ND-GAr Magnet System

TBD

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1 Introduction (ABr)

A key aim of the DUNE experiment is to measure neutrino interaction rates from which can be extracted the oscillation probabilities for muon (anti)neutrinos to either remain the same flavor or oscillate to electron (anti)neutrinos. The DUNE Far detector located 1300 km away from the neutrino source at Fermilab, will measure the neutrino interaction rate after oscillations. The Near Detector complex located on the Fermilab site $\simeq$ 570m from the neutrino target measures the unoscillated neutrino flux and serves as the experiments control. There are three components of the Near detector suite of detectors consisting of 1. A modular LAr detector (ND-LAr) with pixel readout, 2. A high-pressure gaseous TPC system (ND-GAr) and 3. A beam monitor called SAND (System for on Axis Neutrino Detection). See Figure 1. ND-GAr is a magnetized detector system consisting of a high-pressure (10

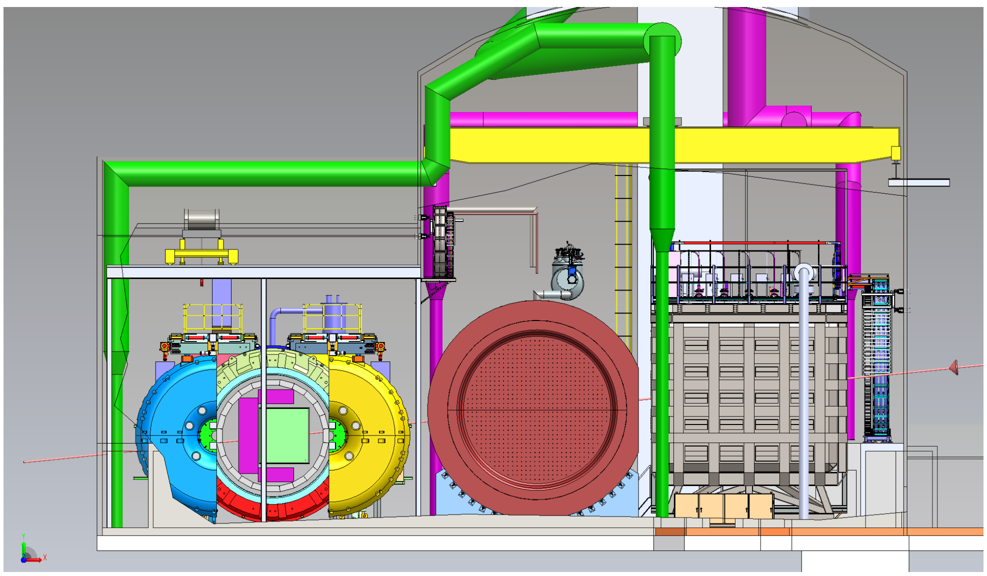


Figure 1: The Near Detector Suite of Detectors

bar) gaseous argon TPC (HPgTPC) surrounded by an electromagnetic calorimeter (ECAL). Both are inside a magnet system which consists of a solenoid magnet with a 0.5T magnetic field and return iron. The return iron is not a complete cylinder so that muons that exit ND-LAr can be accurately measured in ND-GAr without scattering or losing energy in the iron. The system is called SPY – Solenoid with Partial return Yoke. There is a muon tagging system outside the yoke. A schematic of ND-GAr is shown in Figure 2 (Left). A cut-away view is shown in Figure 2 (Right) which shows the coils, ECAL components and the HPgTPC and the "window" in the yoke shown in Figure 2 (Left). Development of the design concepts for the HPgTPC and the ECAL continue. Changes in the ECAL design will have the largest impact. However, the design changes currently under consideration (thinner ECAL thus less mass and more available space in the magnet bore) all have a positive impact on the magnet design.

The experiment is also considering a temporary initial configuration of ND-GAr that does not include the HPgTPC or the ECAL (to be installed at a later time) that would only have a scintillator tracker inside the magnet bore. This configuration is called ND-GAr-Lite (see Figure 3).

In this document we will layout the requirements for the ND-GAr magnet system and present details on the conceptual design. In many cases we are following the design of existing magnets and using known best practices in the field of superconducting magnet technology. In no area do we feel we are near the state-of-the-art in superconducting magnet or superconducting cable technology.

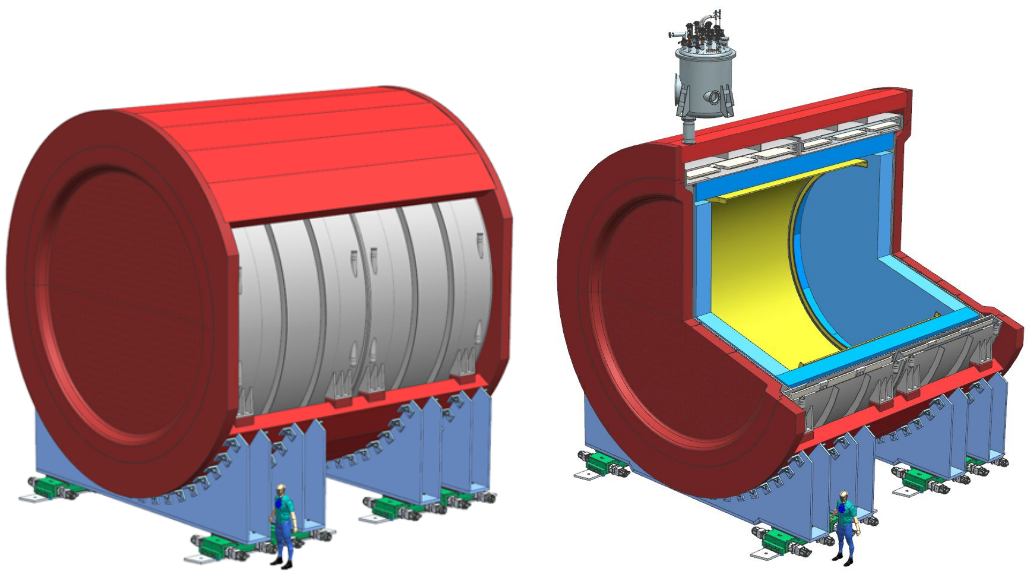


Figure 2: The SPY magnet system (Left). ND-GAr cut-away view (right) Grey: Solenoid,Blue: ECAL, Yellow: HPgTPC

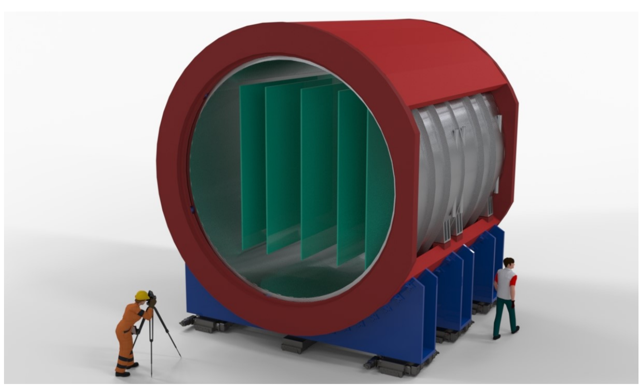


Figure 3: ND-GAr-Lite with the end iron removed showing the scintillator tracker planes

2 Requirements

In Table 1 we give the overarching requirements for the ND-GAr magnet system.

Table 1: Requirements for ND-GAr's magnet system.

Parameter	Value	Notes
Bore	6.725m	Reduction possible with HPgTPC and ECAL optimization
Length	7.788m	Cryostat length
Max OD	7.85m	Cryostat diameter at stiffening rings
Central field	0.5T	
Field uniformity	± 10%	
Ramp time to full field	30 min	
Stray field		

3 Magnetic system specifications (ABe)

As discussed in Section 1, ND-GAr is one component of the 3-component suite of detectors at the DUNE near site and as such has to operate within a number of constraints listed below:

- Geometrical: ND-GAr must provide good acceptance for muons exiting ND-LAr and must fit within the space constraints imposed by the Near Detector hall design.
- Mechanical: ND-GAr's magnet system must present as little material as possible in the path of the exiting the ND-LAr.
- Magnetic: The momentum analyzing power of ND-GAr must provide at least 3% momentum resolution for the ND-LAr muons and must be able to provide E_ν reconstruction precision at least as good as that in the Far detector for neutrino interactions that occur in the Ar gas.

In this section we will describe in detail the ND-GAr magnet design requirements and specifications.

3.1 Field and field quality

The main requirement on ND-GAr magnet system is on the magnetic filed that will be needed by the charged particle tracker that will be used in this detector. The technology that has been chosen, a Time Projection Chamber filled with high pressure gaseous Argon [1] (HPgTPC), will provide excellent tracking resolution and we have determined that a relatively low magnetic field of 0.5 T will be sufficient. The HPgTPC design is based on the previous experience of the ALICE TPC [2] at the LHC, in particular, the volume will be exactly the same. It will have a cylindrical shape, $\simeq 5.2$ m long and 5.27 m in diameter; its axis will be horizontal and perpendicular to the neutrino beam direction.

Thanks to the recent and expected future improvements in software reconstruction and computing power, the requirement on field uniformity is significantly looser than in previous TPC-based detectors. The requirement is $\pm 20\%$, but an accurate field map of the "as-built" system will need to be performed. At present the field quality that can be achieved in our magnet system design is already much better than this specification.

3.2 Geometrical constraints

The overall size of ND-GAr magnet system is tightly constrained by several geometrical limits. The subdetectors that will be installed in the warm bore of the magnet drive the design of the warm bore. The HPgTPC will have a diameter of $\simeq 5.2$ m and needs a pressure vessel to be safely operated at 10 bar (1 MPa). In addition, a 4π electromagnetic calorimeter (ECAL) will also reside in the magnet warm bore, which will need an additional 60 cm clearance on the radius. The length of the magnet system (including the iron return yoke) is also driven by the size of these detectors. To achieve the best exploitation of the available space, a novel and aggressive integration approach has been developed, which will be shown in the next sections.

The outer size of the magnet system is constrained by the available space in the experimental hall. The maximum height is defined by the clearance under the overhead crane, 12 m. This is not a real constraint for the magnetic design, but it will be for the definition of the proximity cryogenics. The width of the iron return yoke, in the beam direction, is in fact the most constrained dimension. The available space is 8.82 m, in which clearance between ND-GAr and ND-LAr on one side and between ND-GAr and the wall is required. The length of the magnet, along the magnetic axis, is limited by the hall width and by the requirement of having 30.5 m travel for the detector to move off axis.

3.3 Material budget (ABr)

One of the key performance requirements of ND-GAr is to accurately measure the momentum of muons that exit ND-LAr. In this way the momentum of the muon at production can be accurately determined. One systematic uncertainty on this measurement that is imposed by the ND-LAr plus ND-GAr design is the uncertainty on the energy muons loose as they pass through the non-active material of ND-LAr and ND-GAr. In order to determine the muon momentum with the required precision, we have imposed a requirement that the total amount of dead material that the muon sees as it travels from the active region of ND-LAr to the active region of ND-GAr be less than 100 gram/cm^2. The assigned proportion to ND-GAr is 50 gram/cm^2. This represents the total mass allowed for the solenoid (the return iron is not an issue due to the opening). The material budget for the current solenoid design is shown in Table 4. We are currently safely below the 50 gram/cm^2 limit.

Table 2: Material budget for solenoid.

Component	Material	Thickness (mm)	ρ (g/cm^3)	g/cm^2
Outer vacuum vessel wall	Stainless steel	25	7.87	19.68
LN_2 shield	AL	4	2.70	1.08
Cooling tubes	AL	18	2.70	4.86
Bobbin	AL	22	2.70	5.94
LN_2 shield	AL	4	2.70	1.08
Inner vacuum vessel wall	Stainless steel	16	7.87	12.59
TOTAL				**45.23**

3.4 Loading (DM, CN)

HPgTPC The HPgTPC weight of $\simeq$ 14t is supported by 2 rails that are attached to the inner surface of the ECAL.

ECAL The ECAL weight of $\simeq$ 150t is heavy. It is installed in wedge-shaped segments to the inner diameter surface of the pressure vessel.

4 Cold mass design (ABe)

4.1 Design principles

Several different layouts have been studied in order to meet the complexity of coping with the strict geometrical requirements for ND-GAr. Among the proposed solutions, a concept using a "Helmholtz-like" five coil configuration [4] was developed. However, a new concept based on a continuous thin solenoid is now regarded as the baseline design, the main advantages over the previous design being the management of the stray field and the field quality.

The design is based on the decades-long evolution of internally wound, aluminium stabilised superconductor magnets, since CELLO [5], through CDF [6], Delphi [7], BaBar [8], to many others. The required field in the warm bore is relatively low, 0.5 T, therefore a single layer coil is sufficient to provide the needed current density even if the diameter is $\sim$ 7 m. The design parameters are conservative if compared to previously built magnets.

As already mentioned, the iron yoke must be asymmetric to guarantee a sufficiently low material budget between ND-LAr and ND-GAr. An entrance window is foreseen on on side of the yoke, making the design of SPY unique. An analogous window on the opposite side has been ruled out due to magnetic containment and to provide a proper amount of material for efficient muon tagging. A non magnetic material could have been used, but this would decrease the overall amount of iron in the return yoke, reducing the stray field containment, or would force us to increase the overall weight of the detector, which is already above 1000 t and is reaching the limits of the proposed movement system (see section 9). We decided to maintain the asymmetry and use carbon steel also for the "exit window" I'm not sure what is meant here.

