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Solenoid Magnets for the Front End of a Neutrino Factory

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This report describes the solenoid magnets in the front end (the section between the pion capture solenoid and the linear acceleration section) of the Level 2 study of a neutrino factory[1,2]. The magnets described in the report start with the decay channel magnets that starts 18 meter downstream from the start of the pion production target. The magnet string ends with the transition solenoids that match the muon beam from the last cooling cell to the superconducting linear accelerator section. All of the magnets described in this report are solenoids. The field on axis in the solenoidal channel ranges from 1.25 T to just over 5.5 T. This report shows that the magnets in the front end of the neutrino factory are feasible.

I. INTRUDUCTION

This report describes the string of solenoids at the front end of a neutrino factory uses an intense stored muon beam in a storage ring to generate the neutrinos. The first magnets in the front-end magnet string are solenoids downstream from the target and capture solenoid where pion decay occurs[3,4]. These magnets have an on axis field of 1.25 T. The on axis field varies about ± 2.5 percent. The periodicity of the field in the decay and phase rotation channel was set at 500 mm. Pions decay to muons starting just downstream from the target to well into the first induction linac section. The 500 mm field periodicity sets up oscillations in the pion and muon beam that will kick out particles with an energy less than 75 MeV. For the most part, these particles would be lost anyway.

About 36 m from the start of the target, most of the pions have decayed to muons. At this point, phase-rotation starts. In both Study I and Study II, induction accelerators are used to accelerate the slow muons and decelerated the fast muons[4-6]. In Study II, the phase-rotation uses three induction accelerators. Between the first and second accelerators is a pair of hydrogen absorber mini-coolers and a field flipping region[2]. The final two induction linacs complete the phase-rotation process. Overall the phase-rotation and cooling occurs over a length of about 330-m. All of the solenoids in the phase-rotation channel produce 1.25 T ± 0.03 T on axis.

As one moves into the bunching and cooling channels, the field flips from one polarity to the other with each cell[2,4.7,8]. The matching section, the bunching section, and the first part of the cooling channel consists of forty-one cells that have a period of 2.75 m. The second part of the cooling section and the matching section to the linear acceleration section consists of forty-four cells that have a periodicity of 1.65 m. The 2.75-m cells have a peak on axis induction of 3.5 T near the field flip region. The peak induction on axis in the 1.65-m cells is 5.5 T.

II. THE PHASE-ROTATION CHANNEL

Within this decay and phase rotation region, there are four types of solenoids[2]. They are: 1) There is a decay section that has a warm bore diameter of 600 mm. Around this warm bore is a water-cooled copper shielding that is 50 to 100 mm thick. Thus the solenoid cryostat warm bore is 800 mm. The 18 meters of decay solenoid is divided into six cryostats that are each 2.9-meters long. Three of these magnets can also be used for the 9-meter long mini-cooling sections that are on either side of the field flip solenoid between the two absorbers. As a result, it is assumed that there are twelve magnets of this type. 2) The first induction linac solenoids extend 110 m from the pion decay section to the first mini-cooler. These magnets have a beam bore diameter of 600 mm. Around this bore is a 10-mm thick water-cooled copper radiation shield. Thus the warm bore diameter of this magnet cryostat is 620 mm. There are one hundred-ten magnets of this type. 3) The second and third induction linacs and the drift section between them extend 197 m from the second mini-cooler to the start of the matching section before the muon bunching section[2,6]. Since the muons have gone through the hydrogen absorbers, there are no stray particles from the target left to interact with the magnets. The solenoids for the induction cells downstream from the mini-cooler have no shield; thus they have a cryostat warm bore diameter of 600 mm. There are one hundred ninety-seven magnets of this type. 4) The field flip solenoid between the two min-cooling absorber sections is 2.0-meters long with a warm bore diameter of 400 mm. There is only one of these magnets. The field flip solenoid between the two cooling absorbers is not discussed in this report

Table I shows the design parameters for the induction linac solenoids and the solenoids in the decay channel and mini-cooling channel. The 2-m long field flip solenoid is not included in Table 1. Figure 1 shows a cross section of the induction cell with its solenoid.

