PRELIMINARY TESTING OF THE DØ SUPERCONDUCTING SOLENOID

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PRELIMINARY TESTING OF THE DØ SUPERCONDUCTING SOLENOID

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ABSTRACT

Toshiba Corporation has fabricated a thin superconducting solenoid [1–3] for the upgraded tracking system of the DØ Detector at the Fermilab Proton-Antiproton Collider. The magnet was successfully tested at the Toshiba Keihin Works in Yokohama before it was shipped to the US. The results of the Keihin tests are presented.

INTRODUCTION

The DØ solenoid was specified[4] by Fermilab to cool down easily, charge rapidly, operate stably at either polarity, quench safely without a protection resistor, and provide a 2.0 Tesla solenoidal field with enhanced uniformity which is accurately aligned to the axis of the cryostat. The major parameters of the magnet are listed in Table 1.

Because the magnet must fit into the existing DØ detector the cryogens and electrical current are supplied to the magnet via a 14 m long narrow chimney which connects the magnet cryostat to the system control dewar. The control dewar contains the vapor cooled leads, a subcooler to recool the inlet two phase helium, control valves, bayonet connections, flow instrumentation, and relief valves.

The tests at Keihin demonstrated that the magnet fully met all specifications. When the magnet is later operated in the DØ Detector it will be the first thin superconducting solenoid to operate at 2.0 T in a particle physics detector.

Table 1: Major Parameters of the DØ Solenoid

Central Field	2.0 T
Operating Current	4820 A
Cryostat Warm Bore	1.067 m
Cryostat Length	2.729 m
Integrated Field Homogeneity	$\pm 5.0 \times 10^{-3}$
Stored Energy	5.6 MJ
Inductance	0.48 H
Cooling	Indirect, 2-phase forced flow helium
Cold Mass	1500 kg approx
Conductor	18 Strand Cu:NbTi, Cabled
Conductor Stabilizer	High purity Aluminum
Transparency	0.9 X_o
Cooldown Time	$\leq$ 120 hours
Magnet Charging Time	$\leq$ 30 minutes
Fast Discharge Time Constant	$\leq$ 15 seconds
Slow Discharge Time Constant	$\leq$ 330 seconds
Total Operating Heat Load	$\leq$ 18 W plus 1 g/s liquefaction
Operating Helium Mass Flow	$\leq$ 4 g/s

MAGNET COOLDOWN

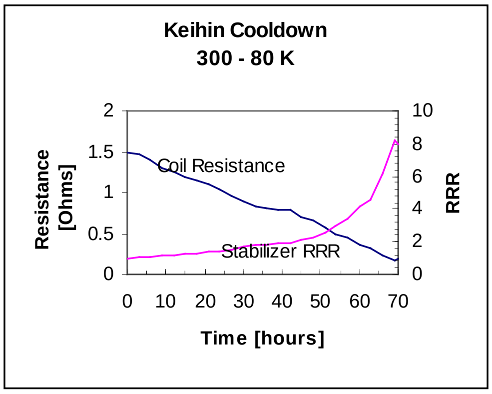
The magnet system was precooled to 80 K in approximately 70 hours using an available refrigerator at Keihin. Cooldown from 80 K to 4.5 K was completed in slightly less than four hours by the transfer of approximately 600 liters of liquid helium into the system.

The rate of cooldown during refrigerator operation was limited by the requirement that the temperature gradient between the support cylinder and the coil not exceed 30 K at any time. This restriction was imposed to limit the axial thermal shear stress in the epoxy bond between the coil and the support cylinder during cooldown. It was found this restriction could be satisfied by limiting to 25 K the temperature difference between the inlet and exit helium flows to the coil. During refrigerator operation the circulating helium gas was maintained at a pressure of approximately 1.6 atma.

The amount of liquid required to complete the cooldown was quite close to that expected from considerations of the heat of vaporization of the liquid and the enthalpy of the cold gas.

The magnet resistance and residual resistivity ratio (RRR) of the conductor during the cooldown are shown in Figures 1a and 1b.

A one-Ampere current source and microvoltmeter were used to measure the resistance of the coil during cooldown. The measured data clearly showed that RRR = 500 was surpassed and observation of the behaviour of the microvoltmeter after RRR = 1000 was reached strongly suggested that RRR exceeded 1000 before the coil made the final transition to the superconducting state. The lack of an easily observed change of slope in the cooldown data beyond RRR = 1000 was likely due to the coil not cooling everywhere at precisely the same rate during the relatively rapid final cooldown.