4.2 Coil design

The coil will be built in segments, to be jointed before the insertion in the cryostat. Six identical sub-coils are foreseen, each with a 7000 mm internal diameter, 900 mm in length and 20 mm in thickness. Each sub-coil will be internally wound in a coil former made of aluminium alloy. The sub-coils will then be mechanically joined with spacers and the electrical connections between the superconducting cables will be performed. Each sub-coil will provide 550 kA $\cdot$ turn, for a total of 3.3 MA $\cdot$ turn. As a design guideline, we decided to keep the current below 5000 A, to avoid high voltages during quenches. This can be achieved with 120 turns for each sub-coil and $\sim 4585A$. The calculated stored energy with this configuration is $\sim$ 32.5 MJ. The inductance of the magnet is therefore $\sim$ 2.75 H.

The cable will be rectangular, with a "hard-way" bend in the winding, with an insulated width of 7.5 mm. The height can be optimised with the supplier. In our calculations we estimate it to be $\simeq$ 20 mm. With this cross section, the overall current density is $\sim 30.5\,\mathrm{A/mm^2}$. The amount of superconductor will be defined on the basis of the magnetic calculations. The maximum field on the cable, according to our calculations, is below 1 T. The requirement to the cable supplier will be a sufficient amount of superconductor to carry twice the design current at twice the maximum field at the operating temperature, i.e. 10 kA at 2 T and 4.2 K. Both a conservative solution based on niobium-titanium and a novel one based on magnesium diboride are being investigated. The superconductor will be co-extruded in high purity aluminium to provide quench protection in either case.

Table 3: Coil Dimensions.

Measurement	Bobbin (mm)	Coil (mm)
ID	6990	7000
OD	7120	7040
Length	1000	900

The coil will be cooled indirectly via forced circulation of liquid helium in pipes welded on the outer surface of the coil former. The operating temperature of the cold mass will therefore be $4.2 \div 4.5$ K, depending on the pressure of the liquid helium circuit. A thermal shield operating at $50 \div 70$ K is foreseen, either based on cold helium gas or on liquid nitrogen. The former has the advantage of operating at lower temperature, the latter the advantage of being more efficient. The current leads will be cooled with part of the evaporating helium gas from the primary cooling circuit.

5 Mechanical design (DM, CN)

5.1 Overview

ND-GAr is an integrated system containing a multi-component neutrino detector, a 10-bar gaseous pressure vessel, a superconducting solenoid magnet with its commensurate cryogenics, a partial return yoke and electronics. The detector system consists of a large

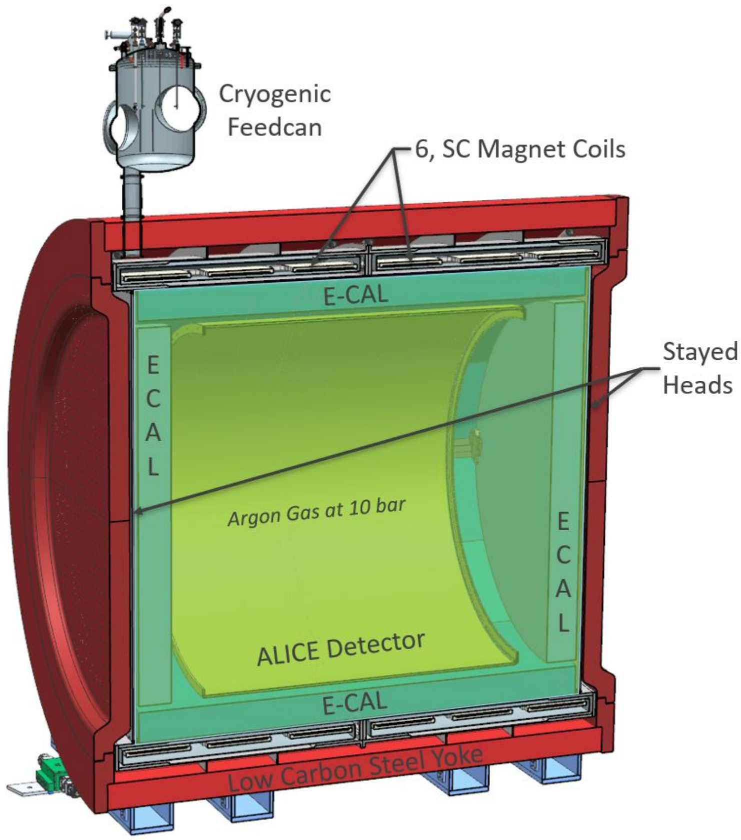


Figure 4: General Layout of ND-GAr

high-pressure gaseous TPC (HPgTPC) and an electromagnetic calorimeter with barrel and end-cap sections. Both the HPgTPC and the ECAL operate within the 10-bar pressure vessel. The vessel that houses the 6-coil solenoid magnet is under vacuum with the coils cooled to 4K. See Figure 4. ND-GAr is required to measure muons coming from neutrino interactions in ND-LAr, the liquid Argon detector just upstream of the ND-GAr. ND-LAr is not large enough to fully contain many of the muons produced in charged-current neutrino interactions, so ND-GAr is needed to measure the momentum of the exiting muons. Therefore, this means that there should be a minimal amount of material between the ND-LAr detector and the ND-GAr detector. This requirement drove the yoke design where a portion of the half cylincer that faces ND-LAr is removed (see Figure 2, Left). Initial designs of the pressure vessel utilized a thick-walled cylindrical vessel with spherical heads to accommodate the 10-bar pressure. The vessel heads added excessive length to the detector, complicated the design of the magnet and put the ECAL behind the Al of the pressure vessel which degraded the ECAL's performance. A shorter system with less mass was needed. To satisfy these requirements, we determined that the magnet vacuum vessel/cryostat could serve two roles with the following design parameters:

1. Cryostat under vacuum to house the coils
2. The inner wall of the cryostat could serve as the outer wall of the pressure vessel
3. The pressure vessel end flanges could be supported by a very thick end yoke
4. The yoke design would produce a uniform 0.5T central field and contain the stray field.

An additional physics requirement is to measure neutrino interactions in an off-axis position. To meet this requirement, ND-GAr must be able to move on tracks to various locations in the hall transverse to the beam . This motion is provided using eight, motorized Hilman rollers each with a 200-ton capacity. With a currently designed weight of 1,239 tons (2,000 pounds per ton), a quick estimation has each roller supporting 154.85 tons. However, after an analysis of the load distribution and an optimization of the location of each roller, the loading is not uniform, and in fact, two of the rollers peak near the roller's capacity. A final design will need to address this concern and design optimizations to decrease the overall weight should be considered.

Table 4: Weight of Components.

Component	Weight (pounds)
Yoke	1,664,626
Cradles	98,102
Cryostat/PV	238,420
Coil/Bobbins	58,962
ECAL Barrel	280,000
ECAL Ends	100,000
Thermal Shields	3,283
Coil Spacers	1,092
Coil Restraints	168
HPgTPC	28,000

5.2 Pressure Vessel Requirements

Analysis of ND-GAr's pressurized system was performed to meet the requirement's of Fermilab's Environment, Safety, and Health Manual (FESHM), Chapter 5031[9]. The requirements of the chapter apply to any vessel that is designed, fabricated, tested, or operated on Fermilab's site. To be acceptable for use, ND-GAr's pressure vessel needs to meet one of the following requirements:

- Include an ASME BPVC U-Stamp
- Include a European Commission Pressure Equipment Directive (PED) CE-mark and be built per either standard EN-13445, Unfired Pressure Vessels, or AD 2000, Code of Practice for Pressure Vessels.

- Conform to another more applicable code in its entirety. Before fabrication, allowance for use of another code shall be approved and documented in a signed memo by the Division/Section/Center Head or designee in consultation with the MSS and CSS
- Designed to meet the Experiment vessel requirements as defined by FESHM 5031

Vessels that do not meet any of the above requirements are classified as exceptional and require a Director's Exemption. These vessels must show a level of safety greater than or equivalent to the ASME BPVC.

Due to the unique design of the vessel, the design and analysis of ND-GAr's pressurized system has been performed to meet the Experiment vessel requirements using the 2019 version of the ASME BPVC VIII, Division 2 [10], further referred to as The Code. The safety factors used for determining the thicknesses of components, were performed following the requirements listed in The Code for a Class 2 vessel .

5.3 Cryostat/cold mass

The cryostat/cold mass has developed from a 2-part design that required field assembly, but now in the current design requires the magnet to be completely fabricated and tested at a vendor's site and then delivered to Fermilab as a single, tested unit. A single magnet sounds like the obvious choice but there are complications with this approach. A single magnet is quite large as shown in Figure 5 and has a total weight approaching 151 tons. The size and mass of this magnet requires special handling and shipping methods. Handling the cryostat in the hall will require special rigging as the hall crane capacity is limited to 60 tons. The design shown here was originally developed under the two-cryostat approach but was modified to accommodate the single-cryostat design.

The cryostat shown in Figure 6 represents the two-vessel design approach and uses 48 radial restraints and six axial restraints. In a single cryostat design, we will explore a 36 radial restraint design to minimize thermal losses in the future. Due to the span of the vessel, stiffening ribs are used to strengthen the outer shell. The stayed heads and cryogenic feed-can are not included in the initial installation of the cryostat.

The cryostat is designed as an insulated vacuum vessel to house the six internal superconducting magnet coils (see Figure 7) but is also designed to house the internal neutrino detector operating in a 10-bar atmosphere. The inner shell of the cryostat must accommodate this large pressure. The flat heads at each end of the cryostat, at 38.1 mm thick (1.5 inch), cannot withstand the 10-bar pressure on their own. The design requires that the heads be supported by the yokes using 798 "stays" per each head creating a "stayed head" design. The internal pressure vessel cannot be tested without being completely installed and supported in the magnet yoke.

The cryostat is a welded and bolted assembly fabricated from 316L stainless steel and was designed using the ASME Boiler and Pressure Vessel code, Section VIII, Division 2, Design by Analysis, Elastic-Plastic analysis method, see section 4.4, ANSYS analysis. The cryostat is mounted in the yoke at 8 locations, but this design parameter can also be readdressed with a single cryostat design approach – potentially using only six supports.

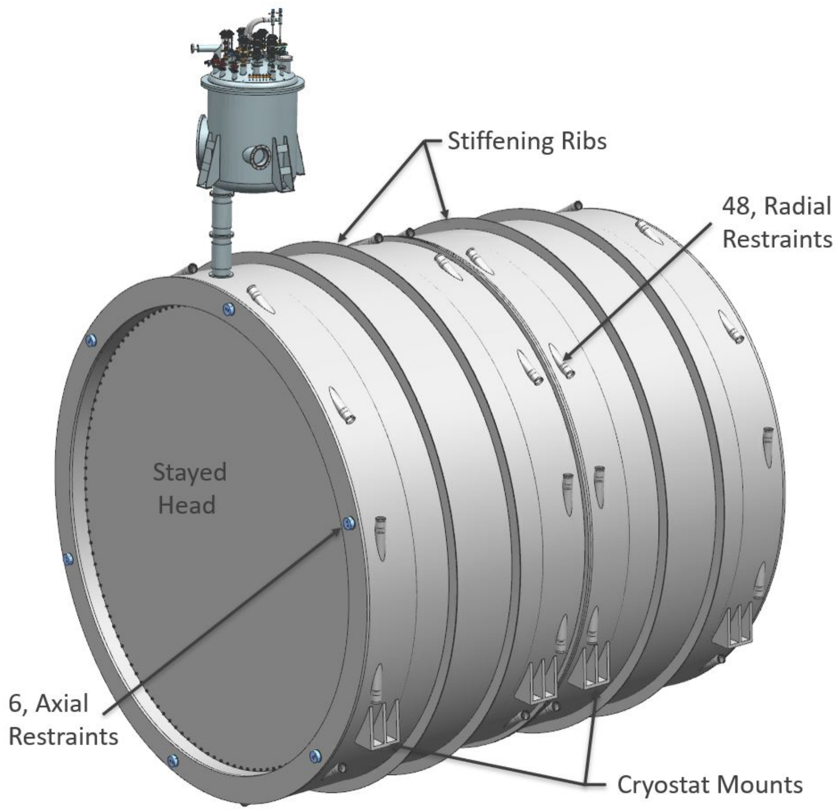


Figure 5: Cryostat External Features

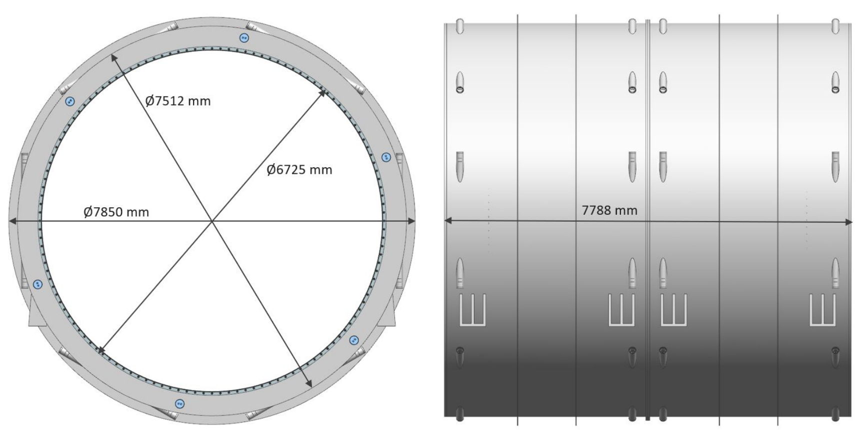


Figure 6: Cryostat General Dimensions

The stayed heads add a complication to the cryostat design. Due to the large flat surface area, there is a large force and bending moment at the inner mounting flange that creates

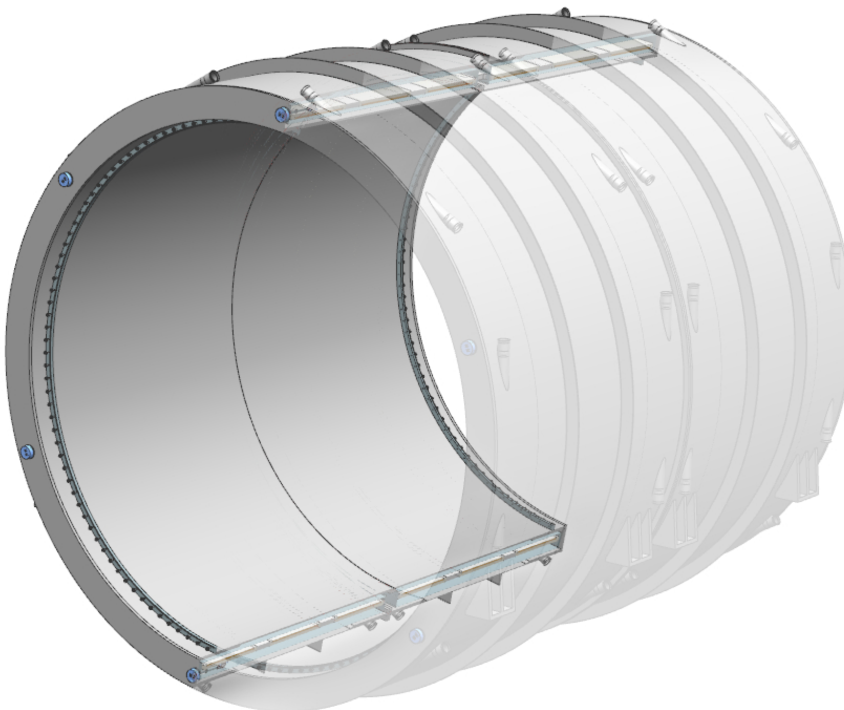


Figure 7: Sectioned cryostat showing internal magnet

a potential failure mode. Refer to Section 11, Failure Mode Analysis, for more details.