TABLE I. Parameters for the solenoids for the decay channel, phase rotation channels, and the mini-cooler channel

	1st Induction Linac Magnets	Later Induction Linac Magnets	Decay & Cooling Magnets
Number of Cells of This Type	110	197	12
Cell Length (mm)	1000.0	1000.0	3000.0
Magnet Cryostat Length (mm)	900.0	900.0	2900.0
Number of Coil Packages per Cell	1	1	3
Magnet Coil Package Length (mm)	860.0	860.0	860.0
Number of Coils in the Coil Package	2	2	2
Length of Each S/C Coil (mm)	360.0	360.0	360.0
Inner Cryostat Radius (mm)	310.0	300.0	400.0
S/C Coil Inner Radius (mm)	334.0	324.0	429.0
S/C Coil Thickness (mm)	9.6	9.6	9.6
Support Structure Thickness (mm)	6.4	6.4	6.4
Magnet Cryostat Thickness at Ends (mm)	55.0	55.0	80.0
Magnet Cryostat Thickness at Center (mm)	80.0	80.0	80.0
Cold Mass per Magnet Cell (kg)	207.6	201.1	911.1
Overall Mass per Magnet Cell (kg)	277.3	268.0	1151.1
Average Central Induction (T)	1.25	1.25	1.25
On Axis Induction Variation (%)	±2.5	±2.5	±2.2
Peak Induction in the Windings (T)	~1.6	~1.6	~1.6
Number of Turns per Cell	2532	2532	7596
Magnet Design Current (A)	392.8	392.8	392.8
Magnet Stored Energy per Cell E (kJ)	224	211	1103
Magnet Self Inductance per Cell (H)	2.90	2.74	14.3
Superconductor Matrix J (MA m^{-2})	249	249	249
E J^2 Limit per Magnet Cell (J A^2 m^{-4})	1.39×10^{22}	1.31×10^{22}	6.86×10^{22}

