Presented at the ICEC19 International Cryogenic Engineering Committee Conference, Grenoble, France

# Cryogenic Operation and Test Results for BNL Built LHC Insertion Magnets

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The D1 and D2 magnets, the first two types of magnets Brookhaven National Laboratory (BNL) is building for the Insertion Regions of Large Hadron Collider (LHC), are being constructed and tested in the BNL magnet test facility. The D1 magnet is cooled using 4.5 K forced flow cooling with three types of bore tube conditions. The D2 magnet is cooled using both liquid helium and forced flow cooling. The liquid cooling scheme, using the shell of the D2 cold mass as the helium vessel and a level gauge in the end volume of the cold mass for liquid control, has been successfully demonstrated. Test results prove that both D1 and D2 meet the performance requirements and that the 4.5 K liquid cooling scheme to be used for D2 and other magnets in the Insertion Regions of LHC is adequate.

## INTRODUCTION

Since 1996, BNL has been working on magnets D1, D2, D3 and D4 for the Insertion Regions of LHC [1]. The cooling scheme for these magnets using the LHC cryogenic distribution system was initially reported in [2]. The cooling scheme for D1, D2 and D4 was finalized in 2001 [3], [4] and [5]. In LHC, D1 is to be operated at 1.9 K using pressurize helium II. D2, D3 and D4 will be cooled at 4.5 K using liquid helium. In 2001, construction for all five D1 and several D2 was completed. Cold test for magnet in cryostat began. At BNL, D1 is cooled using 4.5 K forced flow cooling. D2 is cooled using both liquid helium and forced flow cooling at 4.5 K. As of June 2002, tests for all five D1 and the first two D2 were completed. This paper describes the cryogenic test facility, operating experience and test results.

## MAGCOOL TEST FACILITY

The MAGCOOL facility was built in the early 80's for testing magnets using forced flow cooling [6]. The facility was used extensively for testing the RHIC magnets. Over the years, a few modifications were made for testing other magnets or components under various cryogenic requirements. The basic operations are Pump & Purge, Cooldown to 100 K, Cooldown to 5 K, Test & Measure and Warm Up.

For forced flow cooling, the facility is capable of operating with 1) 65 g/s of cold helium at 12 bar and 4.5 K and 2) 150 g/s helium at 5 bar and 4.5 K. For testing D1 and D2 in forced flow, we use 65 g/s since this operation is simpler.

For testing D2 in the liquid helium bath, a JT valve on the new Feed Can is used to supply liquid. The boil–off returns to the low pressure line in MAGCOOL.

For testing a magnet in MAGCOOL, a Feed Can and an End Can are installed in the two ends of the magnet to provide 1) a complete vacuum enclosure with provision for penetration of a warm bore tube, and 2) a lead pot with current leads to a power supply. Existing Cans are used for testing D1. The newly constructed Cans are used for testing D2, D3 and D4.

