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A Test of a Superconducting Solenoid for the Mucool RF Experiment*

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Abstract— This report describes the results of a series of tests of a 440-mm warm bore split solenoid used for testing 805 MHz RF cavities. The solenoid consists of two coils each 250-mm long separated by a gap of 140 mm. The solenoid was designed to operate in two modes; a solenoid mode with the two coils hooked in the same polarity and a gradient mode with the two coils hooked in opposite polarity. In the solenoid mode, the magnet is designed to produce an induction of 5 T over a region that is about 400 mm long. In the gradient mode, the solenoid produces a field gradient of 25 T per meter along the axis over a distance of about 300-mm. The solenoid was designed to carry a force of over 3 MN that pushes the two coils apart, when the magnet is operated in the gradient mode. In order to carry this force, the coils are encased within aluminum shells, both inside and outside. Since this solenoid is encased in aluminum and the coils are potted, training was observed. The magnet training history and magnet field measurements are presented in this report.

I. INTRODUCTION

The proposed muon collider requires that the muons be cooled so that their emittance is reduced by several orders of magnitude. Many of the proposed cooling systems for the muon collider will consist of an alternating polarity field channel of solenoids. Transverse cooling occurs where the uncooled muon beam has a minimum physical size. Muon cooling occurs when the beam momentum is reduced by entering a flask of liquid hydrogen. Once the muon beam has had its transverse and longitudinal momentum reduced, a 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 for each cell. Depending on the type of cooling channel, the field reversal will either occur in the RF cavity or in the the liquid hydrogen absorber.

Studies of RF cavities at the Stanford Linear Accelerator Center (SLAC) have shown that high frequency RF cavities behave differently in a solenoidal magnetic field than in a case when there is no external field. The SLAC study showed that a RF cavity in a solenoidal field takes more time to be conditions 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 two or three cells of a high gradient 805 MHz RF cavity to a near constant solenoidal field or a solenoidal field that reverses polarity. The magnet described here will be 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 4 to 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 opposite polarities.

II. The Superconducting Solenoid

The superconducting solenoid is wound with a formvar insulated MRI superconductor with insulated dimensions of 1.0 mm by 1.65 mm. The conductor copper to superconductor ratio is 4 to 1. The superconducting filaments are 87 μm in diameter. The Nb-Ti in the conductor has a design critical current density of 2500 A mm^{-2} at 5 T and 4.2 K. The conductor twist pitch is 12.7 mm.

The coil package consists of two coils that are 250 mm long separated along the axis with a gap of 140 mm. The coil inner radius is 260 mm, and the coil thickness is 61 mm. The coils are wound on a 6061 aluminum bobbin and they are supported in the radial direction with a layer of 5082-H38 banding. The coils are wet wound using a Stycast potting compound. Each coil consists of 58 layers of conductor with 147 turns per layer. The winding bobbin is part of the liquid helium vessel for the magnet cryostat.

When the magnet coils operate in the solenoid mode (the two coils have the same polarity) the longitudinal forces pushes the two coils toward each other. When the coils operate in the gradient mode (the coils are at opposite polarity), there is a force of up to 3 MN pushing the coils apart. This longitudinal force is carried by the magnet bobbin and a 12.7 mm thick sheet of aluminum that connects the two bobbin flanges together outside of the coil packages.

A cross-section of the RF test solenoid system and its cryostat is shown in Figure 1. Table 1 presents the basic parameters for the RF test solenoid. The original design induction for the magnet in the solenoid mode was 4 T. Later the solenoid design induction was changed to 5 T, but the actual design of the magnet system was not changed.

