Chapter 10

Superconducting Solenoid Magnets

10.1 Introduction

The Neutrino Factory [1], [2], [3], beyond approximately 18 m from the target, requires three solenoid-based magnetic channels. In total, more than 530 m of solenoids with different magnetic strengths and bore sizes are used in order to prepare the muon beam for injection into the muon acceleration system. This is followed by the pre-acceleration linac with several different low-stray-field solenoids.

10.2 Decay and Phase Rotation Channel Solenoids

The decay and phase rotation region includes the muon decay channel, an induction linac (IL1), the mini-cooler and two additional induction linacs (IL2, IL3). This region extends from $z = 18$ m (from the target) to $z = 356$ m; within it, there are four types of solenoids.

- From $z = 18$ m to $z = 36$ m, the decay section has a warm bore diameter of 600 mm. Around this warm bore is a water-cooled copper shield that is 100 mm thick. The solenoid cryostat warm bore is 800 mm. The 18 m of decay solenoid is divided into six cryostats, each 2.9-m long. This same type of magnet is used for the 9-m long mini-cooling sections on either side of the field-flip solenoid. As a result, there are twelve magnets of this type.

- The IL1 solenoids, which extend from $z = 36$ m to $z = 146$ m, have a beam aperture of 600 mm diameter. Around the 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 110 magnets of this type.

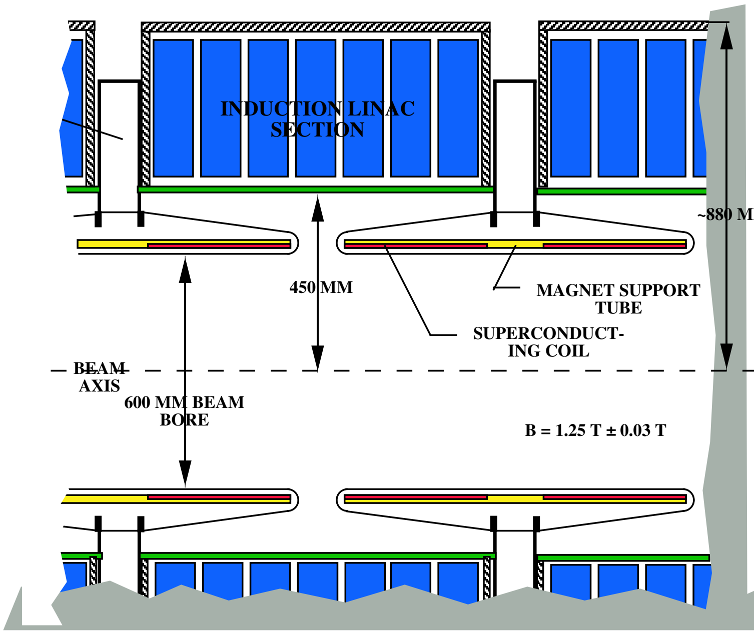

Figure 10.1: Cross section of the induction cell and mini-cooling solenoids.

- The IL2 and IL3 solenoids, and the drift between them, extends from $z = 166$ m to $z = 356$ m. These solenoids do not require a radiation shield and have a cryostat warm bore diameter of 600 mm. There are 190 magnets of this type.
- The field-flip solenoid between the two mini-cooling sections is 2.0-m long with a warm bore diameter of 400 mm. There is only one such magnet.

Table 4.1 shows the design parameters for all of these magnets; the last magnet, the 2-m long field-flip solenoid is not included. Figure 10.1 shows a cross section of the induction cell and mini-cooling solenoids.

The basic requirements for the phase rotation solenoids, from $z = 36$ m through $z = 146$ m and from $z = 166$ m through $z = 356$ m, are as follows: The magnetic induction in the phase-rotation and mini-cooling channel has been set to 1.25 T and the beam pipe diameter is 600 mm. The periodicity of the varying magnetic field on axis of the phase rotation channel has been set to 0.5 m, to avoid potential particle losses due to resonances in the channel. This constraint requires the coils in the cell to be of equal length with equal length gaps between them. A 1.0 m cell has two equal length coils and two equal length spaces between coils, yielding a period length for the magnetic field of 0.5 m. The radial thickness of the solenoid cryostat is minimized to permit the induction linac structure to be brought as close as possible to the axis of the machine. The distance of the induction cell from the magnetic field axis is also influenced by the magnetic flux leakage through the gaps between the superconducting coils. Therefore, 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 cryogenic feed system must be kept to a minimum. In addition, steering dipoles are mounted on the inside of the solenoid coils. The pair of dipoles is 1.0 mm thick and they can correct alignment errors up to 5 mrad.

Figure 10.2 shows a cross section of a typical superconducting solenoid 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/c 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 is reduced to 20 mm. (If an additional support clip were needed at the end of the coil, the coils can shortened to accommodate the clip in the space shown.) The coils in the solenoid shown in Fig. 10.2 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.

The conductor for the coils shown in Fig. 10.2 is a standard MRI magnet conductor that is 1 part Nb-Ti and 4 parts RRR = 70 Cu. This conductor has fifty-five 85μm filaments 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, each one 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 393 A. The peak induction in the coil winding is 1.6 T, which gives a coil operating temperature margin of over 2.5 K.

The coils can 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 coil is machined, it can be shrunk fit into a 6061 Al support structure that has been machined so that the coils closely fit within it. The 6061 Al support structure on the outside of the 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.

The longitudinal space at the center of the magnet, 85 mm, is available for leads, cryogenic services and cold mass supports. The cold mass of the phase-rotation solenoids

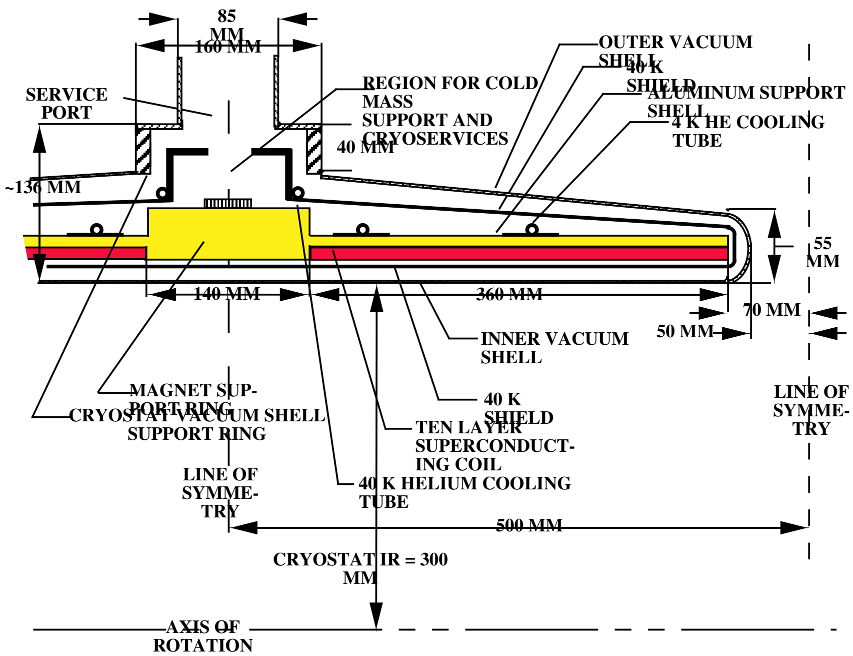

Figure 10.2: A cross section of the induction linac superconducting coil and cryostat.

(including the 40 K shield and lower lead assembly) is about 210 kg. The largest 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 20,000 N in any direction. A pair of 60 mm diameter oriented carbon fiber tubes (with a wall thickness of 3 mm) will be used to carry forces from the cold mass to room temperature.

Since there is a solenoid magnet every meter down the phase rotation channel and the drift spaces between the phase rotation linac sections, leads must be brought out for each of these magnets. All of the magnets in 25-m long sections are hooked in series and powered from a common power supply. Interconnects between the solenoids use conventional copper cable. A long string of magnets can be run from a single power supply in this case 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. We use quench-back to protect a string of these magnets as well. When a quench is detected in one magnet, the current in the string is discharged through a varistor resistor, causing all coils to go normal through quench-back from the support structure. Quench-back eliminates the forces between solenoids that would result when only one goes normal. Each 1 m magnet section has its own set of leads to room temperature. The leads between 4 K and 50 K are made from high-temperature superconductor (HTS). The leads from room temperature to the top of the HTS leads at 50 K are gas cooled. Gas from the refrigerator that is used to cool the magnet shields and cold mass support intercepts can also be used to cool the gas-cooled leads. This gas must be returned to the refrigerator compressor intake at room temperature. See Fig. 10.3 for a schematic representation of the cold mass support system, the helium supply system, and the current leads. The cross section shown in Fig. 10.3 is taken at the center of the magnet along the magnet axis.

