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Solenoid Magnets for Phase-Rotation, Bunching, and Muon Cooling in a Neutrino Factory

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Abstract

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 start 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 T. All of the solenoids in the channel have coils that are cooled by conduction from the magnet support structure that is cooled by two-phase helium circulating in tubes attached to the support structure. This report shows that the magnets in the front end of the neutrino factory are feasible.

Introduction

The first magnets in the front-end magnet string are solenoids where pion decay occurs[3,4]. These magnets have a field on axis 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, which continues the field structure of the adiabatic field decay section upstream. Pions decay to muons starting just downstream from the target well into the first induction linac section. The field periodicity sets up oscillations in the pion and muon beam that will eventually kick out particles with energies less than 75 MeV. For the most part, particles with energy below 100 MeV will 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 is three induction accelerators. Between the first and second accelerators is a hydrogen absorber mini-cooler and field flipping region[2]. The final two induction linacs complete the phase-rotation. Overall the phase-rotation and mini-cooling occurs over a length of 330-m. All of the solenoids in the phase rotation channel produce 1.25 T ± 0.03 T on axis.

The periodicity of the field changes as one moves into the bunching and cooling channels[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 meters. There is a field flip region in every cell. 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 meters. The 2.75-m cells have a peak on axis induction of about 3.5 T near the field flip region. The peak induction on axis in the 1.65-m cells is about 5.5 T. Because there are field flips in each cell in the bunching and cooling sections, the coils around the flip region must be specially designed to carry the large magnetic forces generated in that region[2,8].

The Decay Channel, Phase-Rotation Channel, and Mini-Cooler Solenoids

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. 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. This same type of magnet can be used for the 9-meter long mini-cooling sections on either side of the field flip solenoid. 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. The warm bore of this magnet cryostat is 620 mm in diameter. 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]. These solenoids have no shield to absorb energy from particles; 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.

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

Table 1. Decay, Phase Rotation, and Mini-cool Solenoid Parameters

	1st Induction Magnets	Later Induction Magnets	Decay & Cool Magnets
Magnet Physical Parameters			
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
Magnet Coil Package Length (mm)	860.0	860.0	860.0
Number of Coil Packages per Cell	1	1	3
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
Magnet Electrical Parameters			
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 Design Operating Temperature (K)	4.4	4.4	4.4
Conductor Critical Current at Operating T (A)	~1600	~1600	~1600
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 (A mm^{-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}
Quench Protection Method	quench-back	quench-back	quench-back

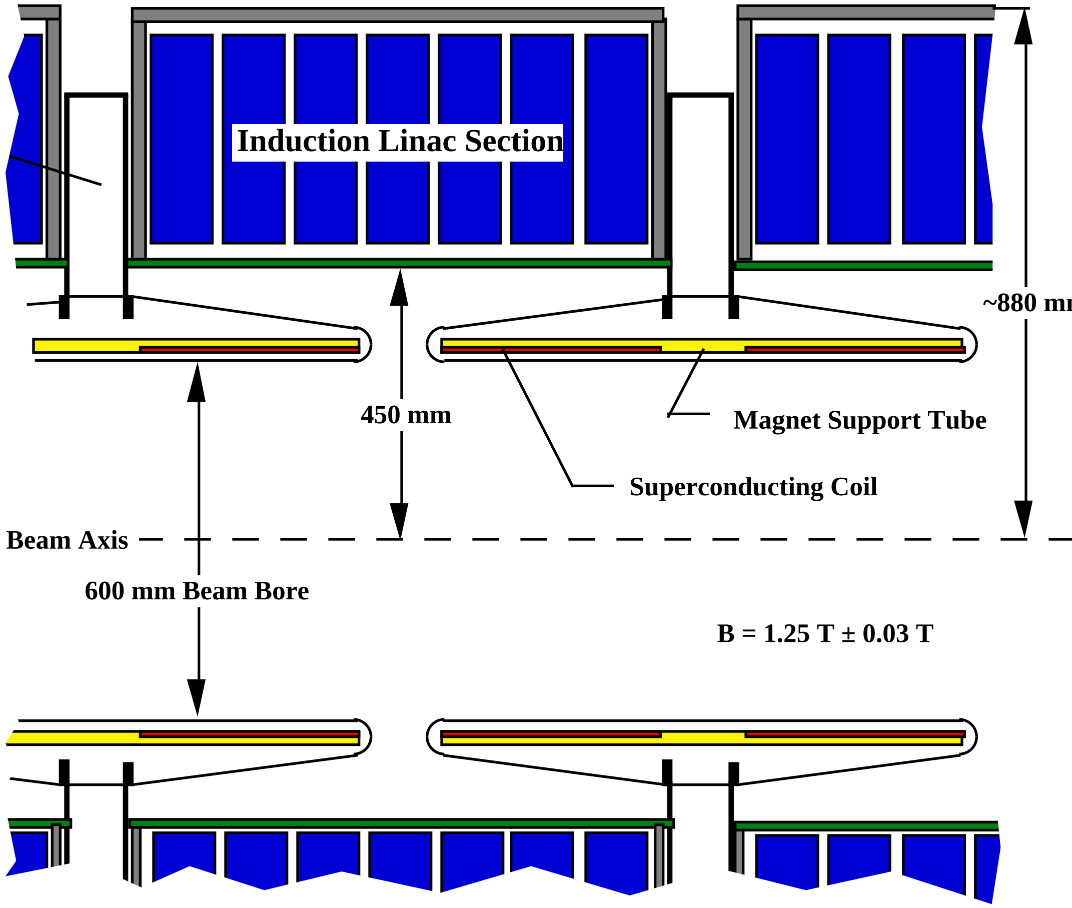

Figure 1. A Cross-section of the Solenoid in an Induction Linac Cell

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 varying magnetic field on the axis 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.

Figure 2 shows a cross section of a typical 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.