Interior to the cryostat is a radially and axially supported coldmass consisting of a 6-coil magnet/former assembly and a 3mm thick aluminum thermal shield as outlined in Section 4.2. The coil and bobbin assembly weigh 30 tons. The coil assembly outer diameter is 7,040mm and inner diameter of 7,000mm. The coil spacing is shown in Figure 8. The coils are connected in series and due to the nature of the solenoid coils and their symmetry, a force balance in the magnet is achieved. Having the coils powered in series means that potential coil failures would force the power to ramp down uniformly. Any potential imbalance of force and forces produced by the proximity of the SAND magnet are constrained by six axial restraints mounted at only one end of the magnet as shown in Figure 9.

The radial supports, as shown in Figure 10, are designed to support the coil assembly's dead load, the magnetic load created from the proximity of the SAND magnet, and the ND-GAr magnetic loading due to a non-symmetric yoke design. In addition, forces develop in the radial supports when the magnet shrinks due to cooling from room temperature to 4K. To minimize or even cancel out the loading due to shrinkage, the radial supports are designed at a specific angle and with ball joint end connections to allow the supports to rotate as the coil bobbin shrinks radially inward. When designed properly, the support rods will simply rotate to the new alignment and not develop any additional axial loading.

There are available options for designing the radial supports. Both options utilize an

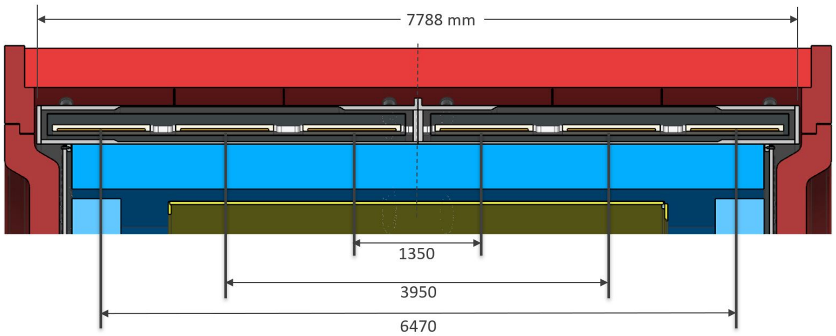


Figure 8: Coil Dimensions

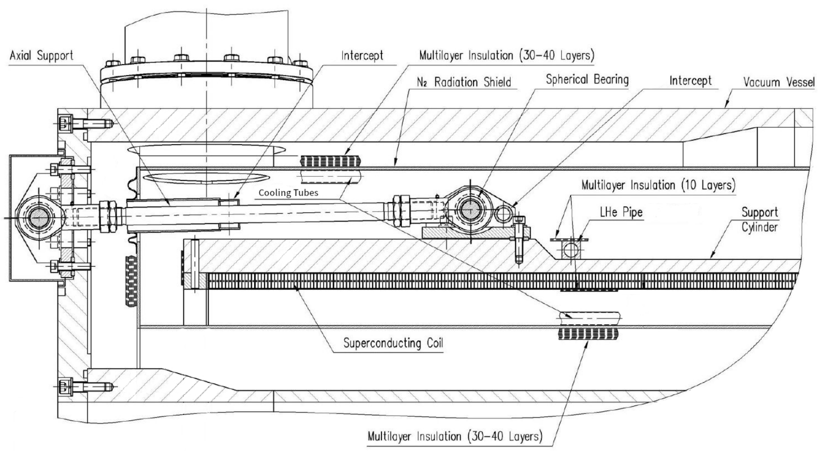


Figure 9: Axial Support Rods

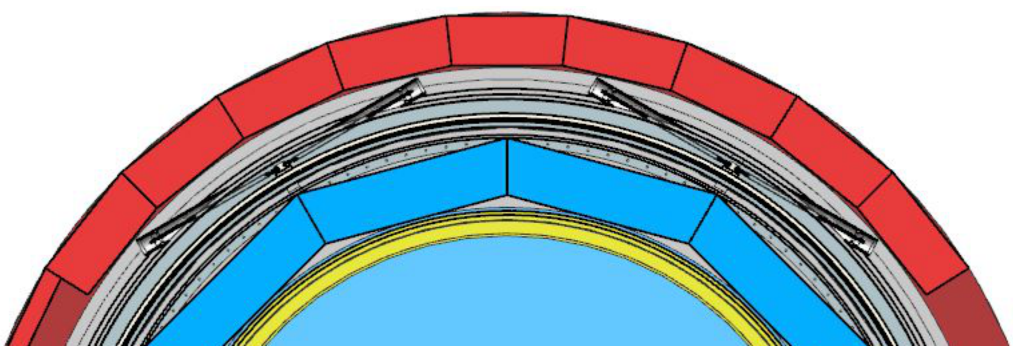


Figure 10: Radial support rod configuration

intermediate heat sink at 50 – 77K. In option 1, a solid metallic rod is used as shown in Figure 11. This design option is straight forward but produces a large heat leak. Option 2 greatly reduces the thermal leak but is a more complicated design. As shown in Figure 12, the support can be developed as a 2-stage assembly separated at the 50 − 77K thermal sink. One portion of the support is constructed from invar, or a similar material, while the other stage is constructed from G10 or carbon fiber thermal straps. Commercial sources for this type of strap exist. In option 2, the lengths of the stages can be fine-tuned along with adjusting the mounting angle to optimize the strength of the support and minimize the stresses. Ideally, the dead load of the coils is supported by only the downward hanging, vertical supports. All other supports maintain the circularity and centering of the coil bobbin assembly and withstand all magnetic forces.

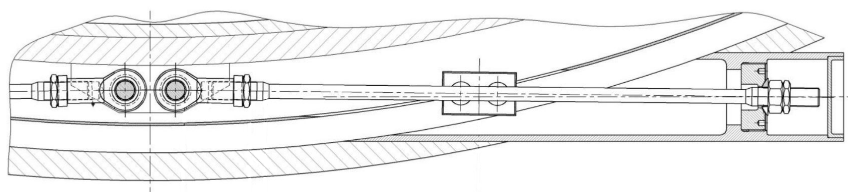


Figure 11: Radial support rod - Option 1

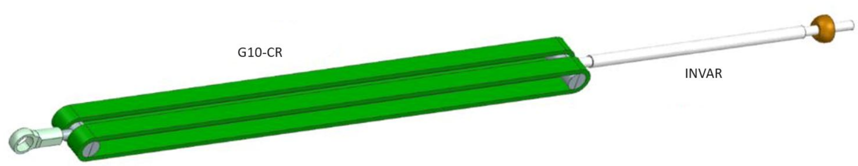


Figure 12: Radial support rod - Option 2

Regardless of the axial and radial supports used in the final design, attention must be given to shipping requirements. Either these supports must withstand shipping loads or additional shipping restraints will need to be incorporated into the design that can be removed after installation.

5.4 ANSYS analyses

Analysis of the ND-GAr pressurized system was performed to meet the requirement's of the FESHM 5031 [9] and the BPVC VIII, Division 2 [10]. Analysis was performed using the safety factors of a Class 2 vessel and derated by 0.85 to account for the joint efficiencies of the welds. To meet the FESHM 5031 requirements, the saftey factor was further derated by 0.8.

When it was possible, initial calculations were performed using Part 4 of the ASME VIII Div. 2, however the calculations were verified using the Design by Analysis Methods as Described in Part 5 of ASME VIII Div.2. Due to the complex loading conditions and asymmetrical design of the cryostat, the Elastic-Plastic Stress analysis process was performed for all components as recommended in 5.2.1.2.

There are generally four steps that are needed to be performed to show an acceptable design following the guidelines of Part 5 of the code:

1. Protection Against Plastic Collapse
2. Protection Against Local Failure
3. Protection Against Collapse from Buckling
4. Protection Against Failure from Cyclic Loading

Each section was examined when performing the analysis of the ND-GAr System, however, minimal attention was paid to the protection against failure from cyclic loading as it relates to the lifetime of the assembly. As there are many smaller details that have not been defined yet that will determine the overall lifetime of the assembly, this should be a focus when the details are better defined.

There were two general areas of analysis that were performed: The analysis of the cryostat head and the analysis of the shell thicknesses of the cryostat.

5.4.1 Cryostat Head Analysis

The cryostat head was examined firstly using the methods described in 4.6 of The Code[10]. Determining the thickness of the head indicates that to resist the 10 Bar operating pressure, the head would be required to be approximately 11 inches thick. This is not an acceptable thickness due to the amount of space available, the operating parameters of the ND-GAr system, and the downstream design consequences of using a large head.

To reduce the required minimum thickness of the head, stay bolts were used to brace the head of the cryostat against the iron yoke. Following the rules for stayed heads, as defined in 4.9 of The Code [10], a range of parameters was defined. Using a 3/4" stay-bolts, the resulting minimum pitch distance with respect to the minimum thickness was determined within the range of allowed plate thicknesses as seen in Figure 13.

Following the results of the calculations, a simplified model of the Stayed Flat Head was created following the calculated parameters. The model, with quarter symmetry can be seen in Figure 14.

Using the simplified stayed head model, the cover was examined using a 10 bar external pressure to determine if it would meet the plastic collapse requirements. Scaling the loads accordingly, the local failure and plastic collapse requirements were examined using the Elastic-Plastic Method. Scaling the loads by the FESHM required factors and re-running the simulation, the loads converged at the Plastic Collapse required load. The results of the analysis can be seen in Figure 15.

In the event that the internal volume of the Cryostat is ever brought into vacuum, the assembly will also need to be able to meet the protection against buckling requirements. Running the corresponding simulations, it was determined that buckling will occur over the allowable limit. However, buckling will first occur in the stay bolts, not on the pressure boundaries of the cryostat.

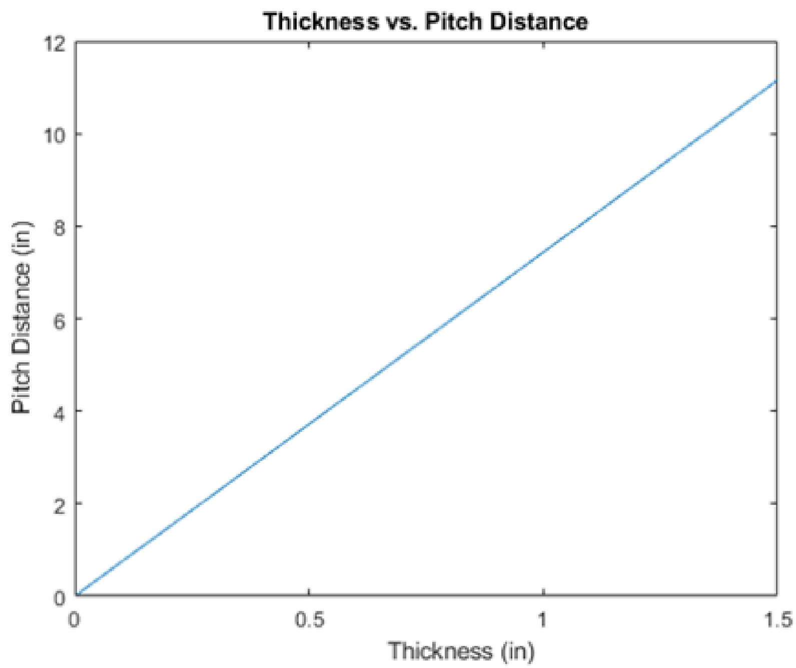


Figure 13: Minimum thickness of stayed head as a result of the pitch distance between stay-bolts.