The solenoids for the decay channel and the mini-cooler section use basically the same magnet design as those in the induction linac cells. The primary difference is the inside diameter of the superconducting coil (858 mm bore versus 648 mm for the induction cell coils). Another difference is that three coil modules share 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 external leads powering the modules in the magnet cryostat. In the magnets that are next to the flip region, individual power supplies are used to power the coils to shape the magnetic field within the flip region.

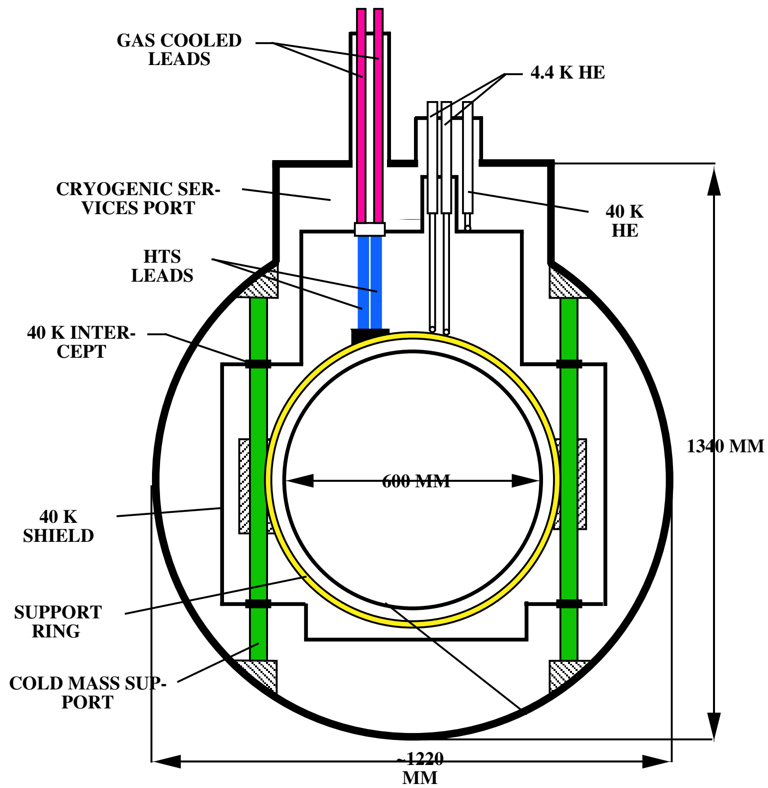

Figure 10.3: Induction cell solenoid cold mass support system and leads.

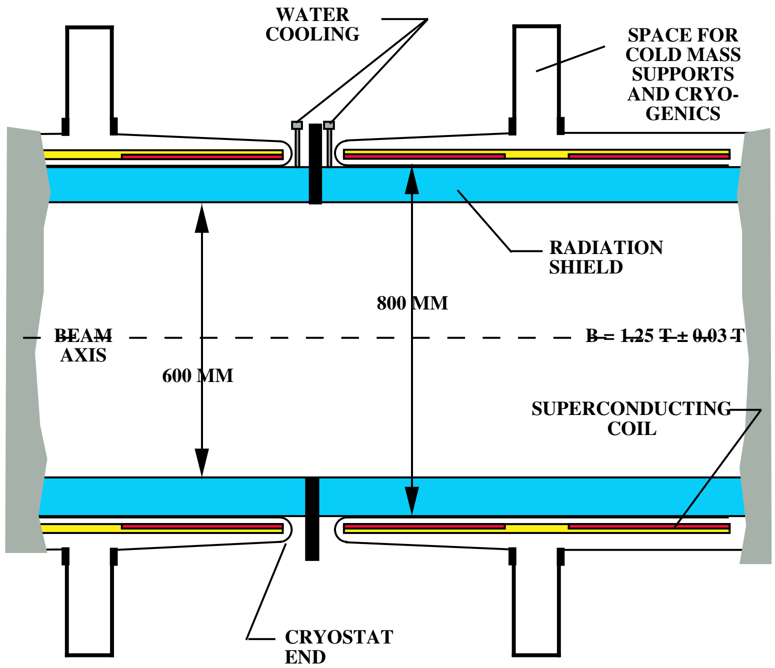

Figure 10.4: A cross section of the solenoids in the pion decay channel.

The solenoids for the flip region of the channel are the same as those used for the decay channel, except that the warm bore diameter of the magnet sections is set at 800 mm. This diameter should provide enough space for the 1.75 m hydrogen absorbers that have window diameters of 600 mm. It allows for a 50 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. About 5,500 W of refrigeration at 16 K is needed to cool the absorbers. This is equivalent to 1,600 W of cooling at 4.4 K. The cryogenic services to the hydrogen absorber go through the 100 mm space between the magnet cryostats. Additional room for services for the hydrogen absorber could be made available by going through the magnet cryostat between magnet coil modules.

Figure 10.4 shows a schematic representation of the solenoids in the decay region. All the solenoids in the decay channel will be powered from the same power supply. Field correction dipoles are mounted on the inside of the solenoid coil. These coils are 1 mm thick and can correct magnet alignment errors up to 5 mrad.

As noted earlier (see Section 4.5), the decay region and the first induction cell solenoids are subject to additional heat loads caused by radiation emanating from the target.

Depending on the location, the radiation heat loading is estimated to vary between 2 and 20μ W/g of cold mass. For the well-shielded decay solenoids, the maximum heat leak per module is about 2.4 W. However, the first magnet modules of IL1 may have heating rates as high as 4.5 W per magnet module. The additional heat load goes down over an order of magnitude farther down the channel. Spent particles from the target that remain beyond IL1 will be absorbed by the first hydrogen absorber of the minicooling. Half of the radiation heat from the target is deposited in the magnet coils. The number of coil layers was increased to six in order to maximize the magnet temperature margin where the magnet is subjected to radiation heating. The induction cell solenoids and the decay channel solenoids are cooled by conduction from the 6061 Al support structure. The Al support structure itself will be cooled by two-phase helium flowing in attached tubes. Two-phase helium cooling is commonly used to cool large detector magnets; its advantages are:

- there is very little helium inventory within the magnet
- the two-phase helium tubes have a high pressure rating; this means that the magnet cryostat itself need not be a pressure vessel
- two-phase helium cooling does not require a cold compressor or a helium pump to circulate the helium through the magnet cooling system
- the temperature of the helium in a two-phase helium cooling circuit decreases as it moves along the flow circuit
- the pressure drop along a two-phase helium flow circuit is lower than for a supercritical helium forced-flow circuit

About twenty to twenty-five magnets are cooled in series from the two-phase helium refrigerator and control cryostat, requiring a mass-flow rate through the flow circuit of about 2.5 g/s. The two-phase helium tube is attached to the superconducting coil support structure, the base of the HTS leads and the attachment points of the cold mass supports. The static heat load into a typical 1 m magnet cryostat at 4.4 K and 40 K is summarized in Table 10.1.

The heat that is added to the two-phase helium flow stream at 4.4 K in each meter of solenoid varies from 0.45 W to 5.0 W, depending on the heat input due to ionizing radiation from the target. The peak temperature at the inside of the superconducting coil when the ionizing radiation heat load is highest (a maximum value of 4.5 W in the first solenoid of IL1) will be less than 5.5 K. Except for heat from ionizing radiation from the target, the heat load at 4.4 K is dominated by the heat leak down the HTS

Table 10.1: Sources of heat at 4.4 K and 40 K in a 1-m induction cell magnet.