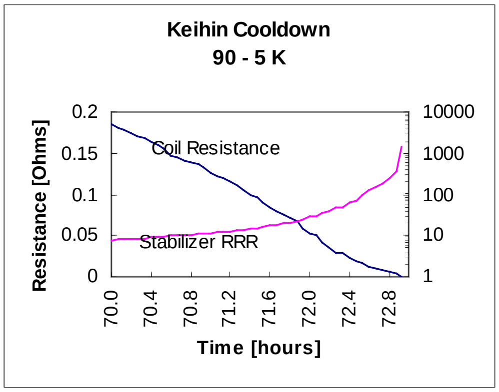


Fig. 1. Magnet Resistance and Stabilizer RRR During Cooldown

CRYOGENIC PERFORMANCE

During the Keihin tests the radiation shields were supplied with liquid nitrogen from a 100 liter supply dewar and the magnet system was supplied with liquid helium from a 1000 liter supply dewar. Both dewars were manually repressurized as required using helium gas cylinders and the mass flow from the helium dewar was calculated from changes in the liquid level in the dewar.

A programmable logic controller (computer system) operated the flow control valve which regulated flow of two phase helium into the magnet cryostat. The gas flow from the vapor cooled current leads was measured and regulated by automatic flow controllers. In the event of a quench a bypass valve was provided which permitted excess return flow from the magnet to be vented to the atmosphere instead of being returned to the subcooler heat exchanger. The steady-state discharge of cold gas from the subcooler vessel was regulated with a pressure regulating valve and measured with a flowmeter.

Because the temperature of the cold gas leaving the subcooler vessel was not measured it was not possible to accurately measure the instantaneous total heat leak to the system during operation.

Typically the flow of helium and nitrogen was stopped at the end of each day and the system was allowed to warm overnight. During a nominal eight hour standby period the radiation shield warmed to about 125 K and the cold mass to about 30 K. From the enthalpy change of the cold mass and the exact duration of the standby period the 4K heat leak to the cold mass can be obtained. An average value of about 6 W was obtained from these calculations.

VAPOR COOLED LEADS

The vapor cooled leads were designed by Toshiba for trouble-free service. Each consists principally of a round ETP copper rod with a helical helium channel machined into its periphery then encased in a tubular stainless steel jacket. The length and cross sectional area of the

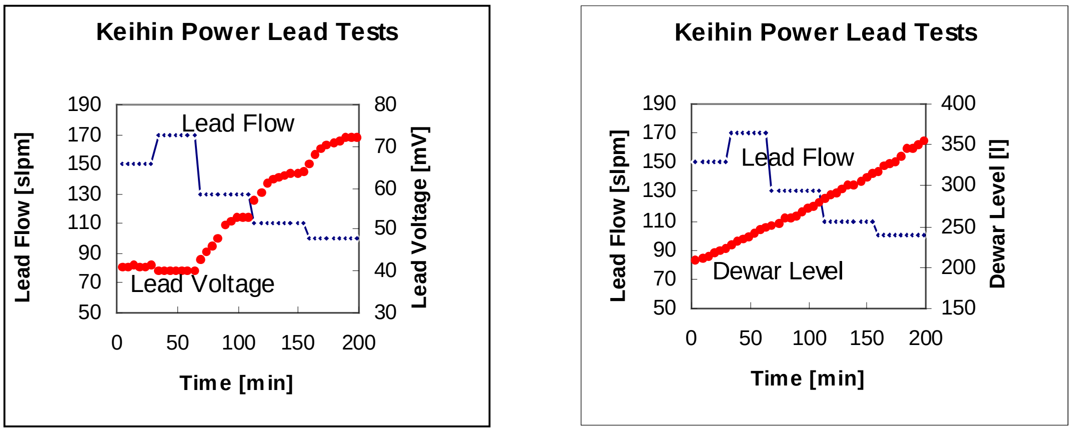


Fig. 2. (a)Lead Voltage and (b) Dewar Level (Total System Flow) vs. Lead Flow at 2.0 Tesla

copper was selected so that in terms of standard descriptions[5] of ideal "self-sufficient" leads the DØ magnet leads were optimized for service at about 1.1 times nominal magnet operating current.