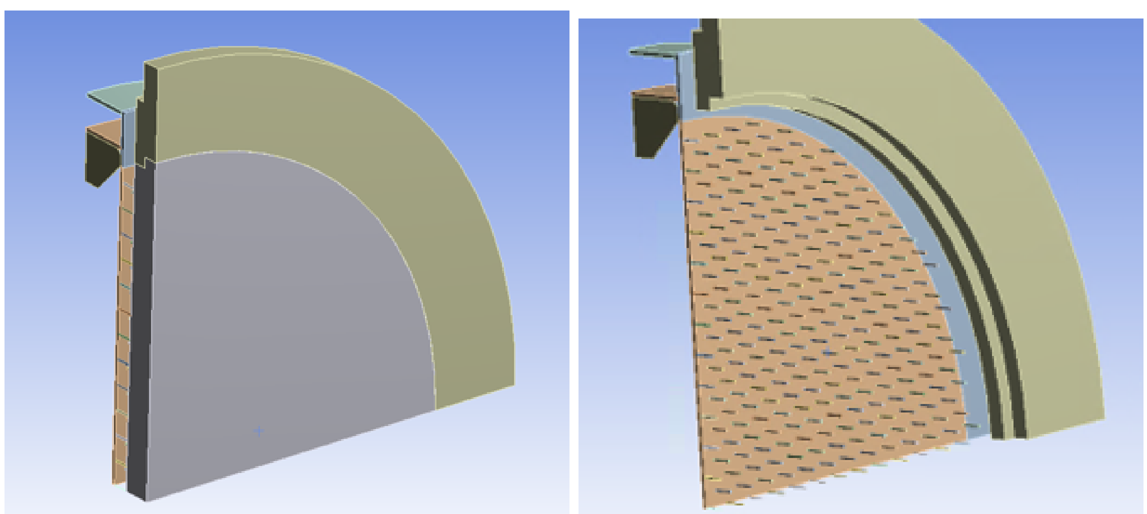


Figure 14: The simplified initial stayed head design: with yoke cover (Left), without yoke cover (Right)

The results of the initial analysis of the stayed head showed that the design meets the requirements of The Code. Further investigation will be needed for the final design, however

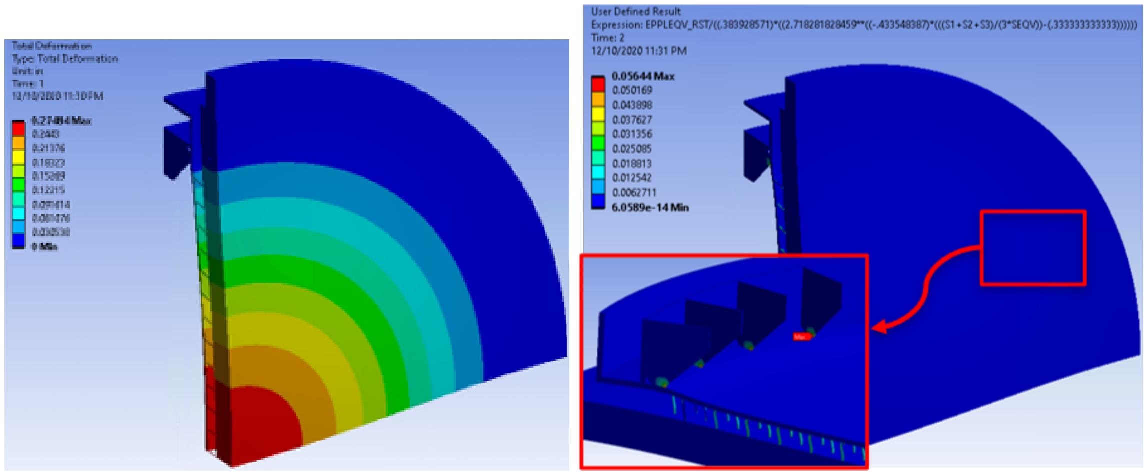


Figure 15: The simplified initial stayed head analysis: Deformation (Left), Local failure check (Right)

the initial results indicate that the design concept is feasible.

5.4.2 Cryostat Shell Analysis

To verify and size the thickness of the cryostat, a three sets of analysis were performed. The first set were of calculations were performed as per 4.3 and 4.4 of The Code. The purpose of this assessment was to verify the feasibility of the design. Due to the complex combination of load paths because of the unique design, further refinement was needed. Using the methods described in Part 5, the second set of assessments looked at optimizing the thickness of the internal shell. For this assessment, the thickness cryostat was parametrically varied to determine the required minimum thickness. The results of the assessment indicated that the thickness of the thinner section of the cryostat could be reduced to about 0.5” and the thickness of the thicker section of the cryostat inner shell could be reduced to about 1” thick.

Using the optimized thickness values, final assessment performed was an In depth FEA assessment using an optimized thickness and loads from other assessments. The weights of other components were applied as forces assuming the HPgTPC was 15 Tons and the calorimeter was 200 Tons. An internal pressure of 10 Bar and an external pressure of 1 bar were used for the pressure loads on the surface.The force and moment reactions from the assessment performed in section 5.4.1 were used along with reaction forces from the initial assessment on the magnet reaction forces [11]. The analysis was solved using Elastic-Plastic methods as described in The Code using a simplified symmetrical model seen in Figure 16. The model was also assessed for ratcheting failure as per 5.5.7 of The Code, and there was no indication of failure due to ratcheting.

Resolving the simulations showed that the model was able to converge on a solution, meeting the plastic collapse requirements. At the same load step, the assembly also met

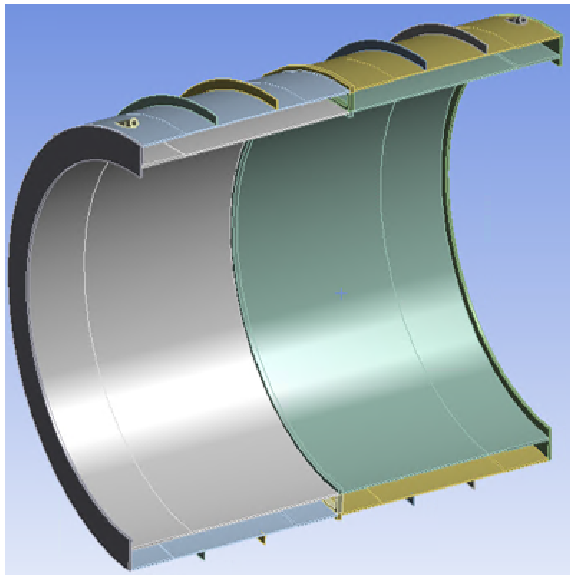


Figure 16: Model Used in Cryostat Shell Analysis

the local failure requirement of having a local strain limit lower than the value 1.0. Both of these results can be seen in Figure 17.

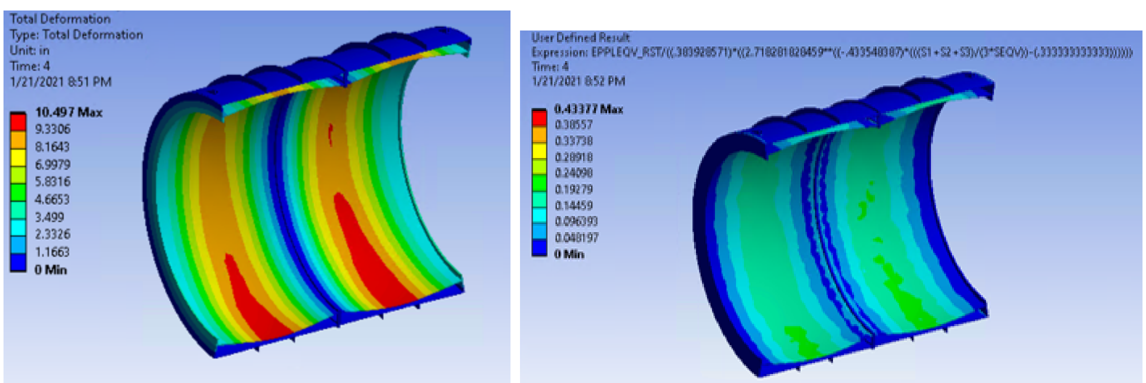


Figure 17: Results of Cryostat Shell Analysis, Plastic Collapse Requirment (Left), Local Failure Requirement (Right)

The loaded shell from the assessment was then used to determine if the shell would be able to resist buckling. Finding the mode shape, indicated that the model will collapse with a load factor of (resolving model find this answer) seen in Figure 18. As per section 5.4.1.2, for a Type 2 Elastic Plastic Assesment, a minimum load factor of 2.08 is needed. As the predicted buckling load factor is greater than the required minimum load factor, the cryostat meets the protection against buckling requirements.

As the protection against plastic collapse, local failure, and buckling requirements have

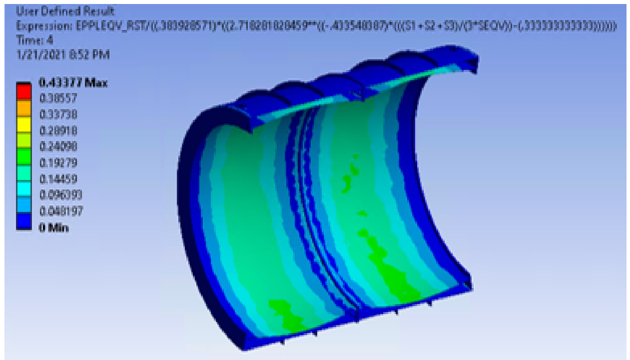


Figure 18: Results of Cryostat Shell Buckling Analysis

been met, the results of the analysis indicate that the Design of the ND-GAr Cryostat is feasable, however further refinement is needed. The final design of the calorimeters, flanges, and yoke will affect the liftime of the Cryostat. These details should be refined before the fatigue life of the cryostat is addressed. As there is room for the current design to be thinned out a bit, and still hold up, the fatigue life of the assembly does not seem to be a major issues.

5.5 Final assembly scenario

This assembly overview addresses the installation of the main sections of the system. Quite a bit of tooling must be designed and engineered to safely rig and install the components of this assembly. Note that all components apart from the full cryostat, are under the 60-ton weight limit set by the hall crane. Within the hall and somewhere along the ND-GAr floor tracks, an assembly area must be identified that will allow full access for personnel and rigging equipment while not impeding other work in the hall. Once identified, place the eight, motorized Hilman rollers on the ND-GAr tracks. Install the four cradles, each weighing 10.7 tons, and align properly to establish the base for the rest of the installation. The lower steel axial plates are then bolted to the four cradles and aligned. (see Figure 19) Using an external crane located at the surface (150-ton capacity), lower the cryostat down the access shaft onto a transportation table. Using rigging techniques, move the transport table and cryostat to the assembly area. Utilizing a combination of cribbing, tooling, and the existing 60-ton capacity crane in the hall, raise and position the cryostat onto the mounting points located on the lower yoke. Bolt securely in place and test for electrical shorts. (see Figure 20)

The electromagnetic calorimeter is installed next and although the concept model shown in Figure 21 looks simple, the segments are complex and pose an engineering challenge for installation onto the inner surface of the cryostat. The entire ECAL barrel weighs $\simeq$140 tons.

Following the ECAL installation, rails for the Time Projection Chamber (HPgTPC) are installed.(see Figure 22 The HPgTPC is installed onto the rails and slid into position.

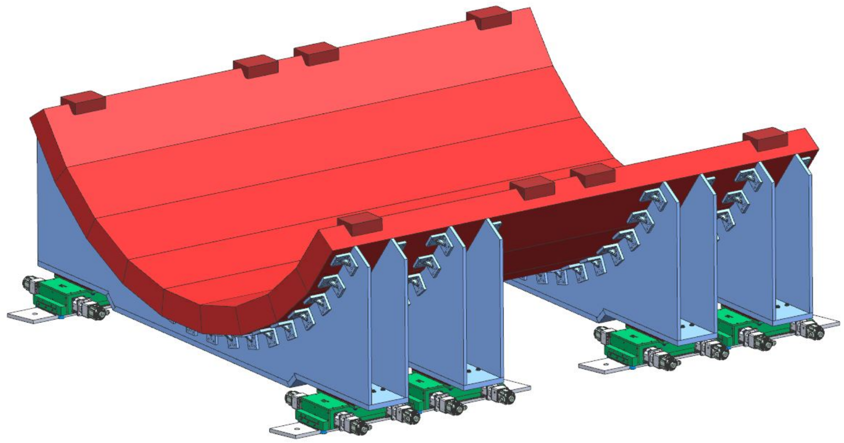


Figure 19: Install cradles and lower Yoke

Electronics readouts and all wiring for the barrel ECAL and HPgTPC should be routed and tested. Any necessary electrical rework should be completed before the ECAL end-plugs are installed as shown in Figure 23. Again, for simplicity, the end-plugs are shown as basic cylindrical bodies when in fact, they are complex assemblies and require unique tooling and a complete installation plan. Route and test all electrical cables.

Install the cryostat end flanges, as shown in Figure 24, and route all DAQ cables through electrical feed-through connections and temporarily place on the cryostat outer surfaces so that they will not impede the installation of the yoke end-rings shown in Figure 25. The final location of cables is to be determined, although a logical location would be to pass them through the large opening in the yoke between ND-GAr and ND-LAr or through special-purpose slots machined in the yoke staves. The end-rings are massive at 46.3 tons each yet under the 60-ton crane limit. They sit on top of the lower steel and bolt into position. For safety precautions, cross-bracing should be installed to stabilize the end-rings while the remaining yoke steel plates are being installed (see Figure 26).

Each yoke end-plug is a two-piece construction due to the overhead crane weight limit. Each of the four pieces weighs 54.5 tons; 2 pieces per end. Tooling and rigging fixtures similar to the concept shown in Figure 27 are used to assemble and then position each end-plug onto ND-GAr where they are bolted into position. The 1,956 stay bolts are tightened to specification against the cryostat end flange. Refer to section 9 for more details on the yoke and stayed head design. The cryogenic and vacuum connections can be completed and prepared for an Operational Readiness Clearance Review. The completed ND-GAr is shown in Figure 28. Once completed, the Hilman rollers can be tested and ND-GAr can be moved along its tracks.

