Fermi National Accelerator Laboratory

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A NEW HIGH-GRADIENT CORRECTION QUADRUPOLE FOR THE FERMILAB LUMINOSITY UPGRADE

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Summary

Special superconducting correction quadrupoles are needed for the luminosity upgrade of the Fermilab Tevatron Collider. These correctors are part of the low-beta system for the interaction regions at B∅ and D∅. The requirements are high gradient and low current.

A quadrupole has been designed that meets the operating gradient of 0.63 T/cm at 1086 A. The one-layer quadrupole is wound with a cable consisting of five individually insulated rectangular strands. The five strands are overwrapped with Kapton and epoxy impregnated glass tape. The winding, curing and collaring of the magnet is accomplished in the same manner as Tevatron-like magnets using Rutherford style cable. Once the magnet is complete the five strands are connected in series.

A prototype quadrupole has been assembled and tested. The magnet reached a plateau current of 1560 A corresponding to a gradient of 0.91 T/cm without training. The measured field harmonics are substantially better than required.

Introduction

There are a number of applications for low-current superconducting magnets both in accelerators and in beam transport systems. The advantage of lower current is that current leads can be made smaller with correspondingly lower heat leak. Correction magnets in accelerators are examples of individually powered magnets requiring low current.

The low-beta system for the Fermilab Collider luminosity upgrade requires three high-gradient quadrupole correctors on each side of both the B∅ and D∅ interaction areas. These quadrupole correctors replace standard correction packages in the existing spool pieces.

Historical Background

The low current (50 A) in correction elements in the Tevatron is achieved by large numbers of turns of small diameter (0.020 inch) individually insulated conductors.[1] The conductors are randomly wound and vacuum impregnated with epoxy. If the current densities are suitably chosen, correctors made in this way can easily meet system requirements. The correctors in the Tevatron have demonstrated outstanding reliability over the past five years. The fields required of these magnets are rather modest (<1 T). When higher fields (>1.5 T) are needed, however, the increased forces require that the conductors be better supported and bathed in helium to improve stability.

The present approach has its roots in a scheme by Satti et al. to make a Rutherford cable in which the individual strands are insulated.[2] Once the coil was wound using the standard Tevatron-type winding, molding and collaring techniques, the individual wires are connected in series. In this method, however, the strand insulation is compromised by the large stresses to which the wires are subjected in the cabling process.

Lundy and Remsbottom invented another scheme in which the "cable" is made up of five parallel monolithic conductors each individually Kapton wrapped.[3] A prototype two-shell quadrupole was successfully made from this five-in-one cable for the final focus of the Stanford Linear Collider.

Design Requirements

The requirements for the new quadrupole corrector are shown in Table I. It was found that a single shell of five-in-one cable could achieve the required gradient. The conductor configuration resembles that of the single-shell quadrupole designed for the RHIC Collider at Brookhaven National Laboratory.[4]

TABLE I. Quadrupole Corrector Requirements.

Aperture	3.00 inches
Maximum gradient	0.633 T/cm
Current	≤1000 A
Maximum ramp rate	50 A/sec
Magnetic length	24 inches
Overall length	30 inches
Outside diameter	7.25 inches
Integrated 12-pole harmonic	<15 units

The Conductor

The dimensions of the five-segment cables are shown in Fig. 1. The specified cable width shown in Table II was selected so that the coil could be wound and cured using the same mandrel and mold tooling as used on the inner layer of the main low-beta quadrupole.[5] The lack of keystone is compensated by copper wedges between coil blocks. For convenience the material from which the strand was drawn was the same used in the main low-beta quadrupoles. The strand for the prototype, however, was drawn from standard Tevatron material. The characteristics of both conductors are shown in Table II.