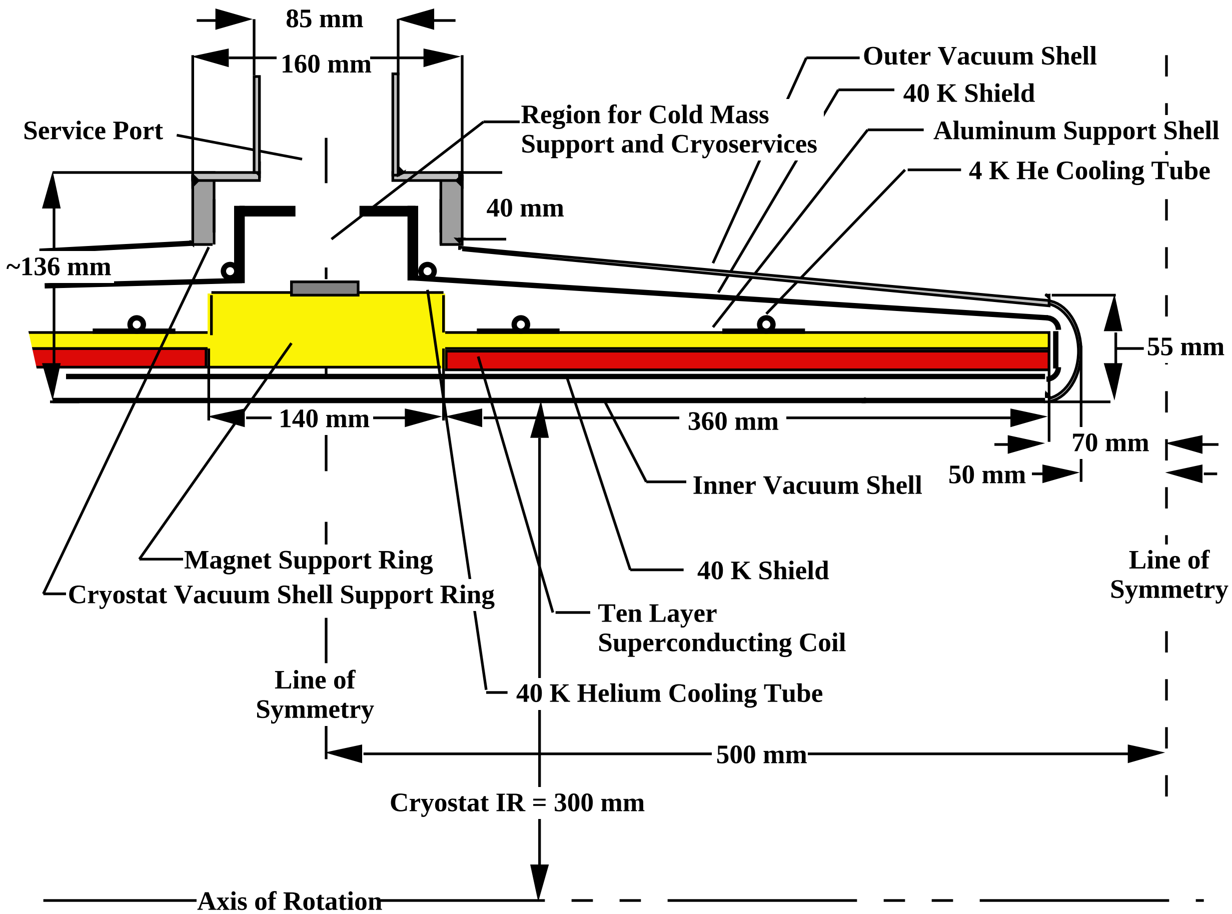

Figure 2. A cross-section of the Induction Linac Superconducting Coil and Cryostat

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 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 shrunk fit 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. A single magnet is entirely self-protecting through quench back from the support structure. One can use quench back to protect a string of these magnet as well. When one detects a quench in one magnet, the current in the string can be discharged through a varistor resistor, causing all coils to go normal through quench back from the support structure.

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 20000 N in any direction. It is proposed that a pair 60 mm diameter oriented carbon fiber tubes (with a wall thickness of about 3 mm) 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. Interconnects 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-meter long magnet section will have its own set of leads to room temperature. The leads between 4 K and 50 K will be made from high temperature superconductor (HTS). The leads from room temperature to the top of the HTS leads at 50 K will be gas-cooled. Gas 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 must be returned to the refrigerator compressor intake at room temperature. See Figure 3 for a schematic representation of the cold mass support system, the helium supply system, and the current leads. The cross-section shown below is taken at the center of the magnet along the magnet axis.

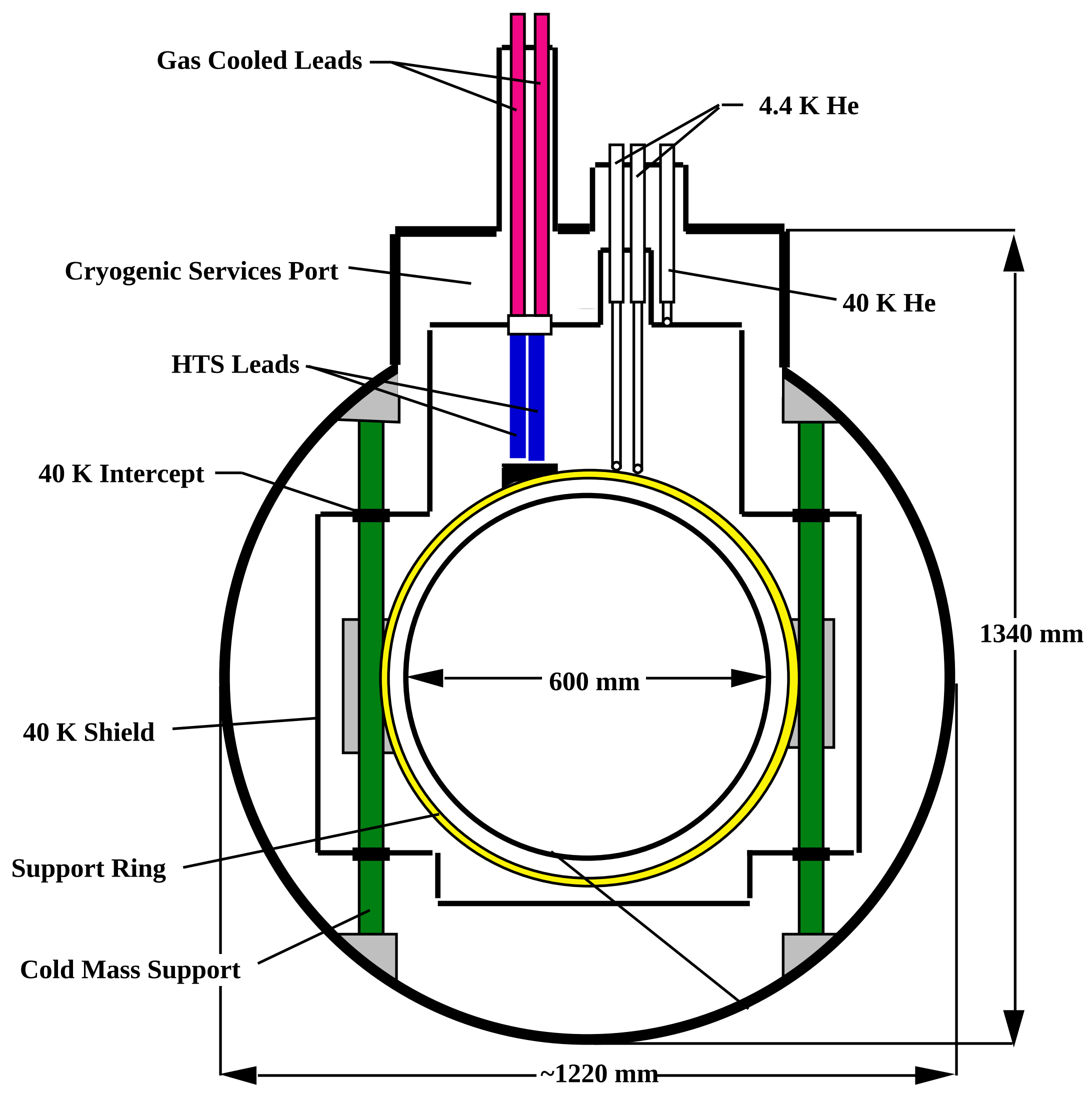

Figure 3. Induction Cell Solenoid Cold mass Support System and Leads

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 field flip channel are the same as those proposed for the decay channel except the warm bore diameter of the magnet sections is set at 800 mm. This diameter should provide enough space for the 1.75 meter 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. About 5500 W of refrigeration at 16 K is needed to cool the absorbers. This is equivalent to 1600 W of cooling at 4.4 K. The cryogenic services to the hydrogen absorber can go through the 100-mm space between the magnet cryostats. It is also possible for services to enter the hydrogen absorber by going through the magnet cryostat between magnet coil modules.

The decay region and the first induction cell solenoids are subject to additional heat loads caused by radiation heating from the target. Depending on the location, the radiation heat loading is estimated to be between 2 and 20 µW per gram of cold mass. For the well-shielded decay solenoids, the maximum heat leak per module is about 2.4 W. The first magnet modules of the first induction linac may have heating rates as high as 4.5 W per module. The rate of heating goes down over an order of magnitude as one goes down the channel. Spent particles from the target that remain beyond the first induction linac will be absorbed by the first hydrogen absorber of the mini-cooling station. Fifty percent of the radiation heat from the target is deposited in the magnet coils. The number of coil layers was set at six to maximize the magnet temperature margin where the magnet was subject to radiation heating.

The induction cell solenoids, the decay solenoids, and the induction cell solenoids are cooled by conduction from the 6061-aluminum support structure. The aluminum support structure will be cooled by two-phase helium flowing in tubes attached to the support structure. Two-phase helium cooling is commonly used to cool large detector magnets. The advantages of two-phase tubular cooling are as follows: 1) There is very little helium inventory within the magnet. 2) The two-phase helium tubes have a high pressure rating. This means that the magnet cryostat is not a pressure vessel. 3) Two-phase helium cooling does not require a cold compressor or a helium pump to circulate the helium through the magnet cooling system. 4) The temperature of the helium in a two-phase helium cooling circuit decreases as it moves along the flow circuit. 5) The pressure drop along a two-phase helium flow circuit is lower than for a supercritical helium forced flow circuit.

