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# HIGH GRADIENT SUPERCONDUCTING QUADRUPOLES

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## Abstract

Prototype superconducting quadrupoles with a 5 cm aperture and gradient of 16 kG/cm have been built and tested as candidate magnets for the final focus at SLC. The magnets are made from NbTi Tevatron style cable with 10 inner and 14 outer turns per quadrant. Quench performance and multipole data are presented. Design and data for a low current, high gradient quadrupole, similar in cross section but wound with a cable consisting of five insulated conductors are also discussed.

## Introduction

Achieving the design luminosity at the SLAC Linear Collider depends on focusing the beams to an extremely small spot size ($\sigma<2\mu m$) at the interaction point. In general, the stronger the focusing power of the final quadrupoles, the higher is the luminosity that can be obtained. In this paper, we report on the development of superconducting quadrupoles for this application.

The basic design of these quadrupoles is an extrapolation of the design used in the Fermilab Tevatron.[1] They differ in having a smaller aperture, improved conductor, and they contain no ferromagnetic materials. The resulting magnetic field gradient is greater than 16 kG/cm, and is substantially higher than any previously used in a high-energy accelerator application.

In the final beam-transport telescope of the SLC, the minimum aperture required is determined primarily by background considerations. Off-axis electrons originating from beam-gas interactions upstream follow trajectories that make their maximum excursions from the nominal beam center occur in the three final quadrupoles. It has been estimated that a clear aperture of about 1.5 inches is necessary in this section to avoid an intolerable flux of secondary scatters into the experimental detector. Using this aperture as a design constraint, it became important to find the highest possible quadrupole gradients. Two options are being pursued. Conventional iron quadrupoles with a gradient of about 5 kG/cm are being built at SLAC for the start-up and initial operation because of their simplicity and relatively low-cost.

The superconducting quadrupoles described here are being built as replacements for these conventional quadrupoles. There are two reasons for doing this. The first is that with higher-gradient quadrupoles, a luminosity improvement of roughly a factor of two is possible over the initial machine configuration. The second reason for developing the superconducting quadrupoles is that they can be operated inside the experimental detector, immersed in a 6 kG solenoid field. This becomes especially important when a large second-generation detector, such as the proposed SLD, is brought into the SLC.

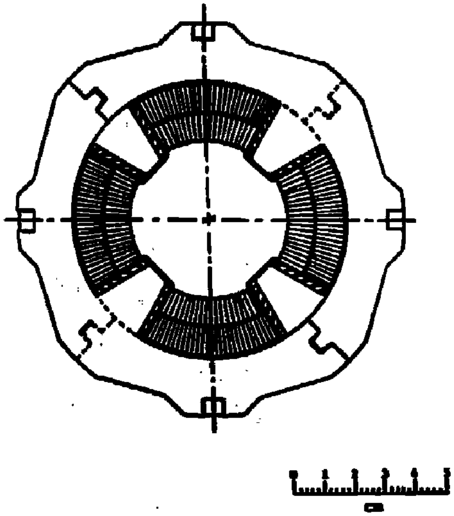

Figure 1-Quadrupole Conductor & Collar Cross Section

## Design & Construction

Figure 1 shows a cross section of the collared coil geometry that has been built and tested. The two shell design consists of 10 inner and 14 outer turns per quadrant. This arrangement fills up the angular space in the ±30° region about the x and y axes which implies a vanishing 12 pole normal moment for the magnet. The next symmetry allowed multipole, the normal 20 pole, is calculated to be $3 * 10^{-6}$ at 1cm. Here the multipole moment is defined as the field due to the multipole divided by the quadrupole field at the same reference radius, 1cm in this case.

Three different varieties of conductor have been used in prototype quadrupoles. The standard Tevatron superconducting high current (~5000 A) cable was used e.g. in magnet SL001. This Rutherford style cable consists of 23 strands each with a diameter of

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0.0268". There are 2050 Nb46.5w/oTi filaments with average diameter 8.7 μm. The strand has two complete twists per inch to minimize ac losses in applications where the magnets are ramped. The copper to superconductor ratio (Cu/SC) for this standard cable is 1.8/1. This ratio is relevant for longer magnets where the amount of Cu determines the temperature rise in the magnet winding when the magnet is quenched and all the stored energy is dissipated in the conductor.

Cable similar to the standard in cross section but with a lower Cu/SC ratio (1.3/1) was used in the construction of test quadrupoles SL003 and SL007. This cable is referred to as low beta cable since it is the conductor that exists in Fermilab quadrupoles that make up the Tevatron low beta insertion. Its virtue is the higher gradient that can be achieved due to the increased amount of superconductor. Although the filaments in this cable are larger (19 μm) and consequently produce increased ac losses, the planned operation of the final focus quads is dc.

