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# INTERNAL TRIM COILS FOR CBA SUPERCONDUCTING MAGNETS*

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## Abstract

In order to correct iron saturation effects and shape the beam working line, superconducting trim coils have been constructed, which operate inside the main coils.[1-2] Detailed studies of mechanical properties, quench behaviour, fields produced and hysteresis have lead to the production of accelerator quality coils generating the required strength harmonics up to cos (7θ). These are routinely installed in CBA main magnets and operate at 80% of short sample with negligible training in an ambient field of more than 5.3T.

## Introduction

Because of the high dipole fields (5.3T) employed in the CBA main ring and the comparitively large size of the beam at injection, the required capacity of trim coils producing multipoles higher than quadrupole is surprisingly large. This requirement arises from two sources: compensating for harmonics in the fields of the main dipole and quadrupole magnets, and tuning the beam. The approximate field strengths required at the 44 mm radius for beam tuning are:

$$
\begin{array}{lll}
B_1 & \cos 2\theta & 0.077\ \mathrm{T} = 145 \times 10^{-4}\ B_0 \\
B_2 & \cos 3\theta & 0.053\ \mathrm{T} = 100 \times 10^{-4}\ B_0 \\
B_3 & \cos 4\theta & 0.037\ \mathrm{T} = 70 \times 10^{-4}\ B_0 \\
B_4 & \cos 5\theta & 0.004\ \mathrm{T} = 8 \times 10^{-4}\ B_0
\end{array}
$$

Figure 1 shows the computed current needed in the 2θ, and 5θ coils for the combined effects.

## General Design

Because of space limitations and the large capacity required, the trim coils will be located concentric with the main magnets. This greatly increases the available length but generates other constraints:

i) The coils must be superconducting.
ii) The critical current of the superconductor will be degraded by the superimposed ambient field.
iii) The interaction of this large field and the current in the trim coil will produce large forces.
iv) Figure 2 shows that the space available for these coils is minimal.

## Coil Configuration

Because of the small space available the only practical solutions seem to be 2 or 3 layer coils made of cable roughly 1 mm in diameter. Two coil configurations have been considered: pure multipole layers where each layer is a single multipole, and nested windings[3]. This configuration makes it possible to produce several separate multipoles per layer. It was decided that the simplicity of 2 layers compensated for the complexity of the nested geometry, shown in Fig. 3.

## Conductor Choice

Experiments with rectangular conductor of the appropriate dimensions proved that it was extremely difficult to wind so a circular 7 or 10 strand cable has been used.

## Mechanical Construction

The inner and outer diameters are determined by other accelerator constraints. The Kapton layers are for electrical insulation. The thin layers of fiberglass on both radii of the coils are to assure a strong epoxy bond. It was found that this bond is one of the crucial parameters in successful operation. The coils are wound flat between constraining plates, then bonded with flexibilized epoxy resin and formed around the diameter of approximately 125 mm.

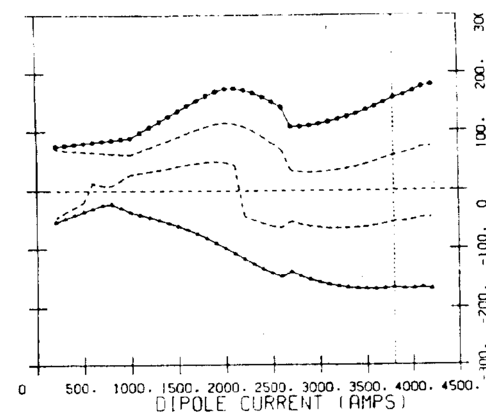


Figure 1. Peak currents expected in 3θ, 5θ combined coil as a function of main dipole current. The upper and lower dashed lines include the minimum requirement for positive and negative sextupole; the solid curves the maximum.

The Kevlar layers are pretensioned to constrain the coils radially. Kevlar was chosen because of its strength and non-conductivity. The G-10 stand-offs serve to locate the trim coil package within the main coils and provide the space between the trim and the main coils for coolant flow.

