

## A Test Report for the MUCOOL RF Solenoid

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This report discusses the results of tests that were done on the MUCOOL RF solenoid between 1 September 1999 and 19 January 2000. This report includes the following tests and test observations: 1) The results of the cryostat proof pressure tests are presented. The proof pressure tests were made at room temperature on the cryostat helium vessel, the cryostat nitrogen vessel, and the cryostat insulating vacuum vessel. 2) a typical cool down from 290 K to 4.2 K using liquid cryogenics is presented. 3) The quench history of the solenoid is presented for tests in September 1999, November 1999, December 1999 and January 2000. The results of twenty magnet runs are documented. 4) Magnetic measurements of the magnet operating as a superconducting magnet are presented. Magnetic measurements made at 77 K at low current are also presented. The magnetic measurements include individual coil measurements as well as magnet measurements in the solenoid and gradient modes.

### Parameters for the RF Solenoid

When discussing the test of the RF solenoid, it is useful to know the basic physical and electrical parameters of the magnet. The physical parameters include; the coil dimensions, the outside cryostat dimensions, the cold mass at 4.2 K, and the overall mass of the magnet and its cryostat. A cross-section view of the RF Solenoid is shown in Figure 1 below. The physical and electrical parameters are given in Table 1 on the next page. The 4.2 K mass within the cryostat is 540 kg. The overall mass of the magnet is 1182 kg.

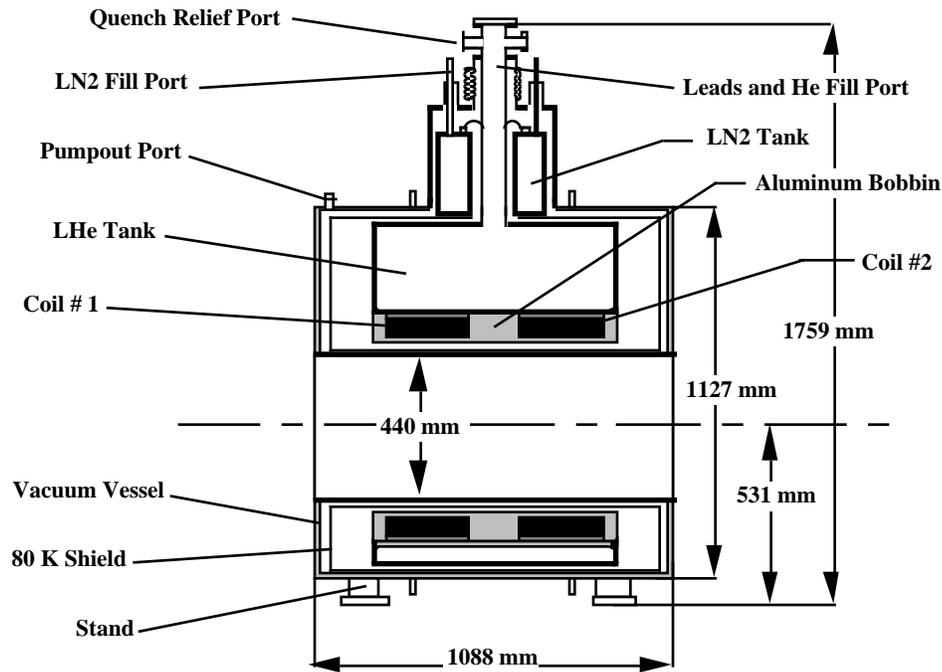


Figure 1. A Cross-section View of the RF Solenoid from the Side

Table 1. RF Test Solenoid Physical and Electrical Parameters

	Single Coil	Solenoid Mode	Gradient Mode
Physical Parameters			
Active Coil Package Length (mm)	250	640	640
Location of the Peak B Point on the Axis (mm)	±195	±105	±240
Electrical Parameters			
Magnet Design Current $I_d$ (A)	270	230	265
Probable Short Sample Quench Current (A)	not known	286	323
Design Margin along the Load Line at 4.2 K	not known	0.803	0.821
Induction on Axis at $I_d$ at R=0 and Z=0 (T)	~3.24	4.99	0.00
Maximum Induction on Axis at $I_d$ (T)	4.64	5.04	3.48
Maximum Induction at R=20 cm at $I_d$ (T)	not known	5.85	5.13
Maximum Induction in the Coil at $I_d$ (T)	not known	6.82	6.52
Maximum Gradient on Axis Z=0 at $I_d$ (T m <sup>-1</sup> )	-NA-	-NA-	24.0
Coil Average Current Density at $I_d$ (A mm <sup>-2</sup> )	150.55	128.24	147.76
S/C Matrix Current Density J at $I_d$ (A mm <sup>-2</sup> )	171.34	145.96	168.17
Magnet Self Inductance (H)	41.67	98.22	68.46
Magnet Stored Energy E at $I_d$ (MJ)	1.519	2.598	2.404
EJ Limit for the Magnet at $I_d$ (J A <sup>2</sup> m <sup>-4</sup> )	4.46x10 <sup>22</sup>	5.54x10 <sup>22</sup>	6.78x10 <sup>22</sup>

### Cryostat Pressure Tests

Room temperature proof pressure tests were made on the cryostat helium vessel, the cryostat nitrogen vessel and the cryostat vacuum vessel. All of these tests were done with dry nitrogen gas. The test pressures were in excess of 1.25 times the working pressure for these vessels. The next three pages of this report are the pressure test reports for the cryostat helium vessel, the cryostat nitrogen vessel, and the cryostat vacuum vessel.

The pressure test for the helium vessel was made on 1 September 1999. The nominal design working pressure for the helium vessel was originally set at 31.25 psig. A 25-psig-rupture disc will protect the helium vessel. In addition to the burst disc, there is a 10-psig circle seal relief valve. The helium vessel was tested with the cryostat vacuum shell evacuated. The minimum test pressure for the helium vessel was set at 42.73 psig (1.25 times working pressure). At 14:04 on 1 September 1999, the helium vessel was pressurized to 51 psig. The pressure in the vessel was held at 51 psig for 30 minutes.

The nitrogen vessel pressure test began at 14:37 on 1 September 1999. The nominal working pressure for the liquid nitrogen vessel is 15 psig when the cryostat vacuum vessel is evacuated. The nitrogen vessel is open to the atmosphere in two places. The nitrogen vessel was pressurized to 30 psig at 14:37 and it was held at 30 psig until 15:09.

The cryostat vacuum vessel is not a pressure vessel, but it is designed to handle a positive pressure of at least 15 psig. The pressure test on the magnet cryostat vacuum vessel occurred when the helium vessel cold mass was at 240 K. The cryostat vacuum vessel was pressurized to a pressure of 10 psig at 15:35 on 7 January 2000. At 15:40 the pressure in the cryostat vacuum vessel was increased to 12 psig. At 15:50, the vacuum vessel was depressurized to 0 psig and held at that pressure for about three days when the magnet temperature reached 280 K. The relief valve for the cryostat vacuum vessel is the standard 1 inch Cryofab relief and fill valve that relieves when the cryostat vacuum vessel at a pressure that is 1 to 2 psig above the pressure of the room air outside of the vessel.

## Cryostat Helium Vessel Pressure Test

Calculated Burst Pressure for the Vessel at 273 K = 1.3126 MPa (177.8 psig)  
The maximum Working Pressure for the Vessel at 4.2 K = 0.3235 MPa (32.25 psig)  
Margin of Safety to Maximum Allowable Pressure = 4.05  
Maximum Pressure for the Vessel Relief Device = 0.2736 MPa (25 psig)

Date of the Pressure Test 1 September 1999

Location of the Pressure Test Wang NMR Incorporated  
550 North Canyons Parkway  
Livermore CA 94550  
  
Tel: (925) 443-0212  
Fax: (925) 443-0215  
Email: wangnmr@ix.netcom.com

Pressure Test Medium Dry Nitrogen Gas

Minimum Test Pressure 0.3958 MPa (42.7 psig)

Actual Test Pressure 0.4469 MPa (51.0 psig)

Time the Pressure was Held 30 minutes

Test Performed by \_\_\_\_\_

Test Checked by \_\_\_\_\_

## Cryostat Nitrogen Vessel Pressure Test

Calculated Burst Pressure for the Vessel at 273 K = 0.5876 MPa (70.6 psig)  
The maximum Working Pressure for the Vessel at 4.2 K = 0.2026 MPa (14.7 psig)  
Margin of Safety to Maximum Allowable Pressure = 2.90  
Maximum Pressure for the Vessel Relief Device = 0.1013 MPa (0 psig)

Date of the Pressure Test 1 September 1999

Location of the Pressure Test Wang NMR Incorporated  
550 North Canyons Parkway  
Livermore CA 94550  
  
Tel: (925) 443-0212  
Fax: (925) 443-0215  
Email: wangnmr@ix.netcom.com

Pressure Test Medium Dry Nitrogen Gas

Minimum Test Pressure 0.2532 MPa (22.1 psig)

Actual Test Pressure 0.3080 MPa (30 psig)

Time the Pressure was Held 32 minutes

Test Performed by \_\_\_\_\_

Test Checked by \_\_\_\_\_

## Cryostat Vacuum Vessel Pressure Test

Calculated Burst Pressure for the Vessel at 273 K = 0.3739 MPa (40.4 psig)  
The maximum Working Pressure for the Vessel at 4.2 K = 0.1358 MPa (5 psig)  
Margin of Safety to Maximum Allowable Pressure = 2.79  
Maximum Pressure for the Vessel Relief Device = 0.1151 MPa (2 psig)

Date of the Pressure Test 1 September 1999

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Livermore CA 94550  
  
Tel: (925) 443-0212  
Fax: (925) 443-0215  
Email: wangnmr@ix.netcom.com

Pressure Test Medium Dry Nitrogen Gas

Minimum Test Pressure 0.1699 MPa (9.9 psig)

Actual Test Pressure 0.1840 MPa (12.0 psig)

Time the Pressure was Held 10 minutes

Test Performed by \_\_\_\_\_

Test Checked by \_\_\_\_\_

## A Typical Cool Down of the RF Solenoid to 4.2 K

A RF solenoid typical cool down takes between 10 and 14 hours depending on the kind of nitrogen dewar that is used to cool the magnet and the amount of liquid nitrogen that is left in the cryostat helium tank after the cold mass has been cooled down to 77 K. Figure 2 below presents a typical cool down curve for the RF solenoid. If one cools the magnet from a single large tank of liquid nitrogen, the cool down time from 300 K to 77 K can be reduced from 9 hours to about 7 hours. The cool down rate is dependent on the rate of flow of liquid nitrogen in the tank. The cool down is more efficient if the liquid nitrogen is allowed to evaporate and at least some of its sensible heat is used to cool the cold mass. In the cool down shown in Figure 2, about 500 liters of liquid nitrogen was used.