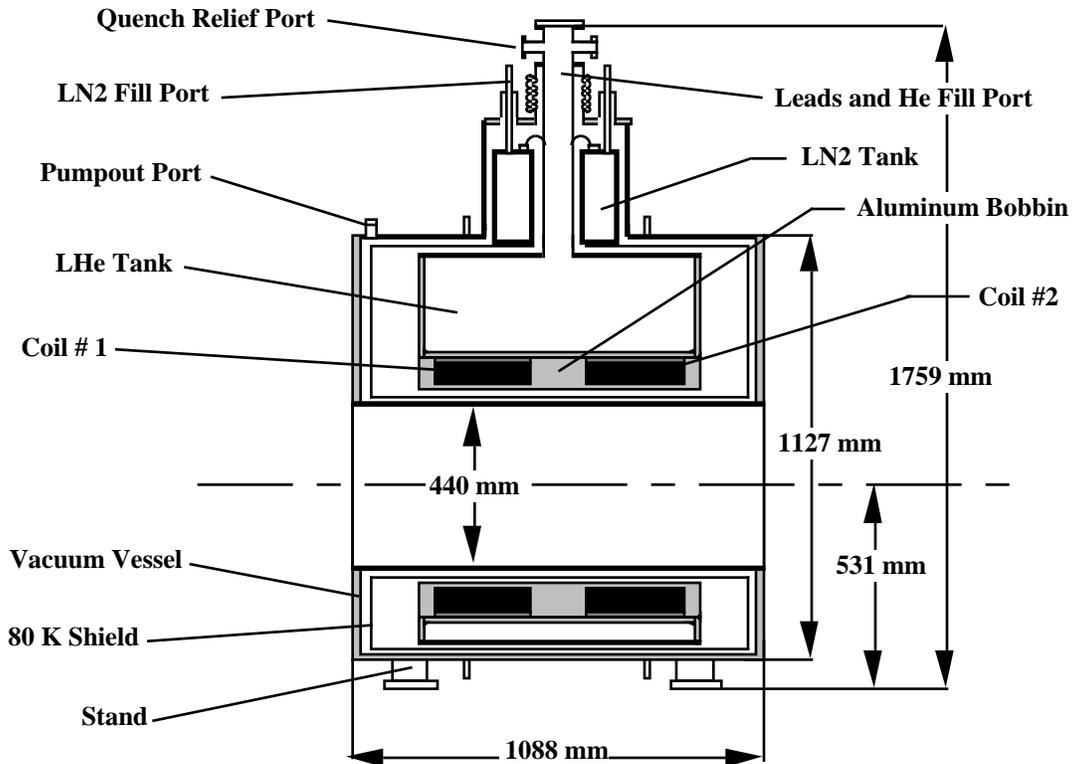


Figure 1. A Cross-section of the RF Test Solenoid and its Cryostat (Note, the magnet and cryostat are eccentric.)

TABLE I. RF TEST SOLENOID PARAMETERS

Parameter	Solenoid Hookup	Gradient Hookup
Design Current (A)	230	265
Induction on Axis at $Z = 0$ (T)	4.99	0.00
Maximum Induction at $R = 0$ (T)	5.00	3.48
Maximum Induction at $R = 20$ cm (T)	5.85	5.13
Maximum Induction in S/C Coil (T)	6.82	6.52
Design Field Gradient on Axis (T/m)	NA	24.0
Coil Current Density ($A\ mm^{-2}$)	128.4	147.8
S/C Matrix Current Density ($A\ mm^{-2}$)	146.0	168.2
Current Margin on Load Line	0.803	0.821
Magnet Self Inductance (H)	98.22	68.46
Stored Energy at Design Current (MJ)	2.60	2.40
EJ^2 Limit for the Magnet ($J\ A^2\ m^{-4}$)	5.54×10^{22}	6.78×10^{22}

Note: All values of field, current density, stored Energy and quench parameters are at the design current for that mode.

The magnet shown in Figure 1 has a horizontal (in the direction of the axis) warm bore of 440 mm. The 805 MHz RF cavity that is to be tested in the solenoid has an outside diameter of 410 mm. The center of the cryostat warm bore is below the center of the cylindrical helium tank and the stainless steel outer vacuum shell. This allows about 130 liters of helium to be in the helium vessel above the level of

the top of the superconducting coils. The magnet is powered using two pairs of 300 A gas-cooled current leads. The estimated boil-off from the helium vessel is 2.3 liters per hour. The bulk of the helium boil-off comes from the gas-cooled leads. When the magnet is powered, the helium boil-off is taken up through the leads.