Superconducting Solenoids for the Muon Bunching and Cooling Cells

The beam bunching and cooling section is between phase-rotation section that ends at z = 356 meters (down stream from the target) and the linear accelerator section that starts at z = 548 meters[2,8]. The bunching section starts with a matching section that is about 11-meters long. This section matches the phase-rotation induction of 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 extends from z = 419 m to z = 469 m. 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 extends from z = 469 meters to z = 530 meters. The final matching section is between the cooling section and the linear accelerator. The matching section goes from z = 530 meters to z = 548 meters. 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 solenoid (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 section downstream. The twenty 2.75-meter long bunching cells are the same as the 2.75-meter long cooling cells. 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. (A coils in Figure 1.) Table 2 below 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 R = 10 meters.

Magnet parameters and a magnet cross section for the 2.75-m long bunching and cooling cell magnets are shown in Table 2 and Figure 4. Note: that the solenoids in the 2.75-m long cells are the same for both bunching and cooling cells. Magnet parameters and a magnet cross section for the 1.65-m long cooling cell magnets are shown in Table 3 and Figure 5. The solenoid magnet cross sections shown in Figures 4 and 5 are through the longitudinal supports. The penetration of the hydrogen absorber plumbing through the space between the A coils is not shown in Figures 4 and 5.

Table 2. Basic Cell Parameters for the Beam Bunching and Cooling Cell

Parameter	2.75 m Cell	1.65 m Cell
Number of Cells of This Type	41	44
Cell Length (mm)	2750	1650
Maximum Space for the RF Cavity (mm)	1966	1108
Number of 201.25 MHz RF Cavities per Cell	4	2
Number of 402,5 MHz RF Cavities per Bunching Cell	1	NA
A Magnet Cryostat Length (mm)	784	542
B Magnet Cryostat Length (mm)	283	209
Aperture for the A Magnet (mm)	650	370
Aperture for the B Magnet (mm)	1390	1334
Maximum A Coil Current Density (A mm^{-2})	128.04	99.81
Maximum B Coil Current Density (A mm^{-2})	98.83	105.53
Maximum Cell Stored Energy (MJ)	13.2	17.6
Maximum Longitudinal Warm to Cold Force (MN)	0.74	1.20
Number of Longitudinal Supports per Coil	4	6 to 8

Figures 4 and 5 show a cross section of the bunching and cooling cell solenoids. The plane for the cross sections is taken through the warm-to-cold supports that carry axial forces. The cross sections in Figures 4 and 5 show the magnet cryostats, the coils, the coil support structure, the 20 K shields, 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 6 shows a cross section through the center of the 1.65-meter long cell A coil pair. Figure 6 shows the location of the longitudinal cold mass supports and the cold mass supports that carry forces in both directions perpendicular to the solenoid axis. Figure 6 illustrates how magnet electrical leads, and helium refrigeration can be brought into the cryostat. Figure 6 is a typical cross section that can be applied to all of the bunching and cooling cell solenoids.

Figures 4 and 5 show the location of the hydrogen absorbers within the bore of the A coil pair. The hydrogen absorber will share the same cryostat with the A coils. 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 made from a titanium tube. Figure 6 illustrates schematically that connections to the hydrogen 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.

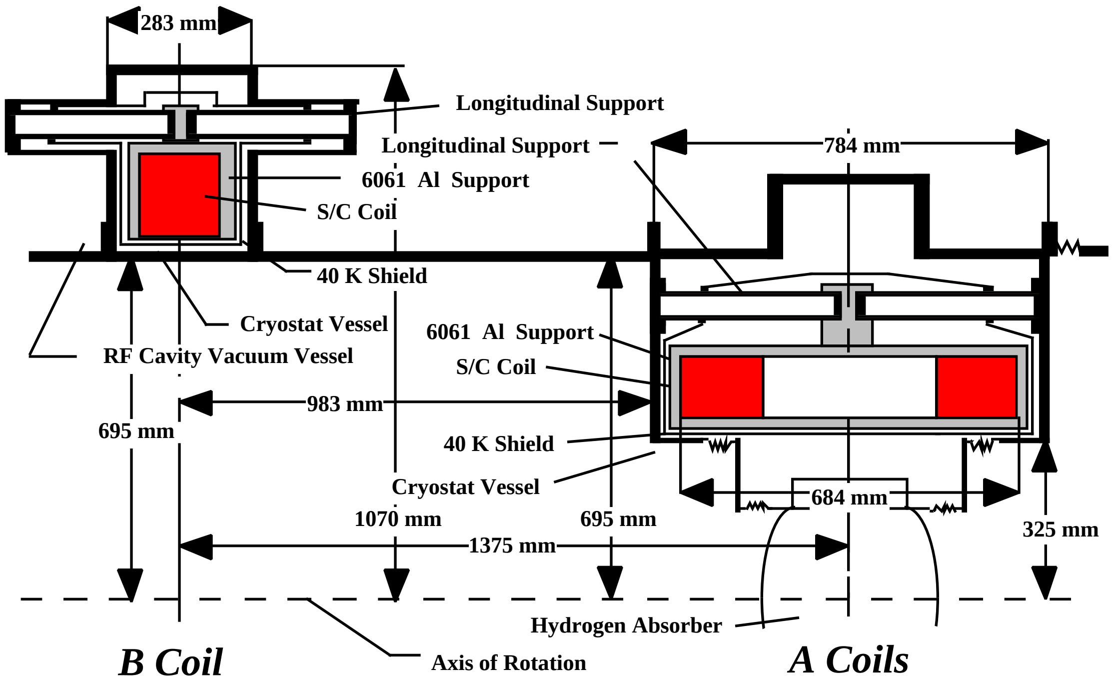

Figure 4. Magnet Cross Section for the 2.75-meter Long Cooling Cell

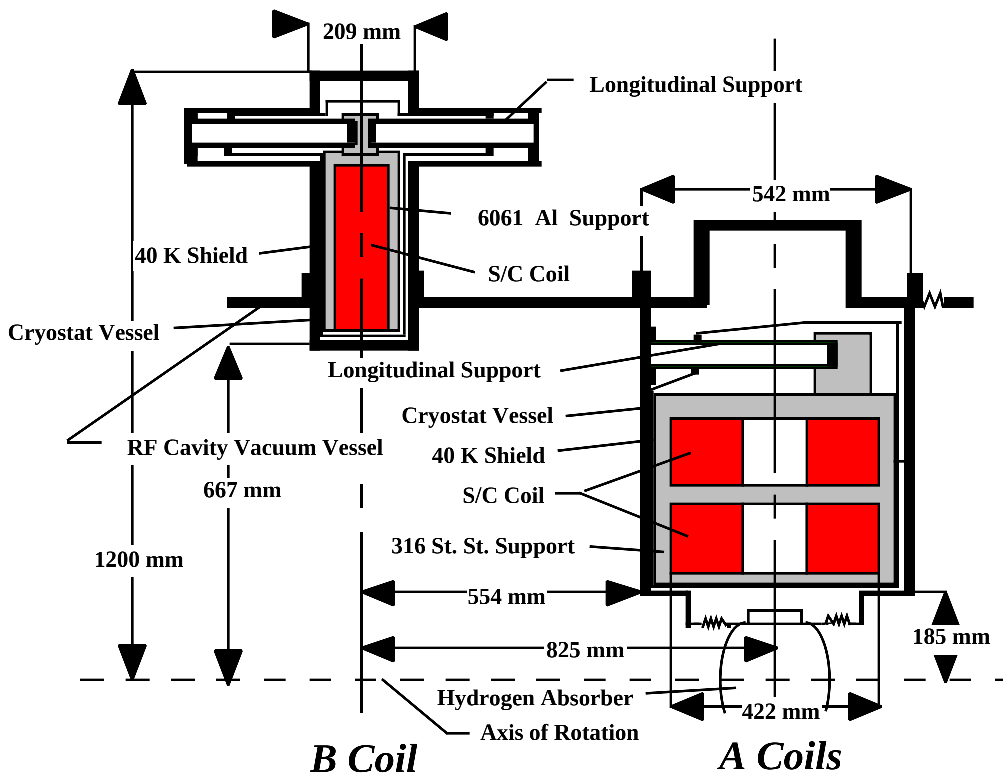

Figure 5. Magnet Cross Section for the 1.65-meter Long Cooling Cell

Table 3. Solenoid Parameters for the 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

Forces in the longitudinal direction are a serious concern for the bunching and cooling solenoids. The field flip coils (the 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 either aluminum of stainless steel 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 in order to reduce the bending stress in the end plates. The large stresses in the end plates of the A coils in the 1.65-m long cooling cell dictate that the end plates and shells around the A coils must made from 316 stainless steel.