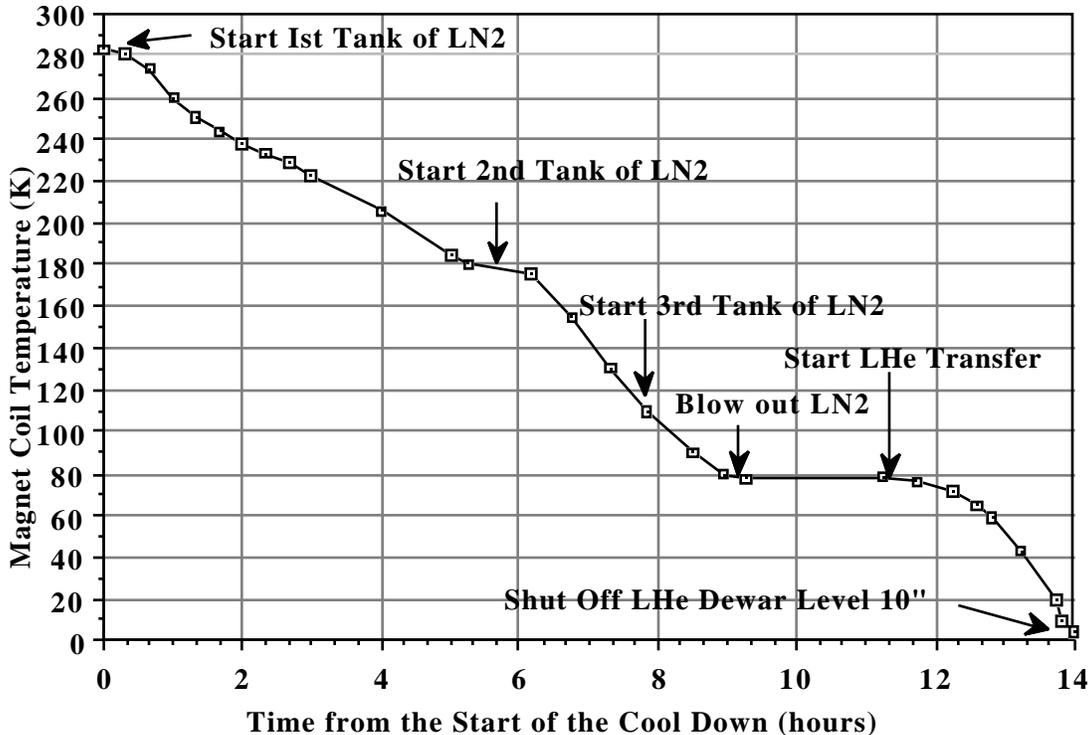


Figure 2. A Typical Cool-Down Curve of Temperature versus Time for the RF Solenoid

Before the liquid helium portion of the cool down could proceed, any liquid nitrogen left in the helium vessel must be removed. The process of removing the liquid nitrogen from the vessel takes about two hours. After liquid nitrogen ceases flowing from the vessel, dry warm helium gas should be put into the helium vessel purging the last of the nitrogen out of the vessel. Depending on the rate of transfer of helium from the 500 liter dewar, the cool down from 80 K to 4.2 K can take from two to four hours. A slow transfer of liquid helium results in less helium being used to cool the cold mass. Once the magnet becomes superconducting, helium will collect in the helium vessel rapidly. One can start to charge the magnet as soon as the liquid level reaches 12 inches. The helium transfer can continue while the magnet is being charged.

Once the helium vessel has been cooled to 77 K, one can fill the 17.5-liter nitrogen shield vessel. The first charge of liquid nitrogen will last about an hour. The second charge will last longer. Eventually, when the helium vessel is at 4.2 K, the liquid nitrogen tank will go as long as 48 hours between charges. If this vessel is put onto automatic fill, one does not have to worry about keeping this tank filled.

## RF Solenoid Cool Down and Quench History

The RF solenoid was first cooled down for the tests on 15 September 1999. The cryostat dewar had been pumped down for nearly three weeks. Helium vessel and nitrogen vessel proof pressure tests were done on 1 September 1999. The magnet was cooled from room temperature to liquid nitrogen temperature starting on the afternoon of 1 September 1999. The temperature at the start of the cool down was about 71 F (295 K). The resistance of the number 1 coil was 250.1 ohms, the resistance of the number two coil was 250.3 ohms. The variation of the resistance is probably due to a difference in the average cross-sectional area of the copper in the superconductor. A variation of one part in a thousand is within the expected range. The coil was kept cold using liquid nitrogen for several days. The nitrogen boil off was not measured, but the expected calculated value is expected to be about 0.3 to 0.4 liters per hour (without liquid nitrogen in the shield tank). Separate measurement for the liquid nitrogen tank shows a boil off rate of about 0.35 liters per hour when the superinsulation and shields are cooled down and there is liquid helium in the helium tank (the cryostat vacuum is very good, because of cryopumping).

Figures 3a and 3b show the resistance of the solenoid coils as a function of their temperature. The residual resistance ratio (RRR) of the copper matrix material in both solenoids is about 65. This RRR is typical for the 4 to 1 copper to superconductor ratio conductor used in the RF solenoid. This conductor has some drawing after its last heat treatment, so the copper in the conductor is in the half hard state. Measurement of the coil resistance is a good way to predict the temperature of the coil. The silicon diode thermometer in the cryostat only measures the temperature of the tip (the end of the tube at the bottom of the helium tank) of the feed tube that feeds liquid cryogen from the top of the magnet to the bottom of the cryostat helium vessel. The coil temperatures quoted in this section of the report are based on coil resistance measurements.

It is interesting to note that the temperature of the superconducting coils lags the temperature of the magnet bobbin during a magnet cool down. The magnet coils may be well above nitrogen temperature and when there is liquid nitrogen in the helium tank. The coils are separated from the bobbin by about 1.6 mm of fiberglass epoxy. The thermal conduction along the winding is pretty good, but the thermal conduction across the coil layers will be poor. The only reliable measure of the coil temperature is its resistance.

On 9 September 1999, the measured resistance of coil 1 was 32.8 ohms. The resistance of coil 2 was 33.1 ohms. The digital ohmmeter did not quite zero on the scale used to measure the resistance. (A dead short is measured as 0.3 or 0.4 ohms.) The measured coil resistances are consistent with the magnet coils being between 77.3 and 78 K. On 9 September 1999, magnetic measurements were made on axis with a current of 0.086 A in the coil while they were at liquid nitrogen temperature. Magnetic measurements were made with the coils hooked in the solenoid mode (the two coils are hooked in the same polarity) and the gradient mode (with the coils hooked in opposite polarity). The measurements were made using a hall probe gauss meter. At best the measurement were good to about  $\pm 1$  percent. The low field measurements showed that the coils behaved as they were expected to behave in the two modes.

The coils were allowed to warm up after the low field measurements. The heat leak into the dewar during a warm up is typically between 15 and 40 watts depending on how good the cryostat vacuum is. If one breaks the cryostat vacuum with dry nitrogen gas the rate of warm up can be increased to as much as 400 watts, depending on the magnet temperature.

On September 15<sup>th</sup> the coils re-cooled to liquid nitrogen temperature. The coil resistance was not recorded at the start of this cool down. On the morning of 16 September, the last of the liquid nitrogen in the helium vessel was removed. At 9:35 helium cooling started. The magnet went superconducting at 13:55 on 16 September 1999.