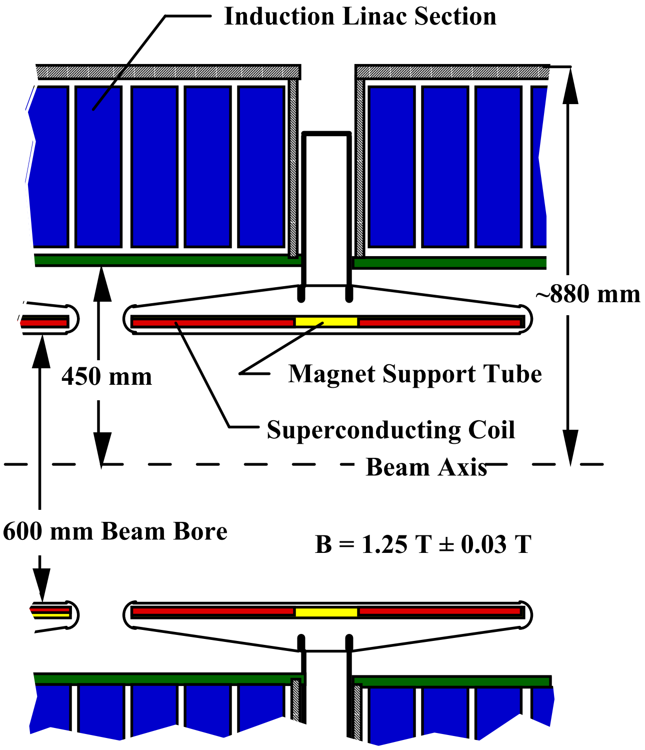

FIG 1. A cross section of the solenoid in an induction cell

The basic requirements for the phase rotation linac are as follows[5,6]: 1) The magnetic induction in the phase-rotation and mini-cooling channel has been set to 1.25 T. This means that the bore diameter for the beam is 600 mm. 2) The period of the on axis field of the phase-rotation channel should be minimized. This means that the coils in the cell should be of equal length with equal length gaps between the coils. A 1.0-meter long cell can have two equal length coils (360-mm long) and two equal length spaces between coils (140-mm long), which yields a period length for the magnetic field of 500 mm. 3) The radial thickness of the solenoid cryostat should also be minimized. This allows the induction linac structure to be brought closer to the axis of the machine. A second factor that influences the distance the induction cell can be from the magnetic field axis is the magnetic flux leakage through the gaps between the superconducting coils. 4) The space between the induction linac cells must be minimized. This means that the space used for the cold mass support system, the electrical leads and the cryogen feed system must fit in this minimum space. 5) Field correction dipoles are assumed to be mounted on the inside side of the solenoid coils. The pair of dipoles is 1.0-mm thick and they will correct alignment errors up to 5 mrad.

Fig. 2 shows a cross section of a superconducting solenoid that is designed to generate an average induction of 1.25 T on the axis of the phase-rotation induction linac. The inner bore radius of the solenoid cryostat is 300 mm.

This allows a 200 MeV muon beam with a nominal diameter of 600 mm to pass through the solenoid without loss (except from muon decay). The distance from the end of the superconducting coil to the outside end of the cryostat was fixed at 20 mm. If an additional support clip is needed at the end of the coil, the coils can be made shorter to accommodate the clip in the space shown. The coils in the solenoid shown in Figure 1 have a length of 360 mm. The gap between the coils is 140 mm and the space between a coil in one magnet and the coil in the next magnet is also 140 mm.

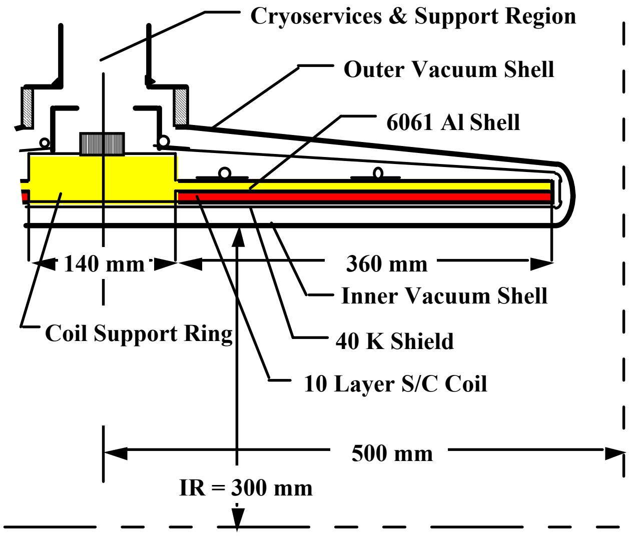

FIG. 2. A cross section of the superconducting magnet for the induction cell downstream from the mini-cooler.

The proposed conductor for coils shown in Figure 2 is a standard MRI magnet conductor that is 1 part Nb-Ti and 4 parts RRR=70 copper. This conductor has fifty-five 85-µm filaments twisted with a twist pitch of 12.7 mm. The bare matrix dimensions of the conductor are 0.955 mm by 1.65 mm. The conductor insulation is 0.025 mm thick. The coils are designed to be 6 layer coils that in 9.6 mm thick, including 2 mm of ground plane insulation. At an average design induction of 1.25 T on axis, the coil design current is about 392.9 A. The peak induction in the coil winding is only about 1.6 T, which means that the coil operating temperature margin is over 2.5 K

It is proposed that the coils be wound and cast on a form that is removed after the coil is cured. After curing the coils are removed from the mold and machined at the ends and on the outer radial surface. After the coils are machined they can be shrink fitted into 6061 aluminum support structure that has been machined sot that the coils closely fit within it. The 6061-aluminum support structure on the outside of coils serves the following functions; 1) It limits the coil strain by carrying some of the magnet hoop forces, and 2) it serves as a shorted secondary to protect the magnet during a quench. Thus the magnet is entirely self-protecting through quench back from the support structure. Since the solenoids are closely coupled inductively, one can use quench back to protect a string of these magnets as well.