Source of Heat	4.4 K load (W)	40 K load (W)
Heat flow down the cold mass supports	0.12	1.9
Thermal radiation through the multi-layer insulation	0.05	2.0
Heat flow down the helium bayonet joints	0.03	1.3
Heat flow down the cold mass supports	0.12	1.9
Heat flow down instrumentation wires	0.02	0.1
Heat flow down the 400 A magnet current leads	0.25	—
Heating due to ionizing radiation from the target	0.0–4.5	0–0.5
Total heat load per meter	0.47–5.0	5.3–5.8

current leads. The heat load into the shield circuit stream is expected to vary from 5.3 W to 5.8 W, again depending on the heat input due to the ionizing radiation from the target. The shield gas comes from the refrigerator at a temperature between 30 and 35 K. (In the region of the mini-cooler, the shield cooling gas comes from the refrigerator and will enter at a temperature of 16 K.) This gas enters the magnet cryostat through a single vacuum-insulated tube. The helium flow in this tube is dictated by the needs of the gas-cooled leads between 50 K and room temperature. The 400 A gas-cooled leads require need 0.05 g/s. The shield gas stream picks up heat from the cold mass supports and from thermal radiation on the shield, helium bayonet joints, and the instrumentation wires. In most of the induction cells, the expected heat load into this stream is about 5.3 W/m. In the first cells of IL1, the shield circuit may pick up as much as 5.8 W. (The extra 0.5 W is due to ionizing radiation from the target heating the 40 K shields.) The helium stream temperature entering the shield circuit from the refrigerator increases from 22 to 24 K as it flows to the base of the gas-cooled leads. The gas used to cool the shields and the cold mass support intercepts is also used to cool the gas-cooled leads between about 60 K and room temperature. The HTS leads are designed to operate with their top end temperature below 70 K. The gas exiting the room temperature end of the gas-cooled leads returns warm to the refrigerator compressor suction. Fig. 10.5 shows the proposed two-phase helium cooling system for a typical 1-m long phase-rotation solenoid. The refrigerator and cryogenic distribution system for the decay solenoids, induction cell solenoids, and the mini-cooling section solenoids are described in Chapter 11.

A string of twenty-five induction cell solenoids has a self-inductance of 68.5 to 72.5 H, depending on which induction linac they are in. A string of six 3-m solenoids for the decay channel and the minicooler will have a self-inductance of 85.8 H. The magnets in

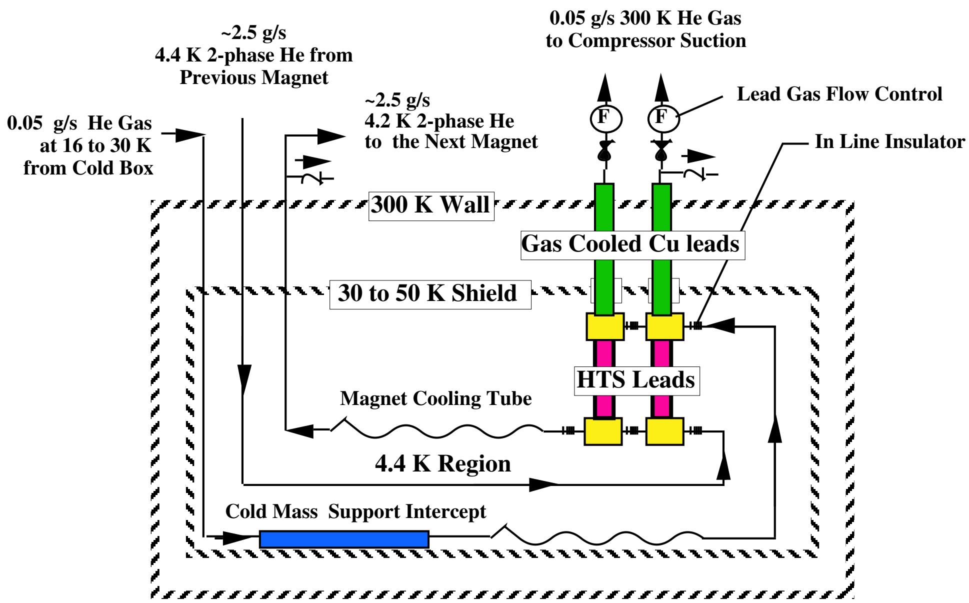

Figure 10.5: Cryogenic cooling system for a typical induction cell.

any of the strings can be charged to full field in less than 1,800 s, by a power supply that delivers 500 A at voltages up to 50 V. The power supply controllers regulate on the voltage across the magnet during magnet charging. When the magnets are charged, the current must be kept constant. Because the magnets are closely coupled, a quench in one magnet of the string will trigger quenches in all of the magnets in that string. A simple resistor across the magnet string leads can protect the entire string during a magnet quench. A typical magnet quench will raise the temperature of the magnet cold mass to about 45 K. The helium refrigerator is sized to allow the magnet to be cooled back down to 4.4 K in less than two hours. To meet this requirement, the helium refrigeration system must deliver helium at 10 to 15 K to the magnets at rate of 4.5 g/s.

10.2.1 Stray Fields

The ferrite cores will carry much of the return flux; what they do not, will be carried in the air between the ferrite cores and the superconducting coils. The induction field at $R = 1.5$ m is below ≈ 0.05 T and at $R = 2$ m it will be ≈ 0.025 T.

10.3 Buncher and Cooling Channel Solenoids

10.3.1 Solenoid Layout and Parameters

We proceed downstream starting at the end of the induction linacs [4]. The matching section between the last induction linac and the beginning of the bunching section consists of four 2.75 m long cells. The focusing solenoids in this matching section must be designed to withstand longitudinal forces of up to 60 metric tons that are imparted on them by the matching solenoids located upstream, at the end of the last induction linac. The bore aperture of the focusing coils for a 2.75-m-ong cooling cell must be about 650 mm in order to accommodate a liquid-ydrogen absorber (se Fig. 5.27). The warm bore aperture for the focusing coils in the bunching section must also be ≈ 650 mm, in order to accommodate the 402.5 MHz rf cavitiies.

Room temperature service ports to the 402.5 MHz rf cavity can go out between two focusing coils running in opposite polarity (*i.e.*, in the flux-reversal region), through the magnet cryostat servicing these two coils. Table 10.2 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. Included in Table 10.2 is the magnetic field 9.9 m from the beam axis. Because the bunching and cooling cell solenoids are constantly changing polarity, there is almost no stray field from these solenoids at a radius $R = 10$ m.

Magnet parameters and a magnet cross section for the 2.75-m-long bunching and cooling cell magnets are shown in Table 10.3 and Fig. 5.27. Magnet parameters and a magnet cross section for the 1.65-m-long cooling cell magnets are shown in Table 10.4 and Fig. 5.28.

Figures 5.27 and 5.28 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. These cross sections also show the magnet cryostats, the coils, the coil support structure, the 30 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. The penetration of the hydrogen absorber plumbing through the space between the focusing coils is not shown in Figs. 5.27 and 5.28.

Figure 10.6 shows a cross section through the center of the 1.65-m-long cell focusing coil pair ("A"). Note the location of the longitudinal cold mass supports and the cold mass supports that carry forces in both directions perpendicular to the solenoid axis. This figure illustrates how magnet electrical leads, and helium refrigeration can be brought into the cryostat. Figure 10.6 is a typical cross section that can be applied to all of the bunching and cooling cell solenoids.

Figures 5.27 and 5.28 show the location of the hydrogen absorbers within the bore of

