Title

Superconducting solenoids for muon-cooling in the neutrino factory

Permalink

https://escholarship.org/uc/item/0hh9h08s

Authors

Green, M.A.
Miller, J.R.
Prestemon, S.

Publication Date

2001-05-12

LBNL-48446
SCMAG-750

SUPERCONDUCTING SOLENOIDS FOR MUON-COOLING IN THE NEUTRINO FACTORY

M. A. Green[a], J. R. Miller[b], and S. Prestemon[a],

a. Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
b. National High Magnetic Field Laboratory, Tallahassee FL 32310, USA

ABSTRACT

The cooling channel for a neutrino factory consists of a series of alternating field solenoidal cells. The first section of the bunching cooling channel consists of 41 cells that are 2.75-m long. The second section of the cooling channel consists of 44 cells that are 1.65-m long. Each cell consists of a single large solenoid with an average diameter of 1.5 m and a pair of flux reversal solenoids that have an average diameter of 0.7 to 0.9 meters. The magnetic induction on axis reaches a peak value of about 5 T at the end of the second section of the cooling channel. The peak on axis field gradients in flux reversal section approaches 33 T/m. This report describes the two types of superconducting solenoid magnet sections for the muon-cooling channel of the proposed neutrino factory.

SUPERCONDUCTING SOLENOIDS FOR THE COOLING CELLS

The beam bunching and cooling section of the neutrino factory is between phase-rotation and the linear accelerator section[1-4]. Like previous designs, the bunching and cooling cells constantly flip in magnet polarity[5]. 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 field flipping structure that characterizes the beam-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.

The beam-bunching section is followed by seventeen muon-cooling cells of that are each 2.75-m long. These cells have four 201.25 MHz RF cavities and a hydrogen absorber that is in the bore of the field flip solenoid. The final cooling section consists of thirty-seven cells that are 1.65-meters long. The 1.65-meter long cooling cells contains two 210.25 MHz RF cavities and a short hydrogen absorber that is in the field flip solenoid. The final matching section is between the cooling section and the linear accelerator. The first 70 MeV of muon acceleration occurs in this section. . Because the cell solenoids are changing polarity with every cell, there is almost no stray field from these solenoids at 10 meters from the axis.

Magnet parameters and a magnet cross section for the 2.75-meter long bunching and cooling cell magnets are shown in Table 2 and Figure 1. The solenoids in the 2.75-meter long cells are the same for both bunching and cooling-cells. Magnet parameters and a magnet cross section for the 1.65-meter long cooling-cell magnets are also shown in Table 2 and Figure 1. The solenoid magnet cross sections shown in Figure 1 are through the longitudinal warm to cold supports. The penetration of the hydrogen absorber plumbing through the space between the A-coils is not shown in cross sections in Figure 1.

TABLE 1. Basic Parameters for the Muon Beam Bunching and Muon Cooling Cells

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	---
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	8

TABLE 2. Mechanical and Electrical Parameters for the Bunching and Cooling Cell Magnet A and B Coils

