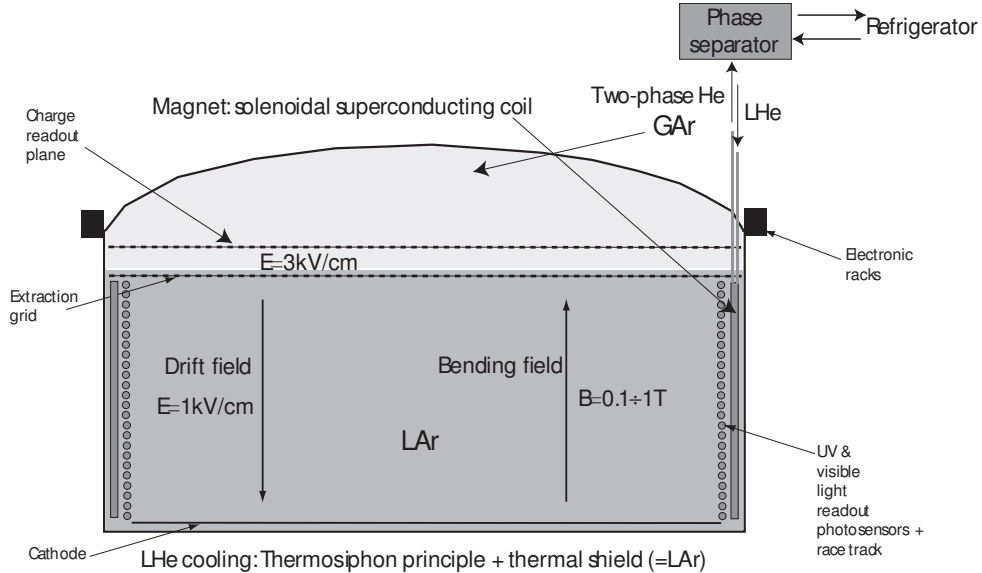


Figure 1. Conceptual design of a superconducting magnetized 100 kton liquid Argon detector. The cryogenic tanker was developed in collaboration with Technodyne International Limited. This design can be scaled down to *e.g.* 10 kton.

tikton range. We present in this paper a design for a superconducting magnetized liquid Argon TPC, based on our design for a large mass detector, described in the next section.

2. A large mass liquid Argon TPC detector with charge imaging and light readout

The success of the fully industrial construction of the ICARUS T600 module and its performance in the surface test run has further motivated the modular idea of “cloning” the T600 module to reach the multi-kton scale. However, modularity was not imposed by the LAr TPC technique itself, but was 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.

On the other hand, we have already presented our conceptual design for a monolithic 100 kton LAr TPC elsewhere [10]. Such a scalable, single LAr tanker design is the most attractive solution from the point of view of physics, detector construction, operation and cryogenics, and finally cost. Our studies show that the maximum size of the single unit is limited by the requirement

to locate the detector in an underground cavern, and not by the cryogenic tanker itself. On the other hand, the design can also be scaled down to 10 kton, or even 1 kton.

For an updated status of this program, see [11].

3. A superconducting magnetized large mass liquid Argon TPC detector

We have recently successfully operated the first experimental prototype of a magnetized liquid Argon TPC [8,9]. These encouraging results allow us to further consider a large detector with magnetic field. Beyond the basic proof of principle, the main challenge to be addressed is the possibility to magnetize a very large mass of Argon, in a range of 10 kton or more, for future neutrino physics applications.

The most practical design, which fits the concept described in the previous Section, is that of a vertically standing solenoidal coil producing vertical field lines, parallel to the drift direction. Hence, **we propose to magnetize the very large LAr volume by immersing a superconducting solenoid directly into the LAr tank** to create a magnetic field, parallel to the

Table 1

Comparison of superconducting solenoidal magnets. ATLAS column corresponds to the solenoid.

	10 kton LAr	100 kton LAr	ATLAS	CMS
Magnetic induction (T)	0.1/0.4/1.0	0.1/0.4/1.0	2.0	4.0
Solenoid diameter (m)	30	70	2.4	6
Solenoid length (m)	10	20	5.3	12.5
Magnetic volume (m ³)	7700	77000	21	400
Stored magnetic energy (GJ)	0.03/0.5/3	0.3/5/30	0.04	2.7
Magnetomotive force (MA _t)	0.8/3.2/8	1.6/6.4/16	9.3	42
Radial magnetic pressure (kPa)	4/64/400	4/64/400	1600	6500
Coil current (kA)	30 (I/I _c =50%)		8	20
Total length conductor (km)	2.5/10/25	12/57/117	5.6	45
Conductor type	NbTi/Cu normal superconductor, T=4.4K or HTS superconductor ? (see text)		NbTi/Cu	NbTi/Cu

drift-field (See Figure 1).

