BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Magnet Note

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Title: Cryogenic Test Conditions for 1st LHC D1 Magnet and Re-commission of MAGCOOL

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Cryogenic Test Conditions for 1st LHC D1 Magnet
And Re-commission of MAGCOOL

Tests Performed

The first LHC D1 magnet, D1L105, was tested in MAGCOOL between September 10 and October 23, 2001. The magnet was cooled from room temperature to 4.5 K three times under three warm-bore configurations. Performance of the magnet, effected strongly by the heat load and magnet temperature, will be given by the Magnet Division. This report presents the cryogenic conditions of the tests, and pressure and temperature rises after the magnet quench.

In the first group of tests, the warm bore tube was inserted and evacuated. The heat load, magnet temperature and quench current are in the middle of the three groups of tests. In the second group of tests, a measuring coil was inserted inside the warm bore tube. The heat load is the largest, the coil temperature is the highest and the magnet performance is the worst. In the third group of tests, the warm bore tube was removed. The heat load is the lowest and the magnet quenches at the highest current.

Since the MAGCOOL facility had not been used for a few years and the process control computer had been upgraded in 2000, a main part of the cryogenic operation was to verify the condition of cryogenic hardware and the validity of previously developed software. There were no major problems in MAGCOOL but minor repair will be needed.

Major Difference between Cooling D1 and RHIC Dipole

Although the D1 magnet is essentially a RHIC dipole, there is a major difference in cooling. The RHIC dipole magnet has incorporated a 3 millimeter gap between the beam tube and the coil for cooling purpose. Due to the need of a large beam tube for D1, this gap was reduced to almost none. For this and other reasons, the large heat transfer capacity Superfluid Helium II is selected for cooling D1 in LHC. There are two Bayonet-type heat exchanger tubes installed inside the two upper by-pass holes of the iron lamination. These heat exchangers are connected to a supply and a return line to provide 1.9 K cooling.

For testing D1 in BNL, standard MAGCOOL 4.5 K force flow cooling is used. D1 is connected to a Feed Can and a End Can as shown in Fig. 1. Helium, from the MAGCOOL supply header, is brought into D1 from the non-lead end near the End Can. Cold helium flows through D1 to provide the cooling. Helium flows through the lead pot, where a small amount of cold helium is used to cool the current leads, and returns to MAGCOOL. Liquid nitrogen is used for the heat shield.