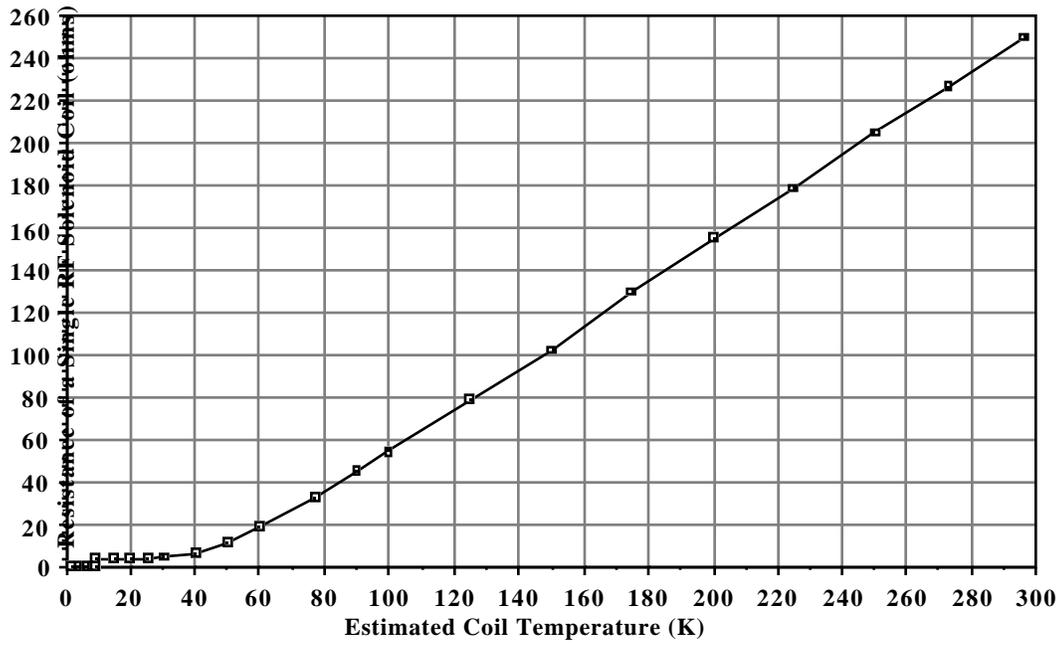


Figure 3a. Magnet Coil Resistance as a Function of Temperature to 300 K

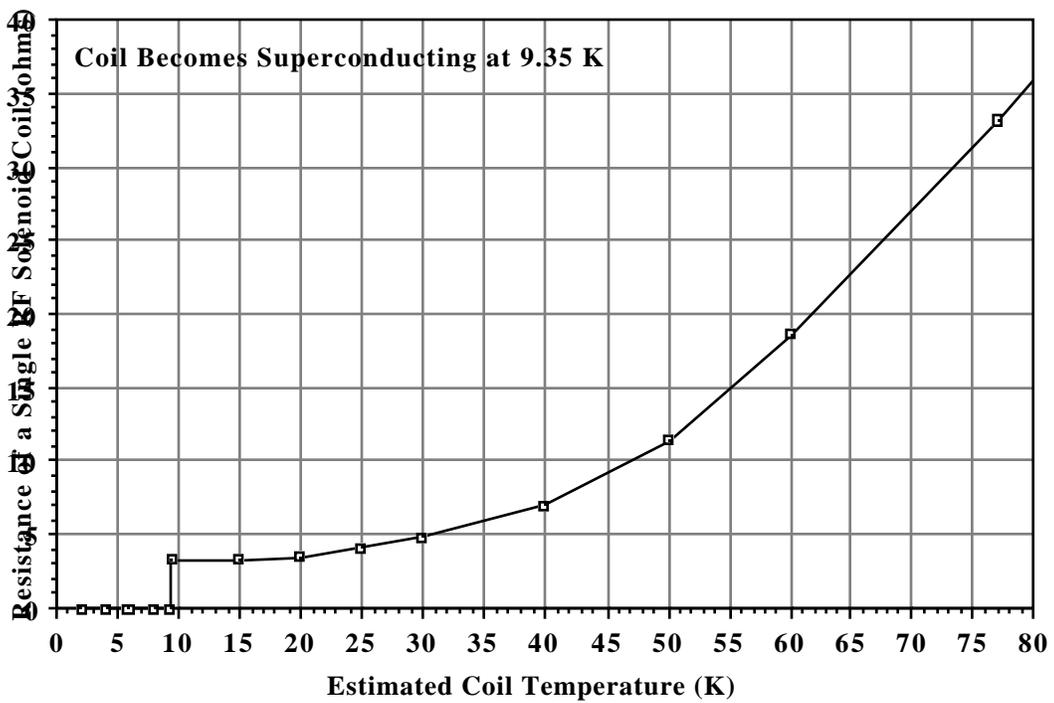


Figure 3b. Magnet Coil Resistance as a Function of Temperature to 70 K

- Run 1 Coils 1 and 2 were hooked in the solenoid mode (with the coil polarities in the same direction) and they were charged until the magnet quenched. Because of a previous LBNL solenoid that was built using the same techniques, it was hoped that the magnet would go up to design current in this operating mode. The magnet had been re-cooled to liquid nitrogen temperature on 15 September 1999. The cool down was finished between 9:36 and 14:00 on 16 September 1999. The magnet charge started at 15:35 on 16 September 1999. This was a virgin magnet in that it had been wound at room temperature and it had never been quenched. The first magnet quench occurred at 16:40. The magnet quench current was 115 A (at 50 percent of design current in this mode). The stored energy released in the helium during the quench ( $E_q$ ) was 0.65 MJ and The highest magnetic induction at the on axis during the quench ( $B_q$ ) was 2.52 T. No magnetic field measurements were made during this run. When the run ended, the magnet cryostat was refilled with helium and allowed to sit over night.
- Run 2 Coils 1 and 2 were kept hooked in the solenoid mode. The charge started at 9:15 on 17 September 1999. The average voltage across the coil was as about 0.78 V (the voltage at the power supply was about 1.9 V) until magnet current reached 61 A. The charge average charge voltage across the magnet was increased to 1.5 V (about 2.9 V across the power supply). The magnet quenched a 14:45 on 17 September 1999. The magnet quench current for the second quench was 130 A (57 % of design current in this mode). The quench stored energy  $E_q = 0.83$  MJ and  $B_q = 2.85$  T. No magnetic field measurements along the axis were made during this run. Magnetic field measurements were made at one point during the run, but the location of the probe point was not recorded in the logbook. After the quench, the magnet dewar was refilled with helium for a third try at training the magnet in the solenoid mode. Re-cooling the magnet took about 30 minutes.
- Run 3 Coils 1 and 2 were hooked in the solenoid mode. The third run charge started at 15:13 on 17 September 1999. During most of the run the charge voltage across the coil was about 1.65 V (about 3.3 V was delivered by the power supply). The magnet sat at a constant 20 A for about 45 minutes starting at 16:00. The charge resumed at 16:47 and continued until 19:40 when the magnet quenched at a current of 137 A (60 % of design current). The quench stored energy  $E_q = 0.92$  MJ and  $B_q = 3.02$  T. No magnetic field measurements along the axis were made, but single point magnetic measurements were made at the same point on axis as in the previous run.

At the end of run three, it was clear that the RF solenoid has a training problem when it is hooked up in the solenoid mode. A comprehensive test program was devised. As soon as the funding for FY-2000 became clear, a contract to Wang NMR was let to do further testing of the magnet. It was decided that LBNL people would be actively involved in the testing process. During this period of time the magnet sat in the Wang NMR shop waiting until testing could resume. The Magnet sat without liquid cryogenics in either tank between 18 September 1999 and 28 November 1999. We do not know what the magnet temperature was when the magnet was re-cooled on 28 November 1999. It is probable that the magnet had warmed to about 270 K during the 70 days between Runs 3 and 4.

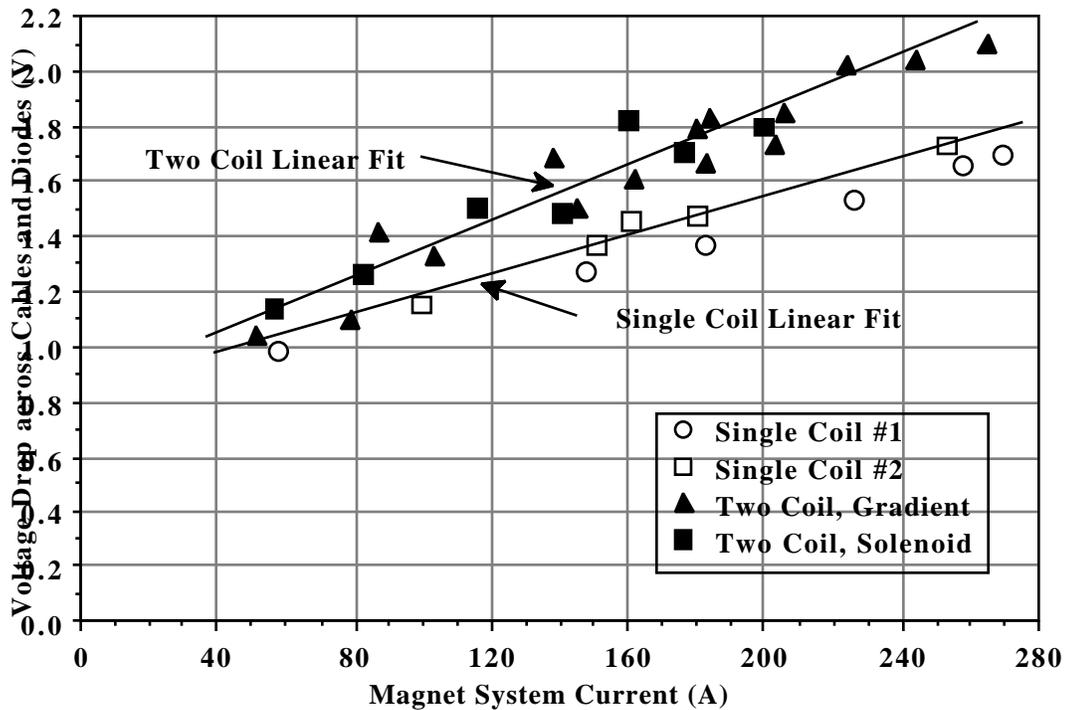


Figure 4. Power Supply and Cable Voltage Drop and a Function of Current

- Run 4 The magnet cool down started at 19:40 on November 28<sup>th</sup>. After 240 liters of liquid nitrogen was put in the dewar, the magnet temperature was about 190 K. It took about 6.5 hours to cool the magnet from 190 K to 80 K using liquid nitrogen. By 17:00 on the 29<sup>th</sup>, the magnet helium tank had liquid nitrogen in it. On the morning of the 30 November 1999, the remaining liquid nitrogen was force out of the helium tank. This process took about 1.5 hours. The helium transfer started at 11:00 on November 30<sup>th</sup>. The magnet became superconducting at 17:05. Coil #1 was hooked up to the power supply alone. The coil charge started at 17:50; the coil current reached 100 A at 18:06. Popping sounds started coming from the cryostat when the coil current reached 50 A. During the charge up to 100 A. The average voltage across Coil #1 was 4.63 V. (the power supply voltage was about 6 V. See Figure 4 above for the voltage drop across the power supply regulators and the coil cables as a function of coil current.) Magnetic field measurements were made at 100 A. The Coil #1 charge resumed at 18:18. Coil #1 quenched at 18:55 at a current of 167 A. The stored energy put into the helium by the quench  $E_q = 0.58$  MJ and  $B_q = 2.87$  T. The resistance of the coil was not measured immediately after the quench, but we estimate that the coil temperature never went above 60 K. The magnet was re-cooled to about 25 K when we ran out of liquid helium.
- Run 5 The cool down was resumed at 9:00 on 1 December 1999. Both coils became superconducting at 10:21. The power supply was hooked up so that only Coil #2 would be charged. Charging of Coil #2 at a power supply voltage of 5 V commenced at 12:00. (The voltage across the coil was about 3.5 V.) No popping sounds were heard in Coil #2 during the charge to 100 A. Magnetic field measurements were made at 100 A between 12:26 and 12:49. Charging

resumed at 12:49 at a power supply voltage of 4 V. The first popping sound was heard at 106 A. Popping continued as the coil was charged. When the charge was stopped and the current was held constant, the popping sound stopped. When the current was reduced, no popping sounds could be heard. Coil #2 quenched at 13:49 on 1 December 1999 at a current of 199 A.  $E_q = 0.83$  MJ and  $B_q = 3.42$  T. . The resistance of the coil was not measured immediately after the quench, but we estimate that the coil temperature never went above 65 K.