During bench tests of the vapor cooled leads made before they were assembled into the control dewar it was shown that after coolant flow was stopped the leads reached 114 C after approximately 13 minutes steady operation at 5000 Amperes. The tests demonstrated that the leads would not be damaged during even a slow discharge of the magnet after loss of coolant flow. The same margin of performance ensured their thermal recovery without current decrease after shorter transient periods of reduced coolant flow.

The behaviour of the leads during steady-state magnet operation at varying coolant flow rates was measured. Figure 2a shows that at higher flow rates the voltage drop on a lead stabilizes at a lower value almost immediately after the flow is increased, but at lower flow rates the voltage drop stabilizes more slowly at higher values.

Under ideal "self sufficient" conditions[5] the leads would be expected to operate stably with approximately $1.1 \times 1.04 \times 10^{-3}\,W/A \times 4820A/20.4\,J/g = 0.27\,g/s = 92$ standard liters per minute boiloff gas flow. Furthermore under these conditions the leads would develop a voltage drop of approximately $80/1.1 = 73mV$. The Toshiba leads are seen to operate stably at flow rates of 100 slpm per lead (0.3 g/s) or less at 4820 Amperes with a voltage drop of about 70 mV.

Figure 2b shows the helium supply dewar ullage increase during the tests. The slope of the curve is perhaps ≈20% smaller (43 l/hr, or 1.5 g/s) during high lead flow (1 g/s for two leads) than it is at the smallest lead flow (0.6 g/s for two leads) when it is approximately 55 l/hr (1.9 g/s).

The test data demonstrate that the system operates within the specified cryogenic budget as indicated in Table 1: a maximum of 1 g/s warm gas flow from the vapor cooled leads plus a maximum of 18 W refrigeration, or a total mass flow of 1.9 g/s.

ELECTRICAL OPERATION

The magnet was specified to discharge at a rate corresponding to the slow discharge time constant without quenching, and to sustain no damage if it quenched without a protection resistor. To ensure the magnet operated stably at design field it was required to operate at 105% of design field for several hours as well.

Prior to energization the cold magnet coil was tested to ± 2 kV, demonstrating DC isolation from ground greater than 100 Mohm. Energization testing then proceeded in steps to increasingly higher final currents. At each step the magnet was discharged in the fast or slow discharge mode. On the eighth energization the magnet reached full field at 4820 A. The magnet was operated at 5000 A for several hours, operated at opposite polarity, and forced to quench without a protection resistor by artificially rapid charging. At no time did the magnet quench unexpectedly or show any training behaviour.

QUENCH TESTING

Carbon glass resistors on the inside of the coil and on the support cylinder, and potential taps at the ends and at the 1/4 and 1/2 points of the coil were monitored during operation of the magnet. The signals from the potential taps were converted to engineering units and recorded by a fast hybrid recorder onto paper strip charts. The signals were also sent to the programmable logic controller which logged them at rates up to about 0.5 Hz. This computer also conditioned the signals from the thermometers and recorded them at 30 second intervals.

Calculations indicated that slow discharges would not quench the coil but fast discharges from currents greater than about 2000 Amperes would cause the coil to be driven normal by AC loss heating in the coil and support cylinder.

The tests showed that slow discharges from all currents equal to or less than 4820 Amperes did not heat the coil above the superconducting transition temperature. A slow discharge from 4820 Amperes caused the coil temperatures to reach only about 7.1 K between 30 and 60 seconds after the initiation of the discharge by which time the current was less than 3570 Amperes. Slow discharges from lower currents resulted in essentially negligible temperature elevations of the coil.

The first fast discharge, from 1500 Amperes, also evidently did not cause quenching in the coil. At some time during the first 30 seconds after the initiation of the discharge the coil temperature reached about 8.4 K (at the thermometer near the center of the inside layer) and it decreased thereafter. No resistive behaviour was seen on any of the potential taps.

The fast discharge from 3000 Amperes caused the potential tap pair which spans the layer-to-layer transition on the far end of the coil to show resistive behaviour about 3.2 seconds after the initiation of the discharge. The coil temperature reached 20.0 K at this end of the coil (and a few K less at the center and near end of the coil). Resistive behaviour was observed on the potential taps on the inside layer of the coil about 10 seconds after the initiation of the discharge.

