Fermi National Accelerator Laboratory

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*Abstract*

Construction and testing of the components for the new Tevatron D0/B0 low beta insertion has been nearly completed. The devices include superconducting cold iron quadrupoles utilizing a 2-shell, cos2θ coil geometry with a 7.6 cm aperture. The maximum design gradient is 1.41 T/cm at an operating current of 4832 A. They have the highest current density with the highest peak field on the winding of any quadrupole yet built. This paper summarizes the quench performance and ramp rate sensitivity of the 2-shell design and relates the performance characteristics to the relevant aspects of design and fabrication.

## INTRODUCTION

The Fermilab Tevatron low beta system was designed to provide a high luminosity interaction region at D0 and an identical insertion which has beeen installed as an upgrade to the current low beta system at B0 [1]. Components for both the B0 and D0 interaction regions required the production of 25 high gradient 2-shell cross section quadrupoles and 34 "spool pieces." Spool pieces are cryogenic devices which typically contain a combination of magnetic correction elements, beam monitoring devices and other instrumentation. Several modified spool pieces were built for the low beta system which contained single- and 2-shell quadrupoles. This paper is a report of the quench performance and ramp rate dependence of the 2-shell quadrupoles. A description of the single-shell quadrupoles and their performance is given in [2,3].

## DESIGN

*Cold Mass*

The accelerator requirements are satisfied using a 2-shell, cold-iron design which at 4.9K has a maximum gradient of 1.4 T/cm at a current of 4.8 kA with a transfer function of 0.2913 T/cm/kA. A cross section of the magnet is shown in Figure 1. The coils have an inside diameter of 7.3 cm and are supported by aluminum alloy collars. The collars are clamped by an iron yoke and a welded, 2-piece, 0.48 cm stainless steel shell to form the rigid cold mass [1,4].

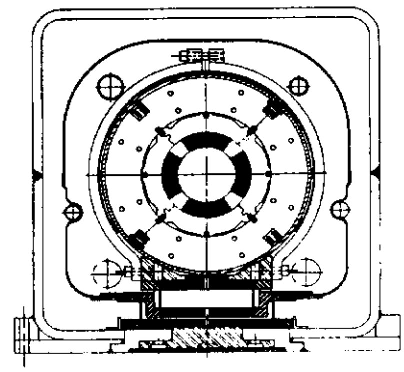

Figure 1. Fermilab low beta quadrupole cross section.

*Conductor and Coil*

The high gradient design produces a coil with the highest current density and the highest peak field on the winding of any quadrupole yet built, imposing strict performance requirements on the strand and cable [5]. Twelve billets of Nb 46.5 wt% Ti composite and Cu, yielding approximately 7 million feet of strand, were produced for the project by IGC/Advanced Superconductor, Inc. The results of short sample measurements made at Brookhaven National Laboratory for representative strands from each billet gave an average Ic of over 212 A @ 4.2K and 6T. Strand specifications are given in Table 1. The 36 strand, Rutherford style cable was produced by Lawrence Berkeley Laboratory on the experimental cabling machine. Techniques were continually improved over the course of cable production resulting in cable with current densities in the superconductor in excess of 3100 A/mm$^2$ at 5T and 4.2K [6]. Cable parameters are listed in Table 2. The inner (outer) coils are wound with 19 (28) turns of Kapton insulated cable.

Table1. Strand specifications.

| | |
|---|---|
| Diameter (mm) | 0.528 + 0.005 - 0.000 |
| Filament twist | 0.8/cm |
| Copper to NbTi ratio | 1.5 |
| Number of filaments | 612 |
| Filament Spacing (s/d) | < 0.2 |
| Filament diameter | 13 μm |
| Filament spacing | > 1.5 μm |
| Ic at 4.2K and 6T | > 193 A |
| Jc at 4.2K and 5T | > 3000 A/mm$^2$ |

* Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy

Table2. Cable specifications.

