The Design, and Construction of a Gradient Solenoid for the High Powered RF Cavity Experiment for the Muon Collider

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ABSTRACT This report describes the construction and test of a split solenoid that has a warm bore of 440 mm and a cryostat length of 1088 mm. (A 750 mm section contains the magnetic field.) When the coils are hooked so the fields are additive, the central induction is 5.0 T at its design current. When the coils are hooked so that the fields are in opposition, the induction at the center of the solenoid is zero and the peak induction on the solenoid axis is ±3.7 T. The on-axis induction gradient is 25 T per meter when the coils are hooked in opposition. When the coils are operated at their design currents in opposition, the force pushing the two coils apart is about 3 MN. The force pushing the coils apart is carried by the aluminum coil mandrel and a solid aluminum sheath outside of the superconducting winding. The coil was wound as a wet lay-up coil using alumina filled epoxy (Stycast). A layer of hard aluminum wire wound on the outside of the superconducting coil carries some of the hoop forces and limits the strain so that training does not occur. At design current, at both polarities, the peak induction in the windings is about 7 T. This report describes the solenoid magnet system and its construction.

1. INTRODUCTION

The proposed muon collider requires that the muon be cooled so that their emittance is reduced by several orders of magnitude. The proposed cooling system for the muon collider will consist of alternating filed solenoids (Palmer et al (1998)and expanded by Green et al (1999)). Transverse cooling occurs at high field where the uncooled muon beam has a minimum physical size. Once the muon beam has had its transverse and longitudinal momentum reduced, an RF cavity re accelerates the muon beam to its former energy. At the end of the RF cavity, the longitudinal momentum is increased back to its former value while the transverse momentum is lower. In order for the muon beam to be matched from cell to cell, the solenoidal magnetic field must be reversed in the RF cavity.

Studies of RF cavities at the Stanford Linear Accelerator Center (SLAC) have shown that high frequency RF cavities behave differently in a solenoidal magnetic fieldwith no external field. The SLAC study showed that an RF cavity in a solenoidal field takes more time to be condition for high acceleration gradients. In order for the muon cooling system to be of minimum length with minimum muon loss, one wants to maximize the acceleration gradient in the RF cavities within the muon cooling channel. The muon collider collaboration has decided to test high gradient RF cavities in a magnetic field. This report describes a superconducting solenoid magnet that is designed to subject a high acceleration gradient 805 MHz RF to a near constant solenoidal field or a solenoidal field that reverses polarity. The magnet is used as part of a two cell 805 MHz high power RF cavity test system for the cooling system for a muon collider. The high power RF cavity will be tested at an acceleration gradient of up to 40 MV per meter in a nearly uniform magnetic field of 5 T and in a field with an on axis gradient of up to 25 T per meter. When the solenoid produces an on axis field gradient, the field reverses in the solenoid because the two solenoid coils operate with their polarities reversed.

2. THE SUPERCONDUCTING SOLENOID MAGNET

The superconducting coils were wound with a formvar insulated MRI superconductor that has dimensions of 0.96 by 1.65 mm. This conductor has a copper to superconductor ratio 4 to 1 and superconducting filaments with a diameter of 87 microns. The superconductor twist pitch is 12.7 mm. This superconductor has a nominal critical current density of 2500 A mm^{-2} at 4.22 K and 5.0 T. The guaranteed critical current for the superconductor at 4.22 K and 5 T is 760 A.

The magnet coil package is shown in Figure 1. The package consists of two 250 mm long coils that are of separated by 140 mm. The coils are wound on a 6061 aluminum bobbin. Each coil consists 58 layers that are nominally 1.055 mm thick. Each layer consists of 147 turns. The ground plane insulation is 0.8 mm of NEMA G-10. The layer to layer insulation is 0.03 mm thick and is made from fiber glass impregnated with Stycast filled epoxy. The formvar on the conductor is the turn to turn insulation for the magnet. The two superconducting coils are reinforced by a 12,7 mm thick layer of 5052-H38 aluminum banding. When the magnet operates with the current in the two coils at opposite polarity, the force pushing the two coils apart is about 3 MN (300 metric tons). This force is carried by the 13 mm thick bobbin and the 13 mm thick longitudinal support structure outside of the aluminum banding.