When the coils are energized in the main dipole field of 5.3 T large Lorentz forces are generated. The detailed analysis of these forces has been carried out by R. Shutt.[4] The stand-offs are placed at 0,90, 180,270° and sized so that a prestrain of approximately 0.2 mm (diameter) is placed upon the coils. This serves to minimize the deformations of the package. The forces and deformations produced for the design under discussion are tabulated in Table I.

Supporting the coils makes a significant reduction in the deformations and adequate support has been a goal of the design and development of these coils. The shear stresses are large (and essentially independent of whether the coil is externally supported or not); this emphasizes the importance of very good bonding within the coil itself.

## General Test Results

The following observations come from study of both small scale and full size coils and are believed to be applicable to any similar coils.

* Work performed under the auspices of the U.S. Department of Energy.

TABLE I

| Harmonic | $F_{radial}$ (N/m-radian) | Maximum Deflection without support (mm) | with support (mm) | Minimum Prestress (mm) | Max. Shear Stress $N/m^2$ |
|---|---|---|---|---|---|
| 3θ at test current | $82 \times 10^3$ | 0.4 | 0.10 | $74 \times 10^3$ | $7.6 \times 10^6$ |
| 4θ at test current | $82 \times 10^3$ | 0.06 | 0.06 | ------- | $4.7 \times 10^6$ |

a) The cable must be wrapped with kapton underneath any fiberglass or epoxy. Omitting this step produced extensive training as low as 50 amps and loss of training with polarity reversal.
b) Removing the outer fiberglass jacket from the conductor degrades the performance.
c) Bonding the conductor to the rest of the structure is very important. The friction produced by the multiple layers of Kevlar is insufficient.
d) Supporting the coil assembly so as to minimize the deformations is probably important. (The data to date do not contradict this idea.)

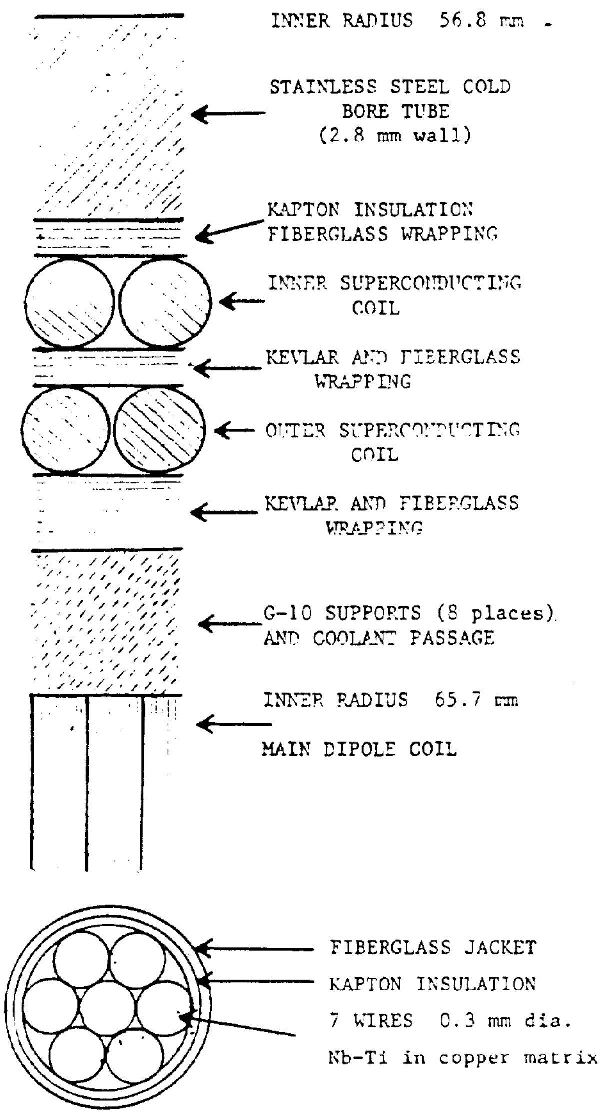


Figure 2. Radial cross section of CBA trim coil assembly, and superconducting cable.