- Run 6 The magnet was re-cooled with liquid helium. Both magnet coils became superconducting at 14:14 on 1 December 1999. Coils 1 and 2 were hooked in the gradient mode and were charged at a power supply voltage of 5 V. The charge started at 16:16. Field measurements were made at 51 A, 103 A and 162 A. There was no popping until the coil reached 141 A. Popping ceased during the magnetic measurements at 162 A. Popping resumed but it was not very frequent even up to the point where the magnet quenched. The magnet quenched at 19:27. The quench current was 228 A (86 % of design current in the gradient mode). The quench energy  $E_q = 1.78$  MJ and the magnet gradient on axis  $G_q = 20.6$  T per m. From coil resistance measurement made just after the quench, we felt that Coil #1 probably caused the quench. Both coils were superconducting by 21:10.
- Run 7 The second series of runs was resumed on the morning of 2 December 1999. The liquid nitrogen usage for a 24 hour period on December 1<sup>st</sup> and 2<sup>nd</sup> . was about 4.1 inches or about 0.34 liters per hour. The heat intercepted by the shield and cold mass intercepts was about 15 W. At 9:15, the helium cryostat temperature was about 20 K. Helium flow into the dewar was started at 9:15. By 9:30, both coils were superconducting. The power supply was hooked up so that only Coil #1 was to be charged. At 10:35 there was 25.5 inches of helium in the tank; the coil charge commenced. Coil #1 was charged to 270 A with no quench. Magnetic field measurements were made at 58 A, 148 A, 226 A and 258 A on the way up. There was some popping starting at 183 A. The rate of popping increased at higher currents. During the field measurement at 258 A, there was not popping sound coming from the magnet cryostat. The magnet stored energy ( $E_o$ ) with 270 A in Coil #1 only was 1.52 MJ and The peak induction on the solenoid axis ( $B_o$ ) = 4.64 T. The magnet was discharged using the leads and the power supply diode as a resistor. The discharge started at 12:42. The current reached zero at 14:29 (107 minutes later).
- Run 8 The power cables were hooked up so that Coil #2 could be charged alone. The charge started at 14:39. The power supply voltage was 5 V up 198 A (an average voltage of 3.8 V across the coil). From 198 A to 253 A, the power supply charge voltage was reduced to 4V (about 2.4 V was across the coil). Magnetic field measurements were made at 253 A. There was very little popping below 200 A. The rate of popping increased above 200 A. The charge of Coil #2 at 253 A resumed at 15:47. The magnet quench occurred at 15:51 at a current in the coil of 266 A. The quench energy ( $E_q$ ) was 1.47 MJ and  $B_q = 4.57$  T. At 15:34, the Coil #2 temperature was 75 K; the temperature of Coil #1 was about 25 K.
- Run 9 By 16:12 on 2 December 1999, the magnet was superconducting. Coils 1 and 2 were hooked in the solenoid mode and the charge commenced at 16:28. Limited magnetic field measurements were made at 152 A. At 18:27 the

magnet quenched in the solenoid mode. The quench current was 214 A (93 % of design current). The quench  $E_q = 2.25$  MJ and  $B_q = 4.65$  T. From resistance measurements we felt that Coil #1 probably caused the quench. The temperature of the magnet was probably over 70 K after the quench was over. We ran out of liquid helium.

At 15:30 on 6 December 1999, the magnet had warmed up to 83 K. The Magnet sat without liquid cryogenics in either tank between 2 December 1999 and 21 December 1999. From 6 December to 15 December, the magnet warmed to about 170 K. Re-cooling of the magnet started on 21 December 1999. The temperature of the magnet on the 21<sup>st</sup> was not recorded at the start of the cool down. The magnet reached 78 K at 17:35.

Run 10 Liquid nitrogen was blown from the helium tank from 9:00 to 10:40 on 22 December 1999. Helium flow was started at 11:05. The magnet became superconducting at 14:01. Coils 1 and 2 were hooked in the solenoid mode. The charge was started at 14:49 at 5 V from the power supply. Field measurements were made at 57 A, 116 A, and 160 A, in this mode. The magnet started popping at about 70 A. The popping was moderate until current reached 167 A when the rate of popping increased greatly. The magnet quenched at 17:04 at a current of 192 A (at 83% of design current). The quench energy  $E_q = 1.81$  MJ and  $B_q = 4.17$  T. Coil #1 probably caused the quench. The measured temperature in Coil #1 just after the quench was 65 K. The measured temperature in Coil # 2 was 62 K, indicating that quench back is an important part of the magnet quench protection process.

Run 11 Both coils became superconducting at 17:30. We continued to fill with helium, but the tank ran dry. The liquid level gauge in the dewar fluctuated between 6.7 and 15.4 inches. We decided to charge the magnet in the gradient mode with a low helium level. As the magnet began to charge the level gauge settled down at 6.4 inches of helium, which barely touches the magnet coil. The charge started at 17:51. Magnetic field measurements were made at 87 A, 138 A 184 A and 224 A. By 19:00 the liquid level had dropped to 5.6 inches; the magnet current was 151 A. We continued to charge the magnet with very little liquid in the cryostat. By 19:45, the liquid helium level was 3.3 inches and the current was 219 A. Virtually no popping noises were heard until 19:57 when the current reached 227 A. Above that level there was a few pops. The magnet quenched 20:05 at a current of 240 A (91 % of design current). The quench energy ( $E_q$ ) was 1.97 MJ and  $G_q = 21.7$  T per m. The quench probably started in Coil #2. It is not clear if the magnet quenched because of coil motion or because the liquid helium level was too low. Just before the quench, the helium level was 2.6 inches. No liquid helium touched the coil. Run 11 taught us that the RF solenoid can operate with very little liquid helium in the dewar. Coil # 2 reached 68 K, and Coil #1 reached 65 K during this quench.

Run 12 Liquid helium cooling resumed at 9:00 on 23 December 1999. The coils cooled from 54 K to 10 K in 73 minutes. The coil became superconducting at 10:13. Magnet charging in the gradient mode commenced at 10:39. There was no popping of the coil. Magnetic field measurements were made on axis at 244 A and 265 A. The magnet was charged in the gradient mode to 276 A (104 % of design current). The stored energy  $E_o = 2.61$  MJ and the gradient on axis  $G_o = 24.9$  T per m. A field distortion due to iron was noted at the coil 1 end of the magnet. This was also the first time that the non-linearity of

the field measurement probe was seen. The magnet discharge started at 13:12. It took 164 minutes to discharge the magnet from 276 A.

Run 13 Coils 1 and 2 were hooked in the solenoid mode and the charge started at 16:00 on December 23<sup>rd</sup>. Magnetic field measurements were made in the solenoid mode at 188 A. Popping sounds from the magnet started at about 155 A. The popping sounds are an indication of training behavior. The popping sounds are probably sudden coil movements due to stick slip behavior in the coil package. As in previous runs, the popping stopped during the magnetic field measurements made when the current was constant at 188 A. The magnet quenched at 17:22 at a current of 199 A (at 87% of design current). The quench energy  $E_q = 1.94$  MJ and  $B_q = 4.35$  T. Coil # 1 probably caused the quench. Just after the quench, the temperature of Coil #1 was 62 K. The temperature of Coil #2 was 60 K.

Run 14 By 17:55, there was liquid helium in the cryostat. The magnet was became superconducting about 18:05. Coils 1 and 2 were hooked in the solenoid mode. The coil charge was started at 18:19 with 17 inches of helium in the dewar. The coil was charged at a voltage at about 4 volts at the power supply. (The average voltage across the coil was about 2.7 V) No magnetic measurements were made during this run. There is no comments about coil popping in the log book during this run, but popping due to stick slip could probably was heard. At 20:24 the magnet quenched at 207 A (at 90% of design current in this mode). The quench energy  $E_q = 2.10$  MJ and highest field on axis  $B_q = 4.53$  T. The quench originated in Coil #1. Shortly after the quench, the temperature in Coil #1 was 65 K. The temperature in Coil #2 was 61 K. The helium supply was exhausted so the test was terminated.

On 27 December 1999, the magnet temperature was 90 K. By 5 January 2000, the magnet temperature had increased to 175 K. At 11:20 on 5 January 2000, the vacuum was broken using dry nitrogen gas. The pressure in the vacuum space was not measured. On 7 January 2000, the magnet temperature had increased to 240 K. At 15:15 on 7 January 2000, the cryostat vacuum space was pressurized to 13 psig to certify the cryostat vacuum vessel. The pressure in the dewar vacuum vessel was bled down to 0 psig (1.0 atm). By 10 January 2000, the magnet had warmed to about 283 K. The magnet cryostat vacuum was put on the vacuum pump on 10 January 2000.

Cool down of the magnet using liquid nitrogen started at 9:40 on 11 January 2000. This is the first time that the silicon diode thermometer at the bottom of the magnet cryostat was used during a cool down. We quickly realized that the diode measured the temperature at the end of the fill tube connected to the cryogen cup at the top of the magnet. The diode does not measure bobbin temperature. It can be used to tell one whether liquid nitrogen or liquid helium is flowing into the bottom of the magnet cryostat. Measurement of the magnet coil resistance is the best way to determine the magnet temperature. The first 240 liters of liquid nitrogen cooled the magnet down to 180 K at 17:20 a second tank of nitrogen was started. By 19:10 the magnet temperature reached 130 K. By 19:48 the magnet temperature had reached 108 K. At this point it appeared that the second nitrogen tank was empty. Whoops we only bought two tanks of liquid nitrogen. We had to order more liquid nitrogen.

At 9:30 on 12 January 2000, the magnet temperature was at 109 K. By 14:25 on the 14<sup>th</sup> the magnet temperature has risen to 160 K. The cool down resumed at 14:30 with a new supply of liquid nitrogen. By 15:50, the magnet temperature had dropped to 141 K. By 17:15 the magnet temperature was 90 K. A magnet temperature of 79 K was reached by 18:00. Liquid nitrogen was put into the tank and the tank was held at 78 K until the 17<sup>th</sup> of January.