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 6 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. At 7.5 T, the proposed conductor will carry about 2500 A at 4.4 K. This conductor could be used in the 2.75-m cell A coils but the margin is rather low. 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. This coil must be operated at reduced temperature (say 2.5 K). To allow for greater temperature margin, all the A coils in the both types of cells will use a conductor with a copper-to-superconductor ratio of 4. The A coils in the 1.65-m cells will be cooled to 2.5 K. An alternative solution for the A coils in the 1.65-m cells is to make them from niobium tin, which can be operated at 4.4 K. The choice of superconductor for the A coils in the 1.65-m cell will be dictated by coil fabrication cost.

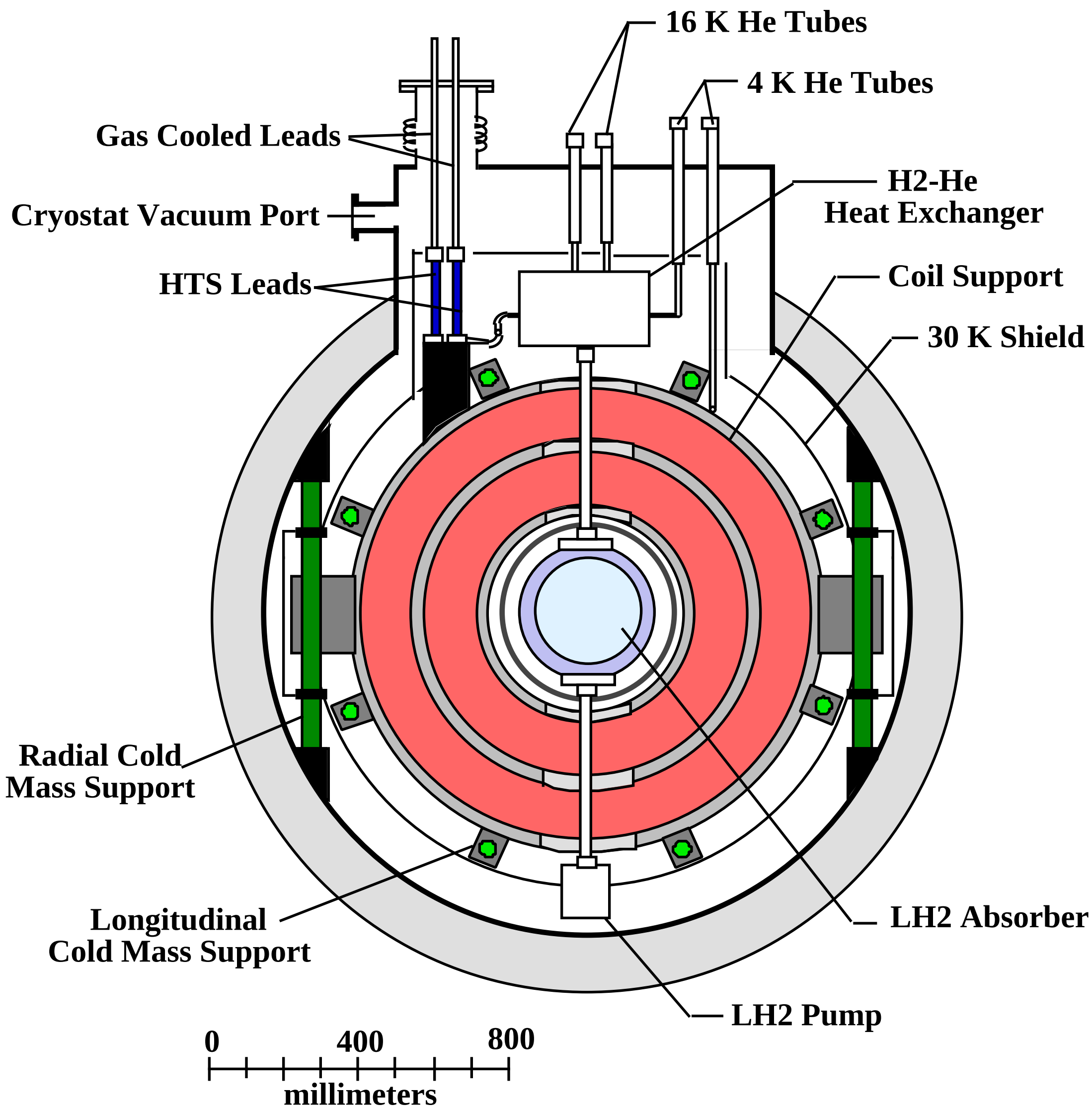

Figure 6. A Cross Section of the 1.65 m Cell A Magnet Perpendicular to the Beam

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. Table 4 shows the average coil current density and coil current for the A and B coils in the various regions of the bunching and cooling channel.

The matching section between the 2.75-m cooling cells and the 1.65-m cooling cells is a single cell with four 201.25 MHz RF cavities. The A coil section is unique with half the A coil from the 2.75-m long cell and the other half from the 1.65-m long cell. Since the forces in this region are peculiar, there is not hydrogen absorber within this A coil set. The currents in the B coils can be adjusted so that a good match can be made. Figure 7 shows what this transition section might look like.

Table 4. Coil Average J and Coil I for various Sections of the Bunching and Cooling Channel

Section	No. Cells	A Coil J(A mm^{-2})	A Coil I (A)	B Coil J (A mm^{-2})	B Coil I (A)
Bunch Match Cells	4	variable	variable	variable	variable
Bunching Cells	20	105.28	1907.7	98.83	1762.0
Cooling 1-1	5	105.28	1907.7	98.83	1762.0
Cooling 1-2	6	117.84	2135.3	92.42	1657.5
Cooling 1-3	6	128.04	2320.2	85.25	1519.9
Cooling 2-1	14	82.34	1471.1	105.53	1899.7
Cooling 2-2	10	89.83	1604.9	95.99	1727.9
Cooling 2-3	13	99.81	1783.2	84.42	1519.7
Accelerator Match	10	variable	variable	variable	variable