Table 1 shows the parameters for the RF test solenoid operating with both coils at the same polarity and at opposite polarity. The magnet power supply system is designed so that the magnet can be operated in either mode. The magnet power supply is designed to deliver up to 300 A and 6 volts. The minimum charge time for the magnet operating in either polarity is about 80 minutes. At the magnet design current, the magnet stored energy is 2.4 to 2.6 MJ depending on the polarity of the two coils. The stored energy is high enough so that quench protection is of some concern. The coils are self protected, but there are diodes and resistors across the leads of each of the coils, even though a normal region in one coil will cause quench back in the second coil because of the induced current in the bobbin.

Figure 2 shows the calculated magnetic induction on the solenoid on axis (R=0 in Fig. 2) and 200 mm off axis (R=200 in Fig. 2)at the design currents shown in Table 1. Figure 2 shows the two cases with the coil polarities adding (at a design current of 230.0 A) and with the coil polarities in opposition (at a design current of 265.0 A). When the coils are powered in opposition, the gradient is about 24 T per meter on axis and 34 T per meter at R =200 mm.
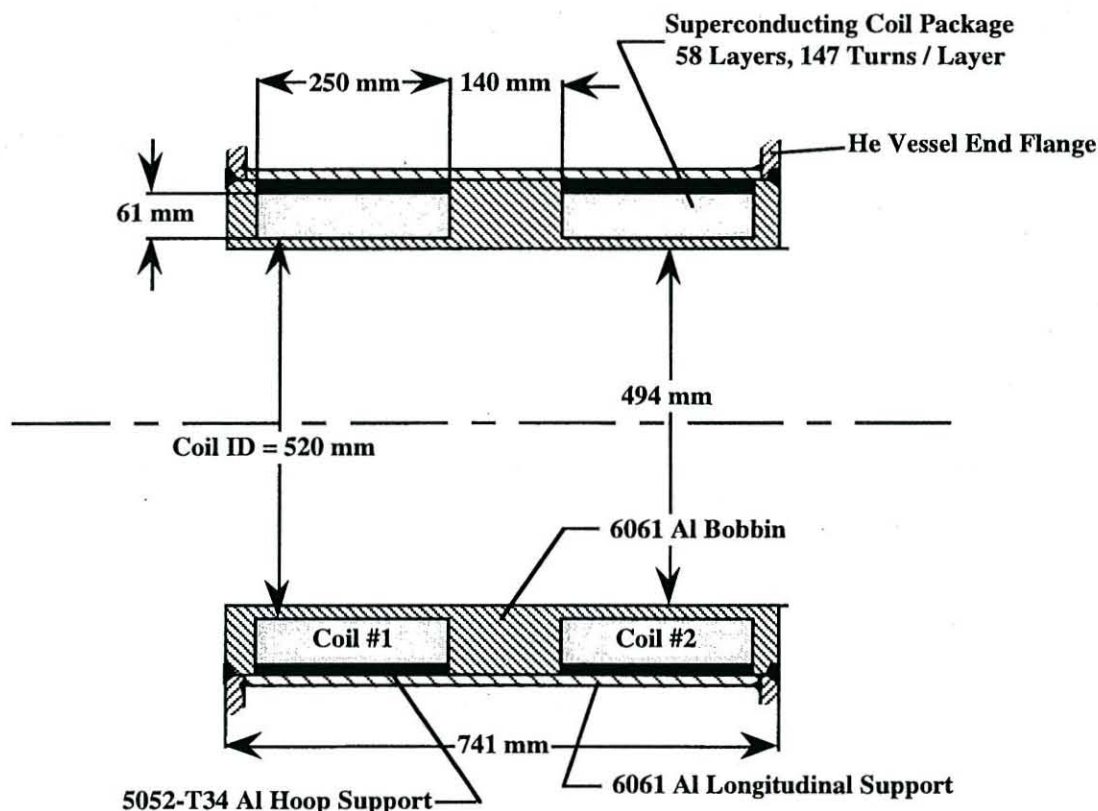

