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A Solenoid with Partial Yoke for the Dune Near Detector

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***Abstract*—The Deep Underground Neutrino Experiment (DUNE) at Fermilab is one the most challenging next-generation experiments in the field of neutrino physics. It will feature two detectors for a detailed study of neutrino oscillations using an unprecedentedly intense neutrino beam. The two detectors are a Near Detector located on the Fermilab site, 574 m away from the neutrino generation, and a Far Detector in South Dakota, 1300 km away. The Near Detector consists of three subdetectors, based on different technologies in order to achieve the best understanding of the neutrino beam. One key element of the Near Detector is a High Pressure Argon TPC surrounded by a calorimeter. This detector will need a 0.5 Tesla magnetic field transverse to the neutrino beam direction, with a 7 m diameter, 8 m long warm bore. A thin superconducting solenoid with a partial yoke, needed in order to minimise the amount of material along the path particles take crossing the different elements of the Near Detector is proposed. In this paper we present a detailed magnetic analysis and a preliminary study of the cooling, the cable and the mechanics for this magnet.**

***Index Terms*—Magnet for particle physics, Aluminum stabilized Rutherford cable, Thin superconducting solenoid**

I. Introduction

NEUTRINO PHYSICS is a growing field in the particle physics community and will implement technologies previously used only in collider physics. The Deep Underground Neutrino Experiment (DUNE) [1] represents a next generation experiment to be built in the next decade. It will be based on a newly-built neutrino beam that obtains its proton power from the Fermilab PIP-II upgrade project. These neutrinos will travel $1300\,\mathrm{km}$ toward a liquid Argon detector in South Dakota (Far Detector, FD), crossing a Near Detector (ND) placed $570\,\mathrm{m}$ downstream of the neutrino production target. The ND will be formed by three sub-detectors, a liquid Argon based TPC (LArTPC), a gaseous Argon TPC with an electromagnetic calorimeter in a magnetic field (ND-GAr) and a second high granularity tracker with calorimeter in a magnetic field (SAND). The second detector, called ND-GAr (Gaseous Argon - Near Detector) will feature the magnet described in this paper.

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II. Magnetic Design

The magnet for ND-GAr must satisfy these requirements:

- $0.5\,\mathrm{T} \pm 20\%$ on the TPC volume, perpendicular to particles path;
- material thickness lower than 0.5 radiation length along particle path;

and optimised with these considerations:

- compromise between stray field and inactive material;
- compromise between warm bore volume and hall constraints.

The TPC will have a $5\,\mathrm{m}$ diameter and will operate at $10\,\mathrm{bar}$, therefore needing a sufficiently strong pressure vessel. A $60\,\mathrm{cm}$ thick electromagnetic calorimeter will surround the vessel. The warm bore of the magnet will need to be $7\,\mathrm{m}$ in diameter and $8\,\mathrm{m}$ in length. The iron yoke will need to minimise the stray field on the other carbon steel structures, mainly the $\sim 1000\,\mathrm{t}$ of the SAND magnet return yoke and leave an entrance window for the particles coming from LArTPC. Finally, everything will be movable along the magnet axis. A schematic of the magnet is shown in Figure 1.

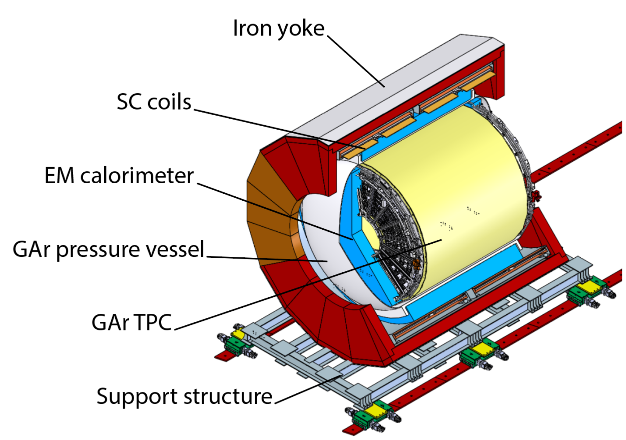

Fig. 1. Cross section of ND-GAr. All the main components of the detectors are labeled. Note that the electromagnetic calorimeter is partially in the pressure vessel, to reduce the length of the active material.