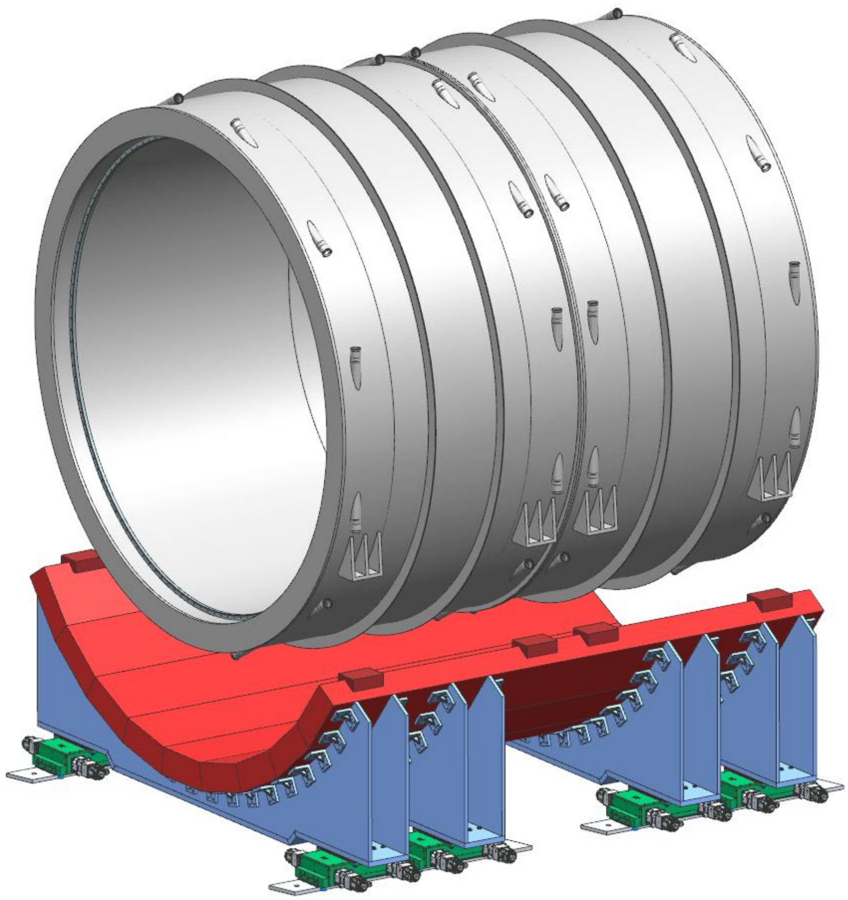


Figure 20: Install Cryostat onto Yoke

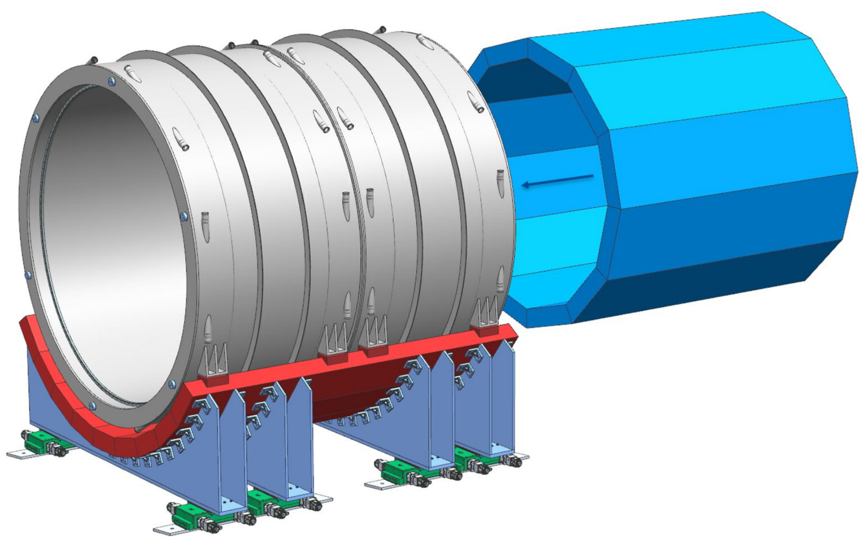


Figure 21: Install Electromagnetic Calorimeter

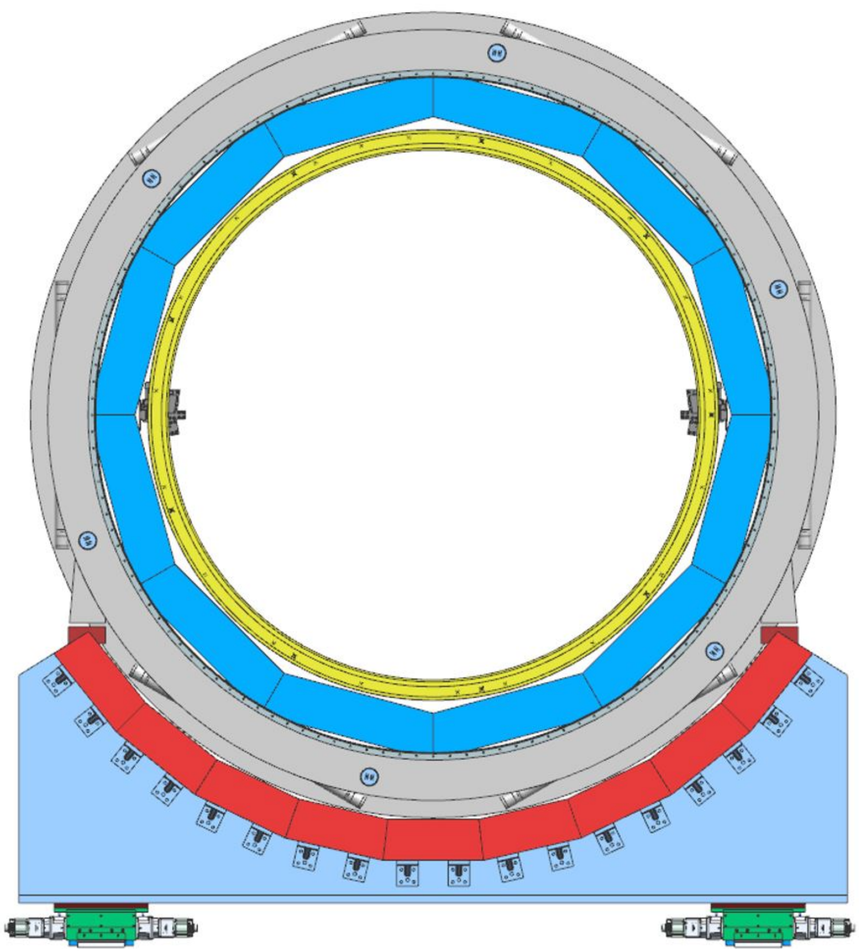


Figure 22: HPgTPC Installation

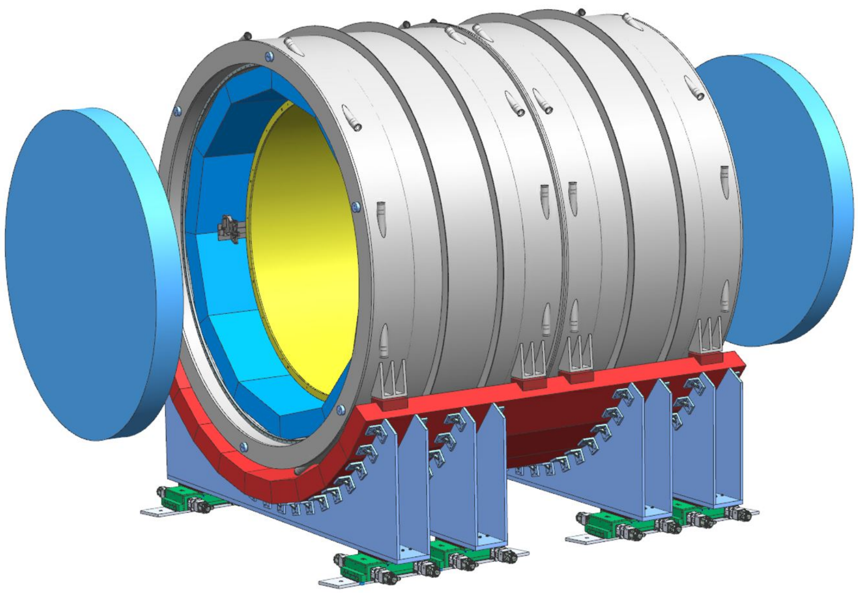


Figure 23: Install E-Cal End Plugs

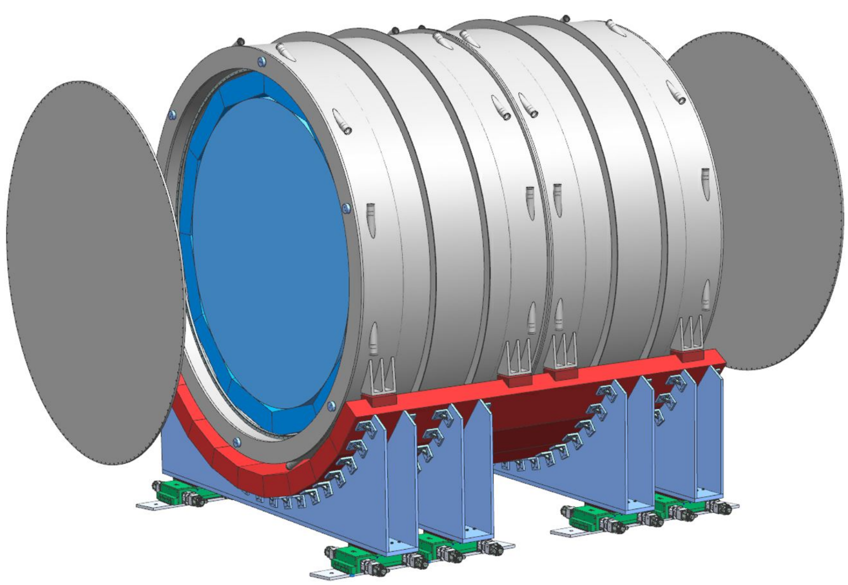


Figure 24: Install Pressure Vessel End Plates

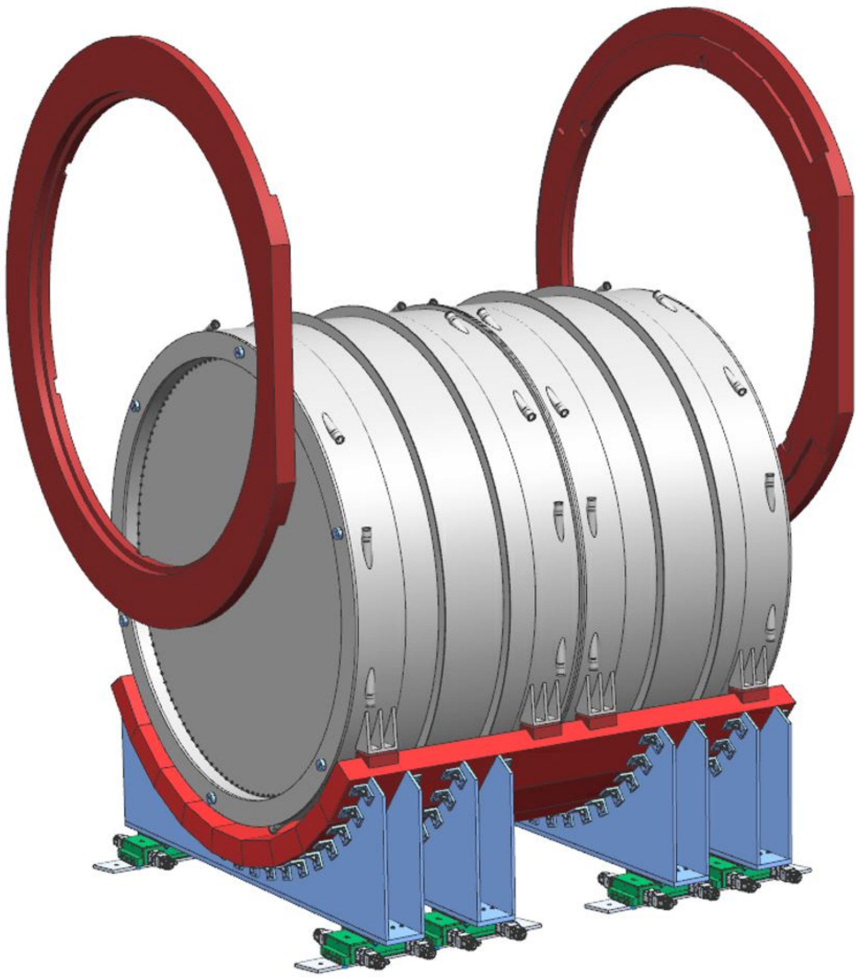


Figure 25: Install Yoke Rings

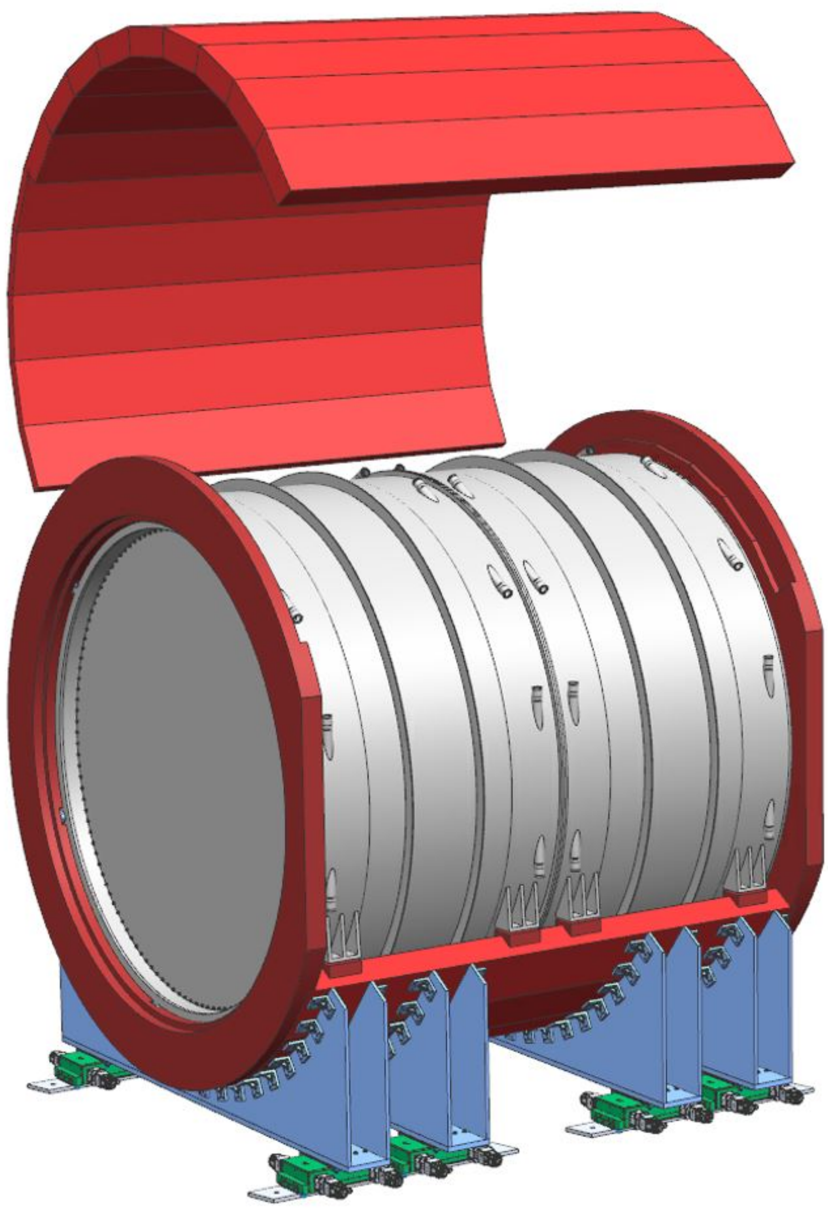


Figure 26: Install Final Yoke Segments

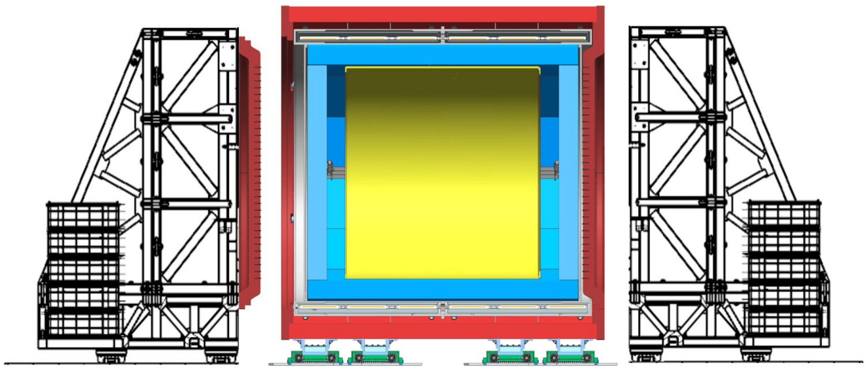


Figure 27: End Plug Yoke Installation

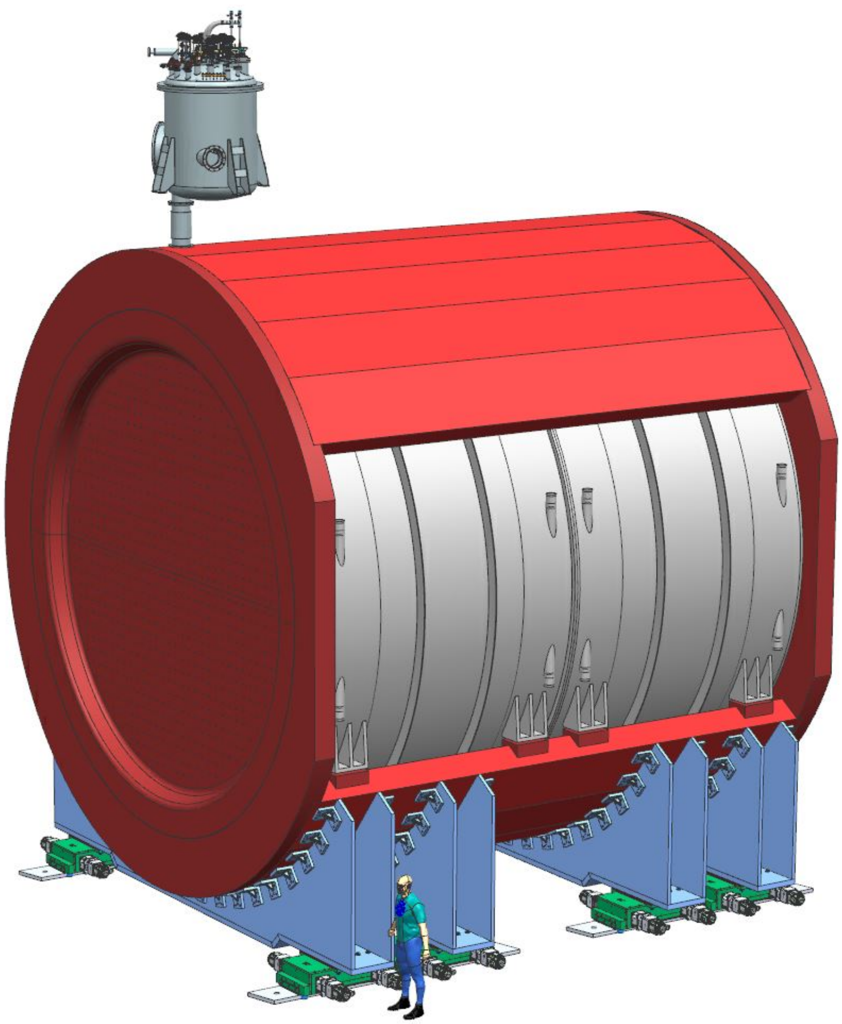


Figure 28: Full ND-GAr with cryogenic feedcan

5.6 Maintenance steps

Answer to the question: What steps and how long does it take to open the magnet to access the subdetectors (+ what kind of access will the subdetectors need.)

6 Thermal design (DM)

The coil will be conduction cooled by forced circulation of liquid helium in pipes welded onto the outer surface of the coil bobbin. The operating temperature of the 6 superconducting coils will be near 4K. An aluminum thermal shield will be either cooled by cold helium gas or by liquid nitrogen depending on the final design. This implies that the shield would operate either near 50 K or near 77K. The current leads will be cooled with part of the evaporating helium gas from the primary cooling circuit. The cryogenic fluids will be provided through a cryo-plant delivery system originating at the far end of the hall and delivering helium and nitrogen in insulated flex-hose supported by an articulating pipe carrier. (see Figure 29) The system provides cryogens to the feed-can mounted on a work platform that is secured to the top of ND-GAr. The cryogenic services will be installed in series during the construction of ND-GAr. (see Figure 30) The feed-can installation followed by cryogenic connections and coil lead splices will be the last thing necessary to complete the cryo system prior to an ORC review. This construction plan will minimize the impact on the schedule. The cryostat will have already been tested at the vendor fabrication site for vacuum leaks, cool-down issues, and electrical shorts.