D1 MAGNET

The cross section of the D1 magnet in the cryostat is given in Fig. 1. The D1 magnet is designed based on the RHIC dipole magnet in a 610 mm diameter cryostat of about 10 meter long. To maximize the aperture of LHC, the outer diameter of the beam tube was increased from 73 mm (for RHIC) to 78 mm (for D1). As a result, efficient cooling cannot be provided at 4.5 K and the 1.9 K cooling was selected for D1 in LHC. There are two bayonet type heat exchanger tubes installed in the two upper by-pass holes of the iron lamination. The four cold pipes in the cryostat are for cooldown-supply, 1.9 K vapor return, heat shield supply and heat shield return. A description of the 1.9 K cooling scheme in LHC is given in [2] and [3]. For testing D1 at BNL, the 4.5 K forced flow cooling is used.
The flow diagram for testing D1 is given in Figure 2. In the Feed Can, the superconducting bus is connected to the two 7500 A leads through a lead pot. For both cooldown and test condition, single phase helium from the supply header flows through the cooldown line (CL/LD in D1 cryostat) to the non-lead end where it enters to cool the D1 cold mass. After flowing through D1, helium exits from the penetration for the bus to cool the lead pot and returns to MAGCOOL. The helium flow at 12 bar and 5 K is further used as the high pressure flow in the MAGCOOL ejector which keeps the supply helium at 4.0 K. Current leads are cooled by a small amount of helium from the lead pot. The 1.9 K line is capped and is evacuated for detecting leaks from the cold mass. The heat shield is kept below 110 K using liquid nitrogen. The 20 K beam screen cooling, to be implemented in LHC, was not installed for the tests.
Penetrations through Feed Can and End Can are available for field measurement using a warm bore tube. During tests for the first two D1's, difficulty was encountered from the heat load of the warm bore. The warm bore tube was redesigned accordingly. Tests have been conducted in three configurations with warm bore tube evacuated, removed and properly heat stationed. Performance of D1 is very good without warm bore tube. The magnetic performance of D1 could be degraded if the heat load from the warm bore is excessive. With a well designed warm bore tube, field measurements were carried out at currents above design value [7].
Cryogenic operation, quench handling and thermal characteristics for D1 were similar to past experience. Since the ejector is connected in series with the magnet, it serves as an "inline" relief throughout the test. Pressure after a quench does not increase as rapidly as otherwise. The vent valve opens only if the pressure reaches 13.7 bar and usually occurs for currents above 6000 A. Both pressure and temperature increases with quench current. For a 7000 A quench, the maximum return temperature is approximately 12 K.