| | |
|---|---|
| Number of Strands | 36 |
| Twist (Lay length) | 7.2 - 8.1 cm |
| Mid-thickness | 0.897 +/- 0.015 mm |
| Width | 9.779 +/- 0.013 mm |
| Keystone angle | 35.95 +/- 1.05 mrad |

*Magnet Configurations*

All of the 2-shell magnets were made from identical tooling and have the same cross section. The only variations are in length and cryogenic configuration. Table 3 gives a list of the different 2-shell magnets and their maximum operating current in collider mode. The maximum ramp rate is 80 A/s in the fixed-target mode of running but the maximum currents required are much less [4].

expected current at a temperature of 4.6K. Figure 2 shows the number of training quenches required to reach operating current (4.8 kA) for magnets tested in the vertical dewar at 4.2K and cryostated magnets tested at MTF at temperatures of 4.6 and 3.8K.

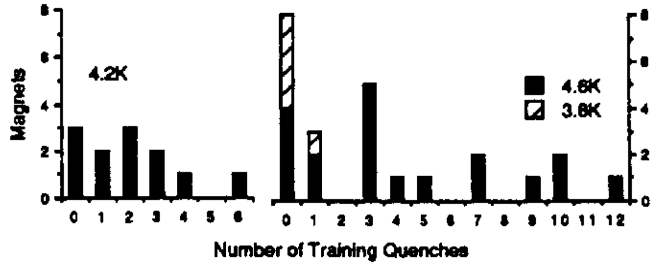


Figure 2. Training quenches to reach operating current.

Table 3. Fermilab low beta 2-shell quadrupoles.

| Device | | Magnetic Length (m) | Max Gradient (T/cm) | Operating Current (A) |
|---|---|---|---|---|
| Q1/Q5 | (N54--) | 1.40 | 0.58 | 2011 |
| Q2 | (N13--) | 3.35 | 1.40 | 4811 |
| Q3 | (N23--) | 5.89 | 1.38 | 4746 |
| Q4 | (B13--) | 3.35 | 1.40 | 4811 |
| T6 | (TSJ/K--) | 0.61 | 1.41 | 4832 |

## TESTING FACILITIES

*Vertical Dewar Facility*

The magnet development facility at Fermilab consists of several vertical dewars which nominally operate at 4.2K but are capable of attaining temperatures down to approximately 3.2K by pumping directly on the helium bath.

*Magnet Test Facility*

The cryogenic system for the magnet test facility (MTF) is essentially the same as it was for the original Tevatron magnet test program [7], except that a cold helium pump and subcooler were added to permit testing down to 3.6K.

## QUENCH STUDIES

*Training Behavior and Quench Performance*

Many of the shorter magnets were tested in the vertical dewar at a nominal temperature of 4.2K prior to insertion in the cryostat. A description of test results of several prototype magnets is given in [8].

Additional magnets for the project were tested in their cryostats at MTF. Most of the magnets were trained at the standard operating temperature of the Tevatron (4.6K). Late in the program an attempt was made to reduce the number of training quenches through "conditioning," by lowering the temperature to 3.8K and training the magnets until they reached a current of 5.3 kA which is slightly above the

Figure 3 is a comparison of maximum quench current and expected performance based on cable short sample measurements expressed as a percentage of the short sample prediction. The operating current at 4.6K (4.8 kA) is approximately 90-92% of short sample. Several of the 1.4 m magnets were not fully quench tested because of time constraints and the low operating current requirement of these magnets. They were trained only until operating current was exceeded.

Many of the magnets underwent thermal cycling as part of the test program and as a consequence of installation and operation in the Tevatron. None of the magnets have exhibited retraining below the operating current.

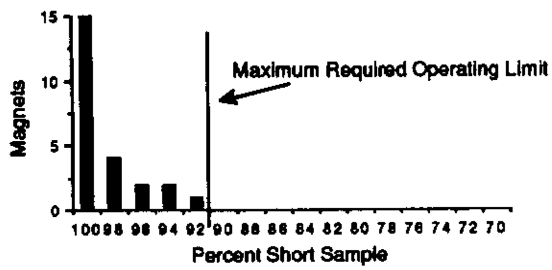


Figure 3. Quench current expressed as percentage of performance based on cable short sample.