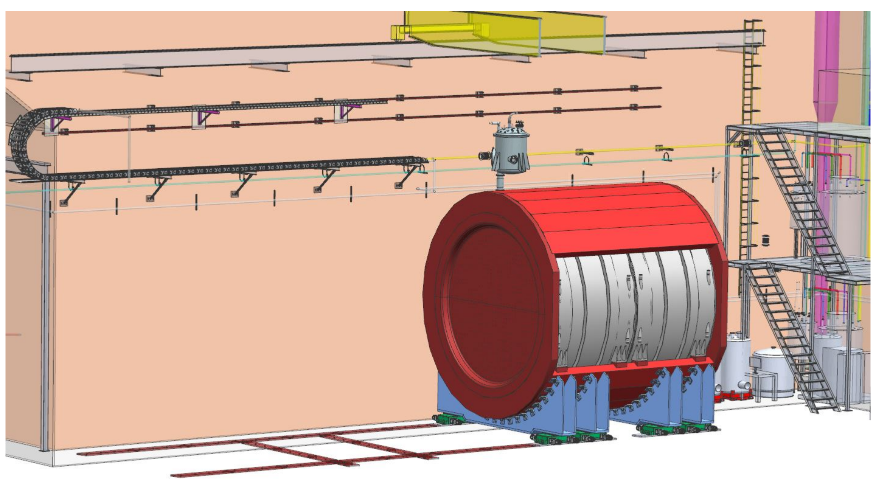


Figure 29: Hall layout showing cryogenic flexhose transport Carrier

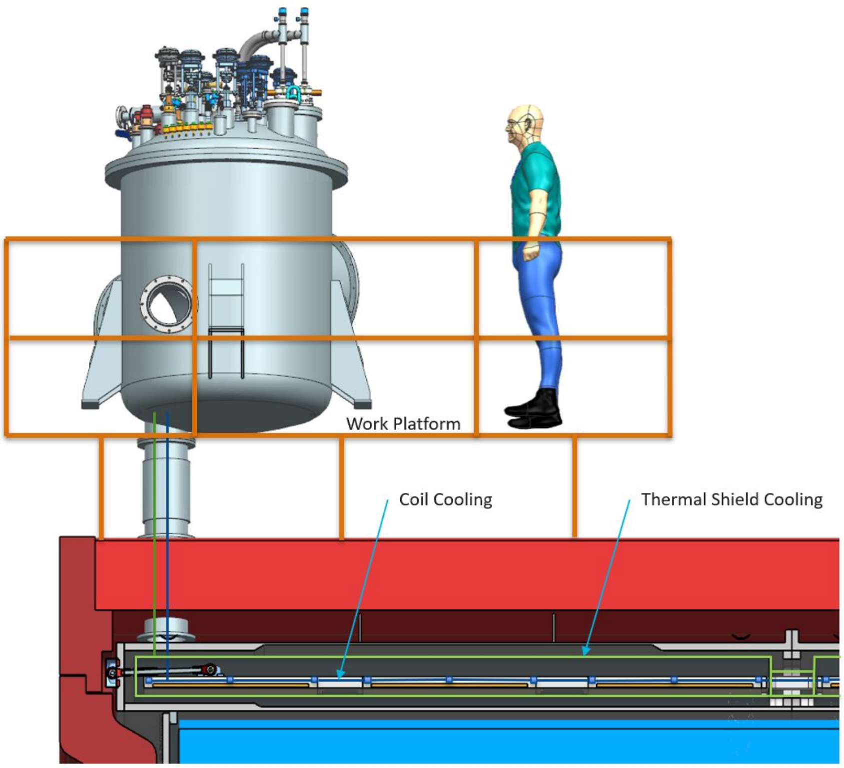


Figure 30: Thermal system and cryo platform

7 Instrumentation (ABr)

Basic instrumentation internal to the solenoid should follow standard practices and should include the following sensor types:

1. Temperature
2. Voltage taps
3. Strain gauges
4. Pressure and vacuum gauges

Since the vacuum vessel will also be used to contain the 10 bar pressure volume of the HPgTPC, additional strain gauges on the inner and outer shells are envisioned.

7.1 In LAr

Since there will be a stray field in the active volume of ND-LAr, adding field sensors (Hall probes) in strategic positions inside the liquid is recommended.

7.2 In Yoke (DM,CN)

Instrumentation from within the detector will pass through electrical feed-through plates mounted along the fixed flange of the pressure vessel so that the large end flange can be removed for repairs or maintenance without the need to disconnect the DAQ cables. The cables will then be routed around or through the magnet yoke be means of penetrations in the steel or by routing to the large yoke opening between ND-GAr and ND-LAr and then on to cable trays mounted along side of the flexible cryogenic lines.

8 Detector interfaces (ABr)

The solenoid will need to carry the load of the HPgTPC and the ECAL. See Figure 31 where the ECAL is shown in blue and the HPgTPC in yellow. The total mass the two detectors will be less than 150t with the majority of the mass being the ECAL. Optimization of studies of the ECAL will likely yield a much lighter detector, but final conclusions have not yet been reached.