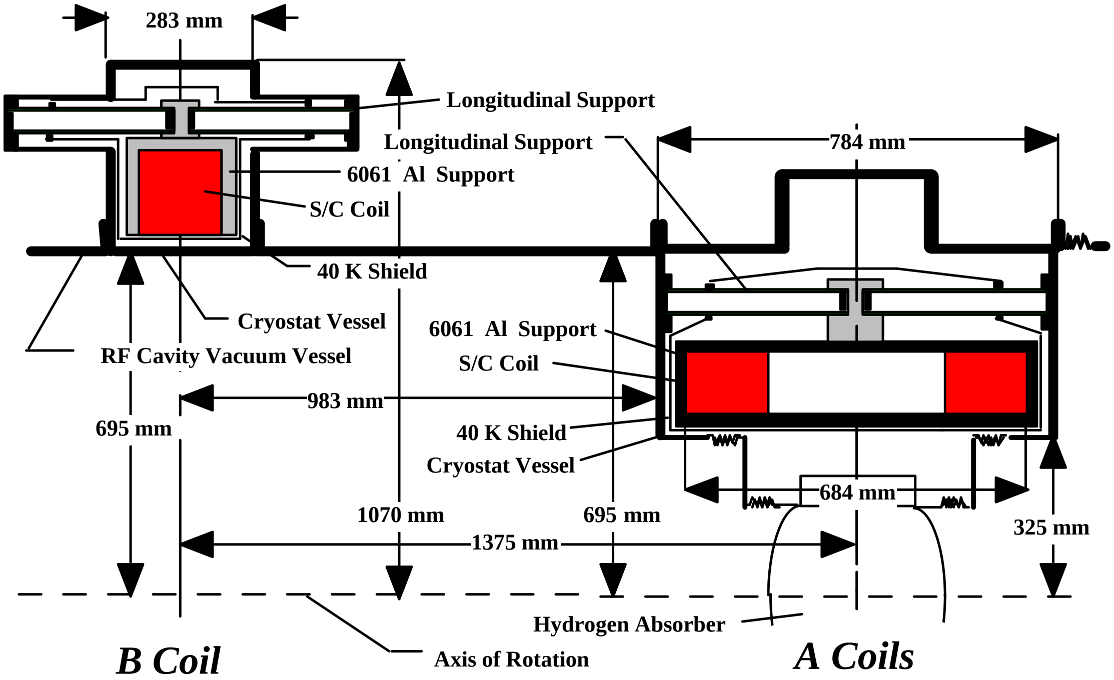
	2.75-m Cell		1.65-m Cell	
	A Coil	B Coil	A Coil	B Coil
S/C Coil Length (mm)	167	162	145	109
Coil Spacing in Z Direction (mm)	350	---	132	---
Number of Turns per Magnet	2304	1472	4480	1974
Magnet Cold Mass (kg)	1430	1245	1995	1750
Magnet Overall Mass (kg)	1870	1570	2430	2290
Maximum Design Current Io (A)	2320.2	1762.0	1783.2	1899.7
Peak B in the Windings at Io (T)	7.5	6.5	8.4	6.5
Coil Stored Energy at Io (MJ)	~7.9	~7.7	~10.7	~10.6
Magnet Self Inductance per Coil (H)	~2.9	~4.9	~6.8	~6.1
Superconductor Matrix J at Io (A mm^{-2})	155	117	119	127
E J^2 Limit per Magnet Cell at Io (J A^2 m^{-4})	$1.89\text{x}10^{23}$	$1.06\text{x}10^{23}$	$1.51\text{x}10^{23}$	$1.71\text{x}10^{23}$
Force Pushing the A Coils Apart (tons)	329	---	1980	---

The matching sections before the bunching section and after the final cooling section have current densities that vary with each coil in the matching section. This permits the tune for the bunching and cooling channel to be well matched with the machine section before and after the bunching and cooling sections. There are three 2.75-m cell cooling-sections 1-1 through 1-3 and three 1.65-m cell cooling-sections 2-1 through 2-3. The coil current and current densities for the bunching and cooling are shown in Table 3.

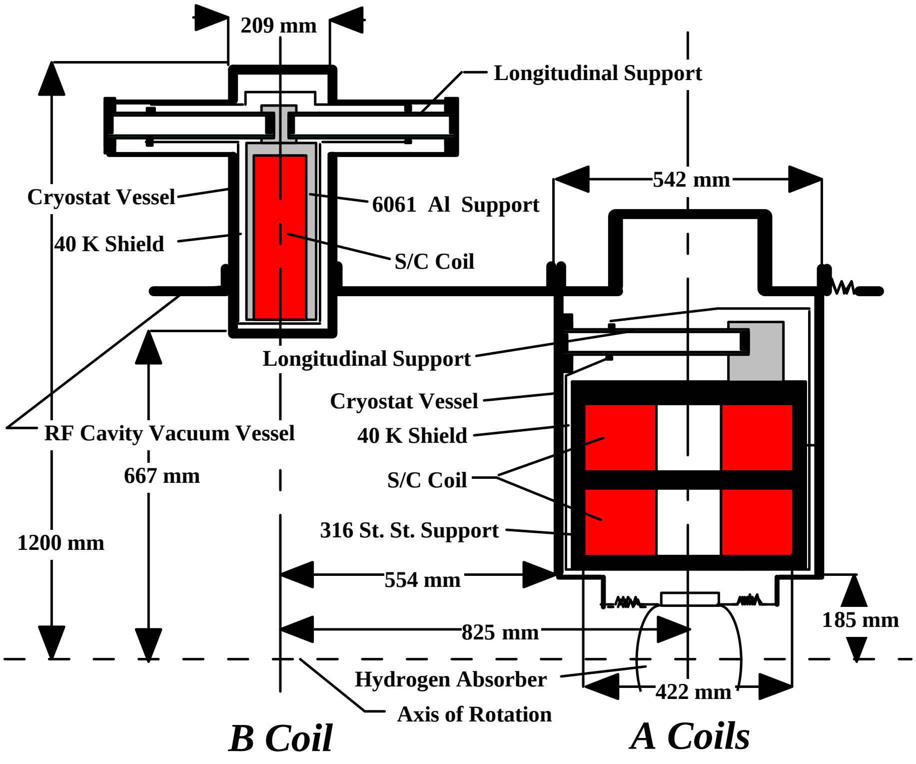
Continuously varying currents on a cell by cell basis may lead to more efficient bunching and cooling.