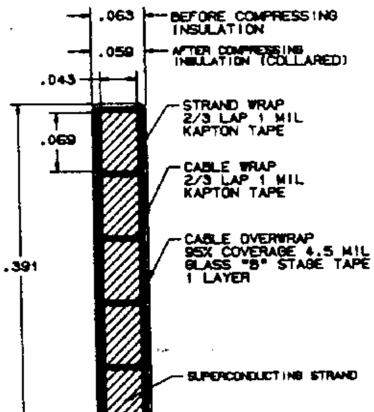

FIG. 1. The five-in-one cable.

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The insulation of the individual strands and the overwrap of the cable with Kapton and glass/epoxy tape requires the specially built wrapping machine schematically drawn in Fig. 2. Strand from five spools is fed into individual but synchronized wrapping heads; the insulated wires then come together and are guided through two more synchronized wrapping heads. The first head wraps Kapton on the cable, the second applies a barber-pole wrap of glass/epoxy tape. The resulting cable very closely resembles that of the Tevatron. It is, of course, much stiffer. The outer insulation wrap is strong enough, however, to hold the cable tightly together during the rigors of winding.

TABLE II. Conductor specification.

Strand (rectangular monolith)	Prototype	Final
Alloy	NbTi	NbTi
Copper to superconductor ratio	1.8:1	1.5:1
Number of filaments	2120	612
Twist pitch (twists/in.)	2	2
Filament diameter (microns)	20μ	44μ
J_c at 4.2 K and 5 T (A/mm^2)		2400
Conductor dimensions	0.043 x 0.069 in.^{2}	
Insulation:	2/3 lap, 1-mil Kapton	

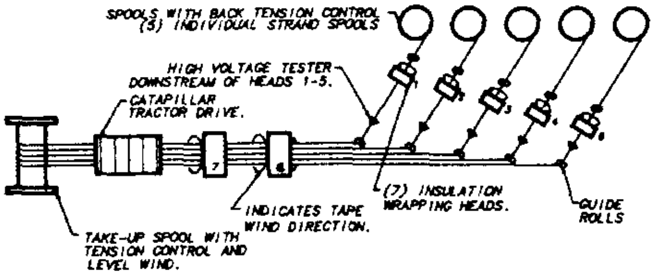

FIG 2. Strand/cable wrapping machine.

The Coil

The coil/cold mass specification is shown in Table III. The conductor geometry is shown in Fig. 3. In this design two wedges are used. Groups of five and three conductors allowed the first two harmonic coefficients (12-pole and 20-pole) to be made to vanish by adjusting the wedge angles and positions. The wedges have reasonable thickness and the conductors are sufficiently radial to provide a mechanically stable coil.

TABLE III. Quadrupole corrector coil/cold mass specification.

Coil Windings	
Number of turns per pole	13
Number of wedges	2
Inner diameter w/o insulation	3.008 in.
Outer diameter w/o insulation	3.778 in.
Insulation	
Parting plane insulation	Kapton (0.010 in. total)
Ground insulation	Kapton (4 x 0.005 in.)
Wedges	Same as cable
Pole Shims	304 stainless steel
Collars	60 mil 2024 T3 Al
Iron	16 ga. steel
Skin	304 stainless steel, 125 mil
Stored Energy	12,040 J/m at 1.1 kA
Inductance	19.9 mH/m

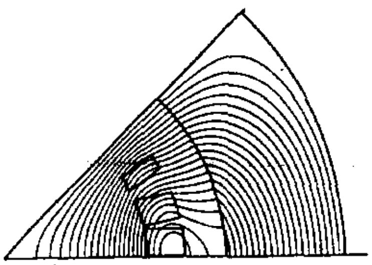

FIG. 3. Coil geometry.

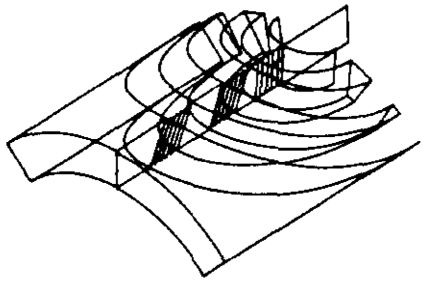

FIG. 4. Coil end geometry.