- Run 15 Liquid nitrogen removal from the helium tank started at 9:45 on 17 January 2000. The last of the liquid nitrogen was cleared from the tank at 11:19. Helium flow into the helium tank started at 11:57. The coils became superconducting at 14:40. The helium tank was filled to 22 inches at 15:16. Coils 1 and 2 were hooked in the gradient mode and the charge was started at 15:17. Popping of the coil started at currents as low as 50 A. Field measurements were made at 79 A. Popping continued as the magnet went to higher current. The magnet quenched in the gradient mode at 16:22. The quench current 183 A (69% of design current) after the magnet was warmed to 283 K. The quench energy  $E_q = 1.15$  MJ and  $G_q = 16.5$  T per m. The quench appeared to originate in Coil #1. Just after the quench, Coil #1 was at 55 K, and Coil #2 was at 52 K.
- Run 16 The cool down of the coil started just after the last quench. The coils became superconducting before 17:00 on 17 January 2000. Coils 1 and 2 were hooked in the gradient mode. The helium level reached 12.4 inches at 17:03 and the coil charge was started at 17:05. Field measurements were made at 202 A. There was almost no popping at currents lower than 202 A. Some popping sounds were noted above 202 A. The magnet quenched at 18:43 at a current of 238 A (90 % of design current). The quench energy  $E_q$  was 1.94 MJ and  $G_q = 21.5$  T per m. Coil resistance measurement made after the quench suggest the quench probably started in Coil #2. At 18:44, the temperature of Coil #1 was 63 K while the temperature of Coil #2 was about 68 K. The magnet was cooled back down to 42 K when the 500-liter helium dewar was empty.
- Run 17 The cool down resumed at 9:19 on 18 January 2000 using a new 500 liter dewar of helium. The magnet became superconducting at 9:56 on the 18<sup>th</sup>. Coils 1 and 2 were hooked in the gradient mode. Charging began at 10:16 when the liquid helium level reached 13 inches. The magnet and charged to 265 A (100 % of design current) without quenching.  $E_o = 2.20$  MJ and  $G_o = 24.0$  T per m. There was no popping of the coil during the charge. Magnetic field measurements were made at 251 A and 265 A. The coil discharge using the power supply diode and the cables as a resistor started at 12:22. From 265 A to 216 A, the average discharge voltage was 2.66 V. From 216 A to 91 A the average discharge voltage was reduce to 2.16 V. From 91 to 20 A the average discharge voltage was about 1.45 V. At low currents, the discharge is governed by the power supply diode. From 20 A to zero the average discharge voltage was about 1.2 V. The magnet was completely discharged at 15:04. (A discharge from 265 A take 162 min.)
- Run 18 At the start of run 18, the helium level in the tank was 18.1 inches. Coils 1 and 2 were hooked in the solenoid mode. The magnet charge was started at 15:10 on 18 January 2000. The field was monitored at a high field point on axis at -12 cm. Field measurements on axis were made at 82 A, and 141 A. There was no popping in the coil below 138 A. There was moderate popping above 138 A. The magnet quenched following a loud pop at 16:41 at a current of 188 A ( at 82% of design current for this mode). The quench energy was 1.74 MJ and  $B_q = 4.09$  T. Coil #1 probably caused the quench. At 16:42 the average temperature of Coil #1 was 68 K. The average temperature of Coil #2 was 62 K.

- Run 19 The magnet was cooled back down from the run 18 quench. The coils became superconducting at 17:33 on 18 January 2000. Coils 1 and 2 were hooked in the solenoid mode. Charging of the magnet started 17:45 at a power supply voltage of 6 volts. The average voltage across the magnet was 4.79 V between zero current and 161 A. The voltage delivered by the power supply was reduced to 5.5 V when the current reached 161. There was no popping in the coil until the current reached about 170 A. At 173 A, the charge voltage from the power supply was reduced to 5.0 V. The field was measured at on point (-12 cm) but no field measurements were made at various points along the magnet axis. Above 170 A, coil pops could be heard until the magnet quenched. The magnet quenched at 18:56 at a current of 192 A ( 83% of design current in this mode). The quench energy  $E_q = 1.81$  MJ and  $B_q = 4.17$  T. Coil #1 probably caused the quench.
- Run 20 Because we made an effort to keep the helium level low in the cryostat while quenching the coil, we were able to cool the magnet down for a third quench with 500 liters of helium. The coils became superconducting between 19:50 and 19:55 on 18 January 2000. Coils 1 and 2 were still hooked in the solenoid mode. The magnet charge started at 19:58. The magnet was charged with a power supply voltage of 6 V up to 153 A. From zero to 100 A the average charge voltage across the coil was 4.96 V. From 97 to 153 A, the average voltage across the coil was 4.58 volts. Field measurement were made at -12 cm as the magnet charged. Field measurements along the axis of the magnet were made at 200 A. The non-linearity of the hall probe was quite evident at an induction above about 3.5 T. There was no coil popping (a manifestation of rapid coil motion) below 170 A. Moderate popping started at about 170 A. There were no coil pops when the field map was made at 200 A. The magnet quenched at 21 :29 at a current of 203 A ( 88% of design current). The quench energy  $E_q = 2.02$  MJ and  $B_q = 4.41$  T. Coil #1 probably caused the quench. About 20 seconds after the quench, the temperature of Coil #1 was about 69 K. The temperature of Coil #2 was about 65 K. At 21:47 the coils had cooled to about 45 K, when we ran out of liquid helium.

The resistance of both coils was measured during the cool down of the magnet. The cryogen levels were monitored during the test. From the experience gained during run 11, it is clear that the magnet can be safely operated even when the helium level is very low in the cryostat. Coil resistance was measured just after many of the quenches. One could determine which coil caused the quench from the resistance measurements. From coil resistance measurement, it was clear that quench back plays a role in the quench protection of the magnet. A quench in one coil drives the other coil normal through quench back. The passive diode and resistor quench protection system in the power supply rack performed as designed.

Figures 5 and 6 show the current and stored energy training history of the RF solenoid. One can see that the magnet requires some retraining after it has been warmed to room temperature. The magnet has been trained to its design current in the gradient mode. Further training is required for the magnet to reach its design current in the solenoid mode. In the solenoid mode, movement of Coil #1 appears to be causing the training above 80 percent of design current.