The longitudinal space at the center of the magnet available for leads, cryogenic services, and cold-mass supports is about 85 mm. The cold mass of phase-rotation solenoid (including the 40 K shield and lower lead assembly) is estimated to be about 210 kg. The primary forces that will be seen between the cold mass and room temperature will be forces due to shipping and forces introduced due to unbalanced magnetic fields. The magnet cold mass supports are designed for a force of 10000 N in any direction. It is proposed that a pair 60 mm diameter oriented carbon fiber tubes (with a 3-mm wall thickness) be used to carry forces from the cold mass to room temperature. Since there is a solenoid magnet every meter down the phase rotation channels and the drift spaces between the phase rotation linac sections, leads must be brought out of each of these magnets. All of the magnets in 25-m long subsets can be hooked in series and run from a common power supply. The inter-connects between the solenoids are conventional copper cable.

A long string of magnets can be run from a power supply because the magnet coils are closely coupled inductively to each other and to the support structure. Quench-back is the primary mode of quench protection for the string of magnets. When quench back is used for quench protection all of the magnets will quench when one does. Quench-back also eliminates the forces between solenoids when one goes normal. Each 1-m long magnet section will have its own set of leads to room temperature. The leads between 4 K and 40 K will be made from high temperature superconductor (HTS). The leads from 300 K to the top of the HTS leads will be gas-cooled. Gas at 16 K from the refrigerator that is used to cool the magnet shields and cold mass support intercepts can be used to cool the gas-cooled leads. This gas is returned refrigerator compressor at 300 K.

The solenoids for the decay channel and the mini-cooler section use the same basic magnet design as the magnets used in the induction linac cells. The primary difference is the inside diameter of the superconducting coil (858 mm versus 648 mm for the induction cell coils). Another difference is that three coil modules are in a single cryostat vacuum vessel. Each module has its own cold mass support system, but the three modules are hooked together using superconducting bus bars cooled with two-phase helium. There is a single set of leads powering the modules in the magnet cryostat. In the magnets that are next to the flip region, individual power supplies may be used to power the coils to shape the magnetic field in the flip region.

The solenoids for the mini-cooling section are the same as those proposed for the decay channel. The warm bore diameter should provide enough space for the 1.75-m long hydrogen absorbers that have window diameters of 600 mm. This allows for up to 70-mm space on the outside of the absorber for cooling of the hydrogen within the absorber. The hydrogen absorbers will use helium coming from the refrigerator at 16 K to cool the liquid hydrogen in the absorber. The cryogenic services to the hydrogen absorber can go through the 100-mm space between the magnet cryostats.

III. SOLENOIDS FOR THE MUON BUNCHING AND COOLING CELLS

The beam bunching and cooling section is between phase-rotation section that ends 356 m from the target and the linear accelerator section that starts at 548 m from the target[2,8]. The bunching section starts with a matching section that is about 11-m long. This section matches the phase-rotation section at 1.25 T with the SFOFO structure that characterizes the muon bunching and cooling sections. Downstream from the matching section are twenty cells of beam bunching. Each cell is 2.75-m long and each cell contains four 201.25 MHz RF cavities and one 402.5 MHz RF cavity. Seventeen cells of muon cooling that are 2.75-m long follow the beam-bunching section. These cells have four 201.25 MHz RF cavities and a hydrogen absorber that is in the bore of the field flip solenoid. The long cell cooling section starts 419 m from the target and ends 469 m from the target. The final cooling section consists of thirty-seven cells that are 1.65-meters long. The 1.65-meter long cooling cells contains two 201.25 MHz RF cavities and a short hydrogen absorber that is in the field flip solenoid. The short cell cooling channel starts from z = 469 m from the target and ends 530 m from the target. The final matching section is between the cooling section and the linear accelerator is 18-m long. The first 70 MeV of muon acceleration occurs in this section.