The design of the magnet ends has two 0.070 inch spacers between the three turns closest to the pole to insure that the maximum field is in the body and not in the ends. Two groups of five conductors were placed to make the 12-pole and 20-pole coefficients vanish. The ends have the additional feature that the cables lie with a constant perimeter and, therefore, minimum stress. The constant perimeter is an especially important requirement given the stiffness of the cable. The end geometry is shown in Fig. 4.

The load line for this coil and the expected characteristics of the production conductor are shown in Fig. 5. The maximum required operating current is also shown. The magnet is expected to have over 50% operating margin.

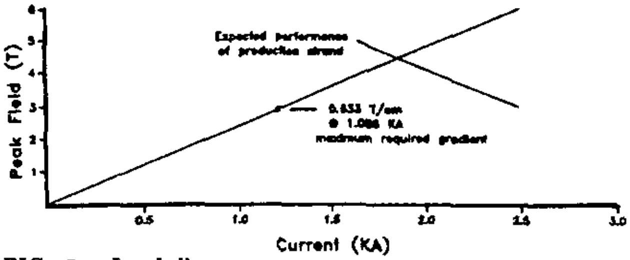

FIG. 5. Load line.

Magnet Assembly

The collared coil assembly (Fig. 6) for these magnets uses the same techniques and equipment employed in constructing the Tevatron quadrupole magnets. Therefore, only the tooling which is specific to this design needed to be designed and fabricated. The specific tooling involves coil winding mandrels, a coil forming/curing mold and interface tooling for the collaring press. The assembly process begins following the insulation of the cable.

The coils are wound onto a mandrel at constant tension (50 lbs.) around a steel winding key. The key end configuration provides a constant perimeter path for the cable to follow thus minimizing stress on the conductor and insulation system. After winding, the coils are packaged using preformed high carbon sheet steel retainers which serve to radially hold the coil and ends in their as-wound condition. Hardened steel bars, which are part of the packaging system, bear azimuthally on the coil. The mandrel, keys and packaging system are all part of a closed cavity mold system. Once packaged, the assembly is moved to a curing mold. The mandrel/mold assembly is then inserted into an existing Tevatron curing press. Following a preheat of 20 minutes at 120°F, the press compresses the tooling and creates a closed cavity mold condition. The constant perimeter ends[6] and coil tooling[7] designs followed a parallel development effort for SSC dipole prototypes being produced at Fermilab and are identical in concept. The coil is cured at 250°F for one hour and cooled to less than 90°F before the press is opened. The cured coil is unpacked and measured to ascertain its absolute size and modulus of elasticity.

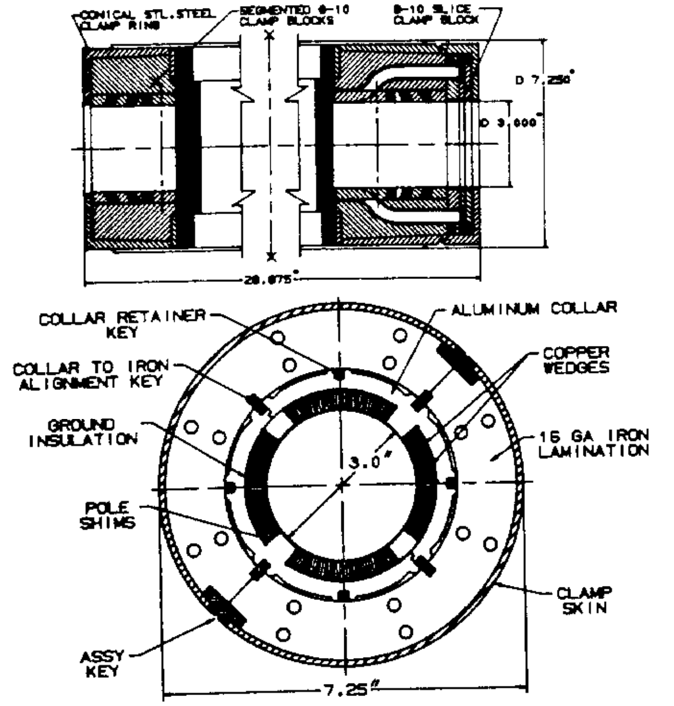

FIG. 6. Cross and longitudinal sections.