In applications that require a single or a few superconducting magnets, rather than long strings characteristic of accelerators, much of the power saved by eliminating resistive losses is used by the load on the refrigeration system due to the multi-kiloampere magnet current leads. For the proposed SLC quadrupole triplet operating at 6300 A the current leads would contribute approximately 1/3 of the total cryogenic load. An alternative cable design with the same magnet cross section but with more turns could operate at a lower current, thus significantly reducing refrigeration costs. For example a low current option with 1/5 the high current capability would save an estimated 25% in refrigeration. In the case of low current dipoles there have been several examples that use low current conductor[3,4]. To follow up this option for the SLC quadrupoles we have developed a cable made from five parallel insulated conductors that allows us to retain most of the features of the high current design including magnet construction with the same tooling and techniques employed with the 23 strand cable. A cross section of this cable is shown in Figure 2 and the transverse dimensions of the five individual conductors are given in Table 1. Since this cable has the same keystoned cross section as the high current cable the collared coils are built the same way. After collaring, the coils' five parallel conductors are connected in series thus providing the same number of ampere-turns as in the high current case.

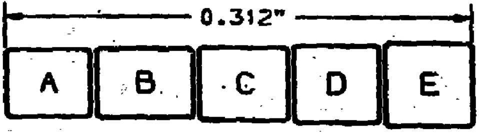

Figure 2-Five In One Cable Profile. Each of the conductors is separated from its neighbor with kapton insulation.

The low current cable is produced in one pass through an insulating machine constructed with seven separate taping heads. Five of the heads apply kapton insulation to the individual conductors, one overwraps the five conductor bundle with kapton, and one puts epoxy-impregnated fiberglass tape on the outside. Each conductor consists of ~480 NbTi filaments 40 μm in diameter embedded in a copper matrix. The Cu/SC area ratio is 1.7/1. Approximately 8,000 feet of each conductor type has been manufactured and tested. Typical short sample data for the separate pieces of conductor are given in Table 1.

Table 1
Five In One Cable Conductor Characteristics

| Conductor Type | A | B | C | D | E |
|---|---|---|---|---|---|
| Dimensions (in.) | | | | | |
| Width | .064 | .061 | .059 | .056 | .054 |
| Height | .043 | .045 | .047 | .049 | .051 |
| Critical Current (A) | | | | | |
| At 5 T | 1400 | 1350 | 1290 | 1271 | 1215 |

Four magnets have been built to completion and tested and a fifth is in the final stages of buss work at the lead end of the coil. They are listed below along with the identification of cable used in each.

| | |
|---|---|
| SL001 | Standard Tevatron Cable |
| SL003 | Low Beta Cable |
| SL005 | 5 in 1 Cable |
| SL006 | 5 in 1 Cable |
| SL007 | Low Beta Cable |

The overall physical lengths of the collared coils is 29 inches with inner winding lengths varying from a minimum of 21 inches to a maximum of 25-5/16 inches. Between the turns at the end of the magnet there are spacers to limit the build up of a high field point. The inductance of the standard quads is 1.1 mh while that of the 5 in 1 cable magnets is 27.7 mh. A picture of the collared coil assembly is shown in Figure 3.

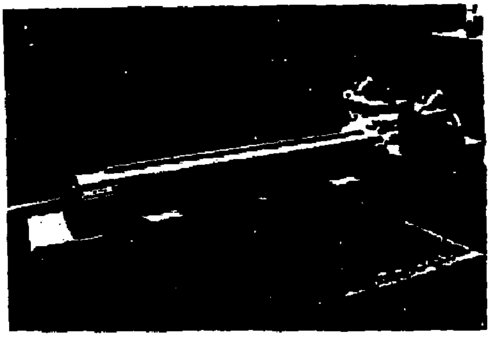

Figure 3-Prototype High Gradient Quadrupole. The overall length of the collared coil assembly is 29 inches. The clear aperture inside the magnet is 1.8 inches.