The magnet is cooled down using liquid cryogenics. Liquid nitrogen is fed into the bottom of the vessel through a tube that carries the nitrogen from the top of the magnet to the bottom of the helium vessel. There is Teflon seal between the end of the transfer line into the vessel and a cup on the line between the top of the coil and the bottom of the helium vessel. Liquid nitrogen is removed from the helium vessel through the same transfer line that brings the liquid nitrogen into the helium vessel. Once all of the liquid nitrogen has been removed from the helium vessel, the cool-down is finished using liquid helium.

The liquid nitrogen vessel is located in the cryostat neck on top of the cryostat. The shields and the cold mass support intercepts are cooled by conduction from this vessel. When the magnet is fully cooled down, the liquid nitrogen boil off is 0.3 liters per hour. One LN2 tank lasts two days.

Since the magnet coils are continuously powered, there are room temperature quench protection diodes and resistors located in the power supply rack. The magnet is further protected by quench back from the aluminum coil bobbin. The magnet is powered using a 300 A, 10 V power supply.

III. QUENCH TESTING

The magnet tests started in September of 1999. The coil was tested in the solenoid mode (with the two coils hooked to the same polarity). The magnet quenched at 115 A roughly half of the magnet design current (230 A for 5 T operation) in this mode. It was clear that there was a training problem once the magnet was quenched a second time in the solenoid mode at a current of 130 A. A third quench at 137 A confirmed the training behavior seen during the first two quenches. A detailed quench history for the magnet is described in Reference 2. Figure 2 shows the quench current for various runs as the magnet was run in various modes.

When testing resumed in November and December 1999, it was decided that individual coils should be trained. The open symbols in Figure 2 show the quench results for coil #1 (open square) and coil #2 (open circle). Individual coils were quickly trained to a current of 265 A or above. The current reached for coil #1 in run 7 was 270 A. No quench resulted. Run 8 shows that coil #2 quenched at 266 A on its way up to 270 A. During charging, a creaking and popping of the magnet coils could be heard. When charging stopped, the popping stopped. When the current was lowered, there was no popping. When charging was started at a lower current popping was not heard until the current reached the previous high for that mode. The solid squares in Figure 2 are when the coil was charged in the solenoid mode; the solid triangles are when the coil was charged in the gradient mode.

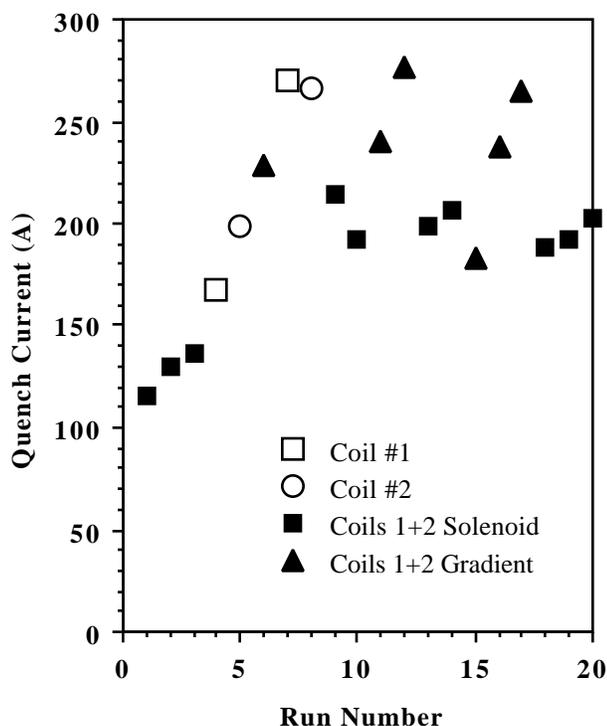


Figure 2. A Quench History for the RF Test Solenoid
This history shows the quench current for each magnet run.