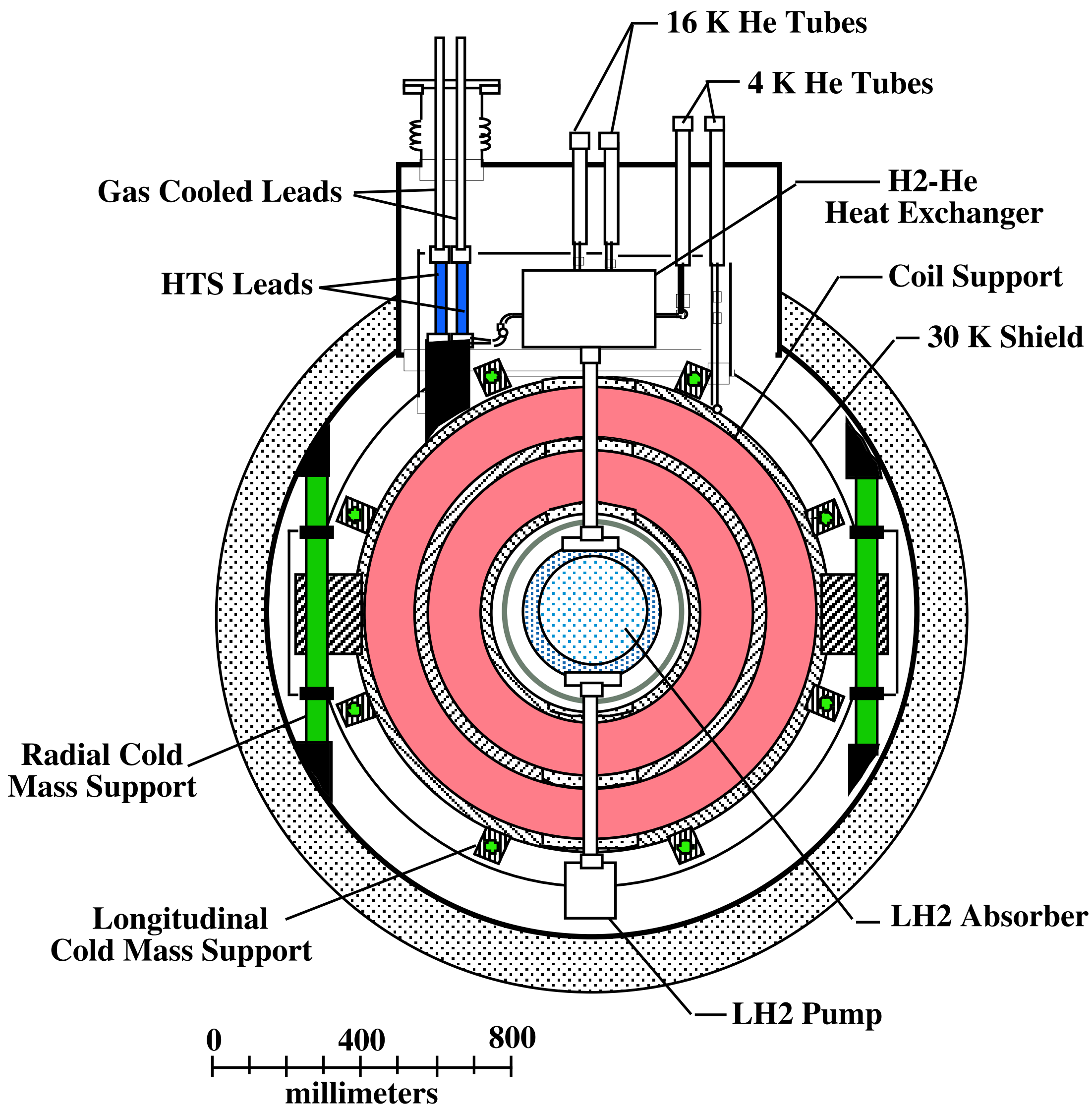

Figure 10.6: Cross section of the 1.65 m cell focusing magnets, perpendicular to the beam.

Table 10.2: Basic parameters for the bunching and cooling cells.

Parameter	2.75 m cell	1.65 m cell
Number of cells of this type	37	37
Cell length (mm)	2750	1650
Maximum space for the rf cavity	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
Focusing magnet cryostat length (mm)	784	542
Focusing magnet cryostat length (mm)	283	209
Aperture for the focusing magnet (mm)	650	370
Aperture for the coupling magnet (mm)	1390	1334
Maximum focusing coil current density (A mm^{-2})	128.04	99.65
Maximum coupling coil current density (A mm^{-2})	99.24	109.45
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
Peak induction 9.9 m from the cell axis (T)	1.18×10^{-5}	2.62×10^{-5}

the focusing coil pair. The hydrogen absorber will share the same cryostat with the focusing coils. The hydrogen absorber and these magnets will have a common vacuum. The hydrogen absorber will be supported from the coil package by a low thermal conductivity support system made from a titanium tube. Figure 10.6 illustrates schematically that connections to the hydrogen absorber can be made between the focusing coils through the support structure that carries the large magnetic forces generated by these coils.

10.3.2 Forces

Forces in the longitudinal direction are a serious issue for the bunching and cooling solenoids. The focusing coils, running in opposite polarity, 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 these coils apart depends on the spacing between the coils, the average coil diameter and the current carried in each coil. The inter-coil forces are carried by either aluminum or 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. Since the force between the focusing coils in the 1.65-m-long cooling cells is so large, these coils must be divided in

Table 10.3: Solenoid parameters for the 2.75-m-long bunching and cooling cell.

	Focusing	Coupling
Mechanical Parameters		
Magnet cryostat length (mm)	784	283
Magnet cryostat bore diameter (mm)	650	1390
SC coil length (mm)	167	162
Inner radius of the coil (mm)	355	729
SC coil thickness (mm)	125	162
Distance between coils in z direction (mm)	350	NA
Inner support structure thickness (mm)	15	0
Outer support structure thickness (mm)	20	25
Number of turns per magnet	2304	1472
Magnet cold mass (kg)	1430	1245
Magnet overall mass (kg)	1870	1570
Electrical Parameters and Magnetic Forces		
Maximum magnet design current (A)	2320.2	1779.9
Peak induction in the windings (T)	7.5	6.5
Magnet stored energy at design current (MJ)	$\approx$7.9	$\approx$7.7
Magnet self inductance per cell (H)	$\approx$2.9	$\approx$4.9
Superconductor matrix $J(A\mathrm{mm}^{-2})$	155	119
E J^2 limit per magnet cell (JA^2 m^{-4})	1.89×10^{23}	1.09×10^{23}
Force pushing the focusing coils apart (metric tons)	329	NA
Peak fault force on a coil (metric tons)	75.3	75.3

the radial direction in order to reduce the bending stress in the end plates. The large stress in the end plates of these focusing coils in the 1.65-m-long cooling cell dictate that the end plates and shells must be made from 316 stainless steel.

If the currents in all of the focusing coils and all of the coupling 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 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. One can attach all of the coils together with cold members, but further examination suggests that this approach would make it difficult to assemble and disassemble the muon cooling system. As a result, every magnet is assumed to have cold to warm longitudinal supports. The cold-to-warm supports in the magnets in the 2.75-

Table 10.4: Solenoid parameters for the 1.65-m-long cooling cell.

	Focusing	Coupling
Mechanical Parameters		
Magnet cryostat length (mm)	542	209
Magnet cryostat warm bore diameter (mm)	380	1334
SC coil length (mm)	145	109
Inner radius of inner coil	210	687
SC coil thickness (mm)	138	326
Distance between coils in z direction (mm)	132	NA
Inner support structure thickness (mm)	20	0
Center support structure thickness (mm)	30	NA
Outer support structure thickness (mm)	40	25
Number of turns per magnet	4480	1974
Magnet cold mass (kg)	1995	1750
Magnet overall mass (kg)	2430	2290
Electrical Parameters and Magnetic Forces		
Maximum magnet design current (A)	1780.5	1896.7
Peak induction in the windings (T)	8.4	6.5
Magnet stored energy at design current (MJ)	≈10.7	≈11.0
Magnet self-inductance per cell (H)	≈6.8	≈6.1
Superconductor matrix J (A mm^{-2})	119	126
E J^2 limit per magnet cell (J A^2 m^{-4})	1.51×10^{23}	1.74×10^{23}
Force pushing the focusing coils apart (metric tons)	1950	NA
Peak fault force on a coil (metric tons)	122	122

m-long cells are designed to carry 80 metric tons (the maximum force during a magnet fault). These forces can be carried by four oriented fiverglass epoxy cylindrical supports that are 50 mm in diameter with a 4-mm-thick wall. Oriented fiberglass rods can carry stresses up to 600 MPa in either tension or compression.

The 1.65-m-long cell magnets have longitudinal cold-to-warm supports that are designed to carry 120 metric tons. Figure 10.6 shows the location of eight of these supports on the 1.65-m-long cell focusin magnet. A six-support longitudinal support system would also be practical. The support shown for the focusing coil in Fig. 5.28 is designed to operate in both tension and compression. Further engineering can define an optimum cold mass support system for these magnets. Compared with other heat loads into the magnets, the longitudinal cold mass supports represent about one quarter of the total heat leak into the magnet cryostat.

10.3.3 Conductor

The magnet conductor that is assumed for all of the coupling solenoids is a conductor that is 7 parts copper and 1 part niobium-titanium. This conductor consists of strands with a copper-to-superconductor ratio of 1:1.3. 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 are 3 mm by 5 mm. This 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. The same conductor could be used in the 2.75-m cell focusing coils but the margin is rather tight. However, it could not be used in the 1.65-m long cell focusing magnet, where the peak magnetic field reaches is 8.4 T within the coil. Therefore, this coil must be operated at reduced temperature (say 2.5 K). To allow for greater temperature margin, all the focusing coils in both lattices will use a conductor with a 4:1 copper-to-superconductor ratio. The focusing coils in the 1.65-m long cell will be cooled to 2.5 K.