The matching section consists of four 2.75-meter long cells and about 3 meters of solenoids (part of the phase rotation section) that have a warm bore diameter of 600 mm. These solenoids must be designed to withstand longitudinal forces of up to 75 metric tons that are imparted on them by the matching process. The solenoids in the four matching section cells are the same as in the cells in the beam bunching and cooling sections downstream. The warm bore aperture of the A coils for a 2.75-meter long cooling cell must be about 650 mm in order to accommodate a liquid hydrogen absorber. The warm bore aperture for the beam bunching cell flux reversal coils must be the same in order to accommodate a 402.5 MHz RF cavity. Room temperature service ports to the 402.5 MHz RF cavity can go out through the flux reversal magnet cryostat between the flux reversal coils.

Table 2 shows the number of cells of each type, the minimum aperture requirements for the magnets and the maximum coil current densities for the coils in each cell type. Because the bunching and cooling cell solenoids are constantly changing polarity, there is almost no stray field from these solenoids at a distance of 10 m.

Magnet parameters for the 2.75-m long bunching and cooling cell magnets are shown in Tables 2 and 3. Magnet parameters for the 1.65-m long cooling cell magnets are also shown in Tables 2 and 3. Figure 3 is an illustration of the design of the magnets for the muon cooling cells. Figure 3 is a cross section of the matching cell between the 2.75-m long cooling cells and the 1.65 m long cooling cells. The solenoid magnet cross section shown in Figures 3 is through the section where the HTS leads are located. Figure 3 shows that there is space between the field flip coils. This space can be used to feed a liquid hydrogen absorber.

TABLE II. Basic Cell Parameters for the Beam Bunching and Cooling Cells

Parameter	2.75 m Cell	1.65 m Cell
No. of Cells of This Type	41	44
Cell Length (mm)	2750	1650
RF Cavity Space (mm)	1966	1108
No. 201.25 MHz Cavities per Cell	4	2
No. 402.5 MHz Cavities per Cell	1	NA
A Coil Cryostat Length (mm)	784	542
B Coil Cryostat Length (mm)	283	209
Aperture for the A Magnet (mm)	650	370
Aperture for the B Magnet (mm)	1390	1334
Max. A Coil J (MA m^{-2})	128.04	99.81
Max. B Coil J (MA m^{-2})	98.83	105.53
Maximum Cell E (MJ)	13.2	17.6
Max. Warm to Cold Force (MN)	0.74	1.20
No Supports per Coil	4	8

Figures 3 show a cross section of the matching section of the cell solenoids. The plane for the cross section is taken through the HTS and gas-cooled electrical leads. The cross section in Figures 3 shows the magnet cryostats, the coils, the coil support structure, the shields, the RF cavities, and the vacuum vessel around the RF cavities. The cryostat vacuum systems are separated from the vacuum around the RF cavities and the beam vacuum. Figure 4 shows a cross section through the center of the 1.65-meter long cell A coil pair. Figure 4 shows the location of the longitudinal cold mass supports and the cold mass supports that carry forces in directions perpendicular to the solenoid axis. Figure 4 illustrates how magnet electrical leads, and helium refrigeration can be brought into the cryostat.

Figures 3 does not show the location of the hydrogen absorbers within the bore of the A coil pair. The transition between the 2.75-m long cells and the 1.65-m long cells is the only cell without a hydrogen absorber. The hydrogen absorber and the A magnet will have a common vacuum and the hydrogen absorber will be supported from the A coil package by a low thermal conductivity support system. Figure 4 illustrates that connections to the LH2 absorber can be made between the A coils through the support structure that carries the magnetic large forces generated by the two A coils that operate at opposing polarities.

Forces in the longitudinal direction are a serious concern for the bunching and cooling solenoids. The field flip coils (A coils) generate large forces (up to 1950 metric tons) pushing them apart. These forces must be carried by a 4.4 K metallic structure between the two coils. The magnitude of the forces pushing the A coils apart depends on the spacing between the coils, the average coil diameter and the current carried in each coil. The inter-coil coil forces are carried by shells on the inside and the outside of the coils. The forces are transmitted to the coil end plates, which are put in bending. Large stresses are developed at the point where the end plates meet the shells inside and outside the coils. The force between the A coils in the 1.65-m long cooling cells is so large (about 1950 metric tons), the A coils had to be divided in the radial direction to reduce the bending stress.