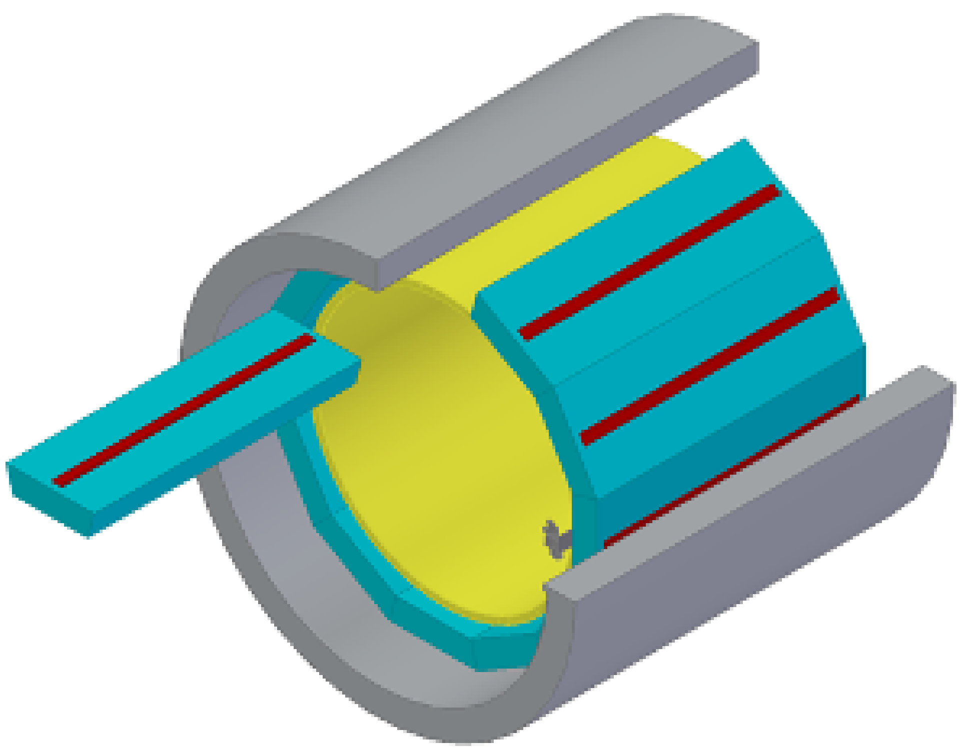


Figure 31: Schematic of ECAL and HPgTPC mounting to solenoid

9 Yoke (DM, CN)

By far, the dominant weight contributor to the ND-GAr is the steel yoke and cradles coming in at just slightly over 881 tons (see Figure 32). The yoke, due to the physical properties of the magnet, must be fabricated from low carbon steel. The four cradles do not contribute to the development of the magnetic field and are designed to be either 18-8 or 304 stainless steel. Each component of the yoke system is designed to be under the crane limit of 60 tons and to fit within the constraints of the shaft. The four end plugs are the heaviest pieces of the yoke assembly. Each end plug weighs 54.5 tons. There are two end rings and each weighs 46.3 tons. The long, axial steel plates that make up the barrel of the yoke come in two thicknesses, 150 mm and 400 mm. The 400 mm thick plates each weigh 26 tons. The cradles each weigh 10.7 tons. End plugs may require special forging or may need to be fabricated using welded plates. A special note about the end plugs – these shaped plates are designed to withstand the 10 bar operating pressure of the GAr system. The pressure vessel end flanges rely upon these yoke plates to provide the support of the 798 stay bolts so any layered plate design must take this loading into account.

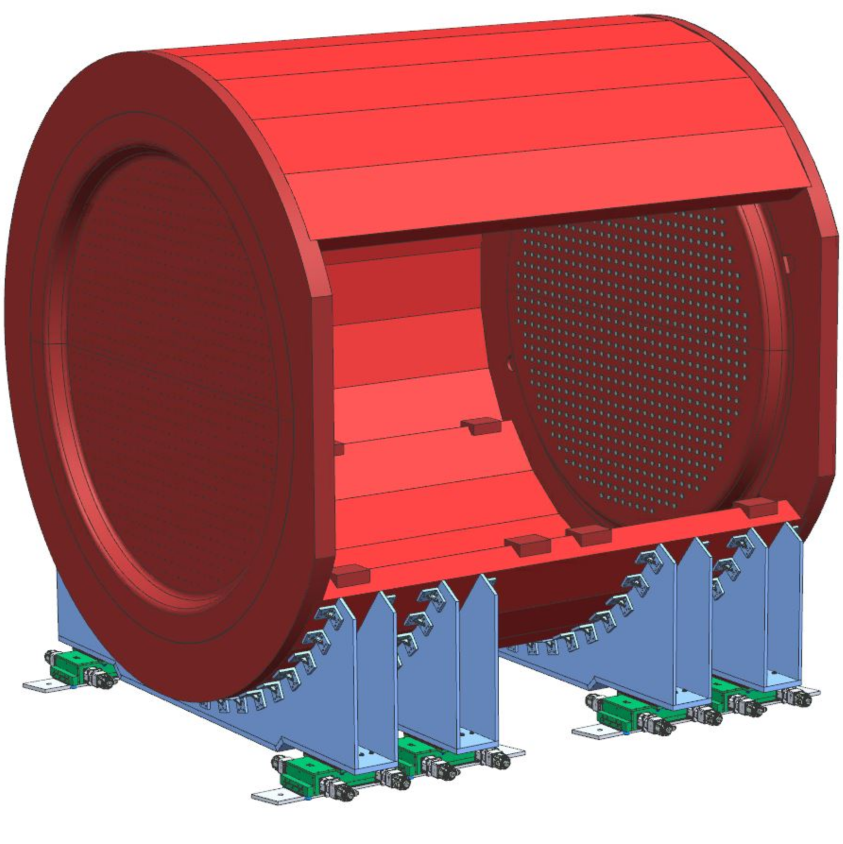


Figure 32: Full Yoke w/o cryostat

The steel axial plates are bolted to the four cradles and after the cryostats are installed, the remaining yoke components are assembled via bolted construction. Finite element analysis results show that the steel under gravity loading has minimal deflection but under magnetic loading and creep conditions, the steel can begin to deform out of alignment. The yoke, not shown in this design, should provide for a constraint system of either bolts, welds, or straps to preserve the design alignment of the separate components. Once the end plugs are installed, the 1,596 stay bolts need to be tightened to provide contact to the cryostat end flanges. The stay bolts are simple threaded rod leveling pads. A custom tool is required to reach each bolt as they are embedded in the steel end plugs.

The entire ND-GAr is supported by eight, motorized, Holman rollers; each with a 200-ton rolling capacity. Due to the track layout in the detector hall, and the nearby placement of the SAND and ND-LAr systems, clearance for ND-GAr is small. There are 435 millimeters of available space and if this space were split equally on each side of ND-GAr, there would only be a 217.5 mm gap between ND-GAr and SAND, and ND-GAr and ND-LAr. ND-GAr is not a symmetric system and if the load is centered in the available space, there would be more load on one side than on the other. In fact, the loading on the Hilman rollers on the ND-LAr side would exceed the 200 ton operational limit. Therefore, ND-GAr must be biased closer to SAND to shift the weight and distribute the loading so that none of the Hilman rollers exceed their capacity. A finite element analysis was performed, and the results helped define the location of ND-GAr. The gap between ND-GAr and SAND cannot exceed 178.8 mm. At this gap, two of the Hilman rollers hit or slightly exceed the load limit of 200 tons. Since there is no additional room for more rollers and no possibility for an additional track, it is critical that the design of ND-GAr pay particular attention to this loading constraint and to try to reduce the weight of ND-GAr to minimize this issue.

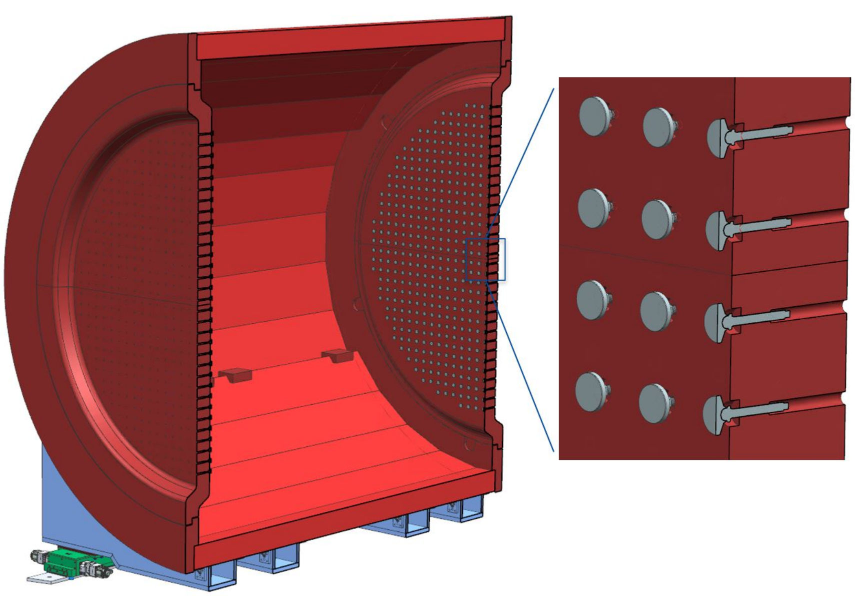


Figure 33: Stayed head conceptual design

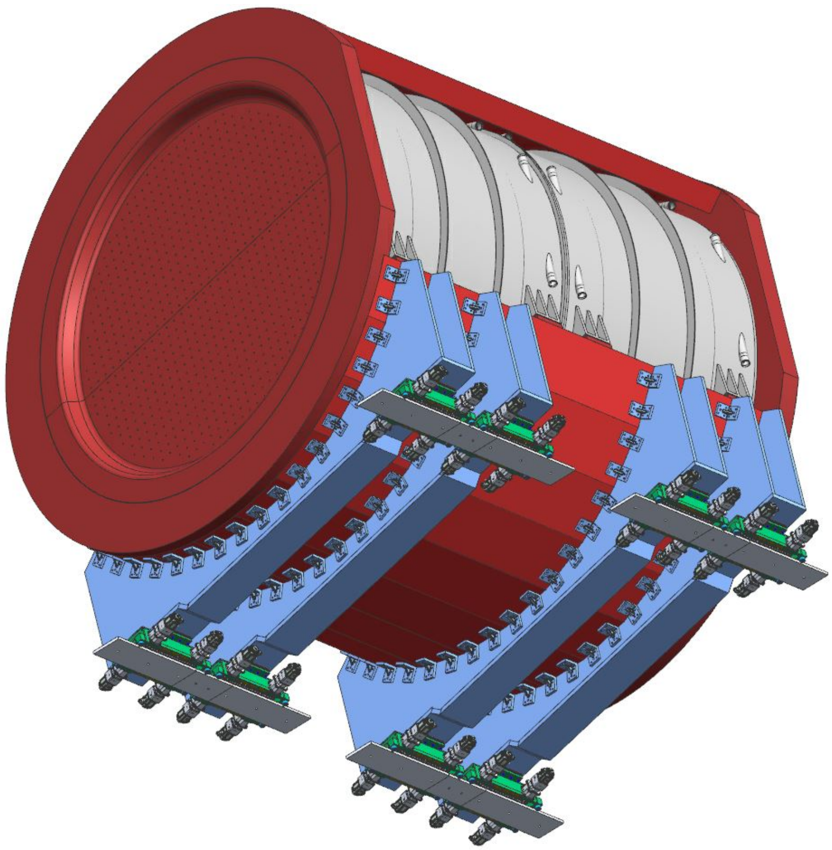


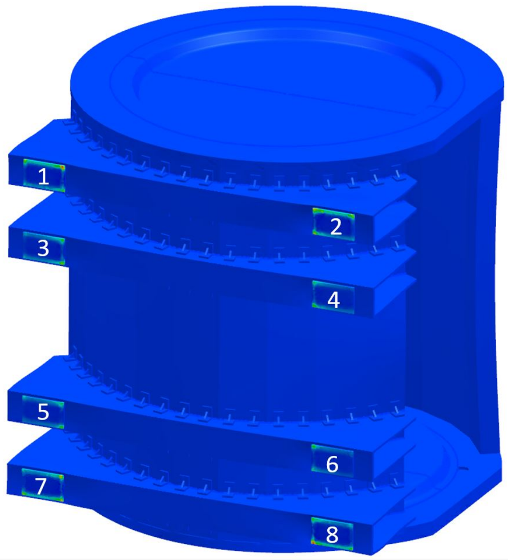
Figure 34: Motorized industrial rollers and support cradles

10 Stray field analysis (ABe)

SPY magnet is expected to operate between two other detectors, all very close to each other, therefore special attention to stray-field is needed. In addition, since the ND-GAr detector will be movable, the cross talk between the three detectors has to be evaluated in different configurations.

10.1 Stray field on SAND

We first evaluated the interaction between ND-GAr stray field with SAND. Since this latter is a magnetic spectrometer as well, the analysis must be performed both ways. The operating parameters for SAND have been recovered from KLOE papers.



Support	Load (Lbs)
1	377,644
2	400,010
3	258,117
4	206,704
5	257,136
6	205,922
7	378,018
8	400,553

Hilmans at
200-ton limit

Figure 35: Non-uniform Loading of industrial rollers

11 Failure mode analyses (EV)

The DUNE ND-GAr pressure containment system utilizes a very large flat circular flange (22' diameter) which will be designed to hold 10 bar of gaseous argon. The flange and flange bolts themselves are not nearly strong enough to support the pressure over such a large area, which equals 8 million pounds of force. However, the cylindrical vessel will have a larger cylindrical yoke (Figure 32) around its circumference and on the ends, outside of the vessel flanges. There will be many stay bolts which will be used between the much stronger yoke on the outside of the flange, and the flange itself; the idea being to transfer the pressure load from the weaker flange to the much thicker yoke which is able to support the pressure. Figure 36 shows a cross section of the cryostat, flange, and yoke, where the central axis of the cylinder is the Z axis, and the bolted flange connection of interest is called out. Conceptual Analyses were performed which showed the method would not work if using traditional flat flange bolt connection methods. While the yoke does take up most all of the pressure force in the central region of the flange, it does not take up the force near the outer portion of the flange as the bolted flange is much stiffer at the outer radius than the yoke at the same radius since the yoke's edge has a larger radius than the flange. This conventional bolted flange connection would fail at the bolts, and the O-ring seal would leak. Over-stress is caused by the moment applied on the bolts due to the prying force caused by the internal pressure and deformation of the flange, and the flange pivoting about its outer edge. Figure 37 shows the radial pressure on the flange from the stay bolts vs. the internal pressure (10 bar) with a traditional flat face bolting method.