The conductor will have a varnish insulation that is 0.05 mm thick. The layer-to-layer fiberglass epoxy insulation is 0.4 mm thick. The ground plane insulation around the coils is 1.6 mm thick. This permits the superconducting coils to be discharged with a voltage across the leads of up to 1200 V. Each focusing coil set and each coupling coil is powered separately. A quench-protection voltage of 1200 V is adequate to protect any of the coils in the cooling cells. Because the conductor current density is high, the focusing coils in the 2.75-m-long cells have the smallest safety margin when it comes to quench protection. Re-optimization of these coils can improve their quench protection.

The conductor currents and current densities are given for the focusing and coupling coils in Tables. 10.3 and 10.4. Listed also are the peak values that would occur in the cells operating at the highest current. The estimated stored energy occurs at the peak design current in the coils. In general, when the current density is high in the focusing coil, the current density in the coupling coil is low. The stored energy for the cooling cells changes very little along the cooling channel. The cell stored energy shown in Table 10.2 is the average stored energy for that type of cell. Table 10.5 shows the average coil current density and coil current for the focusing and coupling coils in the various regions of the bunching and cooling channel.

There are 41 pairs of focusing coils and coupling coils that make up the 2.75-m-long matching, bunching and cooling cells. Likewise, there are 37 sets of coils that make up the 1.65-m-long cooling cells.

Table 10.5: Coil average j and I for various sections of the bunching and cooling channel. The matching sections between lattices have been taken into account.

Section	focusing j (A mm^{-2})	focusing I (A)	coupling j (A mm^{-2})	coupling I (A)
Bunching cells	105.28	1907.7	98.83	1762.0
Cooling (1,1)	105.28	1907.7	98.83	1762.0
Cooling (1,2)	117.84	2135.3	92.42	1657.5
Cooling (1,3)	128.04	2320.2	85.25	1519.9
Cooling (2,1)	82.34	1471.1	105.53	1899.7
Cooling (2,2)	89.83	1604.9	95.99	1727.9
Cooling (2,3)	99.81	1783.2	84.42	1519.7

The last three meters of the induction linac channel must have thicker coils with a separate power supply on each coil. The 1.25 T solenoids at the end of the induction cells must have separate longitudinal warm-to-cold supports to carry forces (up to 60 metric tons) generated by the magnets in the first cells of the bunching section.

The end of the short cell cooling section must be matched to the accelerator section downstream (see Sec. 5.5). 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 this section are longer than the standard 1.65-m cooling cell, but the coupling coils can be made identical to the standard coupling coils. The three focusing coils in the last three cells are special coils with larger spacing between the flux reversal coils. The final two coils have the same diameter as the short-cell coupling coils, but they are longer and powered differently. The last two coils are considered to be part of the solenoids in the superconductiong linac section.

10.3.4 Refrigeration

Refrigeration to the muon cooling magnets and hydrogen absorbers is supplied at 16 K and 4.4 K. The 4.4 K refrigeration is used to cool the superconducting coils except for the focusing coils in the 1.65-m-long cell, which are cooled to 2.5 K. The 2.5 K cooling requires an additional heat exchanger and a vacuum pump to produce nearly 0.3 W of cooling at 2.5 K. Most of the heat into the 1.65 m cell focusing coil package is intercepted at 4.4 K. The hydrogen absorbers are cooled from the same refrigerator as the solenoid magnets. Refrigeration for the hydrogen absorbers is drawn off at 16 K. The 16 K helium used to cool the liquid hydrogen returns to the helium cold box at 19 K. The absorbers in the 2.75-m-long cell contain 35.6 liters of liquid hydrogen. The 1.65-m-long cell absorbers contain about 8 liters of liquid hydrogen. The estimated heat load to the absorbers is between 120 and 130 W. Table 10.6 shows the refrigeration requirements for the 2.75-m-long cells and the 1.65 m long cells with hydrogen absorbers. The equivalent 4.4 K refrigeration reflects the Carnot ratios from 4.4 K to 16 K and the refrigeration lost when helium returns to the compressor by bypassing the refrigerator heat exchangers. The equivalent 4.4 K refrigeration for the bunching cells is 13.3 W per cell. About 10.5 W of equivalent 4.4 K refrigeration are used to cool two pairs of 2000-A gas-cooled leads from 300 K to 40 K.

Figure 10.7 shows a schematic representation of the refrigeration for a pair of focusing coils with a hydrogen absorber. Two-phase helium at 4.4 K is used to cool the superconducting coils. If nineteen magnets are cooled from a single flow circuit, the mass flow of two-phase helium should be 8 to 10 g/s. The flow circuit can have up to 20 magnet coils in series before the helium is returned to the control cryostat. The shields, intercepts, current leads, and hydrogen absorbers are cooled by helium that comes from the refrigerator at 16 K. The helium used to cool the shields and the leads is returned to the refrigerator compressor warm. The rest of the 16 K helium returns to the refrigerator at 19 K.

The helium used to cool the magnet shield intercepts heat from the cold-mass support, the bayonet tubes, the instrumentation wires, and radiation heating through the multilayer insulation before it is used to cool the gas-cooled current leads for the magnets. For the flow circuit shown in Fig. 10.7, the flow of helium gas in the shield cooling circuit is dictated by the needs of the gas-cooled current leads. For the current leads in the cooling and bunching magnets, this flow varies from 0.15 to 0.23 g/s. Depending on the needs of the current leads, the temperature rise in the shield-gas flow circuit will vary from 14 K to 23 K. If we optimize the magnets, the lead current might be as low as 1200 A. With 1200 A current leads, the temperature at the top of the high T_c superconducting leads would be about 50 K.

oth the focusing and the coupling magnet shields will be cooled using the same 16 K source of gas from the helium refrigerator, but this is not optimum from the standpoint of overall refrigeration system efficiency. When the helium refrigerator cools both the hydrogen absorber and the magnets, there will be enough excess refrigeration capacity available to cool down the magnet coils in a reasonable time.

The flow in the 16 K circuit to the hydrogen absorber is dictated by the heat load in the absorber. Without a muon beam, the heat load could be as low as 22 W. With beam heating and the circulation heater operating, the heat load into the absorbers can approach 320 W. The temperature rise in the absorber cooling circuit should be limited to

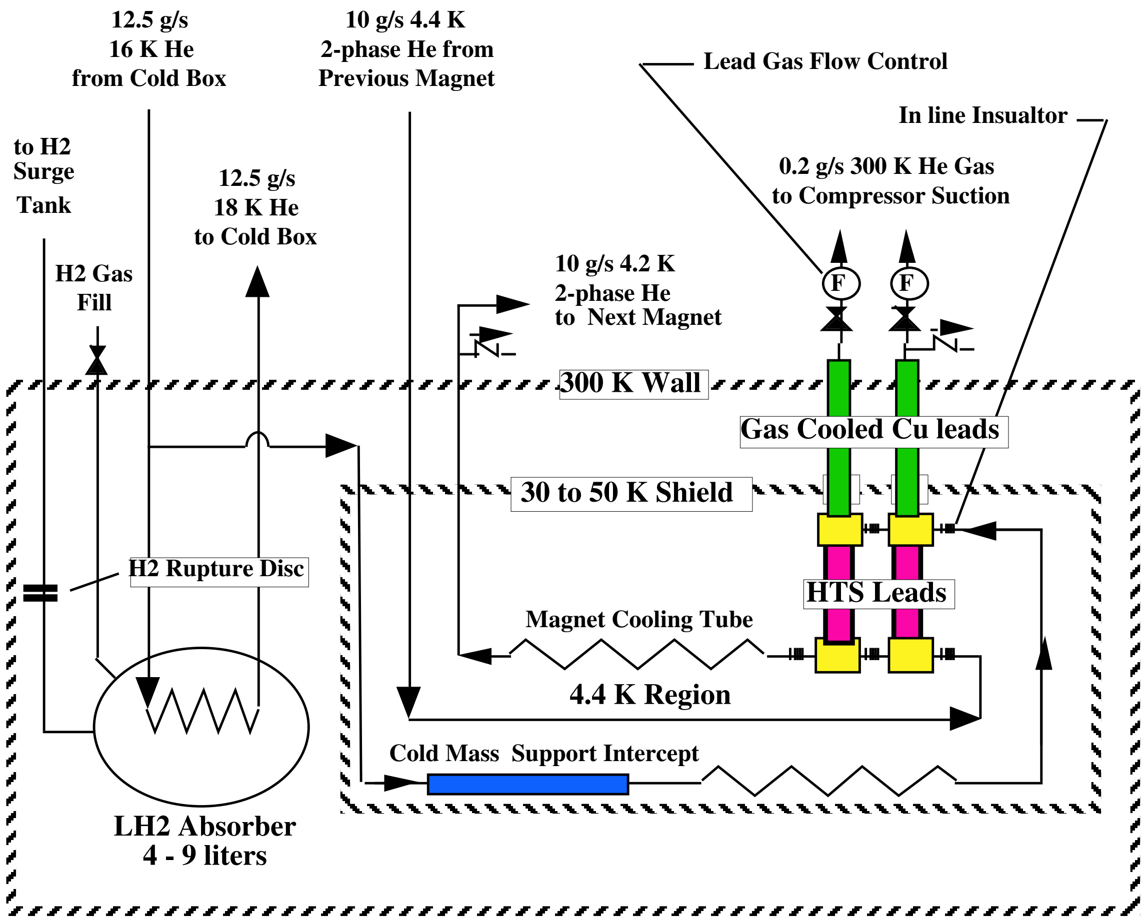

Figure 10.7: Cryogenic cooling system within a typical cooling focusing coil cryostat.