Fig. 1 A cross-section View of the Superconducting RF Test Solenoid Coil Package

Table 1 The Superconducting RF Test Solenoid Parameters

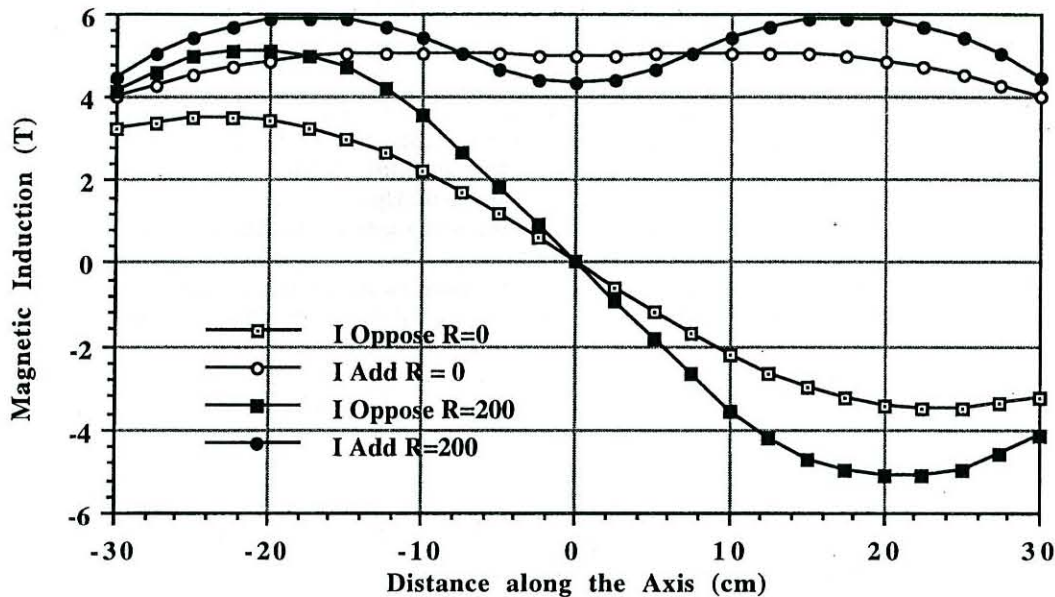| Parameter	Additive Polarity	Opposite Polarity
Design Current I_d (A)	230. 0	265.0
Induction on Axis at Center at R=0 and Z=0 at I_d (T)	4.99	0.00
Maximum Induction on Axis at R=0 at I_d (T)	5.00	3.48
Maximum Induction at R=20 cm at I_d (T)	5.85	5.13
Maximum Induction in the S/C Windings at I_d (T)	6.82	6.52
Maximum Field Gradient on Axis at I_d (T per m)	-NA-	~24.0
Coil Current Density at Design Current at I_d (A mm^{-2})	128.24	147.76
Superconductor Matrix Current Density at I_d (A mm^{-2})	145.96	168.17
Design Current Margin at 4.22 K along the Load Line	0.803	0.821
Magnet Self Inductance (H)	98.22	68.46
Magnet Stored Energy at Design Current (MJ)	2.60	2.40
EJ^2 Limit for the Entire Magnet at I_d (J A^{-2}m^{-4})	5.54×10^{22}	6.78×10^{22}

Figure 2 Calculated and Measured Magnetic Induction along the Axis
for the Coils in Additive and Opposite Polarity

3. RF SOLENOID CRYOSTAT, POWER SUPPLY AND QUENCH PROTECTION

Figure 3 shows the position of the magnet coil package shown in Figure 1 within the cryostat. The cryostat has a horizontal warm bore diameter of 440 mm. Within the warm bore will be a 805 MHz RF cavity that has an outside diameter of about 410 mm. The RF cavities are fed with RF from the ends of the solenoid warm bore. Since, the solenoid is used for a series of experiments that do not require continuous magnet operation, liquid cryogen cooling was selected to cool the solenoid. About 300 liters of liquid nitrogen is needed to cool down 560 kg of magnet and cryostat from 300 K to about 80 K. Approximately 600 liters of helium is needed to cool the solenoid from 80 to 4.2 K and fill the magnet cryostat. The heat leak into the helium dewar is estimated to be 1.63 W. Most of the heat leak is from the four 300 A gas cooled leads. The estimated helium boil off from the magnet cryostat is about 2.3 liters per hour. There is 128 liters of helium above the coils. The solenoid coils can operate at full current for two days between refills.   The estimated nitrogen boil off for the 80 K shields and intercepts is about 0.3 liters per hour. The nitrogen tank will be on an automatic refill system.