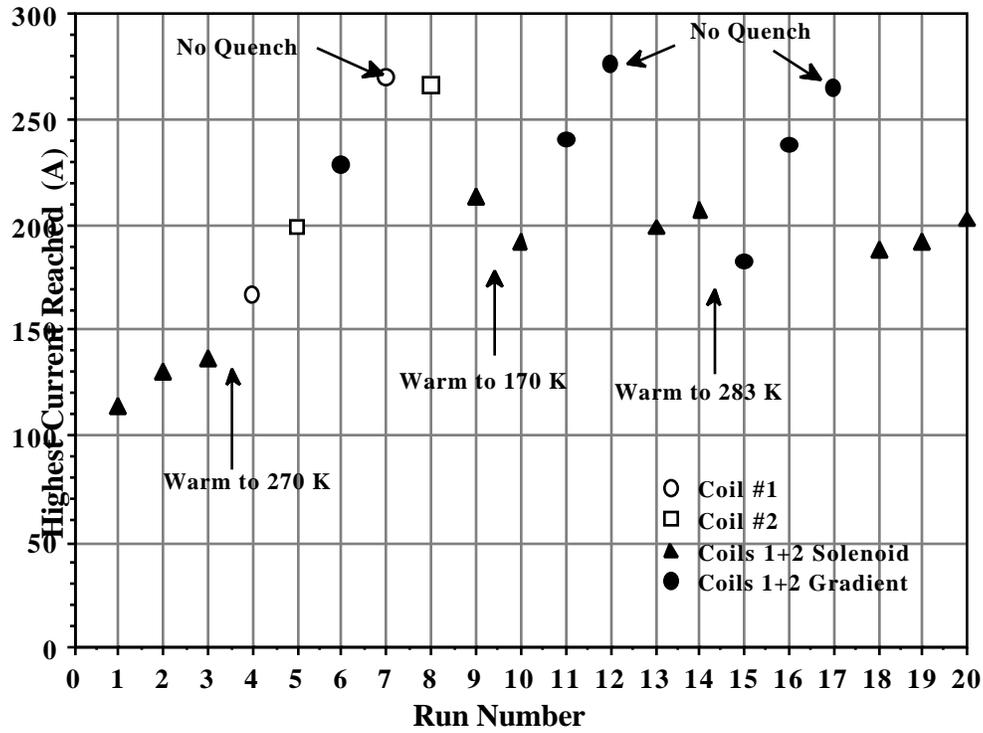


Figure 5. Quench Current or Maximum Non-quench Current Versus Run Number

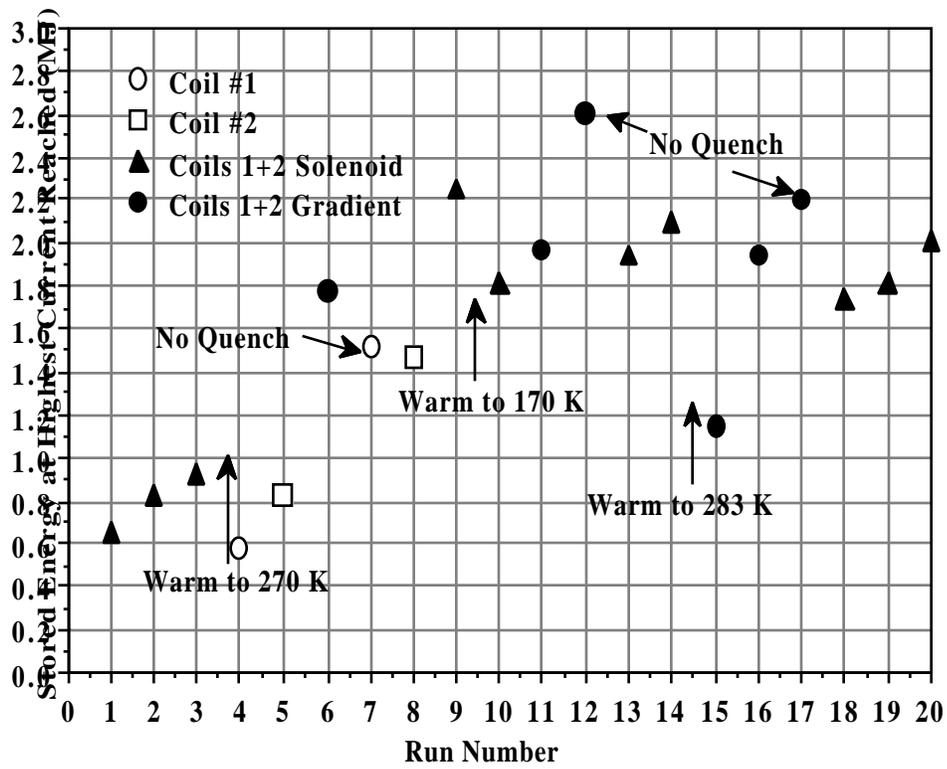


Figure 6. Quench Stored Energy or Maximum Stored Energy Versus Run Number

## RF Solenoid Magnetic Field Measurements

This section presents the results of magnetic field measurement made before the coil became superconducting and the results of magnetic measurements made during runs 4,5 6, 7, 8,10,11,12, 13, 15,16,17,18, and 20. All of the magnetic measurement were made using a hand held Bell 620 Gauss meter. The Bell gauss meter uses a Hall probe as the magnetic field measuring element. Hall probes produce a linear signal with magnetic induction over a wide range of magnetic induction. For the low field measurements, the hand held gauss meter and probe were used directly. For the high field measurement made in November and December 1999 and January 2000, there was a one-decade attenuation between the Hall probe and the meter electronics. In December 1999, during some high field measurements it was observed that the gauss meter reading did not correspond to the actual magnetic induction at induction levels above about 3.0 T. The measured magnetic induction was less than the calculated magnetic induction at high magnet currents but not at low magnet currents. Figure 7 below compares the measured magnetic induction with the calculated magnetic induction for a number of currents for the RF magnet hooked in the solenoid mode. We suspect that the amplifiers in the gauss meter start to saturate when the field measured is too high.

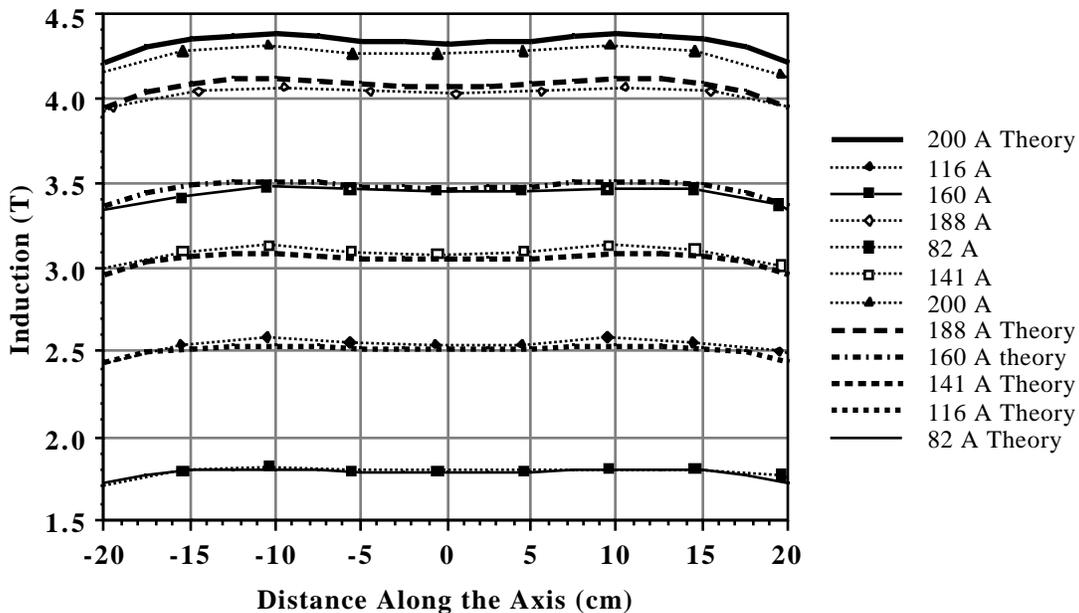


Figure 7. A Comparison of Measured Induction with Calculated Induction  
As a Function of Current and Position along the Axis

The magnetic measurement made with the Gauss meter are probably not good to better than one percent at any magnetic induction. The probable sources of the magnetic field measurement errors are as follows: 1) The current in the magnet was read off of a digital voltmeter in the power supply which gives the current in the coil to the nearest ampere. This means that the current can be the value on the digital meter  $\pm 0.5$  A. At currents below 100 A the error due to the current reading alone is greater than  $\pm 0.7$  percent. 2) There are errors that result from reading the mechanical meter on the electronics box of the Gauss meter. The meter is accurate to two significant figures. A guess can be made for a third

significant figure by interpolating the position of the needle between the meter ticks. The interpolation between ticks is always a source of error. 3) The measurements from the Gauss meter appear to be non-linear above 3 T. The reason for this non-linearity is not known but saturation of an amplifier in the Gauss meter is suspected. Figure 8 below shows the measured induction divided by the calculated induction for various magnetic values of magnetic induction. The data was taken when the magnet was operated in the solenoid mode. The nine point data is averaged measurements taken in the central portion of the RF solenoid at current between 82 A and 200 A.

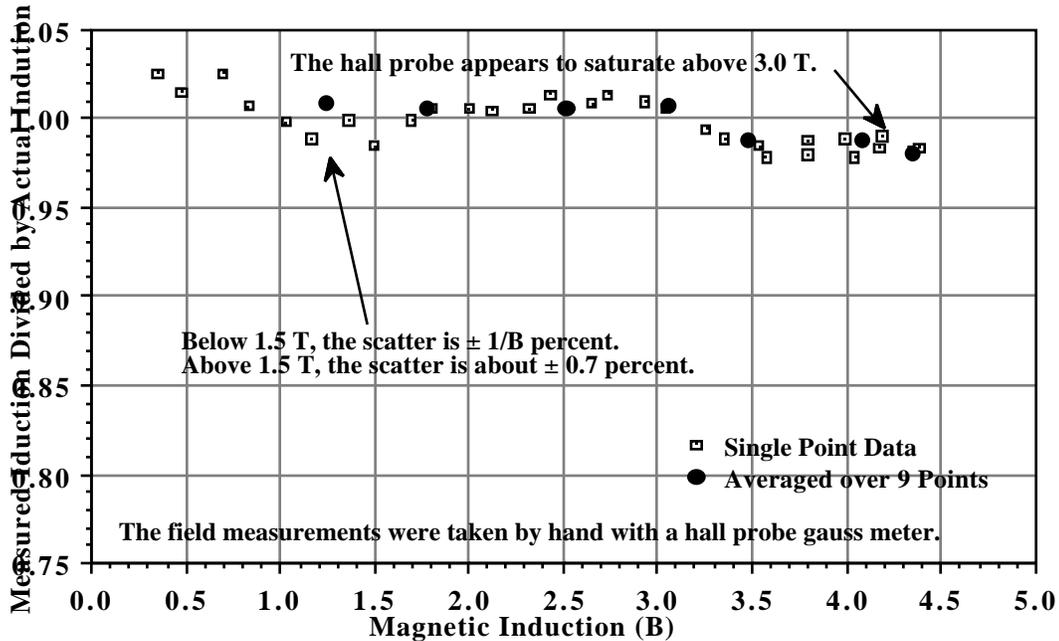


Figure 8. Field Measurement Error Taken as Measured Induction Divided by Calculated Induction as a Function of Central Induction

The first magnetic measurement that was taken with the Gauss meter was taken at a current of 0.086 A while the magnet was cooled to 77 K. Figure 9 on the next page shows a comparison of measured field data with the calculated field with the magnet hooked in both the solenoid and the gradient modes. In the solenoid mode there is good agreement in the center of the magnet but the agreement away from the center is not so good. In the gradient mode agreement between the measured induction and the calculated induction is best where the absolute value of the induction is high.

The maximum error in both cases is of the order of  $5 \times 10^{-5}$  T (0.5 G), which is not much larger than earth magnetic induction. The sources of the error shown in Figure 8 are the same as for the measurement system as a whole plus the effect of earth's magnetic induction (0.3 to 0.5 G), magnetization of welds in the stainless steel warm bore tube and possible magnetized iron near the magnet when it was being measured. Considering the fact that the peak measured induction was only about 18 gauss, the level of agreement between the measurements and theory is quite good.

Figures 10 on the next page and Figure 11 on the following page show measured data for coils #1 and #2 being powered individually. Coil #1 was measured at currents of 58 A, 100 A, 148 A, 224 A, and 258 A. Since the runs at 224 A and 258 A have regions at an induction above 3 T, the measured field is in error up to 2 percent. Coil #2 was only measured at currents of 100 A and 253 A. The 253 A measurements have an error of up to 2 percent because of the apparent saturation of the probe electronics. It is interesting to

note that the highest induction for the individual coil measurements occurs at 18 cm from the magnet center for coil #1 and at plus 21 cm for coil #2. The expected peak field should be at  $\pm 195$  mm. This suggests that the probe position is off compared to the center of the magnet.