about 2 K. As a result, the helium flow circuit used to cool the hydrogen absorbers should be designed to provide 31 g/s of 16 K helium. The heat load in the hydrogen decreases along the cooling channel. At the end of the channel, the heat is load is expected to be as low as 130W[1]. Thus, the 16k helium flow rate for the 1.65-m-long cells should be set to about 15 g/s. In all cases the helium will be returned to the refrigerator cold box at around 19 K (including heating in the return transfer line).

10.3.5 Quench Protection

The bunching section has twenty focusing magnets and twenty-one coupling magnets that have the same current in the coils. The number of cooling section cells where magnets carry the same current is up to thirteen. Each magnet in the bunching and cooling sections has its own leads. The magnets can be powered individually or in strings of magnets that carry the same current. Powering magnets as a string of magnets requires a more complicated quench-protection system that uses diodes and resistors to cause the string current to bypass the quenching magnet. For sake of simplicity, each magnet has its own power supply and quench protection system. A 2500 A power supply for charging and discharging a single magnet coil (either a focusing coil or a coupling coil) should be capable of developing ± 7 V. The magnet quench protection consists of a dump resistor across the magnet leads. When a quench is detected, a fast switch disconnects the power supply from the magnet. In all cases, the power supply control system should permit control of the current and the voltage across the coils as the magnet is charged and discharged. The power supply is not required to operate at both positive and negative currents. A controller is used to control the charging and discharging voltages across each coil and regulate the current once the coil has reached its set current.

10.3.6 Alignment

The coupling coils can be aligned so that the solenoid axis is correct to 0.3 mrad. The magnetic center of the coupling coil can be maintained to about 0.3 mm. The alignment of the focusing coils can probably be maintained to about 0.5 or 0.6 mrad. Correction dipoles could be installed if necessary, correcting the apparent solenoid axis of the coils by $\pm$ 1.5 mrad.

[1]This is due to beam losses

10.3.7 Magnetic Field Outside the Solenoids

The net magnetic moment of the cooling channel is essentially zero; consequently the field falls off quite rapidly away from the magnetic axis. Considering the long cell in isolation, the induction field at different distances from the solenoidal channel is given in Table 10.7

10.4 Linear Accelerator Solenoids

The requirement of a large acceptance for the pre-accelerator linac requires large apertures and strong focusing in both planes. Clearly, solenoids are superior to quadrupole triplets (see Chapter 6).

The present design contains several different solenoid magnets. The matching section has a pair of low-stray-field solenoids with adjustable currents. The short and intermediate cryomodules have a 1 m solenoid and the long one has a 1.5 m solenoid.

Solenoids produce stray fields that have adverse effects on the superconducting rf cavities; therefore, a very important design feature of the solenoids is the need to eliminate the stray fields. The solenoids satisfy the following conditions:

1. are designed to produce zero net magnetic moment. This means that the coil that produces the solenoidal field is bucked by a coil or coils that are larger in diameter.

2. The field from the bucking coils is be distributed in the same way as the solenoid field. This suggests that the bucking solenoid be around the focusing solenoid so that the return flux from the focusing solenoid is returned between the focusing solenoid and the bucking solenoid.

3. The solenoid pair is surrounded by iron, except where the muon beam passes through it.

4. An iron flux shield is installed between the solenoid magnet package and the rf cavity cells.

5. The superconducting rf cells nearest the focusing solenoid are covered with a type 2 superconducting shield. This will not shield the earth's magnetic field, but it will shield the remaining stray flux from a nearby solenoid. A superconducting shield was used to shield the stray field from a superconducting inflector magnet that is located within the good field region (good to better than 1 part in a million) of the $g-2$ experiment at BNL.

It is unlikely that all five steps will be needed to sufficiently reduce the stray field in the rf cavities arising from the adjacent solenoid. The linac solenoids are designed to have bucking solenoid coils on the outside of the main solenoid. The bucking coil is the same length as the main solenoid, and its radius and current are set so that the solenoid pair produces zero net magnetic moment. In order for a solenoid of average radius R_1 with a total current I_1 to have zero net magnetic moment, a bucking coil of radius R_2 larger than R_1, must be around it. The total current of the bucking solenoid I_2 can be calculated using the expression

$$I_2 = -I_1 \frac{R_1^2}{R_2^2}. \tag{10.1}$$

If the coils in both the outer and the inner solenoids in a system of solenoids with zero net magnetic moment are evenly distributed, the induction generated at the center of the nested solenoid pair will be given by

$$B_0 = \frac{\mu_0 I}{L}(n_1 \cos\beta_1 - n_2 \cos\beta_2), \tag{10.2}$$

where

$$\beta_1 = \tan^{-1}\left(\frac{2R_1}{L}\right) \qquad \beta_2 = \tan^{-1}\left(\frac{2R_2}{L}\right), \tag{10.3}$$

I is the current in the solenoid pair, L is the length of the nested solenoid pair, n_1 is the number of turns in the inner focusing solenoid, and n_2 is the number of turns in the outer bucking solenoid. Because of the zero net magnetic moment condition, $R_2 = (n_1/n_2)^{1/2} R_1$ with $I_1 = n_1 I$ and $I_2 = n_2 I$.

Table 10.8 presents the mechanical and electrical parameters for the short and long module focusing solenoids. The matching solenoids at the start of the channel are similar to the first focusing solenoids. All of these solenoids are designed to have zero net magnetic moment. The solenoids in Table 10.8 are assumed to have a warm bore and a warm iron shell around the solenoid pair. It should be noted that the magnet bore does not have to be warm. A cold bore solenoid will be somewhat smaller and the bore can be a cryopump for the beam vacuum. The iron shield around the magnet pair does not have to be warm either, as long as it does not carry large forces. The inner coils and the outer coils of the solenoid in Table 10.8 have an even number of layers. This allows the solenoid leads to be brought out together at one end. The outer solenoid is split with a 50 mm gap between the two coils. This allows the leads and helium cooling tube for the inner solenoid to be brought out through the outer solenoid. Electrical connections and helium into the magnet can be brought in at the center of the solenoid, thus minimizing the stray field that might be produced at or near the connection point. The solenoid pair is assumed to be supplied with current through a single set of high temperature superconductor (HTS) and gas-cooled electrical leads. Since the nested magnets are hooked in series, the focusing solenoids have zero net magnetic moment at all magnet currents.

Figure 10.8 shows a cross section of the short solenoid (1.0 m long with 2.1 T in the inner bore) in a plane that contains the magnetic axis; it also shows the separation of the inner coil and the bucking coil, as well as the magnet cryostat, an electrical lead, and the iron shield around the actively shielded solenoid. The center of the cryostat has no iron shield around it because there is very little magnetic flux leaking outside the bucking solenoid. Not shown in Figure 10.8 is iron flux shield that is about 300 mm from the end of the magnet cryostat. This shield further reduces the field in the rf cavity.