TABLE 3. Coil Current Density J and Current I in 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 variable	4	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	1471.11	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 variable	10	variable	variable		variable



2.75-meter Long Cell



1.65-meter Long Cell

FIGURE 1. Quarter Cross Sections for 2.75-meter Long and 1.65-meter Long Cooling Cells. The cross sections show the location of the ionization cooling hydrogen absorbers. The vacuum vessel for the RF cavity is also shown. The 2.75-meter long cell has four RF cavities; the 1.65-meter long cells have two RF cavities. The RF cavity frequency in both cases is 201.25 MHz.

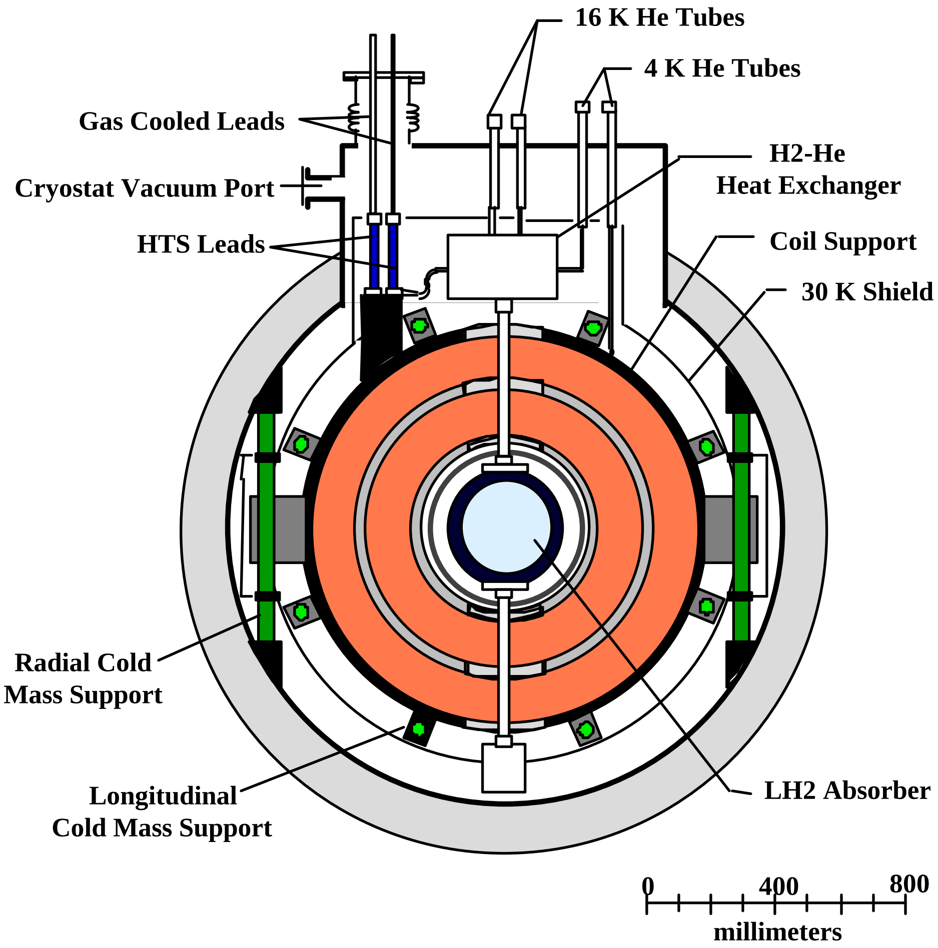


FIGURE 2. A Cross Section of the 1.65 m Cell A Magnet Perpendicular to the Muon Beam Axis

Figures 1 shows quarter cross sections 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 1 show the magnet cryostats, the coils, the coil hoop 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. Figure 2 shows a cross section through the center of the 1.65-meter long cell A-coil pair. Figure 2 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 2 illustrates how magnet electrical leads, and helium refrigeration can be brought into the cryostat. Figure 2 is a typical cross section that can be applied to all of the bunching and cooling cell solenoids.