We have developed a conceptual bolting method for the flange which is a simply supported type connection. This flexible bolted connection practically eliminates the bending

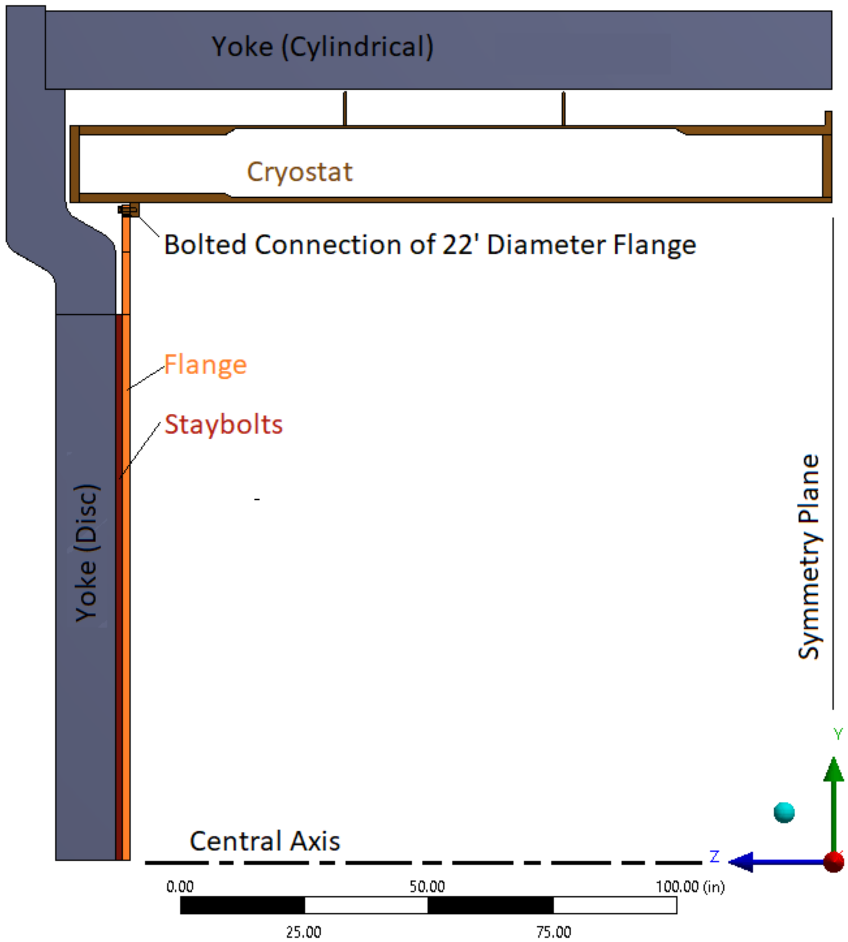


Figure 36: :Cross section of the cryostat, flange, and yoke, where the Central Axis of the cylinder is the Z axis

moment on the bolts, as it allows rotation about the new fulcrum point, which is placed near the O-ring groove instead of at the outer edge of the flange. Since it is more flexible, it also results in more of the total force being transferred to the yoke, as apposed to the flange itself. This connection method is achieved by using a machined recess in the flange as well as spring washers of a required spring constant and excess deformation range. Figure 38 below shows the flange connection. Bolt pretension must be high enough to keep the fulcrum point on the flange in contact with the vessels mating flange. Preliminary analysis shows this flexible flange connection is able to keep the flange sealed, and has adequate bolt strength. Choosing the correct spring washers with additional working deformation, along with the appropriate pre-tension will be of vital importance to making this connection work as intended, which is not a trivial task. High strength bolts will also be useful in the design. Inconel 718 bolts are the strongest ASME Pressure Vessel bolt we are aware of.

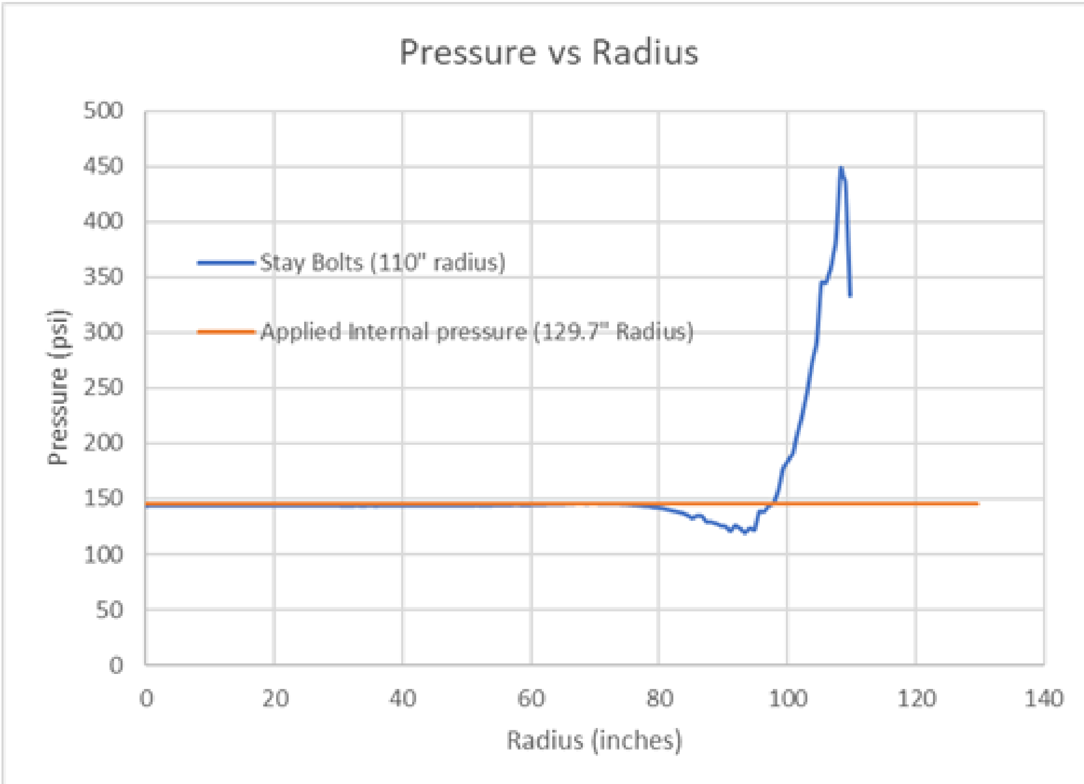


Figure 37: :Radial pressure on the flange from the stay bolts vs the Internal Pressure inside the GAr Vessel (10 bar) with a traditional flat face bolting method.

12 Shipping (ABe, ABr)

Transport from Italy to the US will be via ship and up the Mississippi to the South side of the Chicago. Andrea, can you expand on this with input from ASG?.

We have contacted Emmert International regarding transport from the Port of Chicago to Fermilab. Although there will be logistical issues involved and a study will have to be done to development a plan for the best routing, they do not see any show stoppers given a package size of 9 m × 9 m × 9 m.

13 Preliminary schedule and cost (ABr)

We have developed preliminary cost and schedule data for SPY based on input from ASG Superconductors and experience with previous magnet systems. ASG has provided a cost envelop of between 15M€ to 18M€ for the solenoid. A cost estimate of $3M USD has been provided by our colleagues in India for the return iron sourced in India. Our preliminary schedule is shown in Figure 39. Although this document represents the completion of the

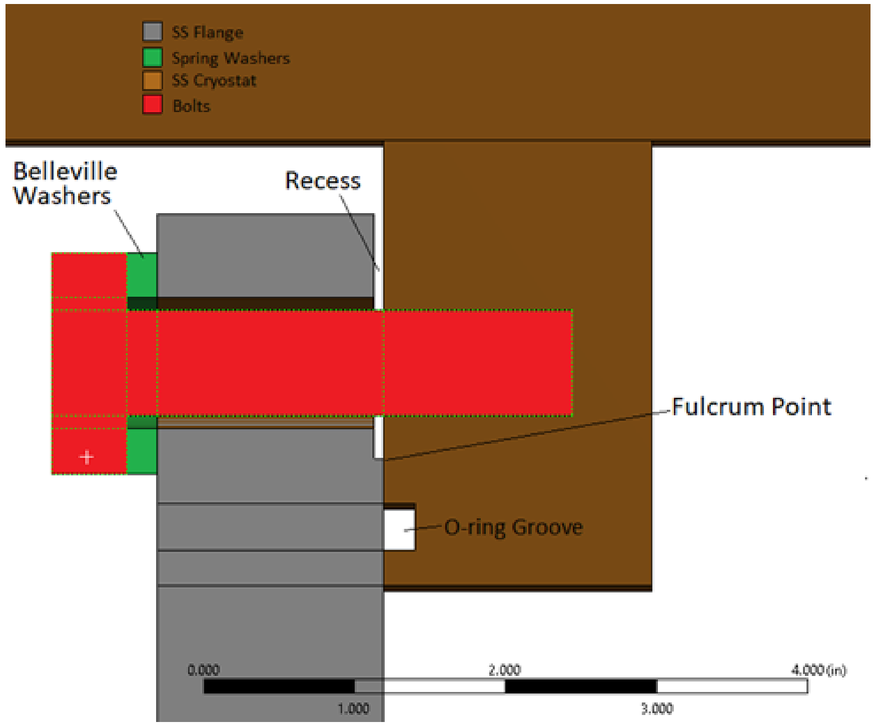
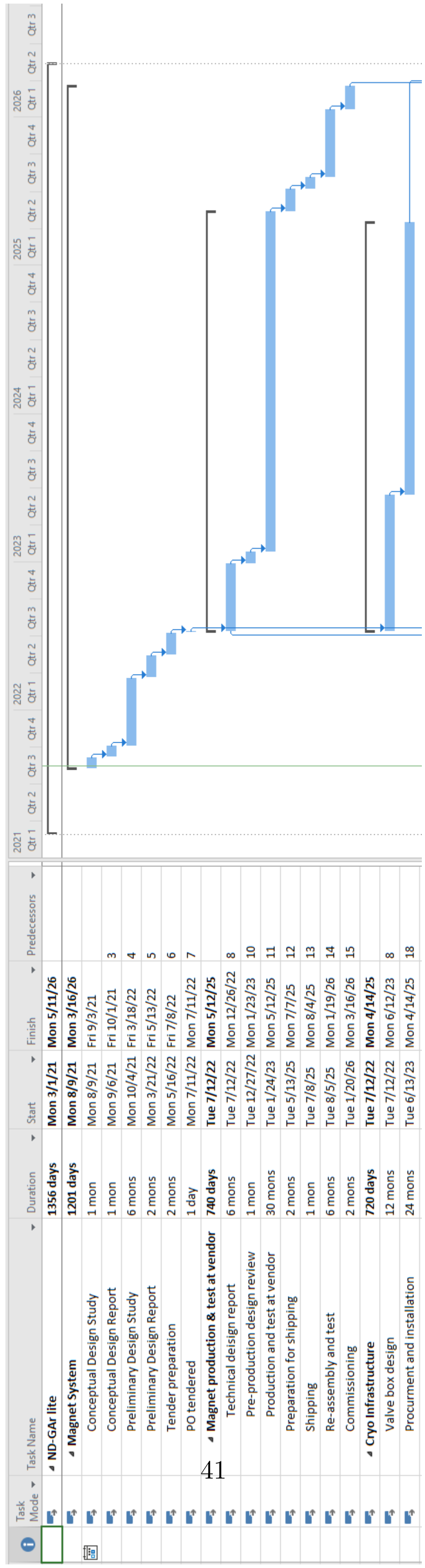


Figure 38: Flexible bolted flange connection allows rotation of the flange end, eliminated the prying force and moment on the bolts, and keeps the vessel sealed. Traditional bolting methods failed with the stayed head design.

Conceptual Design Report task in the schedule, the rest of the dates in Figure 39 should only be viewed in the context of durations, not actual start dates since we do not know when a preliminary design study can be launched.



Task Name	Duration	Start	Finish	Predecessors
ND-GAr lite	1356 days	Mon 3/1/21	Mon 5/11/26	
Magnet System	1201 days	Mon 8/9/21	Mon 3/16/26	
Conceptual Design Study	1 mon	Mon 8/9/21	Fri 9/3/21	
Conceptual Design Report	1 mon	Mon 9/6/21	Fri 10/1/21	3
Preliminary Design Study	6 mons	Mon 10/4/21	Fri 3/18/22	4
Preliminary Design Report	2 mons	Mon 3/21/22	Fri 5/13/22	5
Tender preparation	2 mons	Mon 5/16/22	Fri 7/8/22	6
PO tendered	1 day	Mon 7/11/22	Mon 7/11/22	7
Magnet production & test at vendor	740 days	Tue 7/12/22	Mon 5/12/25	
Technical deisign report	6 mons	Tue 7/12/22	Mon 12/26/22	8
Pre-production design review	1 mon	Tue 12/27/22	Mon 1/23/23	10
Production and test at vendor	30 mons	Tue 1/24/23	Mon 5/12/25	11
Preparation for shipping	2 mons	Tue 5/13/25	Mon 7/7/25	12
Shipping	1 mon	Tue 7/8/25	Mon 8/4/25	13
Re-assembly and test	6 mons	Tue 8/5/25	Mon 1/19/26	14
Commissioning	2 mons	Tue 1/20/26	Mon 3/16/26	15
Cryo Infrastructure	720 days	Tue 7/12/22	Mon 4/14/25	
Valve box design	12 mons	Tue 7/12/22	Mon 6/12/23	8
Procurment and installation	24 mons	Tue 6/13/23	Mon 4/14/25	18

Figure 39: Preliminary schedule for SPY

14 Conclusions

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