The cables from the four coil leads are fed to the magnet power supply rack where the quench protection system is located. The quench protection for the magnet consists of a stack

of room temperature diodes and protection resistors that are located within the power supply rack. This allows the current from a non-quenching coil to be shunted away from the coil turning normal so that the hot spot temperature in the magnet can be minimized. When the solenoids quench, most of the stored magnetic energy will be deposited within the coils and the aluminum bobbin. The coil quench protection system protects each coil independently regardless of the polarity of the coils with respect to each other
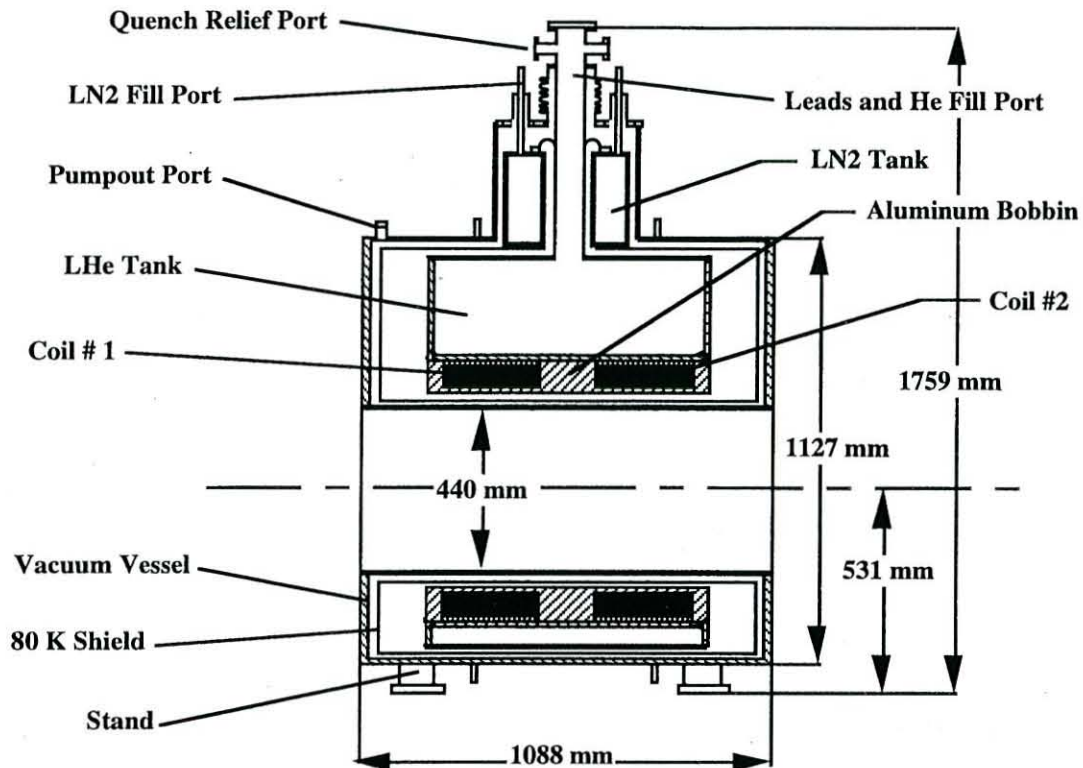

Fig. 2 A Cross-section of the RF Superconducting Solenoid and Its Cryostat

4. CONCLUDING COMMENTS

A superconducting solenoid for testing high gradient 805 MHz RF cavities under various magnetic field conditions has been fabricated. The solenoid is designed to operate with the coil polarities additive or in opposition Preliminary 77 K magnetic measurements show that the magnetic on axis behaves correctly in both modes of operation. Solenoid tests will be completed in the fall of 1999.

ACKNOWLEDGEMENT

REFERENCES

M. A. Green, Y. Eyssa, S. Kenny, J. R. Miller and S. Prestemon, "High Field Solenoids for Muon Cooling," Proceedings of the Fourth European Conference On Applied Superconductivity (these proceedings), Sitges, Spain, 14 through 17 September 1999

R. B. Palmer et al, "Muon Collider: Introduction and Status," Brookhaven National Laboratory Report BNL-65241, January 1998