Figure 2 shows that there is space between the A-coil pair to bring cryogenic service into the hydrogen absorber. The inner diameter of the A-coil structure that carries the force pushing the two A-coils apart is large enough to allow the hydrogen absorbers to slip into the coil package. The hydrogen absorber will share the same cryostat with the A-coils. The hydrogen absorber and the A-coils will share a common cryostat vacuum. The hydrogen absorber will be supported from the A-coil package by a low thermal-conductivity support system. Figure 2 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.

Forces in the longitudinal direction are a serious concern for the bunching and cooling solenoids. The field-flip coils (A-coils) generate very 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 see large bending stresses. Large stresses are developed at the point where the end plates meet the shells inside and outside the coils. The force between A-coils in the 1.65-meter long cooling cells is so large (about 1950 metric tons), the A-coils had to be subdivided in the radial direction in order to reduce the bending stress in the end plates. In addition, the 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 very little net longitudinal force on any of the coils. 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. One can attach all of the coils together with cold members, but further examination suggests that this approach does not make sense if one wants to be able to assemble and disassemble the cooling system magnet channel. As a result, every magnet is assumed to have its own cold to warm longitudinal supports.

The magnet cold to warm supports, in the 2.75-meter long cells, are designed to carry about 80 metric tons (the maximum force during a magnet fault). These forces can be carried by four oriented glass fiber epoxy cylindrical supports that have a 50-mm diameter with a wall thickness of 4-mm. Oriented glass fiber rods can carry stresses up to 600 MPa in either tension or compression. The 1.65-meter long cell magnets have longitudinal cold to warm supports that are designed to carry 120 metric tons. Figure 2 shows the location of eight of these supports on the 1.65-meter long cell A-coil package. The support shown for the A-coil in Figure 1 is designed to operate in both tension and compression. Further engineering can define an optimum cold mass support system for these magnets. Compared to other heat loads into the magnets, the longitudinal cold mass supports represent only about one quarter of the total heat leak into the magnet part of the cryostats.

The conductor current and current density given for the A and B coils in Table 2 are the peak values that would occur in the cells operating at the highest current. The stored energy given in Tables 2 occurs at the peak design current in the coils. In general, when the current density is high in the A-coils, the current density in the B-coil is low. When the current is high in the B-coil, the A-coils current is lower. (See Table 3.) As a result, the stored energy for the cooling cells changes very little as one moves down the cooling channel. The cell stored-energy shown in Table 1 is the average stored energy for that type of cell.

Figure 3 are a schematic representation of the matching section of a 2.75-meter long muon-cooling cell to a 1.65-meter long muon-cooling cell. The A-coil set shown in Figure 3 is the only unique magnet in the entire cooling channel. There are 41 A and B coils that make up the 2.75-meter long bunching and cooling cells. There are 44 A and B coils that make up the 1.65-meter long cooling and accelerator matching cells.

THE BUNCHING AND COOLING SOLENOID SUPERCONDUCTOR

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-meter cell A coils but the margin is rather tight. The problem occurs in the 1.65-meter long cell A-coils where the peak field in the magnet coil is 8.4 T. This coil must either be operated at reduced temperature (say 2.5 K) or the conductor for these coils must be niobium- tin. In order to allow for greater temperature margin, all the A-coils in the both types of cells should use a conductor with a 4 to 1 copper to superconductor ratio. With a 4 to 1 copper to superconductor ratio, the A-coils in the 1.65-meter long cells can be operated at 2.5 K.