The fast discharge from 4000 Amperes also caused resistive behaviour to be seen on the potential taps much as was seen in the 3000 A fast discharge (except the onset of this behaviour was at about 1.8 seconds into the discharge). The coil temperatures reached approximately 27.9 K at the far end of the coil (and a few Kelvins less in the center and near ends of the coil) very much like the 3000 Amperes fast discharge.

The fast discharge from 4820 Amperes warmed the coil to 29.9 K at the far end and the potential tap behaviour was much as in the previous fast discharges.

The quenching was cryogenically very benign. The 0.41 MPa (60 psi) relief valves provided on the helium inlet and outlet pipes to the coil did not open (the supply dewar valve closed and the bypass valve in the return line from the magnet opened to vent excess pressure to atmosphere, bypassing the subcooler vessel) and the coil smoothly and rapidly recooled after each test as soon as the valve settings were restored to normal.

UNPROTECTED QUENCH TESTING

To simulate quenching of the coil with no protection resistor the slow discharge resistor was blocked from the power supply voltage with a large diode. The coil was charged rapidly to induce spontaneous quenching. It was found that charging the magnet at approximately 6.25 V (five times greater than the specified minimum charge voltage) caused it to quench at approximately 4650 A (96% of full current). The very small slow discharge resistor left in the circuit removed only a few percent of the stored energy from the magnet during the quench so the excercise achieved the desired simulation.

A similar unprotected quench induced by a charge voltage of 9.4 volts quenched the coil at 3900 Amperes.

The quenches induced by fast charging were very different than those induced by fast discharging. The fast-chargeup quenches heated the near end of the coil (where the current buses enter and exit) most rapidly and left the final coil temperatures much higher – 135 K in the case of the 6.25 volt chargeup. The potential taps likewise corroborated the fact that these quenches began at the near end of the coil instead of the far end as was the case with the fast discharge quenches.

The peak fields in the conductor occur at the ends of the coil (where high-current density enhancements are located) so it is perhaps not surprising that quenches begin at one end or the other of the coil.

OVERCURRENT OPERATION

At the conclusion of the test where the magnet was operated at 5% overcurrent the coil was discharged into the slow discharge resistor. About 50 seconds after the initiation of the discharge, resistive behaviour was seen on the potential taps at the near end of the coil. Thirty five seconds later the quench wave reached the far end of the coil as signaled by the potential taps at the layer-to-layer transition. The coil temperature reached 43 K at the near end of the coil and 20 K at the far end.

MAPPING THE FIELD

Toshiba carefully recorded conductor placement during coil winding, and the dimensions of the finished coil were measured. The location of the coil within the cryostat was surveyed before the vessel was made vacuum tight. In general the winding dimensions of the coil, and the expected changes upon cooldown, were rather well understood.

A field mapper was prepared by Fermilab to survey the field of the magnet to verify that the desired shape and position of the field had been achieved. The field mapper measured B_r

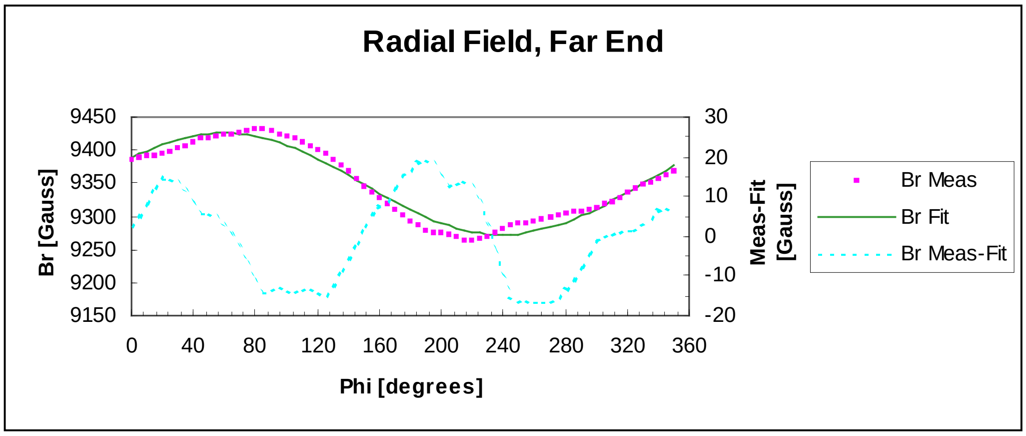


Fig. 3. Measuring the Radial Alignment of the Coil within the Cryostat

at two radial coordinates and B_z at two radial coordinates using precision hall probes mounted on a movable arm. The movable arm could be manipulated under computer control to record the 4 field values stepping in ϕ at a fixed z or stepping in z at a fixed ϕ. Sweeps in ϕ were made near each end of the coil, near the center of the coil, and at one intermediate location. Four sweeps in z at $\phi = 0$, 90, 180, and 270 degrees were made.