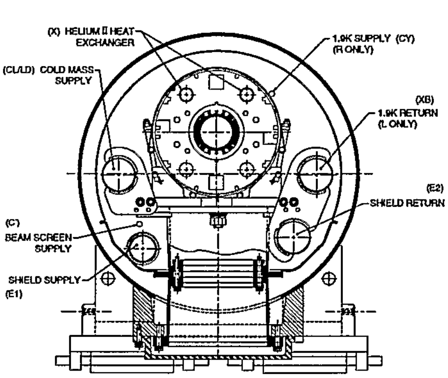


Figure 1. Sectional view of D1cryostat

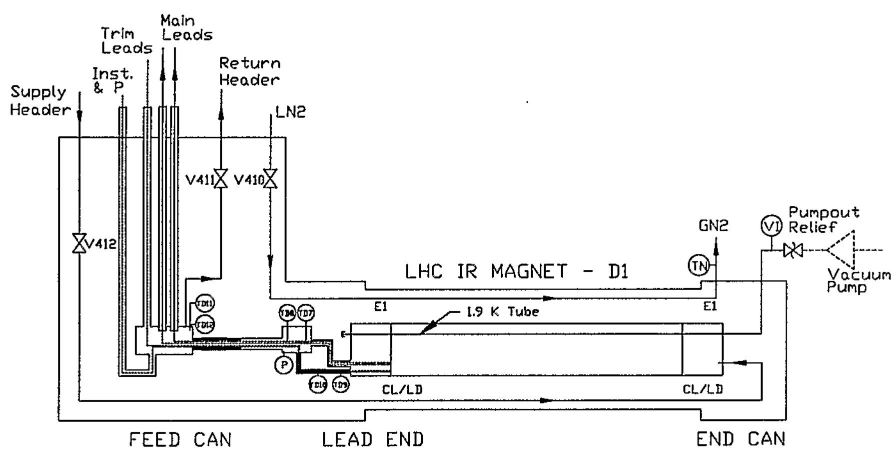


**Figure 2.** Flow diagram with Feed Can and End Can for testing D1 in MAGCOOL

D2 MAGNET

The cross section of the D2 magnet in its cryostat is given in Fig. 3. The D2 has a 914 mm diameter cryostat and is about 10 meters long. It has two coils and two bore tubes. The cold mass has an oval shape (550 x 625 mm) to accommodate separation of two coils. The weight of the cold mass is 19,000 kg. D2 is to be cooled by 4.5 K liquid helium in LHC. The shell of the cold mass is used as liquid helium vessel. Three holes, one 60 mm and two 30 mm in diameter, are introduced near the top of the iron laminations for vapor return. Rectangular openings originally designed for the superconducting bus also become volume for liquid helium or vapor. The liquid level is controlled by a level gage installed in the end volume of the cold mass as shown in Figure 4. For operation, the coil must be immersed in liquid helium. In the test, liquid level is kept about 6 cm above the coil in the high elevation end. The two cold pipes are for heat shield. A 20 K beam screen cooling system will be installed in LHC. The detailed cooling scheme is given in [2] and [4]. The two lines attached on the cold mass are used only for test at BNL. To accommodate the 914 mm diameter cryostat and liquid cooling requirements, a new Feed Can and a new End Can were constructed. The gap between two warm bores is variable for beam separation from 188 mm (for D2) to 420 mm (for D3). On the Feed Can, there are valves designed for cooldown, JT liquid fill, by-pass and quench venting. The slope of the test bay is adjustable between –1.24 and +1.39% to simulate the LHC terrain. Two pairs of 7500 A current leads are installed. One pair is used for powering D2. Both pairs will be used for testing D3 in 2003.