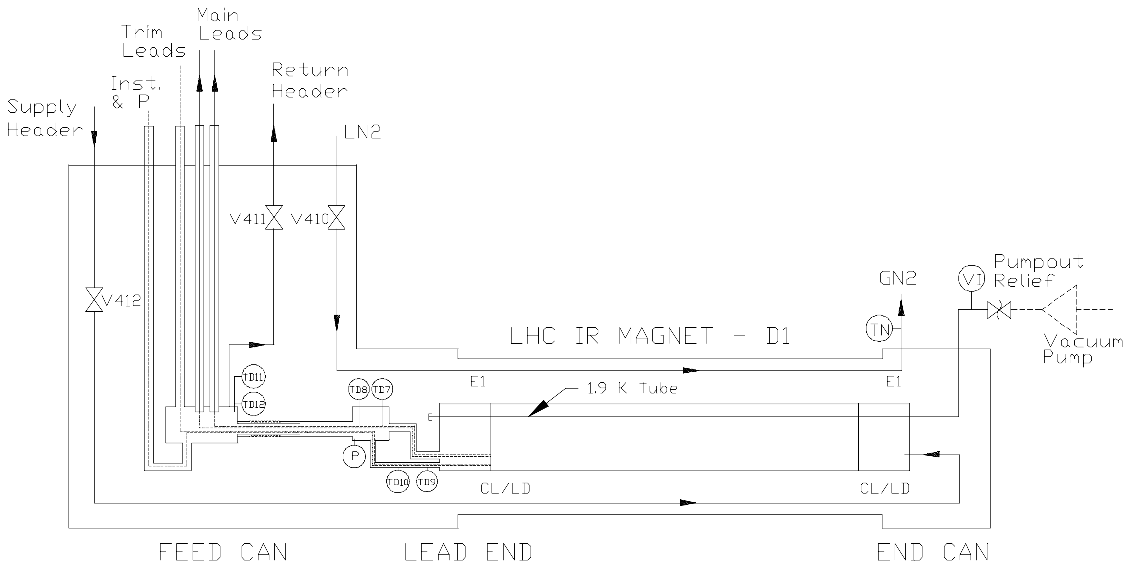

Figure 1 Flow diagram for cooling D1

For testing D1 in this configuration, the coil cooling is not ideal since the coil is cooled mainly by heat conduction. The cooling helium flows in the two lower by-pass holes and other openings in the iron lamination. The coil temperature will be higher than that of a RHIC dipole which has a cooling flow through the passage between the coil and the beam tube. While larger heat loads from the bore tube always lead to higher coil temperatures, the effect seems more dramatic without an effective cooling passage. The differences in heat load among the three different warm bore configurations are large as observed from the temperature at the MAGCOOL return line.

In this test, the 1.9 K system is capped and kept at vacuum for the purpose of monitoring cold leak between the 1.9 K system and the magnet cold mass. As shown in Fig. 1, the 1.9 K line is connected to a vacuum pump through a pumpout line where the vacuum reading is monitored.

Force Flow Cooling in MAGCOOL

In the MAGCOOL low temperature cold box, there are two liquid helium pots Precooler and Subccoler. The Precooler is connected to the low pressure line of the refrigerator, and is typically at 1.34 atm and 4.55 K during the operation. The Subcooler is maintained at 0.7 atm and 3.86 K using an ejector to pump on it. Both Precooler and Subcooler contain a heat exchanger coil to cool single phase helium for force flow cooling. Ejector and Circulator are two modes of operation. Flow diagram of the Low Temperature cold box is given in Fig. 2.