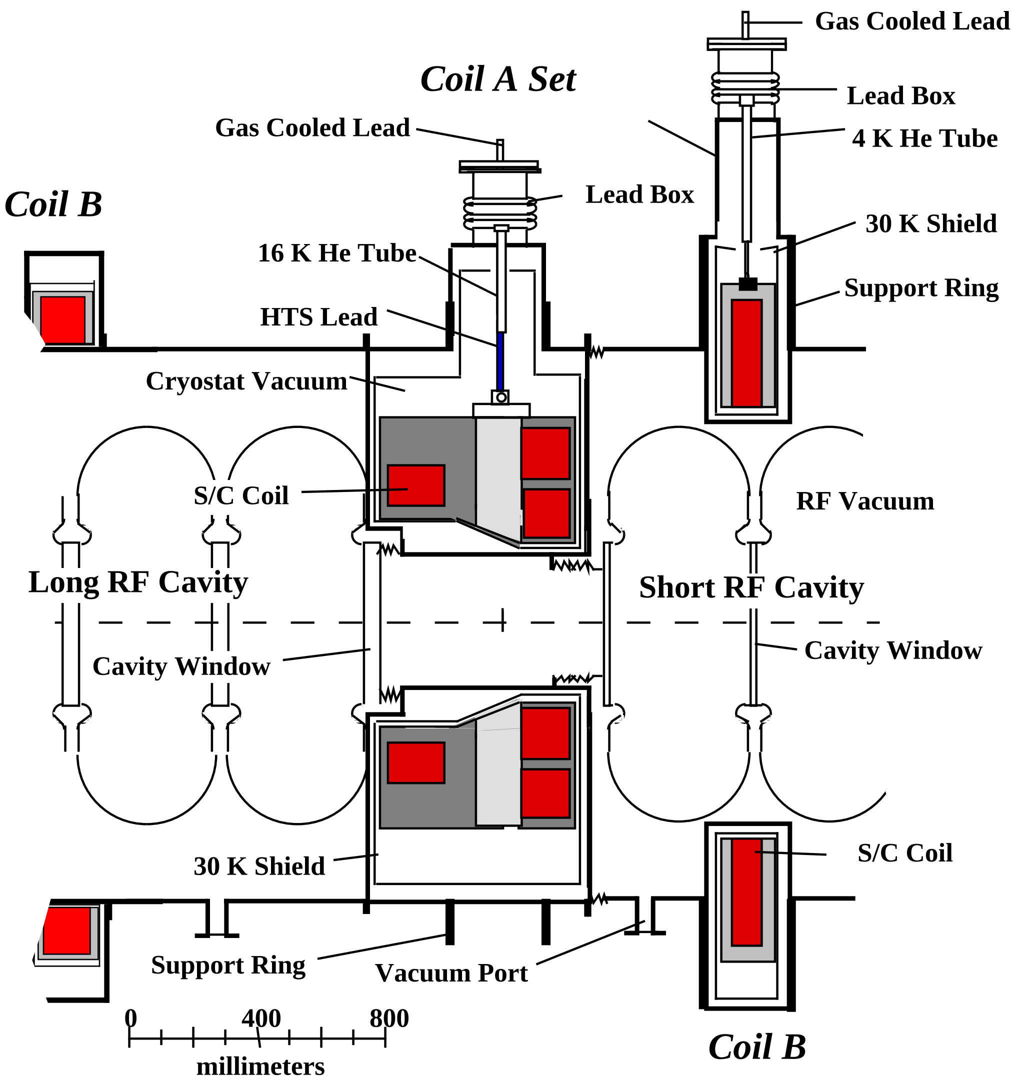

Figure 7. The Matching Section Between the 2.75-m long Cooling Cells
And the 1.65-m Long Cooling Cells

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 superconducting linear accelerator section.

Refrigeration for the Phase-Rotation, Bunching Muon Cooling Sections

The cryogenic cooling needs for the neutrino factory phase-rotation system, bunching system and muon cooling system are as follows: 1) The decay channel and the induction phase rotation sections with their drift section use superconducting solenoids that operate at 4.4 K to guide the muons. 2) The mini-cooling sections needs 4.4 K helium for the solenoids and 16 K helium to cool the liquid hydrogen in the absorbers. 3) The bunching and cooling channel requires cooling at 4.4 K and 2.5 K for the superconducting solenoids. 4) The cooling channel also requires cryogenic cooling at 16 K to cool the liquid hydrogen in the absorbers. All of the magnets require cooling (at 25 K) for shields and leads.

When cooling is required at more that one temperature, a helium refrigerator should be used to provide that cooling. The reasons for this are as follows: 1) Cooling in a couple of temperature ranges means that the refrigerator will be larger. Large refrigerators are more efficient than small refrigerators. 2) A refrigeration system that provides cooling at 16 K will be capable of generating more refrigeration at 4.4 K when needed. This means that one can recover from a magnet quench quickly in the phase-rotation and cooling sections of the machine. This is desirable because the magnets in these sections of the machine are closely coupled to each other inductively.

A basic Claude Cycle helium refrigerator is shown in Figure 8. The machine shown has three stages of helium expansion plus optional liquid nitrogen pre-cooling. The first stage expansion will cool the machine to about 75 K. The second expander will reduce to helium temperature into the 40 K range. The third stage cools to 12 to 15 K. Large machines will use either gas or oil bearing turbine expanders. The machine shown in Figure 8 is a basic large machine. As machines get larger, more stages of expansion are often employed. The machine in Figure 8 will deliver refrigeration at 16 K as well as 4.4 K

The final stage of expansion in Figure 8 is shown as an engine (a near isentropic expander) followed by a J-T valve (an isenthalpic expander). The combination expands the helium down into the two-phase region (where liquid and gas coexist). If the final expander is a positive displacement piston expander, no J-T valve is needed. Piston expanders can run wet without damage. If the final expansion stage uses a turbine, the expansion usually has to be done in two steps to avoid damage to the expansion turbine. The turbine expands the helium to about 0.25 MPa, which is just above helium's critical pressure. The J-T valve completes the expansion into the two-phase dome. The use of the final expansion engines instead of just a J-T valve as the final expansion stage increases the refrigeration efficiency by 25 to 30 percent.

Attached to the final two-phase expansion stage is control cryostat with a heat exchanger. This cryostat shifts the phase of the two-phase helium from the gas side of the two-phase dome to the liquid side of the two-phase dome. The helium leaving the control cryostat to the magnet string leaves as a sub-cooled liquid. The helium returns from the magnet string as two-phase helium that is closer to the saturated liquid line than to the saturated vapor line. Helium phase separation occurs in the control cryostat. The gas phase returns to the refrigerator heat exchanger. This type of control cryostat has been used to cool a large number of large detector solenoids and the g-2 solenoids at Brookhaven. The flow circuit shown in Figure 8 is suitable for cooling strings of superconducting magnets operating at 4.4 K.

Two-phase helium cooling in tubes using a control cryostat offers a number of advantages over supercritical helium cooling in tubes: 1) The operating temperature in magnet coils is lower. 2) For a given cooling rate, the mass flow rate through the tube is minimized. 3) The pressure drop across the flow circuit is also minimized. 4) No cold helium pump is required to circulate the helium. A two-phase force flow circuit can handle wide variations of heat input. However, two-phase flow circuits do not work well when there are altitude variations of over 20 m.