Figure 10.9 shows a cross section of the long focusing solenoid (1.5 m long with 4.2 T in the inner bore) in a plane perpendicular to the solenoid axis. Figure 10.9 shows the 24 layer inner coil and a 4 layer bucking coil; it also shows a cold mass support system that can be used for both types of focusing solenoids. The cold mass support system carries predominantly gravitational loading during magnet operation. The support system is designed to carry shipping loads due to acceleration generated by the truck. Because the focusing solenoids are decoupled magnetically from each other, there are no loads imposed on the solenoid by nearby magnets. Also shown in Fig. 10.9 are the magnet current leads and some of the 4.4 K and 40 K helium plumbing for the magnet. Figures 10.8 and 10.9 represent typical cross sections that can be applied to both types of focusing solenoids.

The focusing 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 it. 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 tubes carrying the two-phase helium 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 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

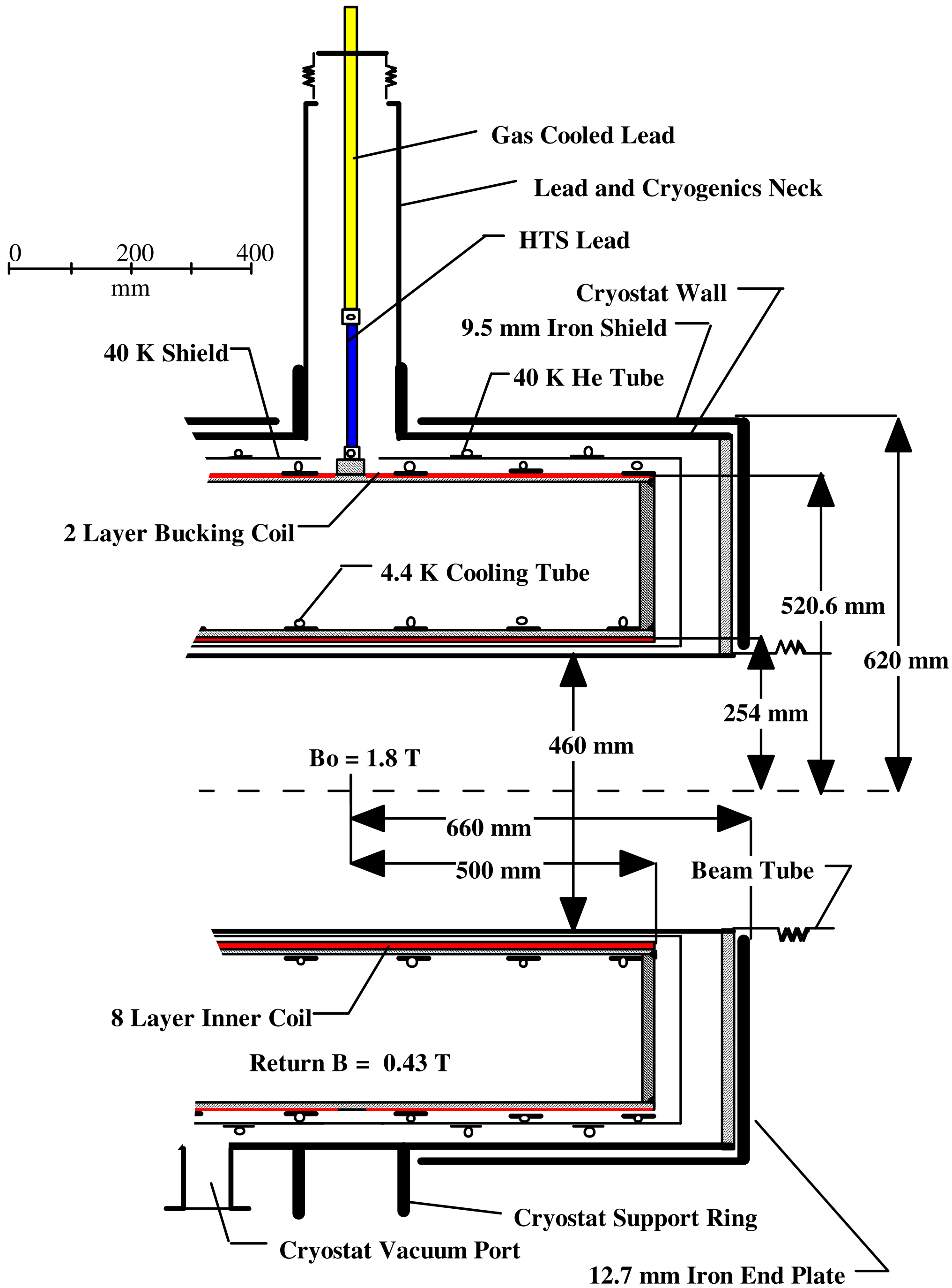

Figure 10.8: A cross section, parallel to the magnetic axis, of a short 1-m solenoid.

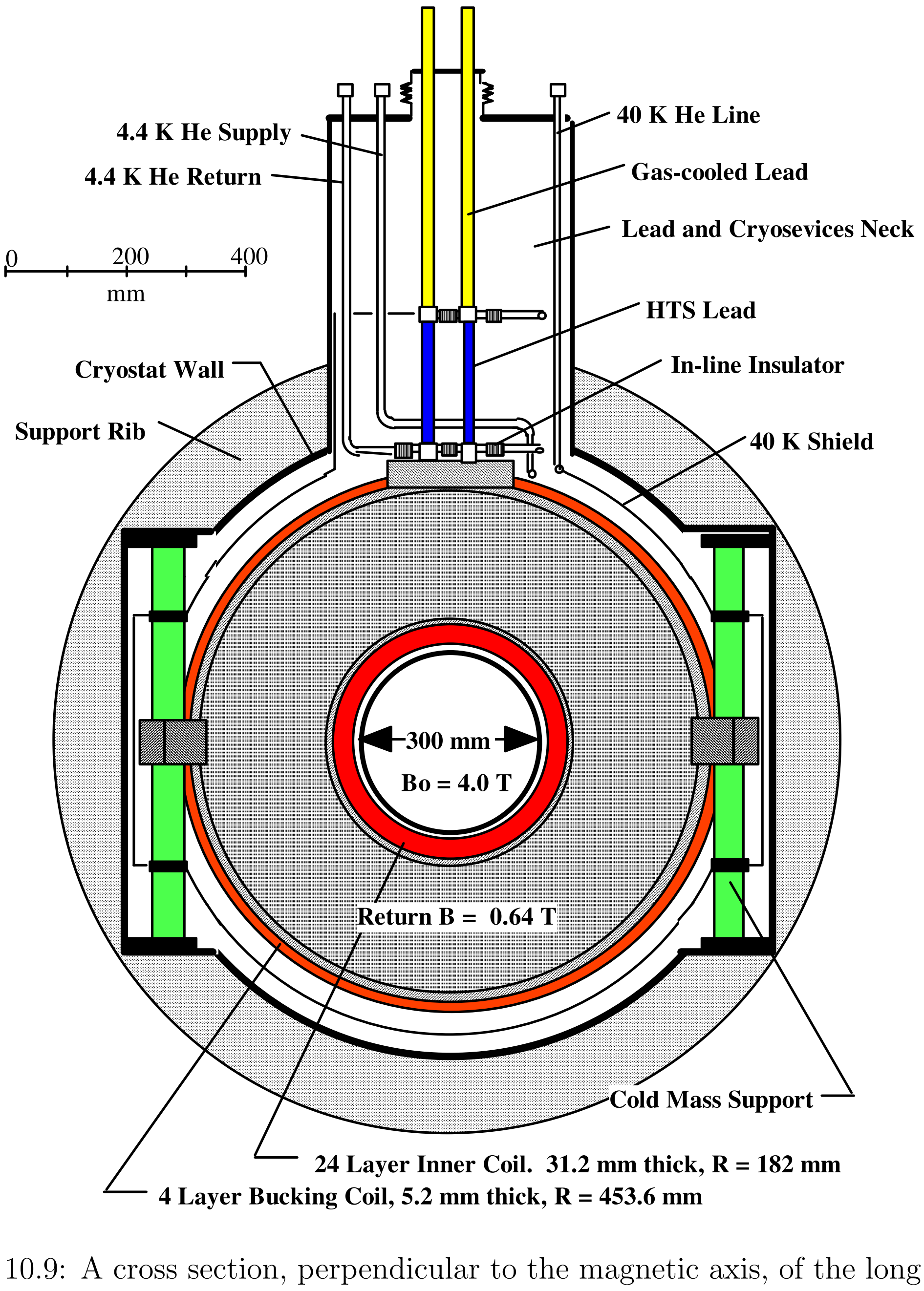

Figure 10.9: A cross section, perpendicular to the magnetic axis, of the long 1.5-m solenoid.