The completed coils are assembled onto a steel assembly mandrel. Ground and parting plane insulation is installed followed by the pole shims. The pole shims distribute the loading on the coils from the laminated collars. The assembly is overwrapped with shrink mylar to hold it together. The assembly is next suspended vertically and the collars are installed starting at the bottom. The shrink mylar is removed as the collaring progresses. The collars are compressed in an existing Tevatron press adapted to the collar geometry and the keys installed to retain the coil stress. Only the body of the coil is collared.

The coil ends are compressed using a collet type clamping system using a four-segment G10 clamp structure which compresses the coil end. The G10 clamps have an inside radius which is equal to the outer radius of the coil plus insulation. The outer surface of the G10 clamps is conical with the axis concentric with the magnet's axis. A conical-shaped clamp ring made of stainless steel is used to compress the G10 clamps radially against the coil ends. The body ground insulation is overlapped by the G10 end clamps (relieved for insulation thickness), so as to provide a minimum 3/8" long electrical leak path to ground.

Splicing of the individual strands is done after collaring and end clamping. To simplify the splice geometry and conserve longitudinal length required that a given strand in a cable be series looped through all coils before returning to an adjacent turn in the same coil. This has the disadvantage of not being able to monitor quarter coil voltage. The magnet, however, is self-protecting and does not incorporate a quench protection system. The spliced strands are insulated with a triple layer of one-mil Kapton. The splices are supported in G10 clamp blocks machined to match the splice geometry.

Iron assembly is accomplished in a special fixture. First the lower/outer skin is installed in the fixture followed by installation of preassembled iron lamination packs approximately 4" long. The collared coil assembly is installed into the lower iron assembly. The collared coil assembly is anchored to the iron through a 1/2" long key at the center. The keys are 90° apart. The key bars are installed followed by the upper iron packs and skin. The key bar on one side is clamped to the assembly fixture to assure the assembly is not twisted. The fixture and skin precision control straightness. Clamp blocks are installed against the upper skin. The clamp blocks are loaded to force the skin into intimate contact with the iron laminations and close the parting plane gap to zero. The skin is then welded to the key bars using a schedule to minimize distortions.

Performance

The first prototype was tested in a vertical dewar at boiling helium temperature. The magnet went to a current plateau of 1560 A without training (see Fig. 7). This corresponds to a gradient of 0.9 T/cm. This is to be compared with the requirement of 0.63 T/cm at 1086 A. The ramp rate dependence of the quench current is also shown in Fig. 7.

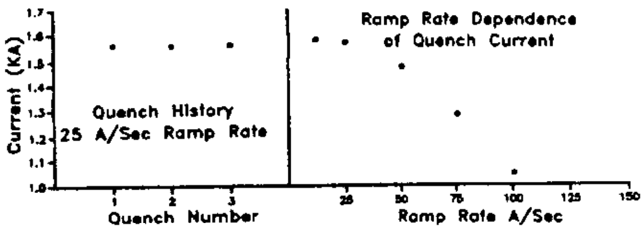

FIG. 7. Quench history and ramp rate.

The measured body field harmonics are shown in Table IV. The measured harmonics are substantially less than the upper limit of approximately 15 units.

The magnet has been shown to be self-protecting.[8]

TABLE IV. Measured field harmonics at one inch radius (x 10^{-4}).

Pole	Normal	Skew	Pole	Normal	Skew
6	-0.2	-2.9	10	1.7	-1.5
8	0.4	4.2	12	-6.4	0.2

Conclusion

A correction quadrupole has been successfully designed and built that is a unique solution to the requirements of the Tevatron low-beta system. The performance of the prototype exceeds all design requirements.

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