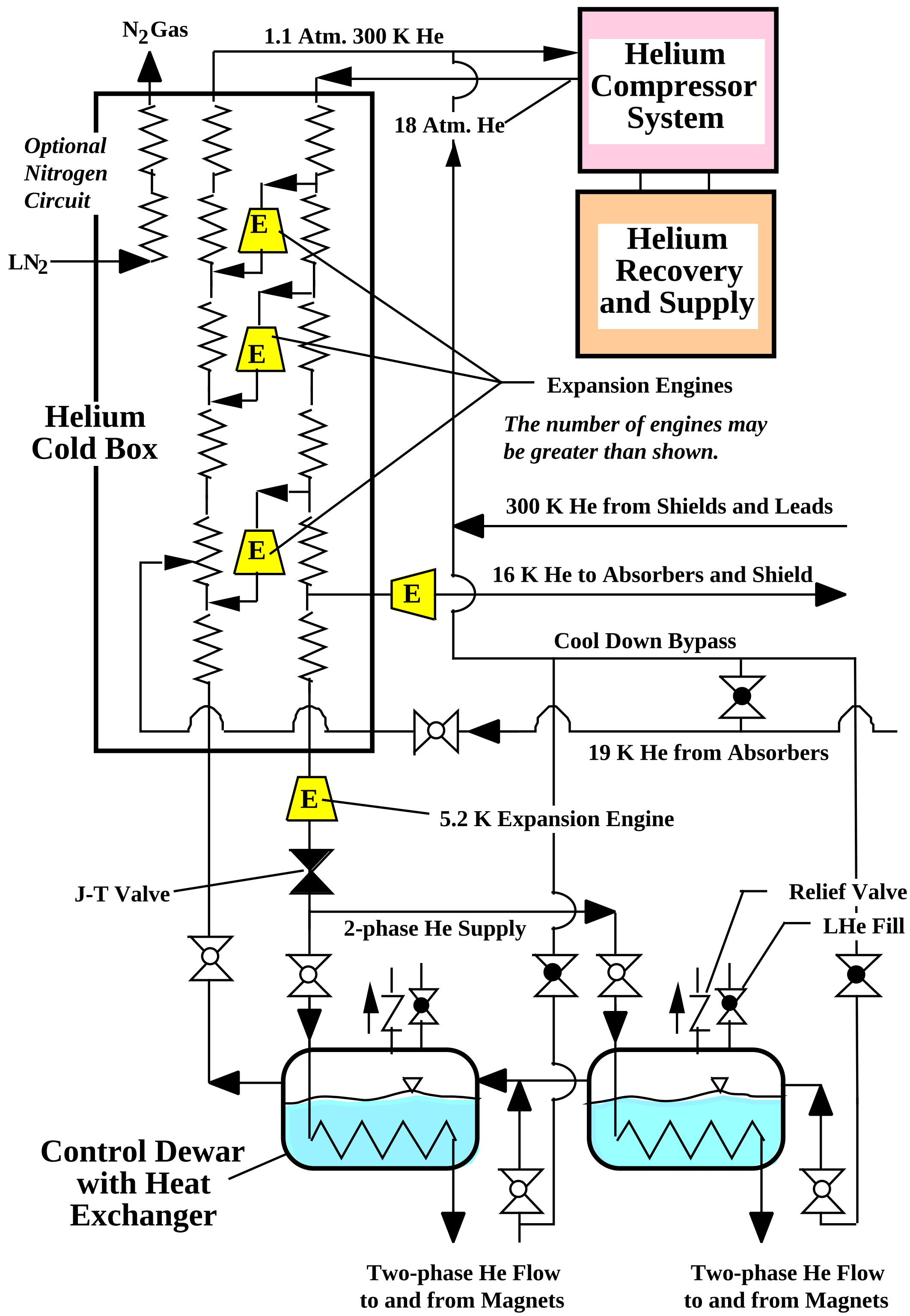

Figure 8. A Basic Refrigerator that delivers Two-phase Helium and 4.4 K and Helium Gas at 16 K

Figure 8 shows a refrigerator that can deliver two-phase helium at 4.4 K and helium gas at 16 K. The helium gas delivered at 16 K is returned to the cold box at 19 K. The mass flow going through the two-phase flow expander is about 0.08-g s^{-1} for each watt of refrigeration delivered at 4.4 K. The mass flow in the circuit delivering gas at 16 K is about 0.07-g s^{-1} for each watt of refrigeration taken up between 16 K and 19 K. A single refrigerator of the type shown in Figure 8 can be used to cool the entire phase-rotation channel, the bunching system and the muon-cooling channel.

In the muon cooling channel and the phase rotation channel, the 16 K stream cools the magnet shields and leads as well as the liquid hydrogen absorbers. Figure 9 shows the cooling circuit for any of the B coils in the muon-cooling channel. The same type of flow circuit would be applied to the solenoids within the induction phase-rotation sections. (The mass flows in the circuits are different.)

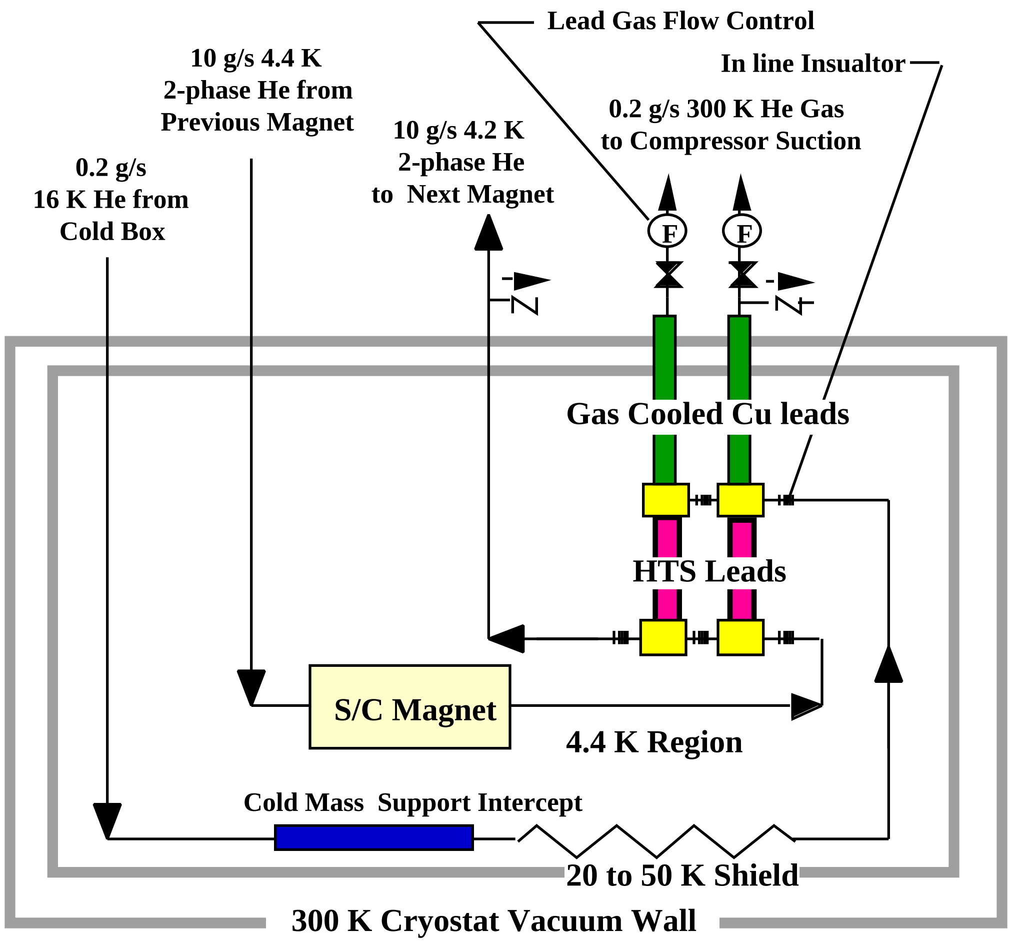

Figure 9. The Magnet Helium Cooling Circuit for the B Coils in the Muon Cooler Section

The A coils in the muon cooling channel have liquid hydrogen absorbers within them. The cryostat for the liquid hydrogen absorber is a part of the magnet cryostat. The 2.75-m cell A magnets operate at 4.4 K. The helium enters the hydrogen absorber at about 16 K. The helium leaves the hydrogen absorber at about 18 K. The helium entering the 2.75-m cell absorber heat exchanger must removes about 330 W of heat from the liquid hydrogen when a full intensity muon beam is cooled. When there is no beam, the heat into the 16 K helium flow circuit is about 55 W. Figure 10 shows helium flow circuit for the 2.75-m cell A coil and hydrogen absorber. As in Figure 9, the shields and leads are cooled from the 16 K helium circuit. The gas used to coil the shield and the leads exits from the cryostat at 300 K.