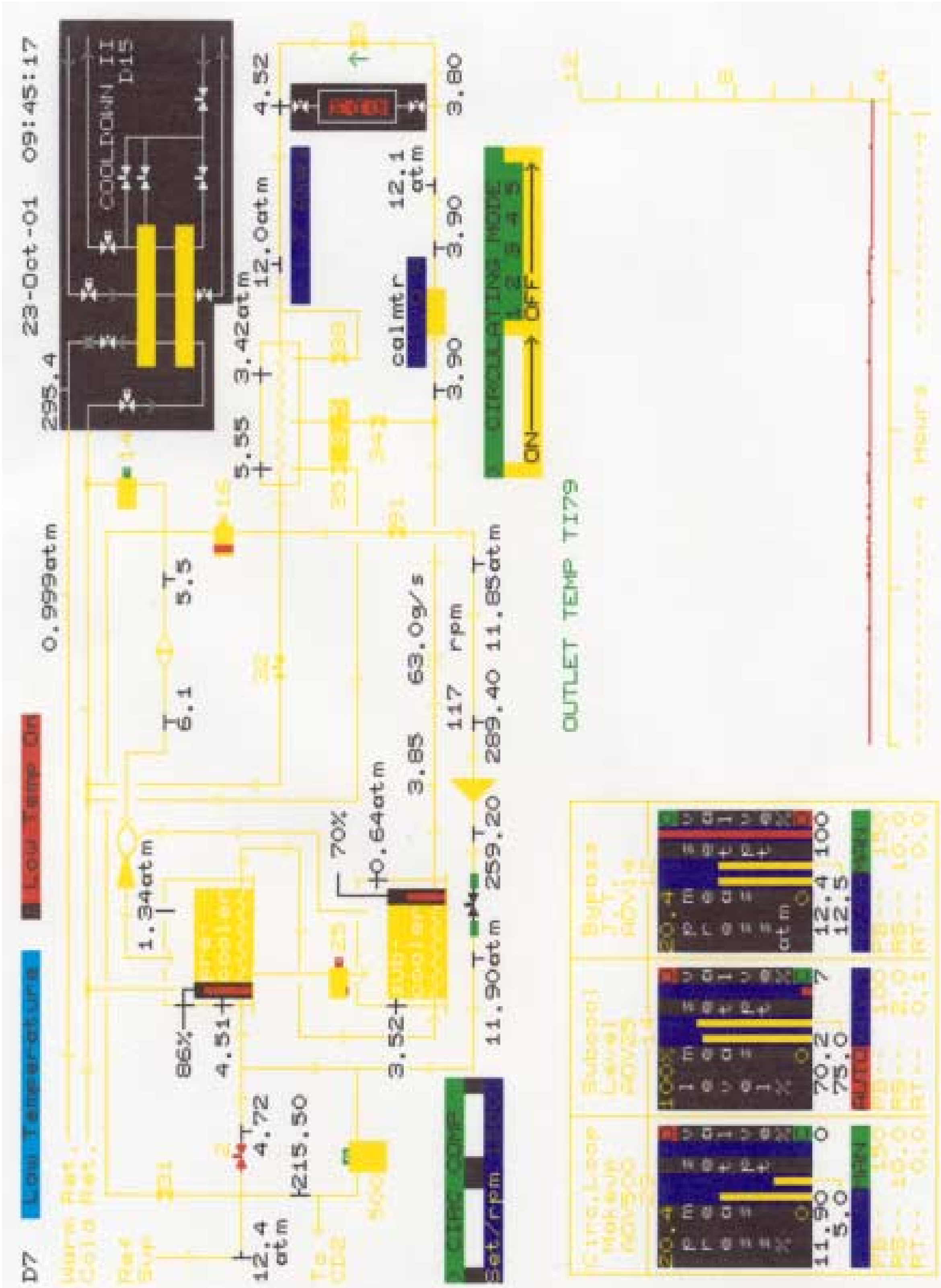

Figure 2 Flow diagram and typical cryogenic test condition for D1

For Ejector Mode cooling, the magnet is cooled by cold helium from the refrigerator at 12.3 atm and the flow rate is approximately 65 g/s. For Circulator Mode cooling, the magnet is cooled by the helium flow in close loop circulation, the pressure is 5 atm and the flow rate is 100 g/s. Temperature in the magnet depends on the operating condition. However, a magnet is often a little bit colder in the Circulator Mode.

For testing a magnet, the cryogenic system needs to handle pressure rise after a magnet quench. When pressure becomes excessive, helium must be vented to prevent over pressure. The quench handling mechanism between the Ejector and the Circulator Modes are different.

Past experiences indicate quench venting in the Ejector Mode is more difficult to manage because cooling helium is operated at 12 atm which is 3 atm below the desired maximum operating pressure. In the Circulator Mode, cooling helium is at 5 atm which is 7 atm lower than that in the Ejector Mode. The Circulator Mode also capable of using the cold surge tank to damp pressure rise.

In this test, D1 is cooled by the Ejector Mode cooling. We carefully investigated pressure rise and quench handling. We found the pressure raise after D1 quench is small and presents no problem for quench handling. Therefore the Ejector Mode cooling is used throughout the tests.

The Circulator Mode was exercised once. Minor problem associated with circulator cooldown prevented the system from cooling down in time for test. The circulator is found in very good working condition. The Circulator Mode was not pursued after satisfactory result on D1 was obtained in the 3rd group of test.

A typical operating condition of the Ejector Mode is given in Fig. 2. D1 magnet is cooled by 63 g/s of helium at 12.4 atm. The magnet temperature is about 4.3 K. Variations of heat load can be seen among the three groups of tests. In the 1st group of test, warm bore tube evacuated, the temperature at MAGCOOL return is approximately 4.6 K. In the 2nd group of test, warm bore tube with measuring coil, the return temperature is 4.9 K. For the 3rd group of test, warm bore tube removed, the return temperature is about 4.5 K. In these tests, the heat load corresponding to a 0.1 K temperature rise is approximately 20 Watts. The heat load from the warm bore tube and the measuring coil appears to be roughly 80 Watts.

Quench Current and Magnetic Stored Energy

In the 1st group of tests, both Strip Heater and Natural quenches were initiated. The current for Strip Heater quench varies from 2,000 to 5,000 Amperes. The Natural quenches occurred between 5,477 and 6,471 A. In the 2nd group of tests, the Natural quenches occurred between 5,452 and 5,936 A. In the 3rd group of tests, the Natural quenches occurred from 6,523 to 7,333 A.