Individual coils were trained to currents above 265 A (the design current in the gradient mode). The magnet was trained to design current in the gradient mode. Run 12 reached a current of 276 A without quenching. Run 17 also reached design current without quenching. During the 20 test runs for the magnet, the magnet did not reach the 5 T design current in the solenoid mode. In a number of runs the magnet reached fields on axis of 4 T or more. When the magnet was warmed up between runs, some retraining was needed for the magnet to return to its previous performance levels.

The most probable cause for training of the solenoid is stick slip behavior in the radial mica slip planes at the sides of the coils. In order for the magnet, to withstand the 3 MN force (300 metric tons of force) that is pushing the coils apart, the coil was encapsulated in aluminum. The differential contraction between the aluminum and the coil puts a force perpendicular to the slip planes of about 4.3 MN. As a result, there is stick slip within the mica slip planes. If the coils were not encapsulated, slip would occur at much lower current, but without a resulting magnet quench.

IV. MAGNETIC MEASUREMENTS

Figures 3, 4 and 5 show measurements of the magnetic field on axis for individual coils, the solenoid mode and the gradient mode as a function of the distance along the axis. In all of the measurements, $Z = 0$ is defined as the point between the two solenoid coils.

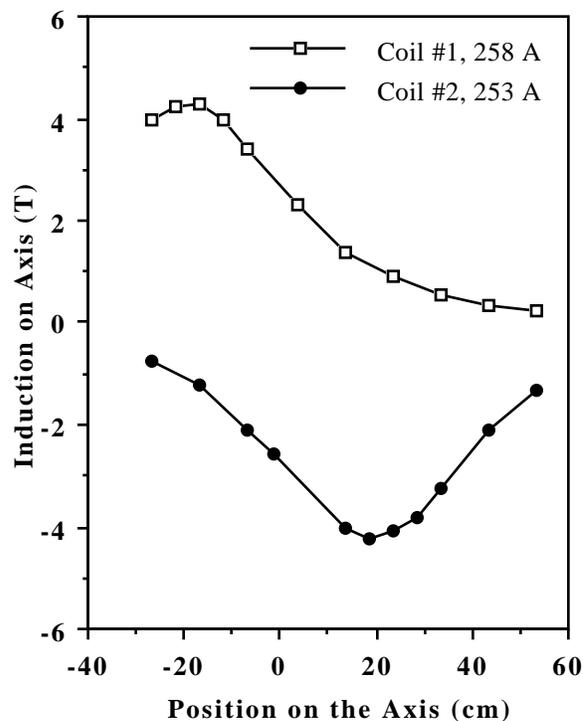


Figure 3. Magnetic Induction on Axis for Individual Coils as a Function of Distance along the Axis and the Coil Current

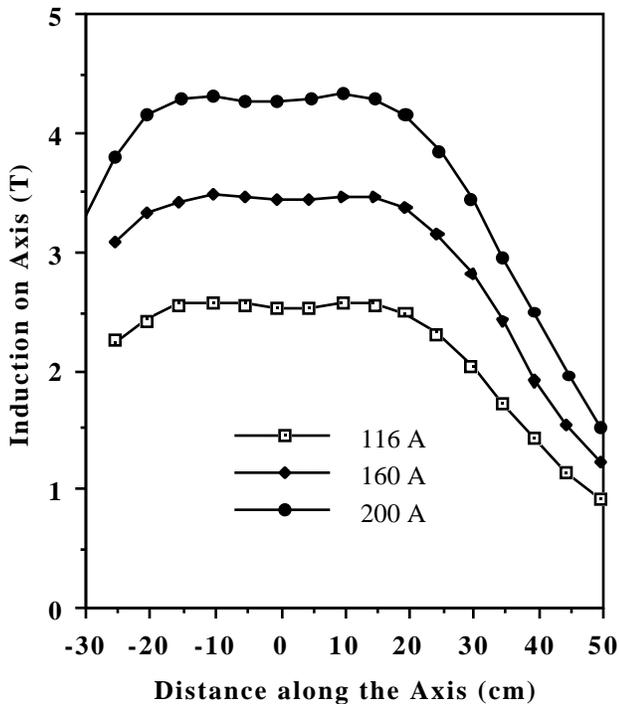


Fig. 4. Magnetic Induction on Axis when the Magnet is Operated in the Solenoid Mode (Coils at the Same Polarity) as a Function of Distance along the Axis and Magnet Current