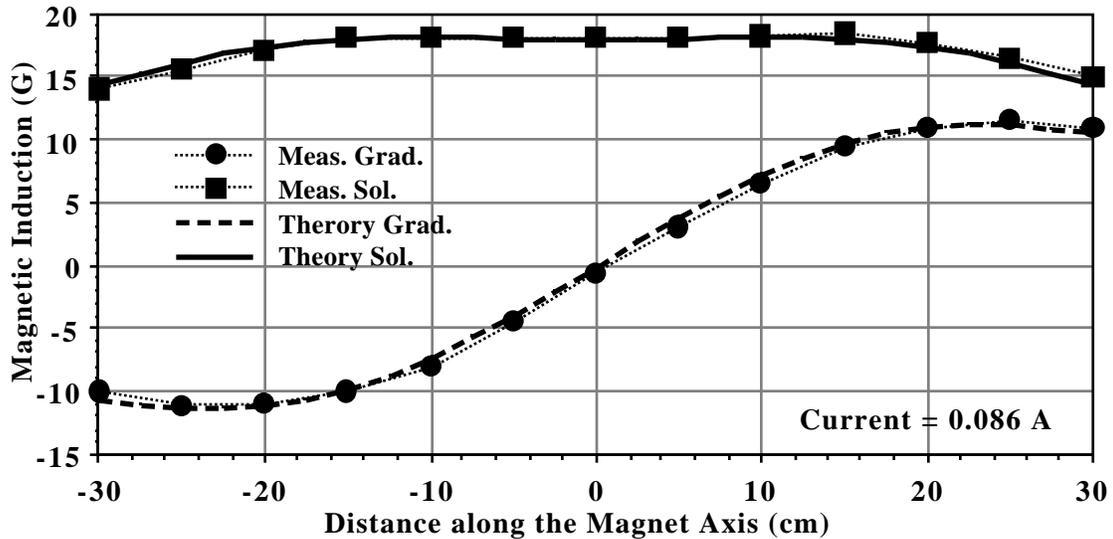


Figure 9. A Comparison of the Measured Induction at Low Currents with the Calculated Induction

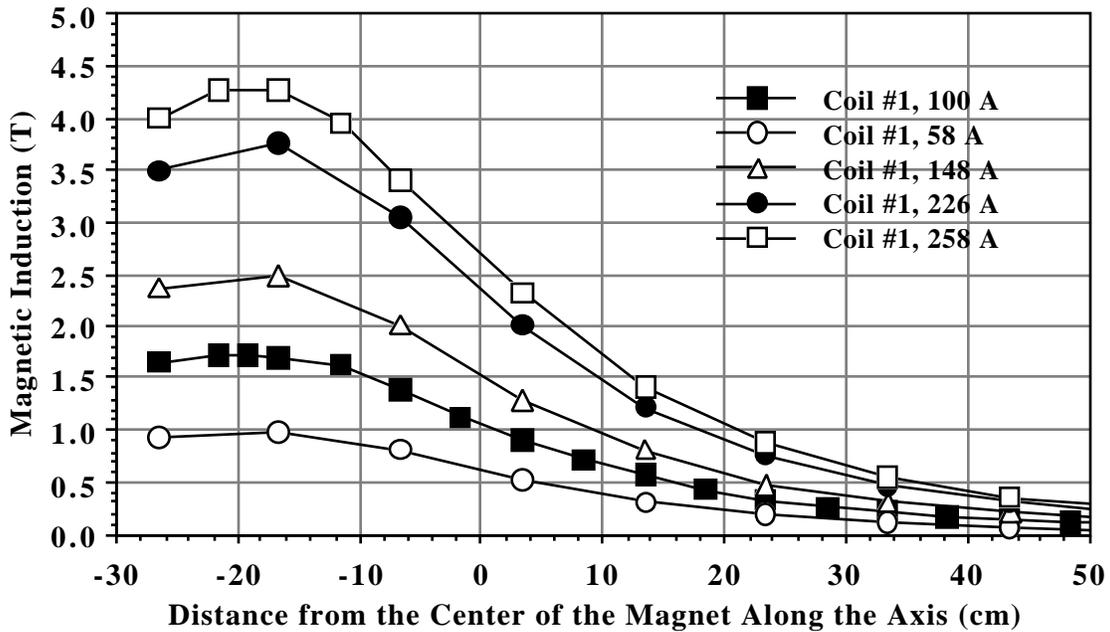


Figure 10. Measured Magnetic Induction with Coil #1 Powered Versus Distance from the Center on Axis and Current

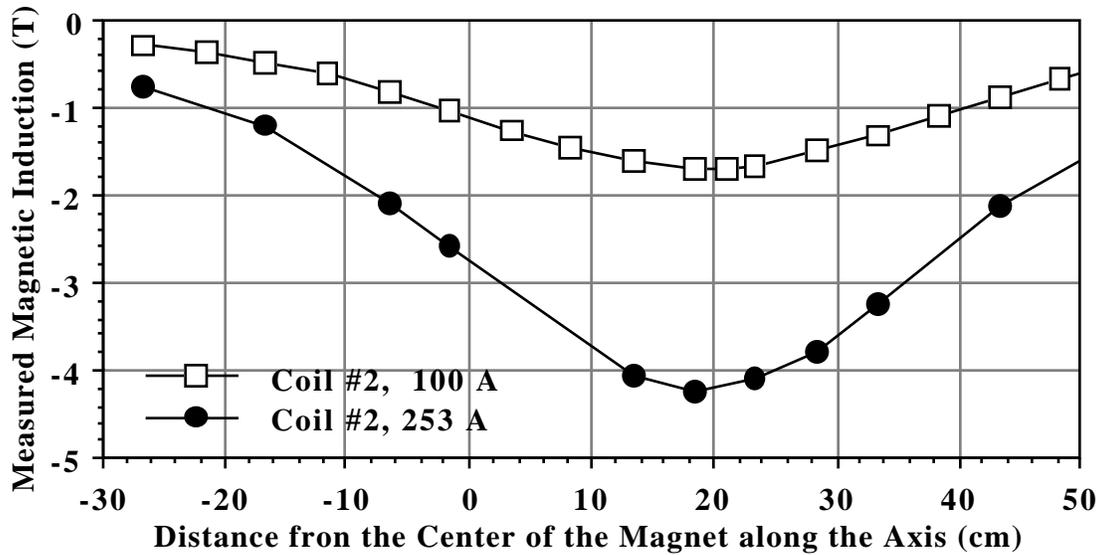


Figure 11. Measured Magnetic Induction with Coil #2 Powered Versus Distance from the Center on Axis and Current

Figure 12 below shows measured data for the magnet in the solenoid mode. (The two coil are powered at the same polarity.) The measurements shown in Figure 12 are for the magnet being powered at currents of 57 A, 82 A, 116 A, 141 A, 160 A, 188 A and 200 A. The design current in this mode is 230 A. The theoretical value for the induction on axis at 200 A is also shown in Figure 12. The effect of probe saturation is clearly visible in Figure 12. In the solenoid mode, the magnetic induction is pretty flat (within  $\pm 2$  percent) over the range from -20 cm to +20 cm. Peaks in the magnetic induction occur at around -11 cm and +11 cm. When an 805 MHz RF cavity is run in the magnet when it is hooked in the solenoid mode, the field should be quite uniform ( $\pm 0.4$  percent) over the length of the cavity, provided the cavity is located at the center of the magnet.

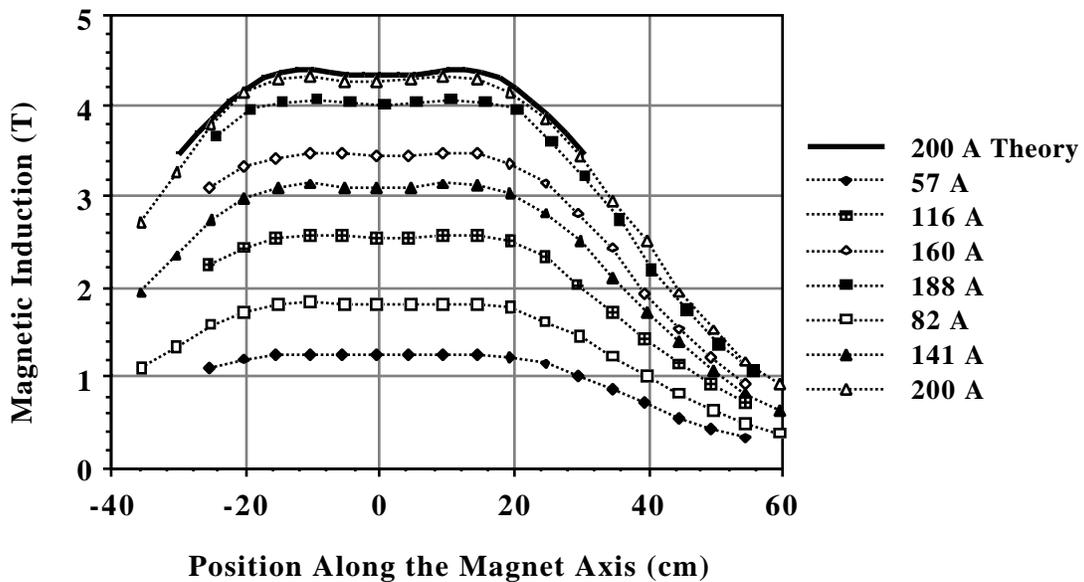


Figure 12. Measured Magnetic Induction with the Magnet Powered in the Solenoid Mode Versus Distance from the Center on Axis and Current

Figure 13 below shows measured data for the magnet in the gradient mode. (The coils in the magnet are powered at opposite polarity.) The measurements shown in Figure 13 are made when the magnet is powered at 51 A, 87 A, 103 A, 138 A, 162 A, 184 A, 224 A, 244 A, 251 A, and 265 A (the full design current in this mode). The calculated magnetic induction on axis at 265 A is also shown in Figure 13. The effect of probe saturation above 3 T is visible. Through most of the field range, the calculated induction and the measured induction agree within  $\pm 1$  percent.

Peak values of the absolute value of the induction occur at  $-24$  cm and  $+24$  cm. The magnetic induction is zero at the center of the magnet within  $\pm 2$  or  $3$  mm. The peak field gradient occurs between  $-10$  cm and  $+10$  cm along the axis. At the full design current for the magnet in the gradient mode a gradient of  $23$  T per meter (along the axis) was obtained in the region from  $-10$  cm to  $+10$  cm. At the magnet center, the gradient was just over  $24$  T per meter. If one looks at the region between  $-20$  cm and  $+20$  cm the average gradient at the full design current for this mode is about  $17$  T per meter. When an RF cavity is operated at the center of the magnet operating in the gradient mode, the average induction gradient in the cavity can be expected to be in the range of  $21$  to  $23$  T per meter along the magnet axis. If the cavity is centered within the magnet, the induction at the cavity center should be about zero.