The Inductance of D1 equals 0.028 Henry. At 5000 A, the magnetic stored energy ½ L I^2 equals to 350 Kilo-joules and amounts boil off 156 Liter of liquid helium. At 7333 A, the magnetic stored energy equals to 753 Kilo-joules and would vaporize 335 L of liquid helium. Quench recovery time is typically from one to two hours depending on the flow rate and amount of energy release.

Peak Pressure and Temperature after D1 Quench

Although there is an energy extraction scheme for the magnet, essentially all magnetic stored energy is dumped into the cooling helium. The pressure and temperature of helium increase accordingly. Depending on the amount of energy release, the pressure could exceed the pressure rating of the system.

To protect over pressure, helium must be vented. When the return pressure reaches 13.7 atm in MAGCOOL, the process control computer open valve 38 to vent helium to the Cold Surge Tank. Helium in the Surge Tank will be bled back to the refrigerator at a slower rate to reduce perturbation on the refrigerator.

The peak pressure as a function of current is given in Fig. 3. The peak pressure as a function of magnetic stored energy is shown in Fig. 4. Both strip heater quench and natural quenches taken at three test groups are shown in different symbols. The initial loop pressure is plotted at 0 current. The venting of helium at 13.7 atm for one of the test is also plotted for reference. As seen, the pressure rise for the Strip Heater quench are higher than that of the Natural quenches. The pressure rise for the Strip Heater quench are linear with the magnetic stored energy as shown in Fig. 4. In all cases, the pressure increase is not large. The pressure rise for the Natural quench more or less increases with the magnetic stored energy, but not in systematic way. These pressure rises, however, seem substantially lower than our past experience on RHIC Dipole. It is difficult to say if removal of the cooling passage in the coil around D1 contribute to a different pressure raise characteristic. We'll investigate the pressure rise for other D1 and possibly under Circulator Mode.