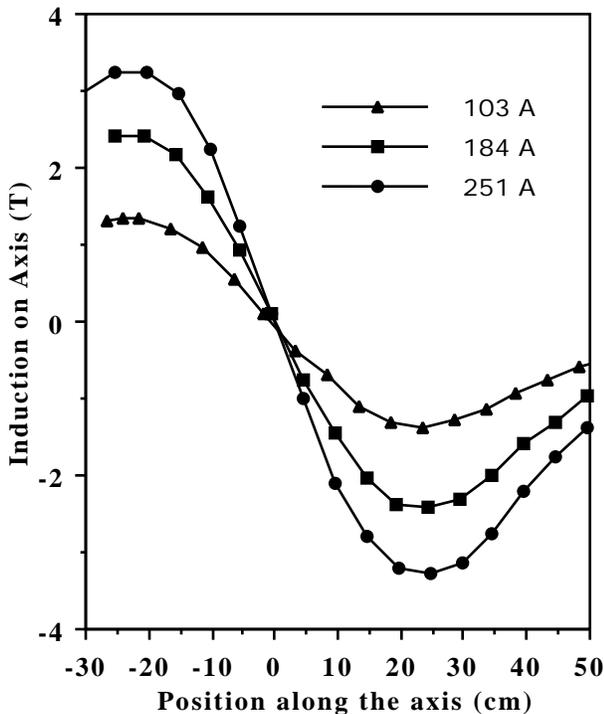


Fig. 5. Magnetic Induction on Axis when the Magnet is Operated in the Solenoid Mode (Coils at Opposite Polarity) as a Function of Distance along the Axis and Magnet Current

The magnetic measurements shown in Figure 3 were taken with each coil separately powered. Coil #2 was powered with a polarity that was opposite that of coil #1. The uniform field region of an individual coil is only about 100 mm or so.

The magnetic measurements of the magnet operating in the solenoid mode in Figure 4 show that the field is quite uniform over a distance of 400 to 450 mm. At 200 A, the induction on axis is about 4.3 T. A field of 4.3 T is more than adequate for testing the performance of a high gradient 805 MHz RF cavity.

The magnetic measurements at 251 A in Figure 5 shows that a gradient on axis of 23 T per meter was developed. The magnet was fully trained to its design gradient in this mode. Operation of the magnet at 200 A in the gradient mode is adequate to test the performance of the 805 MHz high gradient RF cavity.

V. CONCLUDING COMMENTS

The RF cavity test solenoid for the muon collider working group does train. In the solenoid mode, the magnet should produce an induction of nearly 4 T before the first training quench occurs. In the gradient mode the gradient on axis should reach 17 T per meter before training in that mode occurs. The magnet has demonstrated that it will operate at its full design current of 265 A in the gradient mode. Before the RF cavity is operated in the magnet, the individual coils should be trained to 265 A. As long as the magnet stays at 80 K or below, it does not appear to lose its training.

Two factors most probably contributed to magnet training. The constraint imposed by the coil encapsulation in aluminum appears to be the major cause of the training. This was necessary because the magnet was designed to operate in both the solenoid and the gradient mode. Future magnets of this type will not have the aluminum bobbin clamping the coil package. In the gradient mode, the forces between coils could be reduced by moving the coils further apart. Increasing the coil spacing to 250 mm would not decrease the on axis gradient by more than 10 percent, but the force pushing coils apart would go down by a factor of two.

REFERENCES

- [1] M. A. Green, J. Y. Chen and S. T. Wang, "The Design and Construction of a Gradient Solenoid for the High Powered RF Cavity Experiment for the Muon Collider," Institute of Physics Conference Series 167, p 1199, (2000)
- [2] Michael A. Green, "A Test Report for the MUCOOL RF Solenoid," Lawrence Berkeley Laboratory external report LBNL-45148, Feb. 2000