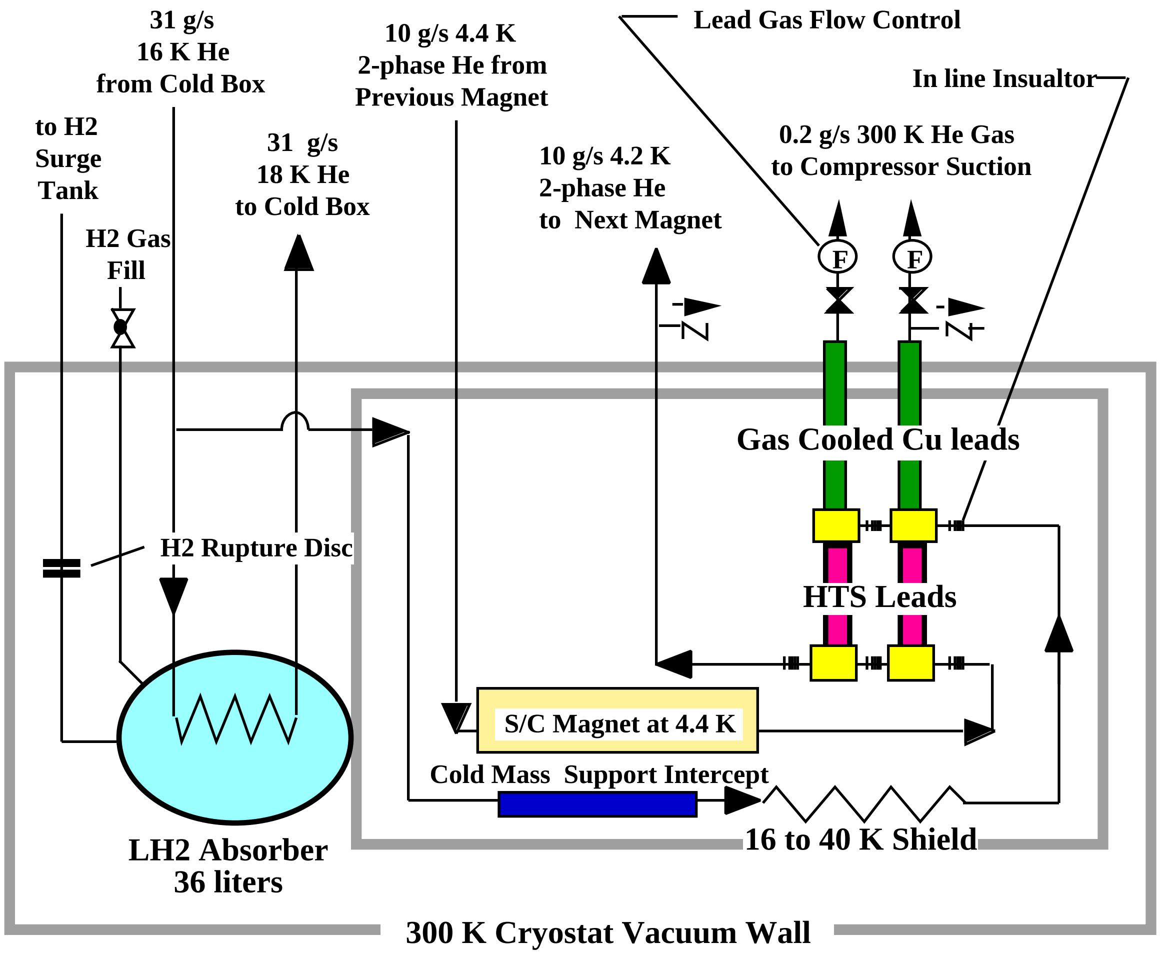

Figure 10. A Helium Cooling circuit for the A Coils and the Liquid Hydrogen Absorber
In the 2.75-meter Long Muon Cooling Cell

The A coils in the 1.65-m cooling cell will have a peak induction in the winding of 8.5 T. In order for these coils to be made from niobium titanium, they must operate at a reduced temperature (between 2.5 and 3.0 K). The A coil heat load comes from the cold mass supports and thermal radiation from the shield. There is almost no heating due to muon decay or AC losses in the superconductor. If one uses the 4.4 K stream to intercept heat from the cold-mass supports and shield, the heat leak into the A coil is about 0.3 W.

A low heat leak at 2.5 K can be removed by using a small 2.5 K cooling circuit that operates off of the 4.4 K refrigeration circuit. The cooling circuit consists of a heat exchanger that takes liquid helium from the two-phase flow circuit. After passing through the high-pressure side of the heat exchanger, the liquid helium is throttled through an expansion valve down to a pressure of about 40 torr. The helium is now two-phase helium at 2.2 K. The two-phase helium is evaporated as it cools the load, then it goes up the low-pressure side of the heat exchanger. The helium gas from the low-pressure side of the heat exchanger is returned to the refrigerator compressor at 300 K. To generate 0.3 W of cooling at 2.2 to 2.5 K a helium flow rate of 0.015 g s^{-1} is needed. Since this helium is returned to the refrigerator warm, it is like helium liquefaction. The liquefaction of 0.015 g s^{-1} of helium is equivalent to about 1.5 W of refrigeration at 4.4 K. Figure 11 shows the helium cooling circuit for a 1.65-m muon cooling cell A coil and its hydrogen absorber. The cooling cycle shown in Figure 11 is not the most efficient way cooling at 2.5 K, but it can be employed within the confines of a 4.4 K magnet system, as long as the heat load at 2.5 K is low. At full muon beam intensity, the 16 K cooling for the 1.65-m cell hydrogen absorber is 150 W. With the muon beam turned off, this heat load is reduced to 40 W.

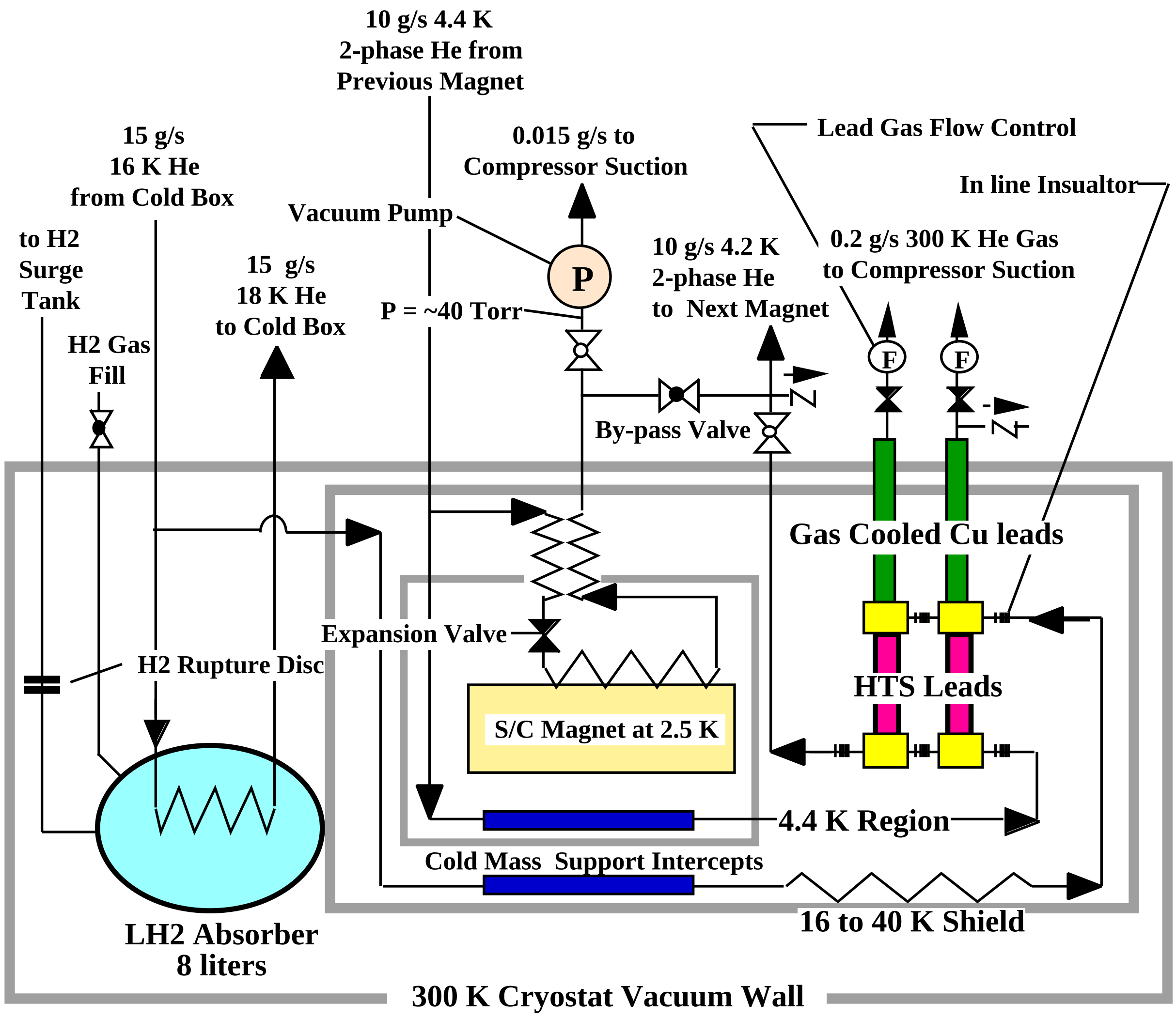

Figure 11. A Helium Cooling circuit for the A Coils and the Liquid Hydrogen Absorber In the 1.65-meter Long Muon Cooling Cell

The magnets in each 2.75-m cell require 2.8 W of cooling at 4.4 K. In addition, the 16 K stream from the magnet shields and intercepts removes 31 W of heat. The 16 K gas used to pick up this heat also cools the 2000 A gas-cooled current leads. There are seventeen liquid hydrogen absorbers in forty-one 2.75-m cells. These absorbers require 5552 W of cooling at 16 K. When there is no muon beam this heat load goes down to 935 W. When the magnet coils quench, there is about 35 W of excess refrigeration (at 4.4 K) per cell available to re-cool the magnet coils in the 2.75-m cells

The magnets in each 1.65-m cell require 3.7 W of cooling at 4.4 K. The A coils in the 1.65-m cell also require an additional 0.015 g s^{-1} of helium liquefaction (at 4.4 K) to cool them. In addition, the 16 K stream from the magnet shields and intercepts removes 40 W of heat. The 16 K gas used to pick up this heat also cools the 2000 A gas cooled current leads. There are thirty-seven liquid hydrogen absorbers in the forty-four 1.65-m cells. These absorbers require 5532 W of cooling at 16 K. When there is no muon beam this heat load goes down to 1480 W. When the magnet coils go normal, there is about 28 W of excess refrigeration (at 4.4 K) per cell available to re-cool the magnet coils in the 1.65-m cells. Re-cooling the magnet coils in the event of a magnet quench should not be a problem for any of the muon cooling cells. Since the phase-rotation mini-cooler section requires 9.8 kW of cooling at 16 K, there should be no problem with re-cooling the magnet coils in that section either.