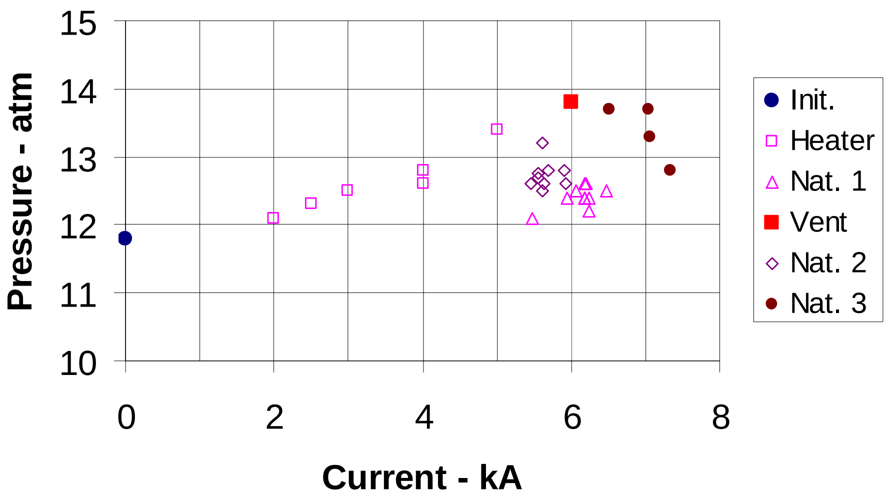

Figure 3 Peak pressure as a function of current after D1 quench

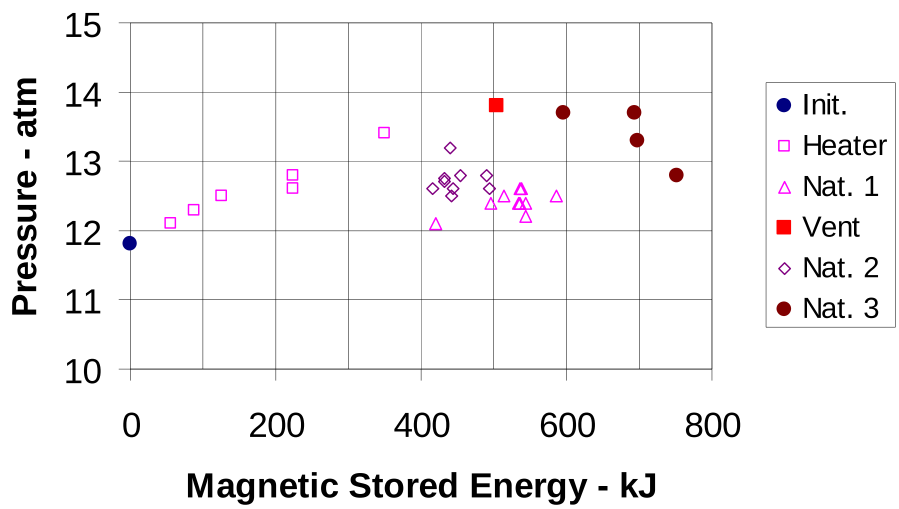

Figure 4 Peak pressure as a function of magnetic stored energy after D1 quench

The peak temperature, measured at the return line of MAGCOOL, as a function of current is given in Fig. 5. The peak temperature as a function of magnetic stored energy is given in Fig. 6. Both strip heater quench and natural quenches taken at three test groups are show. Temperature before quench and one temperature occurred during venting is also plotted for reference. There is no distinguishing between the Strip Heater quench and the Natural quench. The peak temperature, measured at the return line of MAGCOOL, essentially increases linearly with the magnetic stored energy. For the 7333 A quench, the peak return temperature is 12.3 K.

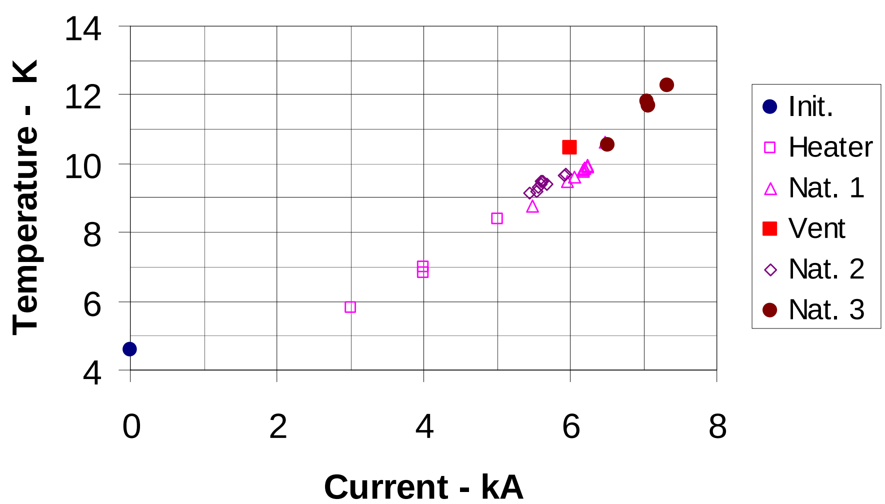

Figure 5 Peak temperature in return line as a function of current after D1 quench

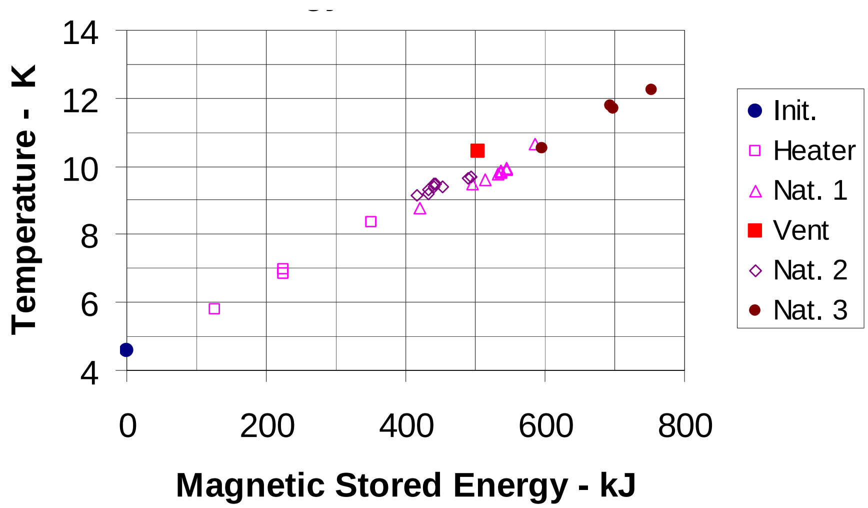

Figure 6 Peak temperature at the return line as a function of magnetic stored energy after D1 quench