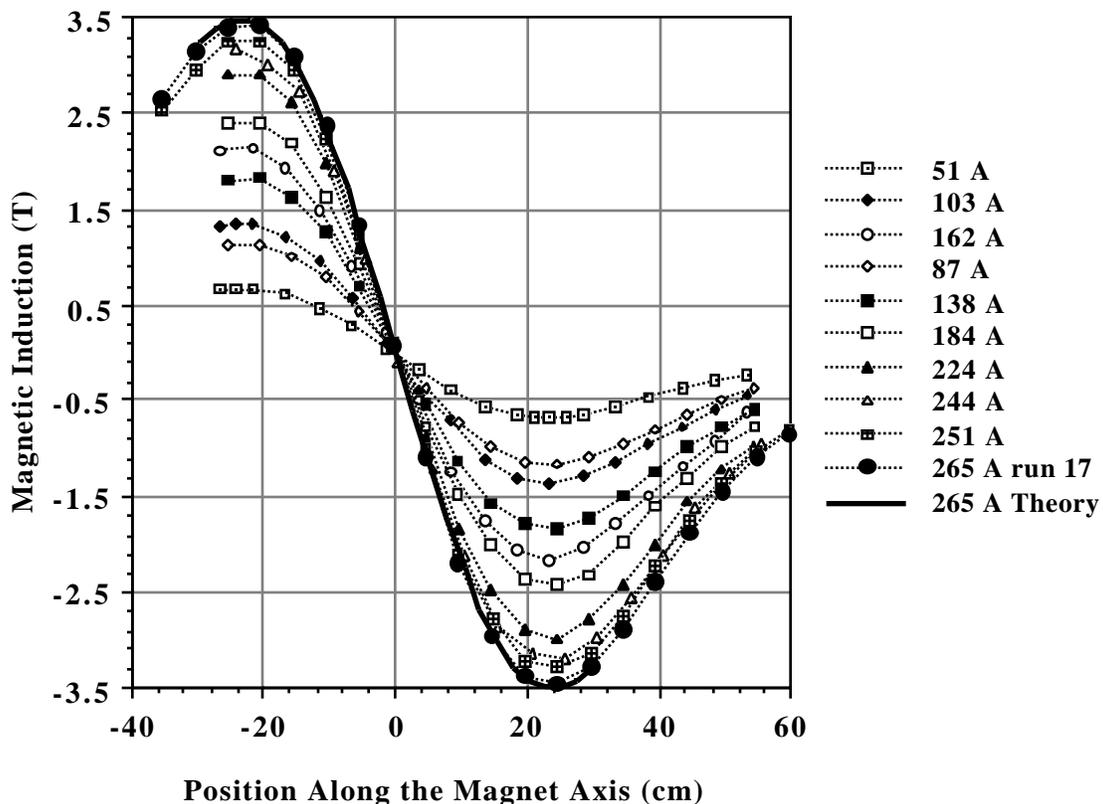


Figure 13. Measured Magnetic Induction with the Magnet Powered in the Gradient Mode Versus Distance from the Center on Axis and Current



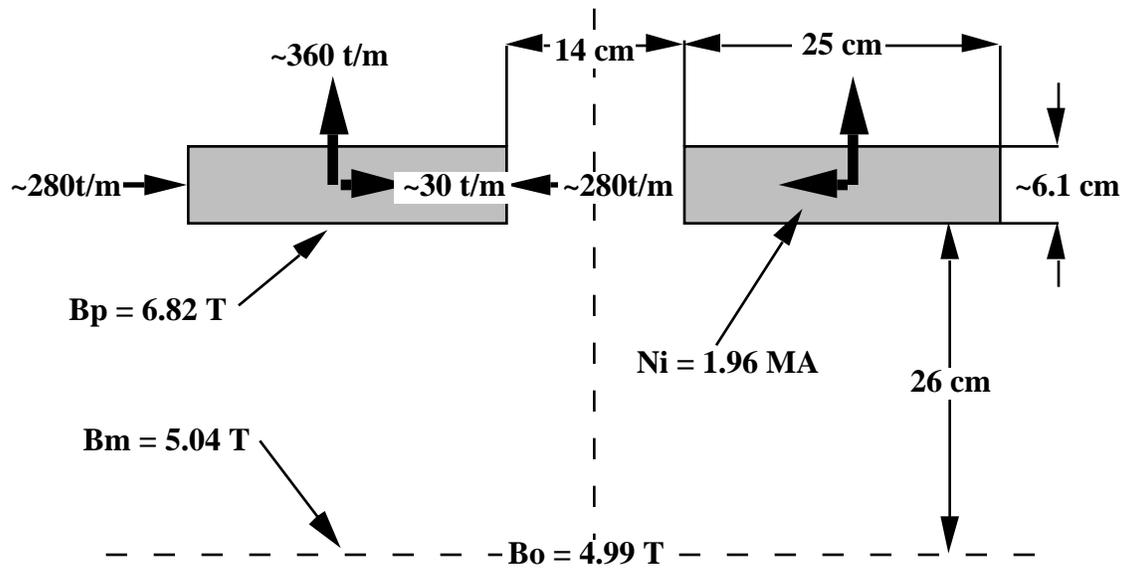
major differences between the RF solenoid and the previous solenoid built by Wang. First the older solenoid was not designed to be operated in a mode where the coils are hooked up at opposite polarity. Second the older solenoid has a stored magnetic energy that is nearly an order of magnitude lower than the RF solenoid. The stored magnetic energy translates directly into increased magnetic stress and strain. If the strain results in stick-slip motion, the magnet trains. This is true for solenoids as well as dipoles.

The second cause for training is stick-slip friction in the mica slip planes at the sidewalls of the coil. This mode is made worse by the 280 metric tons per meter force that is put into the coil by differential thermal contraction between the bobbin and the coil. The bobbin clamps down over the coil packages because the coil is encapsulated in aluminum. The longitudinal pieces of aluminum are needed to carry the 300 metric ton force between the two coils when they are operated in the gradient mode. Mica slip planes are not completely frictionless when large forces are applied perpendicular to the slip planes. Since the coils are clamped in the aluminum, stick-slip friction will occur as the coils are charged. Figure 15 on the next page shows the approximate level of forces on the coils when they are being charged in each mode.

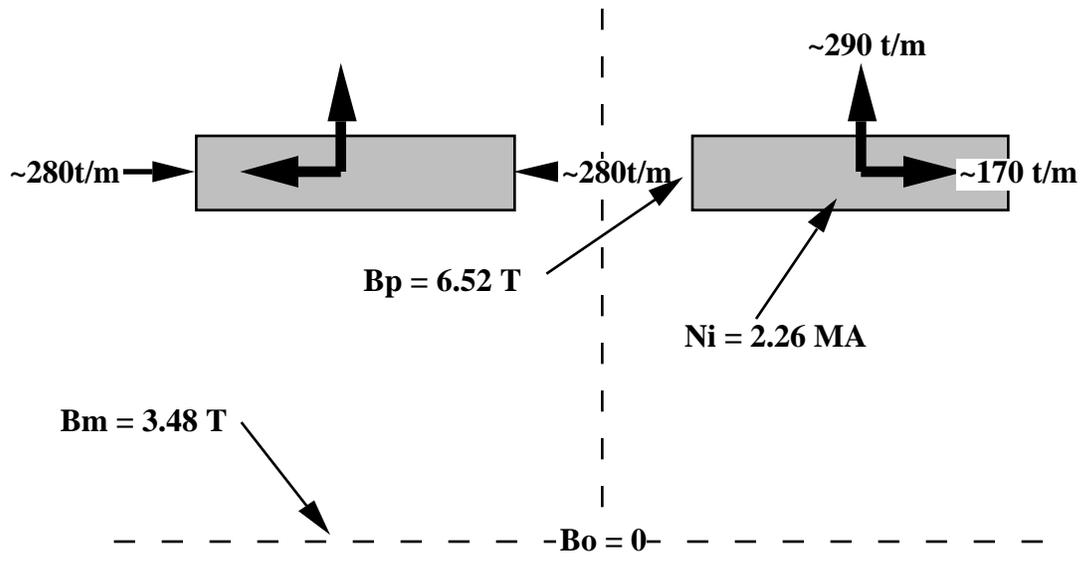
Oddly enough, the training is worse in the solenoid mode than it is in the gradient mode. The hoop forces and slips in the hoop direction will always be worse in the solenoid mode, but the high field point in the solenoid mode is not near the point where stick-slip is occurring in this mode. Coil number 1 is more prone to training than coil number 2. Many of the training quenches in the solenoid mode involved coil number 1, whereas training quenches in the gradient mode involved coil number 2 as much as coil number 1. This is not understood. Why the training is worse in the solenoid mode than in the gradient mode is not completely clear either.

When the magnet is warmed to room temperature, some of the magnet training is forgotten. Warming the coil to 150 to 170 K doesn't seem to have much affect on training, but temperatures above 200 K seem to cause the coils to slip into a position where they need some retraining. This behavior is consistent with the hypothesis that the aluminum clamping the coil in the longitudinal direction is a major player in causing the magnet to train. A breaking of an epoxy bond below the Kapton layer under the coil would not lead to the coil having to be partially retrained after the magnet has been warmed up to room temperature.

Retraining of the magnet is probably not necessary if the magnet is operated below about 70 percent of design current in either mode. If the magnet must be operated at higher currents, train the magnet first. During training the helium level in the cryostat should be low (around 12 inches). Train the individual coils to 270 A or more first. Then train the magnet in the gradient mode. Training in the solenoid mode should be done last. Once the magnet has been trained, it should be kept cold. If one needs to keep magnet cold for a long period of time, allow the magnet to warm up to 80 K, then fill the magnet vessel with liquid nitrogen. The nitrogen boil off rate while keeping the magnet cold is about 0.35 liters per hour. Keeping the shield tank on the cryostat full of liquid nitrogen may be sufficient to keep the whole magnet at 80 K. This has not been tested. After the magnet cryostat has been warmed to 80 K, it may be useful to pump on the cryostat vacuum with a cryosorption pump or a diffusion pump. The cryostat vacuum should be kept in the  $10^{-5}$  torr range or lower.



CASE A Solenoid Mode at Design Current



CASE B Gradient Mode at Design Current

Figure 15. The Force Diagram for the RF solenoid in Both Operating Modes

## **A Test Report for the MUCOOL RF Solenoid**

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**February 2000**

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