The overall concept of this magnet is based on the decades-long evolution of internally wound, aluminium stabilised superconductor magnets, since CELLO [2], through CDF [3], Delphi [4], BaBar [5], to many others. The design parameters are conservative if compared to previously built magnets.

To have a small material budget along particles path, we decided to have an almost continuous thin superconducting

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solenoid and a large cutout in the iron yoke on the side facing the LArTPC. To reduce the imbalance of hoop stress acting on the coils we reduced the thickness of the yoke on the other side, leaving sufficient iron to have a proper screening of stray field and an effective tagging of muons exiting the ND-GAr. The winding is divided into 4 identical coils and the magnetic model is based on one quarter of the physical model. The model and a field map of the whole volume is shown Figure 2.

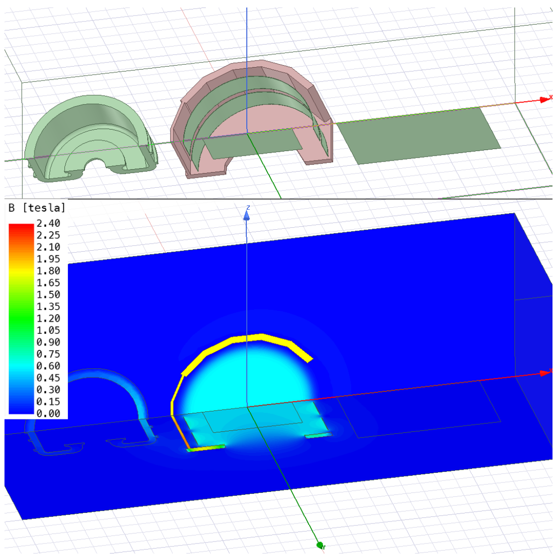

Fig. 2. Magnetic model (above) and calculated magnetic field (below) from ANSYS Maxwell. The SAND yoke is included and the modulation of the ND-GAr magnet yoke is evident, clarifying the name Solenoid with Partial Yoke at DUNE Near Detector, SPY@DND.

Our design envisages 4 identical coils, to ease the construction and modulate the field intensity in the bore. The needed current density is compatible with a single layer, pure aluminium stabilised Niobium Titanium cable winding. The main features of the present SPY@DND design are reported in Table I.

TABLE I
SPY@DND MAIN FEATURES

Parameter	Value
Minimum Field on TPC	$0.47\,\mathrm{T}$
Maximum Field on TPC	$0.55\,\mathrm{T}$
Stored Energy	$42.8\,\mathrm{MJ}$
Field Peak on Cable	$0.9\,\mathrm{T}$
Cold Mass Weight	$24\,\mathrm{t}$
Overall Current Density	$32\,\mathrm{A/mm^2}$

The relatively low field at the cable and engineering current density allows for a conservative design of the cable, as will be shown in the next section.

The design of the coils and of the iron yoke is still under development. In particular, the optimisation of the forces acting on the coils and of the stray field needs a detailed study to achieve the best result with the least material. A preliminary study on the effect of the SAND iron yoke on the field in the ND-GAr TPC shows that the expected effect is some $0.2 \sim 0.8\%$. As a comparison, the deviation from the central value, $0.5\,\mathrm{T}$, in percent, is shown in Figure 3. The percent difference between the field on the TPC with and without the SAND iron is shown in Figure 4.