Magnets with exceptionally large numbers of training quenches and/or lower than expected quench current are suspected to suffer from two possible problems discovered during production.

The splices between the upper and inner coils required forming the cable ends into a precise geometrical shape. This was done by bending the cable in a fixture and filling the cable with solder. In some instances strands popped out of place and were damaged by the fixture with the solder fill preventing detection of the damage. Splice damage is the probable cause of the less than expected quench performance.

Another problem was insufficient loading of the magnet ends. At both ends of the magnet the coil and splices were supported by four G-10 collet pieces. The preload was attained by pressing a tapered stainless-steel end can over the assembly. Variations in size of the G-10 pieces reduced the preload in the ends of several of the magnets. Figure 4 shows an example of the erratic quench behavior of a magnet with low end loading where successive quenches vary by more than 1000 A and the same magnet exhibiting normal training behavior after repair and sufficient end loading is restored.

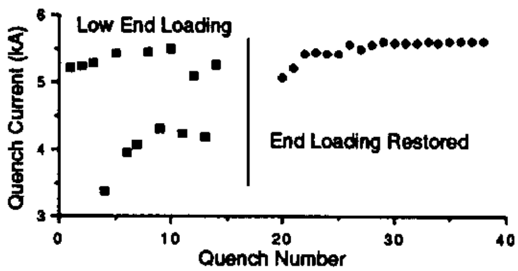


Figure 4. Erratic training behavior exhibited by a magnet (T6-009) with insufficient end loading and normal behavior after proper end loading was restored. The data were taken at 4.2K.

*Ramp Rate Dependence and Quench Locations*

Ramp rate sensitivity studies were done on all the magnets as part of the basic qualification procedure. Figure 5 shows the quench current as a function of ramp rate for several of the magnets. The high field point in the magnet occurs on the inner pole turn and preliminary studies indicate that this is where short sample dominated quenches occur. At high ramp rates, the quenches appear to occur in the solder filled upper-inner coil splice. A few of the magnets exhibited anomalously low ramp rate dependence which could be attributed to variations in production techniques, allowing some of the ends to be more efficiently cooled and therefore have a weaker ramp rate dependence.

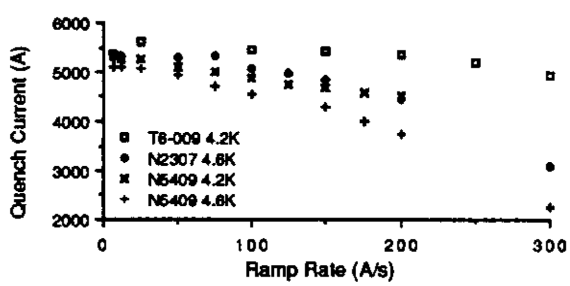


Figure 5. Ramp rate dependence of quench current.

*Temperature Dependence*

The quench plateau was measured for several magnets as a function of temperature both in the vertical dewar system and in the cryostat. Figure 6 is a plot of maximum quench current as a function of temperature for several of the cold masses in boiling helium and a cryostated magnet (B1321) cooled with subcooled helium.

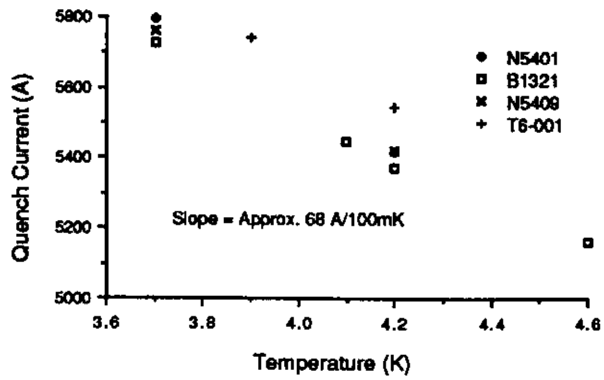


Figure 6. Temperature dependence of quench current.

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