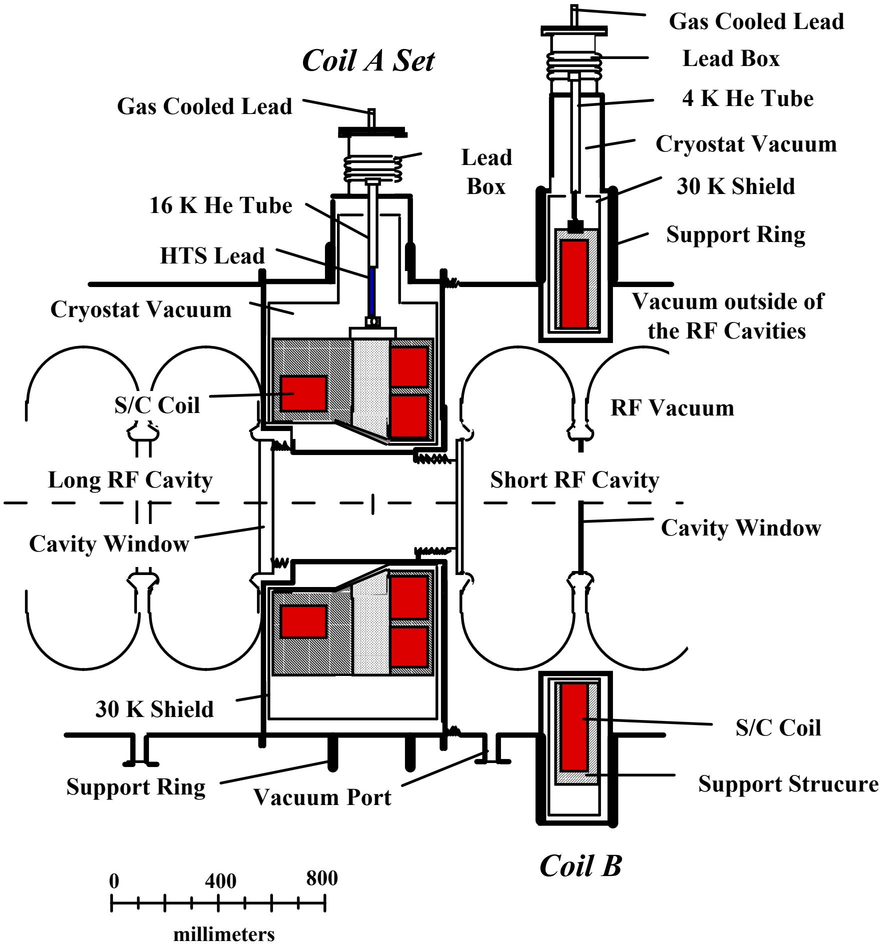

FIG. 3. The matching section between the 2.75-m long and the 1.65-m long cooling cells. Half of a 2.75-m long magnet cell is on the left, and half of a 1.65-m long cell is on the right. There is no absorber within the A coils of this cell.

TABLE III. Superconducting solenoid parameters for the neutrino factory bunching and cooling cells

	2.75-m Cell		1.65-m Cell	
	A Coil	B Coil	A Coil	B Coil
Mechanical Parameters				
S/C Coil Length (mm)	167	162	145	109
Distance Between Coils along the axis (mm)	350	NA	132	NA
Number of Turns per Magnet	2304	1472	4480	1974
Magnet Cold Mass (kg)	1430	1245	1995	1750
Magnet Overall Mass (kg)	1870	1570	2430	2290
Electrical Parameters and Magnetic Forces				
Maximum Magnet Design Current (A)	2320.2	1762.0	1783.2	1899.7
Peak Induction in the Windings (T)	7.5	6.5	8.4	6.5
Magnet Stored Energy at Design Current (MJ)	~7.9	~7.7	~10.7	~10.6
Magnet Self Inductance per Cell (H)	~2.9	~4.9	~6.8	~6.1
Superconductor Matrix J (A mm^{-2})	155	117	119	127