The static heat load into the magnet cryostat at 4.4 K and 40 K for the 1.5-m-long focusing solenoid is shown in Table 10.9. The 4.4 K heat load into a short solenoid is estimated to be about 0.50 W. Most of the difference is heat flow down the HTS leads.

All of the magnets in an acceleration section are cooled in series from the two-phase helium refrigerator and control cryostat. Whether this refrigerator is the same one that cools the superconducting RF cavities depends on the operating temperature of the rf cavities. Cooling for 23 or 24 magnets requires a mass flow rate through the two-phase 4.4 K flow circuit of about 2.5 g/s. The two-phase helium tubes would be attached to the inner coil support structure, the outer coil, the attachment points of the cold-mass supports, and the base of the HTS leads.

The heat load into the shield circuit helium stream is expected to vary from 6.1 to 7.3 W, depending on the length of the magnet. The shield gas comes from the refrigerator at a temperature of 30 K. This gas enters the magnet cryostat through a single vacuum insulated tube. The helium flow in this tube is dictated by the needs of the gas-cooled leads between 50 K and room temperature. The mass flow through the shield circuit is governed by the needs of the gas-cooled leads. The short solenoid leads will need 0.05 g/s; the long solenoid leads will need 0.035 g/s. Gas exits from the gas-cooled electrical leads at room temperature. It returns warm to the refrigerator compressor suction. In the short solenoid, the shield gas enters the gas-cooled leads at about 55 K. In the long solenoid, the top of the HTS leads will be about 70 K. The same HTS leads can be used for both magnets.

For sake of simplicity, each magnet has its own power supply and quench protection system. A 500-A power supply can be used for charging and discharging a single magnet at ± 5 V. The charge time with 3 V across the short magnet is about 600 s. The long focusing solenoid will take about 3200 s to charge with 3 V across the magnet. In all cases, the power supply control system should permit control of the current and the voltage across the coils as the magnet is charged and discharged. The power supply is not required to operate at both positive and negative currents. A controller is used to control the charging and discharging voltages across each coil and regulate the current once the coil has reached its set current. The magnet quench protection consists of a dump resistor across the magnet leads. When a quench is detected, a fast switch disconnects the power supply from the magnet. Both coils in the magnet go normal through quench-back.

The focusing solenoids can be aligned so that the solenoid axis is correctly placed to about 0.5 mrad. The magnetic center of the B coil can also be maintained to about 0.3 mm.

Table 10.6: Sources of heat at 2.5 K, 4.4 K, abd 16–40 K in the bunching and cooling cell magnets. [a] "A" denotes the focusing coil; [b] "B" denotes the coupling coil

Source of heat	2.75 m Cell(W)		1.65 m Cell(W)	
	Coil A[a]	Coil B[b]	Coil A	Coil B
Magnet heat loads at 4.4 K				
Vertical cold mass supports	0.24	0.24	0.40	0.24
Longitudinal cold mass supports	0.36	0.36	0.74	0.54
Thermal radiation through MLI	0.16	0.14	0.01	0.19
Bayonet joints and piping	0.03	0.03	0.03	0.03
Instrumentation wires	0.02	0.02	0.02	0.02
HTS current leads	0.60	0.60	0.60	0.60
Total 4.4 K heat load per coil	1.41	1.39	1.80	1.62
Magnet Heat Loads at 2.5 K				
Vertical cold mass supports	—	—	0.05	—
Longitudinal cold mass supports	—	—	0.10	—
Thermal radiation through MLI	—	—	0.11	—
Bayonet joints and piping	—	—	0.01	—
Instrumentation wires	—	—	0.00	—
HTS current leads	—	—	0.02	—
Total 2.5 K heat load per coil	0.0	0.0	0.29	0.0
Magnet shield and intercept heat loads at 16 to 40 K				
Vertical cold mass supports	3.8	3.8	3.8	3.8
Longitudinal cold mass supports	7.2	7.2	10.8	10.8
Thermal radiation through MLI	2.7	2.9	1.9	3.2
Bayonet joints and piping	1.3	1.3	1.3	1.3
Instrumentation wires	0.1	0.1	0.1	0.1
Gas cooled current leads	—	—	—	—
Total 16 to 40 K heat load per coil	15.1	15.3	17.9	19.2
Hydrogen Absorber (16 K Cooling)				
Cold mass supports	1.5	—	1.0	—
Thermal radiation through MLI	0.3	—	0.2	—
Bayonet joints and piping	1.3	—	1.3	—
Instrumentation wires	0.1	—	0.1	—
Thermal radiation to windows ($\epsilon = 0.2$)	18.4	—	6.9	—
Beam absorption heating	275	—	110.0	—
Circulation heater	≈30	—	≈30	—
Total 16 K heat load per coil	326.6	0.0	149.5	0.0
Equivalent 4.4 K refrigeration per cell	100.7		54.1	

Table 10.7: Stray field at various distances from the axis of a long cooling cell.

R (m)	B (T)
23×10^{-2}	1.5
11×10^{-2}	2.0
18×10^{-3}	4.0
56×10^{-5}	6.0
18×10^{-6}	10.0

Table 10.8: Superconducting solenoid parameters for the linear accelerator.

	Short	Intermediate	Long
Mechanical Parameters			
Beam bore diameter (mm)	460	460	300
Solenoid cryostat length (mm)	1260	1260	1710
Solenoid cryostat outer diameter (mm)	1180	1180	1060
Iron shell length (mm)	1300	1300	1750
Iron shell outer diameter (mm)	1240	1240	1120
Iron shell thickness (mm)	9.5	9.5	9.5
Coil length for both coils (mm)	1000	1000	1500
Inner coil average radius (mm)	254	254	182
Inner coil thickness (mm)	10.4	10.4	31.2
Number of inner coil layers	8	8	24
Number of inner coil turns	4840	4840	21816
Outer coil average radius (mm)	520.6	520.6	453.6
Outer coil thickness (mm)	2.6	2.6	5.2
Outer coil center gap (mm)	50	50	50
Number of outer coil layers	2	2	4
Number of outer coil turns	576	576	3512
Solenoid cold mass (kg)	376	376	746
Solenoid cryostat mass (kg)	166	166	238
Iron shell mass (kg)	485	485	581
Magnetic and Electrical Parameters			
Solenoid average magnetic induction (T)	2.1	2.1	4.2
Solenoid magnetic length (m)	≈ 1.0	≈ 1.0	≈ 1.5
Magnet design current (A)	469.6	469.6	274.0
Peak induction in the inner coil B_p (T)	≈ 2.9	≈ 2.9	≈ 5.8
Magnet conductor I_c at 4.4 K and B_p (A)	≈ 1100	≈ 1100	≈ 590
SC current density (A mm^{-2})	307	307	180
Solenoid stored energy (MJ)	0.421	0.421	1.306
Solenoid self inductance (H)	3.82	3.82	34.8
EJ^2 limit (A^{2}m^{-4}J)	3.97×10^{22}	3.97×10^{22}	4.23×10^{22}

Table 10.9: The sources of heat at 4.4 K and 40 K in a 1.5 m long focusing solenoid.

Source of heat	4.4 K load (W)	40 K load (W)
Heat flow down the cold mass supports	0.12	1.9
Thermal radiation through the multi-layer insulation	0.10	4.0
Heat flow down the helium bayonet joints	0.03	1.3
Heat flow down instrumentation wires	0.02	0.1
Heat flow down the 280 A magnet current leads	0.45	—
Total heat load per magnet	0.72	7.3

Bibliography

[1] M. A. Green, *Design Issues for the Solenoid Magnets for the Neutrino Factory Muon Cooling System*, LBNL-46357, July 2000, http://www-mucool.fnal.gov/mcnotes/muc0165.pdf.

[2] M. A. Green, Y Eyssa, S. Kenny, et al, *Superconducting Solenoids for the Muon Collider*. IEEE Transactions on Applied Superconductivity 10, No.1, p. 196, (2000), http://www-mucool.fnal.gov/mcnotes/muc0162.pdf.

[3] S. Prestemon, J. Miller, Y Eyssa, and M. A. Green *Magnet System Design with Cost Optimization,* IEEE Transactions on Applied Superconductivity 10, No.1, p. 1356, (2000).

[4] A. Green, Y. Eyssa, S. Kenny, J. R. Miller and S. Prestemon, *High Field Superconducting Solenoids for Muon Cooling,* Institute of Physics Conference Series 167, p. 1165, (2000).