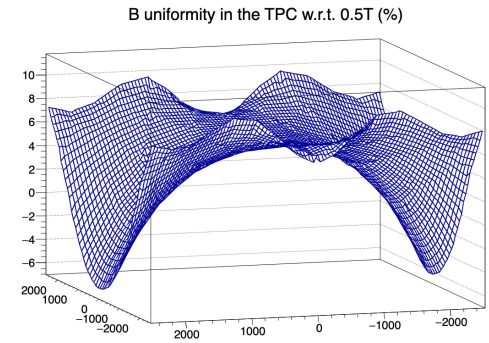

Fig. 3. Uniformity of the magnetic field on ND-GAr TPC, on a horizontal plane crossing the detector centre: the difference in percent with respect to the reference value of $0.5\,\mathrm{T}$ is shown.

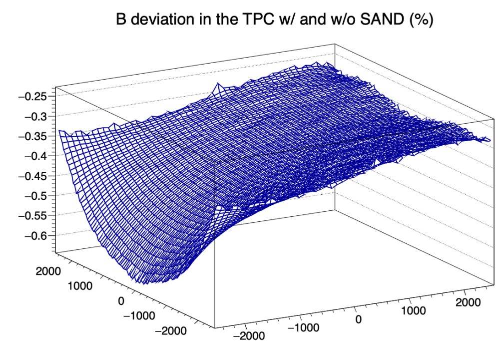

Fig. 4. Different of the magnetic field with and without SAND yoke in the ND-GAr TPC, on a horizontal plane crossing the detector centre. The difference in percent with respect to the values obtained with the SAND yoke is shown. The fluctuations are enhanced by the discretisation of the finite elements model.

In the present design the iron yoke is not segmented and is expected to host muon detectors on the inner and outer surfaces. Different designs with segmented (three layers) iron yokes have been developed in addition to the present one, which allow for the insertion of muon chambers within the yoke thickness. The magnetic design is very stable with respect to these modifications and all the parameters are stable within a few percent. A sketch of the cross section of the present design, with the muon counters arrangement and a particular of the winding is shown in Figure 5.

The length of the iron yoke is driven mainly by the length of the pressure vessel of the TPC. The end caps of the yoke feature a large hole, as in most accelerator experiments. These holes are not needed, of course, to allow the beam entrance, nor to allow the detector to be mounted inside. The end caps could be completely closed, but the magnetic simulations show that this is marginally helpful to shape the magnetic field in the TPC region and that the effect on the axial force acting on the first and fourth coils has a non-linear dependency on the hole radius. Therefore, the design is being optimised to reach the best performances with the smallest amount of iron. In the present design the total weight of the yoke is about $1000\,\mathrm{t}$.

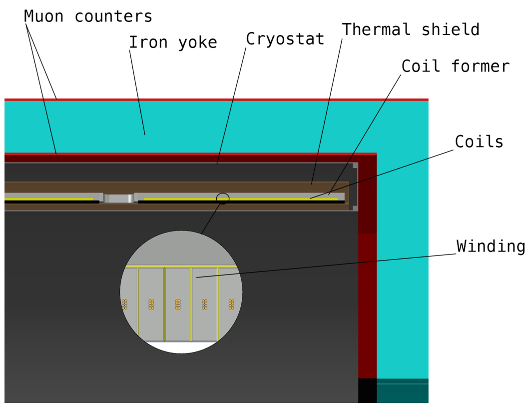

Fig. 5. Cross section of the magnet with muon counters.

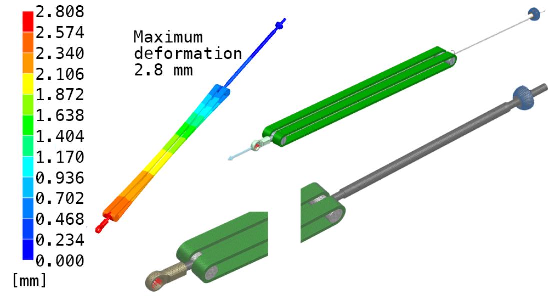

Fig. 6. Deformation of a radial tie rod subject to a 3.5 t load.

The design of the detectors to be installed in the magnet is evolving as the project develops, based on simulations of the magnetic field. For this reason, we are keeping some flexibility in the project to allow for modifications without the need for a complete redesign in case of requirements change.