E J^2 Limit per Magnet Cell (J A^2 m^{-4})	1.89×10^{23}	1.06×10^{23}	1.51×10^{23}	1.71×10^{23}
Force Pushing the A Coils Apart (metric tons)	329	NA	1950	NA

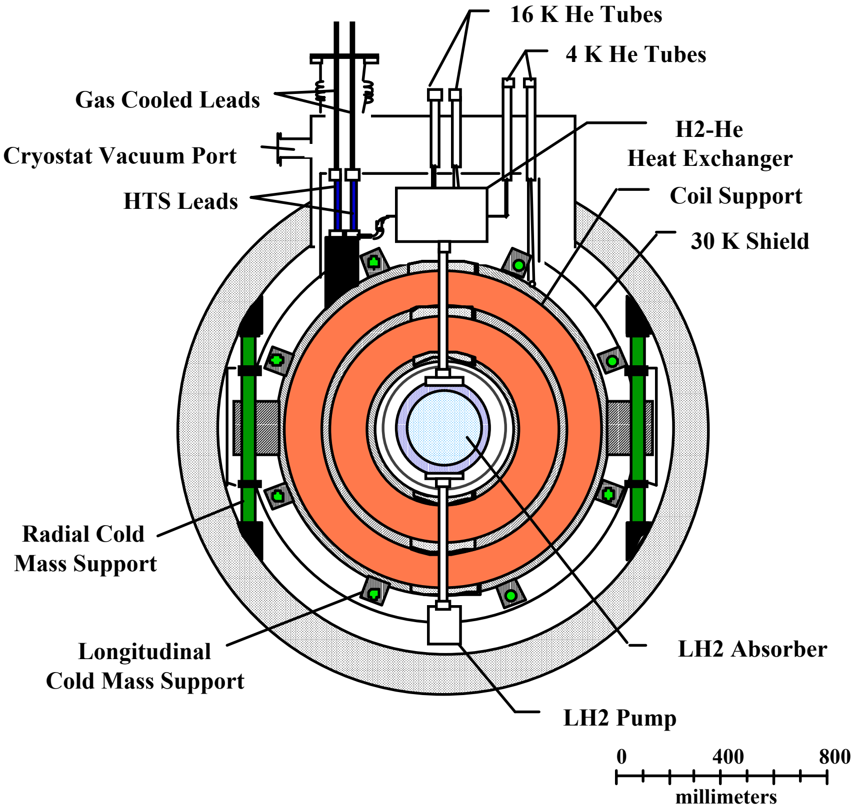

FIG 4. A Cross Section of the 1.65 m Cell A Magnet Perpendicular to the Beam. This figure shows the cold mass supports, the leads, cryogenic service ports, and the force carrying members that carry longitudinal magnetic forces up 1.3 MN

If the currents in all of the A coils and all of the B coils were the same from cooling cell to cooling cell, there would be no net longitudinal force on any of the coils. However, the currents in the cooling cell coils vary as one goes down the bunching and cooling channel. This generates a longitudinal force in various magnet coils. The largest longitudinal forces will be generated at the ends of the string or when one coil quenches and adjacent coils do not quench. Every magnet is assumed to have cold to warm longitudinal supports. The colds-to-warm longitudinal supports in the magnets in the 2.75-m long cells are designed to carry 80 metric tons (the maximum force during a magnet fault). The 1.65-m long cell magnets have longitudinal cold-to-warm supports that are designed to carry 120 metric tons. These forces can be carried by four to eight oriented glass fiber epoxy cylindrical supports that are 50-mm in diameter with a 4-mm thick wall. Oriented glass fiber rods can carry stresses up to 600 MPa in either tension or compression. Figure 4 shows the location of eight of these supports on the 1.65-m long cell A magnet.