Lead Flow

The cooling flow for the current lead is given by the equation 1 and in Fig. 7 as a function of current.

$$Flow = C_0 + C_1 \times I + C_2 \times I^2 + C_3 \times I^3 + C_4 \times I^4 \qquad (1)$$

Where

F is cold helium flow in gram per second, g/s,

I is current in kilo-ampere,

And C_0 through C_4 are coefficients given below

$C_0 = 0.0497$

$C_1 = 0.04414$

$C_2 = -0.146$

$C_3 = 0.004936$

$C_4 = -0.000336$

For reducing heat conduction through the copper, a small flow, called Tare flow, is applied. C_0 is the Tare flow. In the present test, Tare flow was increased to 0.2 to reduce lead pot temperature prior to powering the magnet. Once the lead pot is cold and the current ramping began, the two flow controllers were set to AUTO and lead flow follows equation 1.

The leads are protected by an over voltage safety Bit which upon detection will open a solenoid valve to by-pass the flow controller and to provide a large flow to cool the lead. As described earlier, this Bit was too sensitive and we were unable to set it correctly. It was disabled during the test.

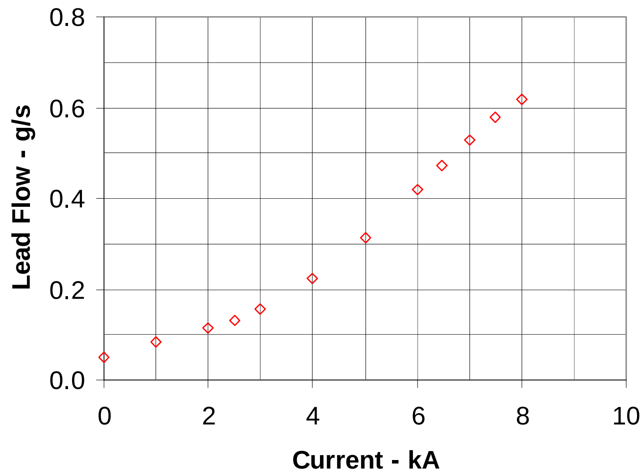

Figure 7 Lead flow as a function of current

Problems Encountered

A small leak to insulating vacuum was observed in the 1st test. This leak is believed to come from the Indium door on the lead pot. Since the leak disappeared in the 2nd and 3rd tests, no leak check is further conducted.

A small leak could develop from the 1.9 K line to insulating vacuum space provided that vacuum in the 1.9 K line was not maintained. After D1 was warmed up at end of the test, the magnet cryostat was disconnected from Feed and End Cans for leak check. We locate the leak on a nozzle temporarily attached on the CY line in the lead end of D1 for this test. Since this nozzle will be removed before shipping, it does not effect the vacuum integrity of D1.

Procedure Verified in MAGCOOL

In this test, all major MAGCOOL procedures have been exercised. A description of the verification and problem encountered are given below:

1). Pump & Purge - No problem encountered.
2). Cooldown I (300 to 100 K) - Typically takes 12 to 16 hours.
 The following problems were corrected:
 Controllers on the Cooldown compressor CS5 & Purge compressor CS4,
 A few I/O cards on computer control rack need to be changed.
3). Cooldown II (100 to 4.5 K) –
 Used in the 1st test – No problem encountered.
 D1 was cooled directly by the refrigerator in the 2nd and 3rd groups of tests.
4). Test & Measure (Ejector Mode) - No problem encountered.
5). Quench Venting (Ejector Mode) –
 No problem encountered. Vent valve opened at expected pressure.
6). Test & Measure (Circulator Mode) –
 Demonstrate the circulator mode in working condition, but was not carried out for the test since the magnet met performance requirement in Ejector Mode.
7). Quench Venting (Circulator Mode) - No problem expected.
8). Warmup – No noticeable problem encountered.
9). Controller for Liquid Nitrogen Heat Shield – No problem encountered.
10). Controller for lead flow –
 No major problem encountered.
 The lead over voltage protection bit was too sensitive and unable to set it correctly. It was disabled for the test.

Acknowledgement

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