III. Mechanical Issues

The magnet is very large, larger than the CMS solenoid, but generates a relatively low field. The resulting magnetic forces acting on the winding are therefore quite manageable with a traditional design, i.e. a single cold mass with all the windings kept in position in a pre-stressed coil former suspended in a single cryostat. Due to the size of the coil, however, it will be impossible to handle a single cryostat containing the whole cold mass, delivering it in the experimental hall and installing it. Two solutions are presently under study.

Thr first one is to have the coil split into two identical cold masses, in symmetric cryostats. This solution has the advantages of allowing for independent tests of the two halves and does not require operation on the cold mass in the cavern. The second solution is joining the cold masses inside the cavern. This solution has the advantage of only needing a single cryogenic turret for the current and fluids supply and makes it easier to manage the axial forces that push the coils towards the centre of the magnet.

The magnetic forces are in fact expected to be small: $100\,\mathrm{kN}$ towards the SAND direction, to be compared to the weight of the cold mass, which is 2.5 times higher. Forces are almost zero in the other directions. These are relatively easy to handle. The compression force along magnet axis, on the other hand, is expected to be large: the first coil will be attracted towards the centre of the magnet by a $1\,\mathrm{MN}$ force, the second one towards the first coil by a $180\,\mathrm{kN}$ force. The third and fourth coils will be subjected to equal and opposite forces. The stress on the conductor aluminium matrix is not expected to exceed $\sim 10\,\mathrm{MPa}$, well below its yield limit. Properly sized tie rods are expected to also work for the axial load. An example of a mechanical analysis performed on a radial tie rod is shown in Figure 6.

IV. Conductor Design

To ensure the feasibility of the project, a preliminary study on possible conductors for this magnet has been performed. Due to the low required field, we decided to go for a single layer winding, with a rectangular section conductor, to be hard-way bent. The superconductor size can be defined from the operating current. For our magnet, we are assuming a range between 4500 and $5000\,\mathrm{A}$, leaving some flexibility to cope with the evolution of the physical design. Presently, we plan to operate the magnet at $4800\,\mathrm{A}$, at $4.2\,\mathrm{K}$. The resulting inductance is therefore $3.8\,\mathrm{H}$.

Keeping in mind the maximum field on the cable, we plan to operate below 60% of the load line, achieving a temperature margin of $2.5\,\mathrm{K}$. Eight strands, $0.67\,\mathrm{mm}$ diameter, 1:1 Cu/SC ratio give a critical current at $1\,\mathrm{T}$ larger than $11\,\mathrm{kA}$, producing a very stable Rutherford cable for this design. The resulting co-extruded cable can have an external size of $19.5 \times 6.65\,\mathrm{mm}^2$, a form factor similar to what has been used recently for the Mu2e Detector Solenoid [6]. In fact, the experience gained from the Mu2e magnets, partially built in collaboration with Genova group, will be helpful for SPY@DND. All the cable parameters measured for this cable are taken as input data for our case. The margin at ultimate current (110% of the nominal one) is shown in Figure 7.

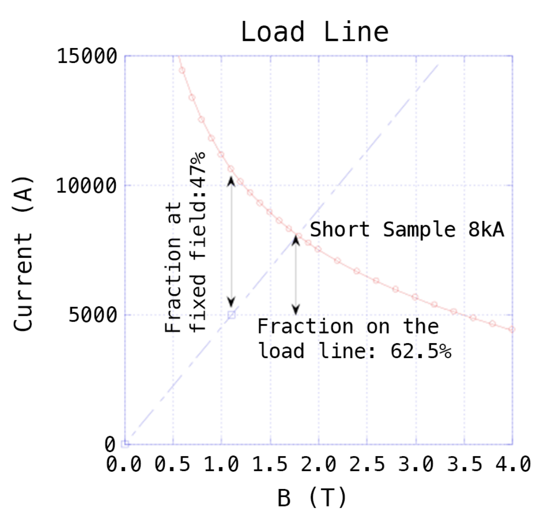

Fig. 7. Operating margin of the foreseen cable at ultimate current (110% of the nominal one).