The magnet conductor that is assumed for the all of the B solenoids is a conductor that is 7 parts copper and 1 part niobium-titanium. This conductor consists of strands of conductor with a copper-to- superconductor ratio of 1 to 1.3. The twist pitch in the superconductor is about 10 mm. The strands of this conductor are attached to a pure copper matrix. The overall dimensions for the finished conductor for all of the bunching and cooling solenoids is 3 mm by 5 mm. The proposed conductor will carry 5100 A at 5 T and 4.2 K. The conductor for the A coils is assumed to have a copper to superconductor ratio of 4. At 7.5 T, the proposed conductor will carry about 4400 A at 4.4 K. This conductor could be used at 4.4 K in the 2.75-m cell A coils. The problem occurs in the 1.65-m cell A magnet where the peak field at the high field point in the magnet is 8.4 T. It is likely that this coil must be operated at reduced temperature (say 2.5 K)..

The conductor is assumed to have a resin based insulation that is 0.05 mm thick. The layer-to-layer fiberglass epoxy insulation is assumed to be 0.4 mm thick. The ground plane insulation around the coils is assumed to be 1.6 mm thick. This permits the coils to be discharged with a voltage across the leads of 1200 volts. Each A coil set and each B coil is assumed to be powered separately. A quench protection voltage of 1200 V is adequate to protect any of the coils in the cooling cells. The conductor current and current density given for the A and B coils in Table 3 are the peak values that would occur in the cells operating at the highest current. The stored energy given in Table 3 occurs at the peak design current in the coils. In general, when the current density is high in the A coil, the current density in the B coil is low. The stored energy for the cooling cells changes very little as one moves down the cooling channel. The cell stored-energy shown in Table 2 is the average stored energy for that type of cell.

The end of the short cell cooling section must be matched to the accelerator section downstream. This matching section consists of seven standard short cooling cells with varying currents in the coil and no hydrogen absorbers. The last three cells in the matching section are longer than the standard 1.65-m cooling cell, but the B coils can be made identical to the standard B coils used in the rest of the 1.65-m cells. The three A coils in the last three cells of the accelerator matching section are special coils with larger spacing between the flux reversal coils. The final two coils in the accelerator matching section are the same diameter as the short cell B coils, but they are longer and powered differently. The last two coils of the matching section are considered to be part of the solenoids in the linear accelerator section.

IV. CONCLUDING COMMENTS

The superconducting magnets needed for muon phase-rotation, muon bunching, and muon cooling in the neutrino factory appear to be feasible. The magnets for the phase-rotation channel are interesting because there is limited space for cryogenic services, leads and a cold mass support system. Additional engineering is required to properly integrate the phase-rotation magnets into the induction linacs. From a quench standpoint, it is clear that a quench in one coil will probably drive adjacent coils normal even if they are on separate power supplies. If groups of coils are hooked together in series the whole string will quench when one coil in the string goes normal. There appears to be adequate available refrigeration to re-cool the entire magnet string.

The muon bunching and cooling cell magnets are larger and more challenging. These magnets require cryogenic supports that can take large forces (up 120 tons) in the axial direction. In addition, the coils will operate at current densities that are high enough to be of concern during a magnet quench. Groups of these magnets can be hooked in series provided that individual coils are protected by by-passing the energy from other coils around them or that all coils in the string are driven normal using quench protection heaters. The cell coils are coupled; a quench in one is likely to quench a string of coils. . There appears to be adequate available refrigeration to re-cool the entire magnet string.

The field flip coils (the A coils) in cells of the bunching and cooling system will require additional optimization[9]. The forces pushing these coils apart are large. By reducing the coil average diameter and increasing spacing between the coils, the forces and the peak magnetic field in the coils can be reduced. Closer integration of the filed flip coils and the hydrogen absorber may be one approach to reducing the fields and forces on these coils.

The level 2 neutrino factory study has also demonstrated that the superconducting magnets can be integrated with the cryogenic cooling system and the liquid hydrogen absorbers.

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