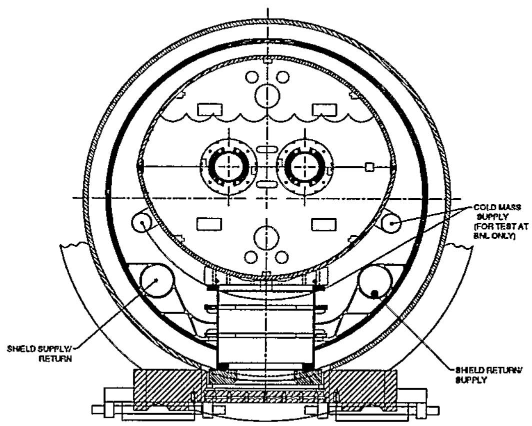


**Figure 3.** Sectional view of D2 with liquid level Indicated in the cryostat

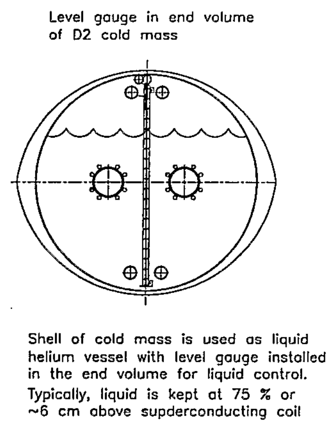


**Figure 4.** The level gauge installed in the end volume of the D2 cold mass

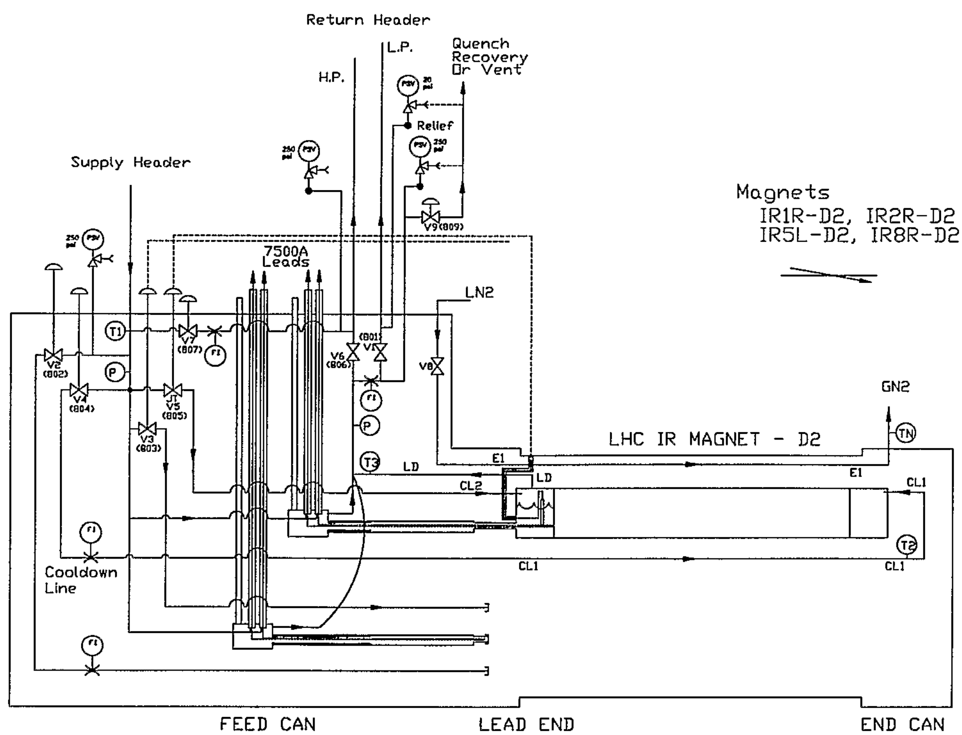


**Figure 5.** Flow diagram with Feed Can and End Can for testing D2 in MAGCOOL

The flow diagram for testing D2 with Feed Can in high elevation end is given in Figure 5. The cold pipe CL1 on the cold mass is used to bring helium from cooldown valve to the low elevation end. Helium returns from the high elevation end to MAGCOOL. A small portion of the helium goes through the lead pot. The superconducting buses of D2 are connected to two 7500 A leads through the lead pot. A JT valve is used for providing liquid helium. A flow by-pass valve is incorporated so that the temperature at the inlet of JT valve can be as low as possible. The leads are force-fed using helium at 12 bar and 4 K directly from the supply header upstream of the JT valve. The heat shield is kept below 110 K using liquid nitrogen. The Feed Can is designed with two sets of JT valves, cooldown valves and lead pots for future testing of D3. For testing D2, one JT valve and one cooldown valve are capped. However, lead flow must be introduced through the two unused leads to reduce heat load to the lead pots.

For forced flow cooling, cold helium enters D2 from the low elevation end. Helium returns to the high pressure line of MAGCOOL. Typical condition through D2 is 65 g/s helium at 12 bar and 4.5 K.

For liquid cool, majority of the supply helium goes through the by-pass valve and returns to the high pressure line of MAGCOOL. A small percentage of helium goes through JT valve for liquid fill. The boil-off returns to the low pressure return in MAGCOOL. Typical liquid cool condition is 1.43 bar and 4.65 K in D2. Helium at the inlet to the JT valve is 12 bar and 4 K. Liquid fraction is approximately 90% after JT expansion. For the $2^{nd}$ D2 (D2L102) test, there was a 1.23% slope on the test stand. Liquid level was 75% in the high elevation end and 95% in the low elevation end corresponding to a change of 10 cm elevation between two ends of D2. Liquid level in the high elevation end was about 6 cm above the coil. In liquid cooling, a quench is handled by venting helium to warm recovery tanks.

Performance for D2L102 was excellent. After two training quenches in forced flow, D2L102 was able to power to 7500 A [8] in either type of cooling. The operating temperature is 4.65 K using liquid cool. It is 0.15 K higher than the 4.5 K design temperature for D2 in LHC.

Large thermal mass and magnetic stored energy of D2 were two concerns prior to the test. In MAGCOOL, it takes about two (2) days to cool D2 from 300 to 100 K, and one (1) day from 100 to 5 K. Average quench recovery time is four hours. Overall cryogenic operation was rather straightforward.

## SUMMARY

Both D1 and D2 magnets have been successfully tested at Brookhaven National Laboratory. The D1 was tested at 4.5 K using forced flow cooling and exceeds the performance requirement for the LHC. The D2 was tested at 4.5 K using liquid helium and forced flow cooling with good results. These tests not only demonstrate the performance of D1 and D2, but also the soundness of the liquid cooling scheme to be used by D2 and other magnets in the Insertion Regions of LHC.

## ACKNOWLEDGEMENT

This work is supported under the auspices of the U.S. Department of Energy US-LHC program. The authors would like to thank R. Hoade for the construction of Feed Can and the support from G. Herbst, W. McKeon, R. Picinich, M. O'Donnell, F. Teich, A. Sauerwald, S. Dimaiuta, J. Cintorino, P. Ribaudo, E. Weigand, J. Gormley, D. Gosline, D. Sullivan, T. Dilgen, R. Ceruti, D. Milidantri and T. Van Winckel.

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