Table 2
Multipole Moments In Units Of $10^{-4}$ at 1 cm
(N = Normal; S = Skew)

| | | SL001 | SL003 | SL007 | SL005 |
|---|---|---|---|---|---|
| 6 P | N | -0.22 | -2.51 | (-16.0) - 8.1 | -1.88 |
| | S | -3.68 | -2.34 | (-13.6) -15.0 | 5.68 |
| 8 P | N | 0.96 | 1.19 | (- 4.5) - 4.0 | -0.71 |
| | S | -7.99 | -5.86 | (- 3.1) - 0.9 | 0.36 |
| 10 P | N | 0.35 | -0.41 | ( 0.74) - 0.63 | 0.73 |
| | S | -0.33 | 0.39 | ( 3.95) - 2.50 | 2.74 |
| 12 P | N | 7.63 | 1.10 | (- 4.27) - 3.11 | -3.79 |
| | S | 0.11 | -0.07 | ( 0.02) 0.04 | 0.27 |
| 14 P | N | -0.05 | -0.04 | (- 0.05) 0.05 | 0.02 |
| | S | 0.04 | -0.02 | (- 0.03) - 0.02 | 0.01 |

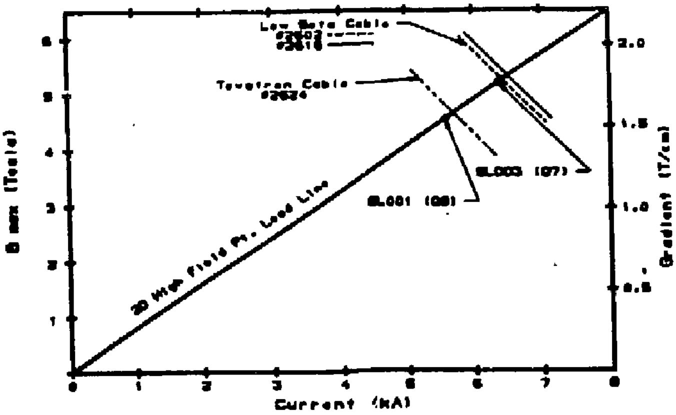

Figure 4-Magnet Performance For SL001 and SL003. The design load line for the magnet is shown as are the short sample data for cable from reels #2602, 2616, and 2624. Q7 and Q9 refer to the quench currents achieved on the seventh and ninth quenches, respectively.

## Tests and Performance

The multipole structure of the magnetic field has been extensively measured at room temperature using a lock-in amplifier technique that requires only a few amperes of ac current and a Morgan measuring coil[4]. Lower harmonics, such as the sextupole, have been checked with a rotating coil installed in a warm finger that is inserted into the magnet when it is tested at 4.2 K. The cold tests were accomplished by placing the collared coil in a vertical dewar of LHe at atmospheric pressure. Quenches are typically detected by monitoring the voltage difference obtained by bucking one half the magnet voltage against the other half.

The harmonic data are listed in Table 2 for each of the tested magnets. A few comments are in order. The moments for magnets SL001, SL003 and SL005 appear to be compatible with what might be expected in extrapolating Tevatron style magnets to smaller aperture. The magnet SL007 appeared to be abnormal as is indicated by the numbers in brackets. After the multipole measurement and cold tests the collars on SL007 were carefully removed and the single cable that passes through the magnet (buss) was observed to have excessive insulation. In fact compared to the other magnets in this series the buss was about 25 mils thicker than it should have been. A new buss cable with standard insulation was subsequently installed in the quadrupole and the moments (not in brackets) for SL007 were obtained. These multipoles are significantly smaller but still they seem rather large. It is conjectured that without recuring the buss coil with heat there will still be some hysteretic deformation of the coil which results in the observed multipoles. The other three prototypes have multipoles that meet the a priori specifications of less than $10^{-3}$ at 1 cm.

The quench test results for two prototype magnets are shown in Figure 4 where the magnet load line and cable short sample are indicated. Both magnets performed at better than 95% of short sample. Even the quadrupole SL001 made with standard Tevatron cable reached 1.5 T/cm by the ninth quench and SL003 made with low beta wire achieved about 1.7 T/cm by its seventh quench. The equivalent current density of the low beta conductor is 1950 A/mm² at 5 T for the cable.

The quench performance of SL005, the first 5 in 1 cable quadrupole, was 1135 A. This is 92% of the short sample for the poorest of the five conductors listed in Table 1. The eight percent difference from short sample is consistent with the inclusion of self field effects. The magnet showed very little ramp sensitivity, less than 1% of critical current, for ramp rates that varied from 4 to 80 A/sec. In general the performance of this magnet and the satisfactory behavior of the cable in winding the coils makes the conductor a good candidate for future low current applications. Its only drawback appears to be the tedious job of connecting all the coils together.

## Conclusions and Outlook

The prototype quadrupoles described here show that the gradient and field quality required for the SLC final focus are achievable. The magnets for the SLC will be fabricated in two lengths, 2.18 feet and 3.96 feet, and will be mounted, three to a cryostat, in a triplet configuration on each side of the interaction point.

## Acknowledgments

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