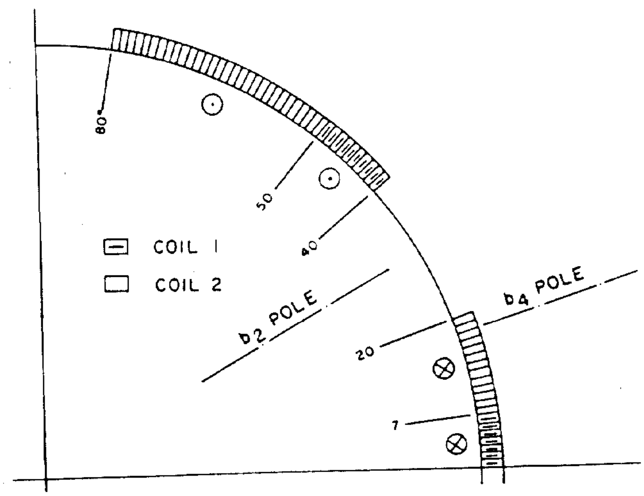


Figure 3. Cross section of coil geometry for a combined 3θ and 5θ coil.[2]

## Full Scale Tests

Thirteen full size long trim coils intended for operation in dipole magnets and two short trim coils intended for use in quadrupoles have been tested to date. The long trim coils have an inner layer which produces 3θ and 5θ harmonics; and an outer layer producing 4θ.

Figure 4 is a comparisonof the quench test results for a "marginal" trim coil and an excellent one. The former (XT9.1) shows a strong dependence of peak current upon the number and polarity of harmonics excited, in addition it shows large amounts of training and some loss of training upon polarity changes. These are all believed to be symptons of mechanical defects in the structure. The data below (for XT15.1) illustrates the performance when the known defects were remedied. There is no training, and only weak dependence upon polarity chosen.

Figure 5 summarizes the results of full scale dipole coil tests to date. Referring back to Fig. 5 one sees that the limiting current which a trim coil can reach is a function of the currents in all segments of the coil and the amount of training. This information has been simplified for plotting in Fig. 5 by considering only the worst combination of currents (which varies from coil to coil); the low point of the arrow is the first quench in this configuration, the dot in the center is the value reached after approximately 5 quenches in each configuration, and the tip of the arrow is the highest value reached after testing. In some cases the coils exhibit detraining (i.e., running with reversed polarity degrades the performance in the original polarity and the coil must be retrained to reach maximum current). For coils where this occurred, the low point of the detraining has been plotted.

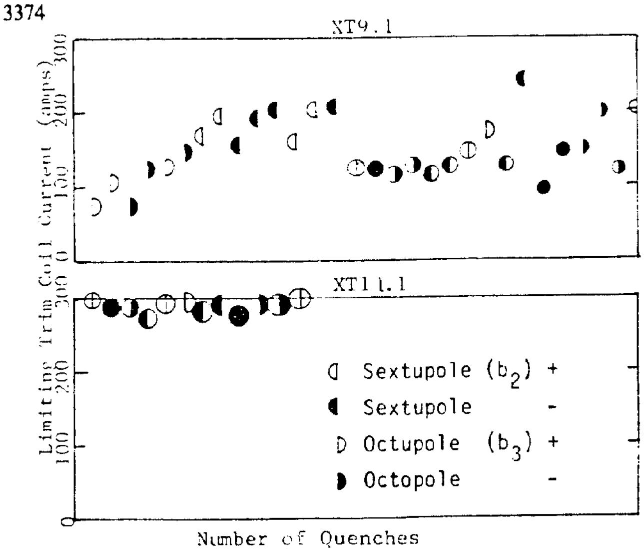


Figure 4. Comparison of training behavior of a "poor" and excellent trim coil.