Table 5 summarizes the cryogenic heat loads in the phase rotation bunching and cooling regions of the neutrino factory. Included in Table 5 is the temperature of the cryogenic refrigeration needed. Since high temperature superconducting leads (HTS leads) are to be used for the superconducting magnets, none of the gas used to cool current leads comes from the refrigerator at 4.4 K. The flow circuits shown in Figures 9 through 11 show that the magnet thermal shields and the gas-cooled leads are cooled with the same gas. This gas is returned to the refrigerator at room temperature, so cooling the shields and leads is treated as a virtual liquefaction at 16 K.

Table 5. The Heat Loads and Temperatures for the Phase Rotation, Bunching And Cooling Systems of the Neutrino Factory

Subsystem	Inlet T (K)	Heat Load (kW)	Gas Flow ($g\ s^{-1}$)[A]
Decay and Induction Phase-Rotation 1 S/C Magnets	4.4	0.560	---
Decay and Induction Phase-Rotation 1 Shields and Leads	16	0.657[C]	~5.9
Mini-cooler S/C Magnets	4.4	0.014	---
Mini-cooler Hydrogen Absorbers	16	10.5	---
Mini-cooler Magnets and Absorber Shields and Leads	16	0.108[C]	~1.1
Induction Phase Rotation 2 and 3 + matching S/C Magnets	4.4	0.180	---
Induction Phase Rotation 2 and 3 Shields and Leads	16	1.113[C]	~10.1
Bunching System and 2.75-m Cell S/C Magnets	4.4	0.115	---
Bunching System and 2.75 m Cell Shields and Leads	16	1.263[C]	~16.4
2.75-Cell Hydrogen Absorbers (17 Absorbers)	16	5.552	---
1.65-m Cell and Matching A S/C Magnets	2.5	0.014	~0.7[B]
1.65-m Cell and Matching S/C Magnets	4.4	0.161	---
1.65-m Cell and Matching Shields and Leads	16	1.744[C]	~18.8
1.65-m Cell Hydrogen Absorbers (37 Absorbers)	16	5.532	---

A. This gas is returned to the compressor suction at room temperature.
B. The 14 W of cooling at 2.5 K is equivalent to the liquefaction of 0.7 $g\ s^{-1}$ of helium at 4.4 K
C. All of the gas used to provide cooling at this temperature is used to cool the leads.

To calculate the size of a refrigeration plant and the installed input power for the cryogenic plant, one converts the refrigeration and gas withdrawn from the plant as equivalent refrigeration at 4.4 K. This permits one to estimate the cost and input power to the cryogenic refrigerators based on existing cryogenic plants.

If one knows the refrigeration required at some temperature T, one can calculate the equivalent refrigeration at 4.4 K using the following expression.

$$Q_{4.4K} = \left(\frac{300 - T}{300 - 4.4}\right)\left(\frac{4.4}{T}\right) Q_T$$

where Q is the refrigeration required at a temperature T. If one knows the rate of helium gas withdrawn from the cryogenic circuit and returned to the plant at room temperature, one can estimate the equivalent refrigeration at 4.4 K from that gas withdrawal using the following expression:

$$Q_{4.4K} = \left(\frac{300 - T}{300 - 4.4}\right)\left(\frac{4.4}{T}\right) \Gamma m$$

where m is the rate at which the gas is being withdrawn from the cryogenic circuit in $g\ s^{-1}$ and Γ is the refrigeration-to-liquefaction coefficient for the refrigerator. For most liquid helium refrigerators Γ varies from 85 J (85 W per $g\ s^{-1}$ liquefaction) to 125 J. As a typical value, one should use Γ = 100 J.

Table 6. Summary of the Cryogenic Heat Loads for the Phase-Rotation, Bunching, And Cooling Systems for the Neutrino Factory

Refrigeration T	Heat Load Q at T (kW)	gas Flow at T (g/s)	Equivalent Q at 4.4 K (kW)
Total Refrigeration at T = 4.4 K (S/C Magnets)	1.138	---	1.138
Total Refrigeration at T = 16 K[A] (Absorbers + Shields)	21.584	---	5.703
Total Gas Flow to 300 K from T = 2.5 K[B]	---	0.7	0.070
Total Gas Flow to 300 K from T = 16 K[C]	---	52.3	1.382
Total Equivalent 4.4 K Heat Load			8.293
Installed 4.4 K refrigeration capacity			10.8
Projected Input Power to the Refrigerator (MW)[D]			~7.0

A. In the cooling section 16 K gas is used to cool the liquid hydrogen absorber. In this case, the gas leaves the cold box at 16 K and returns to the cold box at 19 K.

B. Helium is taken from the 4.4 K circuit and is expanded to produce a temperature of 2.5 K for cooling the A coils of the 1.65-m cooling cells. The gas at 2.5 K is returned through a heat exchanger to cool the incoming liquid helium. The gas is pumped with a vacuum pump and is returned to the compressor suction at room temperature.

C. Gas at 16 K is taken from the refrigerator cold box and is used to cool the magnet shields and gas cooled leads. The gas is returned to the compressor suction at room temperature.

D A ten percent increase in input power is assumed for operating the cooling towers, pumps and the losses in the electrical system delivering power to the compressors,

Table 6 shows the heat load at various temperatures in the phase rotation, bunching, and muon cooling sections of the neutrino factory. Also shown is the equivalent refrigeration at 4.4 K that is needed to remove the heat. Included in Table 6 is the rate of gas withdrawal at various temperatures in the cryogenic system. The equivalent refrigeration at 4.4 K represented by that gas withdrawal is also shown in Table 6. The total equivalent refrigeration at 4.4 K represents about 10-percent of the refrigeration needed for the entire neutrino factory. The installed refrigeration capacity shown in Table 6 is 30-percent more than the estimated heat load.

The input power P_{300} to the helium refrigeration system compressors at 300 K can be calculated using the following expression:

$$P_{300} = \frac{300 - 4.4}{4.4\eta} Q_{4.4}$$

where Q is the equivalent required refrigeration at 4.4 K and η is the efficiency of the refrigerator as a fraction of a Carnot refrigerator. An additional 10-percent should be added to the input power to cover losses in the power distribution system and power needed to provide cooling for the compressors.

The projected input power shown in Table 6 is based on the total equivalent 4.4 K heat load not the installed capacity of the refrigeration plant. The assumed refrigeration efficiency is 30 percent of Carnot. This efficiency is reasonable for an 8 to 10 kW helium plant operating at 4.4 K. The projected input power also includes the extra power needed to cool the water used to cool the compressors.

Concluding Comments

The superconducting magnets needed for muon phase-rotation, muon bunching, and muon cooling in the neutrino factory are 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 A coils in both cells of the bunching and cooling system 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 A coils and the hydrogen absorber may be one approach to reducing the fields and forces on these coils.

The level 2 study has demonstrated that the magnets can be integrated with the cooling system and the liquid hydrogen absorbers. Since all of the cooling for the absorbers occurs in the muon phase-rotation system and the muon cooling system, it makes sense that all of the superconducting magnets proposed for this region be cooled using a single refrigerator that can deliver up to 10.8 kW of cooling at 4.4 K. The refrigerator should deliver refrigeration at both 4.4 K and 16 K cooling simultaneously.

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