The measurements of B_r near the coil ends enables the radial location of the coil with respect to the field mapper to be determined. The data showed a substantial ϕ variation which was fitted with a single sine function. The fit provided a measurement of the direction and extent of the radial offset. For the far end of the magnet, the results are shown in Figure 3. Shown are the measured data, the fitted curve, and fit residuals, as a function of ϕ. The fitting results indicate the radial offset is about 0.95 mm.

A similar fit to the measured data at the near end of the cryostat yield a similar result – an offset of nearly 1.5 mm. The fits indicate that the axis of the magnet is misaligned with respect to the axis of the cryostat by only 0.21 mrad. This alignment accuracy implies that the magnet is completely suitable for use in the DØ detector.

From z-sweep data at a fixed ϕ the field derivative dB_z/dz was calculated. The peaks at the ends of this quantity maximize at the electrical ends of the coil. By fitting the peaks with a polynomial to locate the maxima, the ends of the coil are found. The differences between these two locations then corresponds to the length of the coil. The results of the fits yield a value of 2548 mm for the (cold) length of the coil. This is to be compared with a value of 2543 mm derived from the as-fabricated coil length corrected for cooldown.

Figure 4 shows the measured values of B_z at a radius approximately 1 cm from the vacuum vessel, and the values of dB_z/dz calculated from them. The shape variations in the quantities intermediate between the ends of the distributions reflect the enhanced current density windings at the ends of the coil used to improve overall field uniformity in the bore of the magnet.

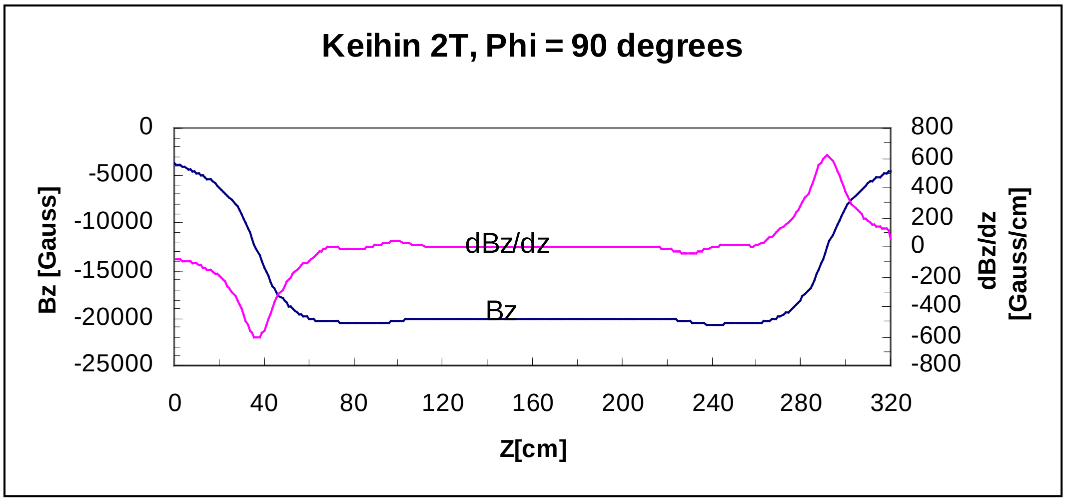


Fig. 4. Measuring the coil length with B_z and dB_z/dz vs. z at $\phi = 90$ degrees

CONCLUSIONS

The DØ magnet fabricated by Toshiba meets all aspects of the detailed specification required for its use in the DØ collider detector at Fermilab. When later installed as part of the DØ Upgrade the magnet is expected to operate easily, efficiently, and safely during physics data taking at the Fermilab Collider at collision energies of 2 TeV/c^2 in the center of mass and at luminosities of up to $10^{33} cm^{-2} s^{-1}$.

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