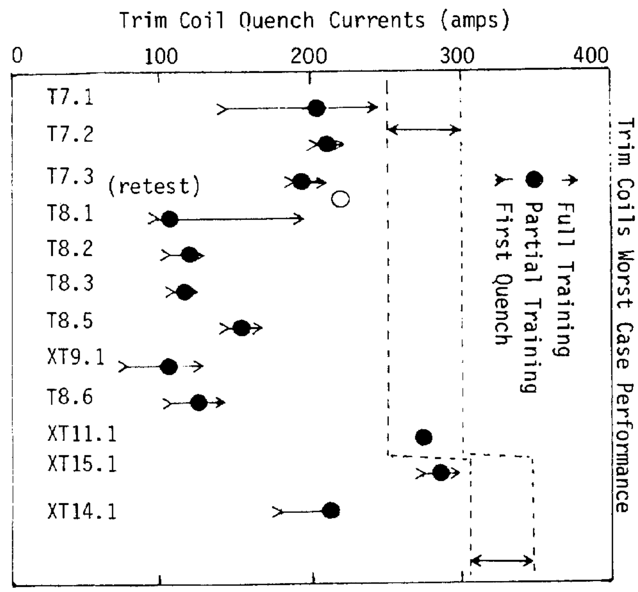


Figure 5. Summary of test results of full size trim coils. The region between the dashed lines is the mesured critical current range for the conductors used.

Coils T7.1 through T7.3 had no known defects in construction, but their mechanical support against the main coils was inadequate. This group of coils exhibited modest amounts of training and limiting performance approaching the conductor critical current. Coil T7.3 was partially retested with adequate support (the open circle in the figure). It is not known whether the improvement in performance is due to the support or to the limitations of the retest.

Coils T8.1 through T8.6 had known defects in their internal structure. All of these coils suffered from extensive training and polarity dependence. XT9.1 did not have a fiberglass jacket around the conductor and seems worse than the rest.

Coil XT11.1 is the end result of the knowledge acquired with the earlier tests. Care was taken to assemble it solidly and to support it rigidly within the main magnet.

Detailed examination of the data for this coil exhibits:

i) no training,
ii) no dependence upon the overall excitation configuration (except for the small effect due to self-fields),
iii) no detraining,
iv) The coil was also tested at 5.0°K in addition to the standard 4.5°K, this reduced its peak current by 48 ± 12 amps, the calculated reduction for this NbTi cable is 58 amps.[5] Together these observations are strong evidence that this coil achieved the conductor critical current.

For XT15.1 and XT14.1 the seven strand conductor used previously was replaced with 10 strand cable, with a 40% higher critical current. The performance of XT15.1 is excellent. Examination of the detailed data indicate that its performance was limited by deformation of the entire structure. XT14.1 did not have the fiberglass outer jacket around the conductor and its performance is inferior.

## Quadrupole Trims

In addition the standard accelerator quadrupole magnets will also contain trim coils. These are designed to provide 1θ(dipole) correction in the inner layer; and 2θ and 6θ in the outer layer. The main quadrupole field at the trim coil location is only 4.3 T compared with the 5.3 T in the dipole magnets. This makes the trim coil construction problem easier, however, the choice of harmonics for the quadrupole trim produces a significant problem. If the 2θ coil is not correctly aligned azimuthally with the main field, it experiences a torque of $9.7 \times 10^3$ N-m/m-milliradian of misalignment. Typical alignment precision in prototype tests has been 4 milliradians. One series of tests were performed with the coil inadequately secured against rotation. It quenched at 70 amps; retests of this coil and a second coil with adequate support and care in alignment produced no quenches at 300 amps. This mechanical coupling precludes any attempt to insert a skew quadrupole trim (rotated by $\pi/4$) in a regular quadrupole.

## References

1. J. Donhowe, ISABELLE Technical Note No. 169 (1980).

2. W. Sampson, et al., BNL 22521 (1977).

3. H. Hahn, ISABELLE Technical Note No. 345 (1982).

4. R. Shutt, ISABELLE Technical Note No. 364 (1982).

5. E. Bleser, ISABELLE Technical Note No. 372 (1982).