The conductor has an enthalpy margin of $0.89\,\mathrm{J/K}$, with a minimum quench energy of $0.15\,\mathrm{J}$. Some preliminary simulations of the quench behaviour of the magnet have been performed assuming a quench resistor of $50\,\mathrm{m\Omega}$. This design gives a maximum quench voltage of $300\,\mathrm{V}$ ($\pm150\,\mathrm{V}$ if middle grounded), close to the Paschen limit of $140\,\mathrm{V}$ for helium. The time constant for the discharge of the magnet on the protection resistor is $76\,\mathrm{s}$.

In the occurrence of a quench, the energy released in the whole cold mass, if evenly distributed, raises the temperature to $71\,\mathrm{K}$, or if completely released in a single cold mass, to $118\,\mathrm{K}$. We therefore consider this design to be safe from the point of view of quenches.

V. Thermal Design

The magnet will be indirectly cooled with liquid helium, via either natural or forced convection in pipes welded on the outer surface of the coil former. The radiation shield will be cooled with cold helium gas at $60\,\mathrm{K}$. Cold gas will be used as well to cool down the current leads. Helium gas will be recovered at room temperature and liquified in a dedicated facility.

The expected heat loads at $4.2\,\mathrm{K}$ for the magnet are summarised in Table II.

TABLE II
SPY@DND Heat Loads at $4.2\,\mathrm{K}$

Source	Value
Radiation load	50 W
Residual gas load	3 W
Cable joints load	1 W
Cryogenic chimneys	20 W
Tie rods	10 W

These numbers have been evaluated as follows. Radiation heat flux has been estimated at $150\,\mathrm{mW/m^2}$, which is a quite conservative value for an aluminium surface facing the radiation shield. This is a value that, based on previous experience, can be considered as very conservative.

Residual gas load in principle should be negligible, but micro-leakages of helium gas in the cryostat can possibly occur and pumping this away is difficult, therefore three Watts are again a conservative estimate.

The number of cable joints, according to a possible cable producer, is expected to be 12 to 20 in the whole cold mass. Joints in the CMS conductor showed resistance below $1\,\mathrm{n\Omega}$ at 1 T [7]. Operating at $5000\,\mathrm{A}$, this corresponds to a total of $1\,\mathrm{W}$ at the maximum. Reasonably, we can expect this to be only a few hundred of mW.

We consider in this estimate to have two independent chimneys, as depicted in the previous sections in the option with two separate and independent cryostats. If the solution with a modular cryostat to be assembled in the experimental hall will turn out to be viable, the thermal load will be reduced to $10\,\mathrm{W}$. This value includes the estimation of the load of current leads with high temperature superconductor terminals [8].

The estimate for the tie rods is very conservative. Again, if the solution with a single cryostat will be viable, the problem of keeping the axial force between the coils will vanish, reducing the heat load of the axial tie rods by a factor of ten, with a reduction of the total load due to the supports of a factor of three.

VI. Future Development

The development of the design of SPY@DND is ongoing. The information coming from the detector simulation groups is driving a continuous improvement of the magnet design. The definition of the position and structural details of the equipment that will be present in the experimental hall, at small distance from the ND-GAr detector, will drive further steps of development of the yoke design in order to guarantee the expected performances.

A preliminary contact with both conductor and magnet manufacturers has been established to ensure the feasibility of the project. We received uniformly positive feedback.

The next steps for the development of the magnet, once the final geometry of all the equipment in the Near Detector hall are defined, are expected to be:

- final optimisation of the magnetic model;
- definition of the cryostat design;
- definition of the support structure design;
- definition or the ramp-up and ramp-down time according to the maximum allowable power loss in the coil former;
- definition of the mounting procedure.

The magnet construction is estimated to last 3 years from the contract signature and the installation is expected for 2027.

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