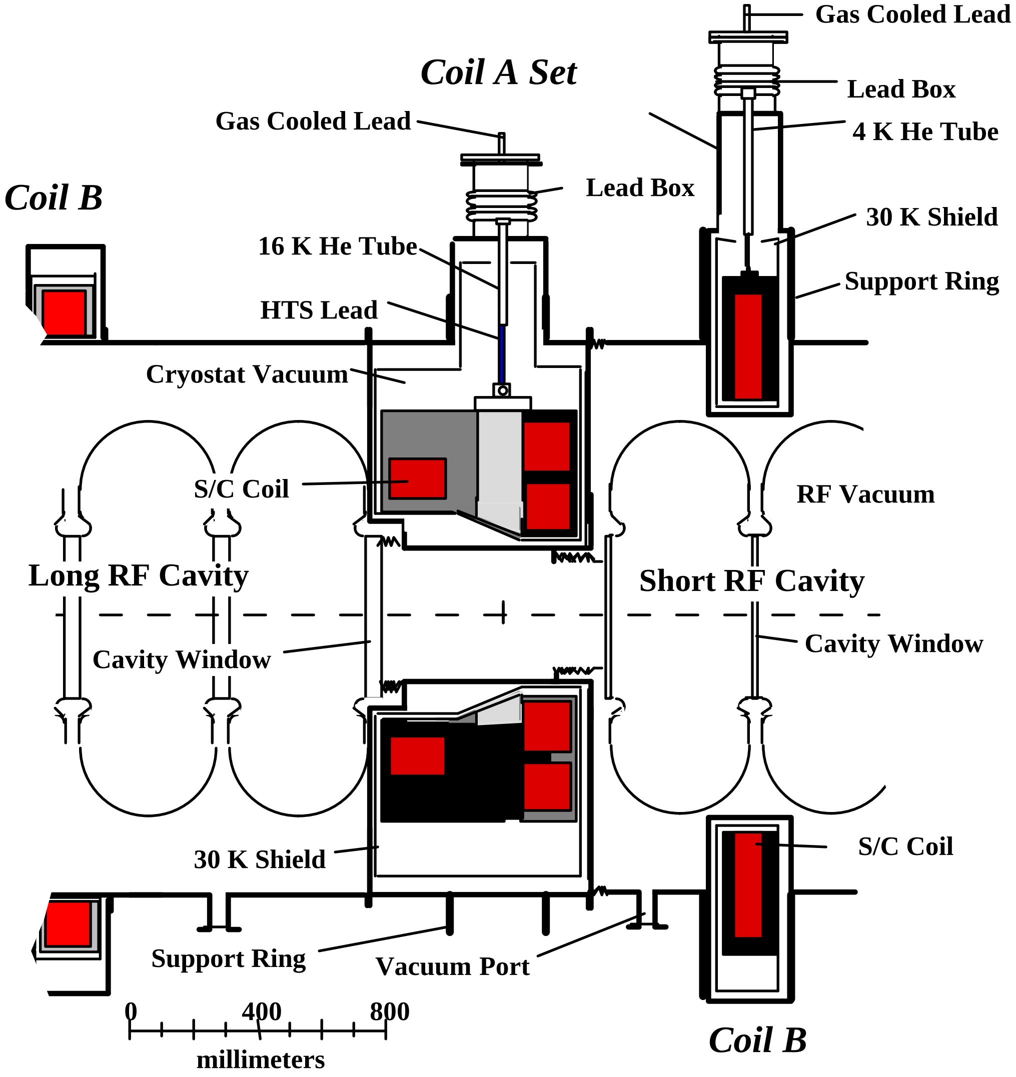


FIGURE 3. A cross Section of the Matching Region between the 2.75-m and 1.65-m Muon-Cooling Cells. This view shows the RF cavities that are within the cooling cells. The special A magnet shown does not have a liquid hydrogen absorber. The muon energy increases about 30 MeV in the matching section.

The superconductor is assumed to have a resin type of 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 superconducting coils to be discharged with a voltage across the leads of up to 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 coils in the cooling channel are coupled. A quench in one coil is likely to trigger a quench in the entire bunching and cooling string.

CRYOGENIC HEAT LOADS AND HELIUM COOLING

Refrigeration to the muon cooling magnets and hydrogen absorbers is supplied at 16 K and 4.4 K. The 2.5 K cooling for the A-coil in the 1.65-m long cell 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-meter cell A-coil package is intercepted by two-phase helium at 4.4 K. The hydrogen absorbers are cooled from the same refrigerator as the solenoid magnets. Refrigeration for the hydrogen absorbers and shields is drawn off at 16 K. Figure 4 is a schematic diagram for helium cooling the A-coils for the 2.75-m long muon cooling cells.