A magnetized LAr TPC was already addressed by Cline et al. [12]. However, the presence of long wires disfavored the use of a magnetic field. In addition, the proposed warm coil would dissipate 17 MW at B=0.2 T (88 MW @ 1 T). Such heat, even if affordable, would impose strong technical constraints on the thermal insulation of the main tank. In contrast, superconductors produce no heat dissipation and the coil current flows even in absence of the power supply.

Can such large volume solenoids be built? In Table 1 we summarize the relevant physical parameters for a 10 and 100 kton liquid Argon detectors for three different magnetic field configurations (0.1, 0.4 and 1.0 T), compared to existing solutions for LHC experiments. Of course, a very large amount of energy will be stored in the magnetic fields. However, owing B² dependence of the energy density, the total amount of magnetic energy is comparable to that of LHC experiments. For example, the magnetic volume of a 10 kton liquid Argon detector is 7700 m³, to be compared to 400 m³ for CMS, *i.e.* an increase by a factor $\simeq 20$. However, the CMS field is 4 T, hence, a 10 kton LAr detector with a field $B \approx 4/\sqrt{20} \approx 1$ T has the same stored energy. Since most issues related to large magnets (magnetic, mechanical, thermal) scale with the stored energy, we readily conclude, that **the magnetization of very large liquid Argon volumes, although certainly very challeng-**

ing, is not unrealistic! More figures of comparison are shown in Table 1.

In the case of quenching, the liquid Argon also plays the role of the thermal bath. In the largest considered volume, *i.e.* for a 100 kton detector, and for a B=0.1T (resp. 1T), the stored energy in the B-field is 280 MJ (resp. 30 GJ). In case of full quenching of the coil, the LAr would absorb the dissipated heat which would produce a boil-off of 2 tons (resp. 200 tons) of LAr. This corresponds to 0.001% (resp. 0.1%) of the total LAr contained in the tank and hence supports the design.

4. The use of High T_C superconductors?

A new era in superconductivity opened in 1986 when Bednorz and Mueller in Zurich discovered superconductivity at a temperature of approximately 30 K. In the following years, new materials were found and currently the world record is $T_c \approx 130$ K. HTS are fragile materials and are still at the forefront of material science research. However, they hold large potentials for future large scale applications. For example, ribbons of BSCCO-2212 ($Bi_2 - Sr_2 - Ca_2 - Cu_3 - O_{10}$) with $T_c = 110$ K are very promising and are regularly produced by *e.g.* American Superconductor [13]. Tapes of Bi2223 or YBCO are promising 2nd generation HTS cables which will find many applications in the next years. Unfortunately, HTS superconductors are much more difficult to use than normal superconductor. In particular, their

Table 2
Tentative parameters for return iron yoke.

Cyl. Fe yoke	10 kton LAr	100 kton LAr
Magn. ind. (T)	0.1/0.4/1.0	0.1/0.4/1.0
Magn. flux (W)	70/280/710	385/1540/3850
Field in Fe (T)	1.8	1.8
Thickness (m)	0.4/1.6/3.7	1/3.7/8.7
Height (m)	10	20
Iron Mass (kton)	6.3/25/63	34/137/342

conductivity depends strongly on temperature and on external perpendicular magnetic fields. Nonetheless, magnets have been constructed with HTS. The development of Superconducting Magnetic Energy Storage (SMES) systems will surely drive the technical developments of these HTS ribbons in the years to come. Today it is conceivable to estimate that very large coils from BSCCO-2212 could be operated at $T=10$ K, with BSCCO-2223 @ $T=20$ K, and possibly YBCO @ $T=50$ K(?). We have started an R&D program to prove the conceptual feasibility of this idea [14].

5. Tentative yoke parameters

In order to close the magnetic field lines, one can think of a simple cylindrical and hollow iron ring to encompass the liquid Argon volume. The thickness of the iron ring is determined by the magnetic flux that needs to be absorbed. We summarize in Table 2 the relevant dimensions.

In the case of SMES considered for underground storage of MJ energy, systems without return yoke buried in tunnels in bedrock have been considered and studied [15]. If an underground location where stray field can be tolerated is considered, then one could avoid using a yoke.

6. What next? A 50 ton magnetized prototype?

Before very large detectors could be considered, a basic proof of the charge and momentum measurements via magnetic analysis should be experimentally demonstrated. To this goal, we point out that a ≈ 50 ton detector in a magnetic field exposed to (1) a charged particle beam (e^\pm , μ^\pm , h^\pm , ...) (2) neutrino beam would be well adequate for such measurement campaign.

7. Conclusion

In this paper, we have presented the conceptual design of a new generation neutrino and astroparticle physics detector exploiting a superconducting magnetized liquid Argon Time Projection Chamber. This detector would open unique new physics opportunities, in particular in the context of a neutrino factory. We have started an R&D program along these lines of thoughts. The operation of a magnetized ≈ 50 ton LAr setup would represent a major important milestone in this context.

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