TABLE 4. The Sources of Heat at 4.4 K, and 16 to 30 K in the Bunching and Cooling Cell Magnets

Source of Heat	2.75-m Cell (W)	1.65-m Cell (W)
Magnet Heat Loads at 4.4 K		
Vertical Cold Mass Supports	0.48	0.64
Longitudinal Cold Mass Supports	0.72	1.28
Thermal Radiation through MLI	0.30	0.24
Bayonet Joints, Piping and Wires	0.10	0.10
HTS Current Leads	1.20	1.20
Total 4.4 K Heat Load per Cell	2.80	3.46
Magnet Shield and Intercept Heat Loads at 16 to 30 K		
Vertical Cold Mass Supports	7.6	7.6
Longitudinal Cold Mass Supports	14.4	21.6
Thermal Radiation through MLI	5.6	5.1
Bayonet Joints Piping and Wires	2.7	2.7
Total 16 to 30 K Heat Load per Cell	30.4	37.1
Hydrogen Absorber Heat loads (16 to 18 K Cooling)		
Cold Mass Supports	1.5	1.0
Thermal Radiation through MLI	0.3	0.2
Bayonet Joints Piping and Wires	1.4	1.4
Thermal Radiation to Windows ($\varepsilon = 0.2$)	18.4	6.9
Muon Beam Absorption Heating	275.0	110.0
Hydrogen Circulation Heater	~30	~30
Total 16 K Absorber Heat Load per Cell	326.6	149.5
Equivalent 4.4 K Refrigeration Needed per Cell	100.7	54.1

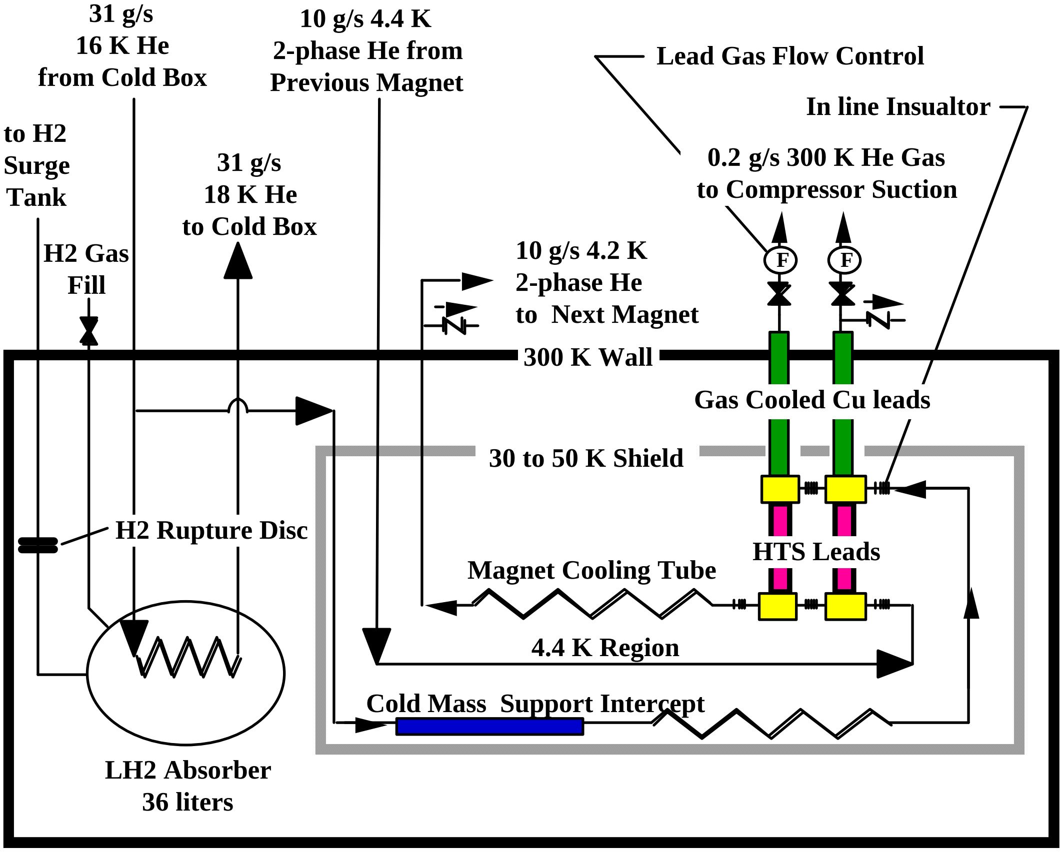


FIGURE 4. A Cooling Schematic Diagram for the A-Coils and LH2 Absorber for the 2.75 m Long Cell

Table 4 shows the heat loads at various temperatures for the 2.75-m cells and the 1.65-m cells. The load not shown in Table 4 is the heat load to the 1.65-m long cell A-coils that is operated removed at 2.5 K. If these coils are fabricated from niobium tin, there is no additional heat load. The 16 K helium used to cool the liquid hydrogen in absorber returns to the helium cold box at 19 K. The 2.75-meter cell absorbers contain 35.6 liters of liquid hydrogen. The 1.65-meter long cell absorbers contain 8 liters of liquid hydrogen.

Since the helium refrigerator cools both the hydrogen absorber and the magnets, there will be enough excess refrigeration capacity available to re-cool the magnet coils, within a reasonable time, after a string of cooling channel magnets has quenched. The maximum heat load in the absorber dictates the flow of 16 K helium used to cool hydrogen absorber. Without a muon beam in the cooling channel, the absorber heat load can be as low as 22 W.

CONCLUDING COMMENTS

Simulations of muon cooling suggests that a 85 cell bunching and cooling channel can cool the muons well enough so that they can be accelerated to energies of 20 GeV or more. The super FOFO channel cells proposed in the level 2 study appear to be feasible from both the magnet and the hydrogen absorber standpoint.

Most of the bunching and cooling cell magnets can be made using commercial niobium-titanium superconductor. The exception if the A-coil set in the 1.65-m long cooling cell. One can fabricate these coils from niobium-tin or one can cool a niobium-titanium version of these coils to 2.5 K. A third approach is to redesign the cell so that the A-coil average diameter is reduced and the spacing between the A-coil pair is increased[6].

The cryogenic system for the cooling solenoids and the hydrogen absorbers is straightforward. The magnet coils can be indirectly cooled using two-phase helium at 4.4 K in tubes. The shields and hydrogen absorbers can be cooled using a separate circuit drawing helium from the refrigerator at 16 K. The shield and lead cooling gas is returned to the refrigerator at 300 K; the gas used to cool the hydrogen absorbers is returned to the refrigerator at 19 K.

ACKNOWLEDGEMENTS

This work was performed at the Lawrence Berkeley National Laboratory with the support of the Office of Science, United States Department of Energy under DOE contract DE-AC03-76SF00098.

REFERENCES

1. N. Holtkamp and D. Finley eds., “A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring,” Fermilab-Pub-00/108E, (2000)
2. S. Ozaki, R. B. Palmer, M. S. Zisman and J. C. Gallardo eds., “Feasibility Study II of a Muon-Based Neutrino Source,” BNL-52623, June 2001
3. M. S. Zisman, “Status of Neutrino Factory and Muon Collider R&D,” to be published in the 2001 Particle Accelerator Conference Proceedings, Chicago IL USA, 18-22 June 2001
4. M. A. Green, E. L. Black, R. C. Gupta, et al “The Role of Superconductivity and Cryogenics in The Neutrino Factory,” submitted to Advances in Cryogenic Engineering 47 (This Proceedings) (2001)
5. M. A. Green, Y Eyssa, S. Kenny, J R. Miller, et al, "Superconducting Solenoids for the Muon Collider." co-authored with IEEE Transactions on Applied Superconductivity **10**, No.1, p 196, (2000)
6. M. A. Green, “Design Issues for the Solenoid Magnets for the Neutrino Factory Muon Cooling System,” LBNL-46357, July 2000

LBNL-48446
SCMAG-750

Superconducting Solenoids for Muon-Cooling In the Neutrino Factory

M. A. Green[a], J. R. Miller[b], and S. Prestemon[a]

a. Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
b. National High Magnetic Field Laboratory, Tallahassee FL 32310, USA

July 2001

Presented at the 2001 Cryogenic Engineering Conference
Madison Wisconsin, USA
17 July through 20 July 2001

---

* This work was performed at the Lawrence Berkeley National Laboratory with the support of the Office of Science, United States Department of Energy under DOE contract number DE-AC03-76SF00098.