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# CORRECTION MAGNET PACKAGES FOR THE ENERGY SAVER

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The design of the superconducting correction coil system for the Energy Saver has been finalized and production is underway. The requirements of low current (50A) and concentric placement of multipole elements posed difficult and unique design problems.

## DESIGN SPECIFICATION

The basic half cell of the Energy Saver consists of four dipoles, a quadrupole, and a spool piece. The spool piece contains all of the multipole elements needed for corrections to the main magnet fields, chromaticity adjustments, and extraction.

In general each spool contains two correction packages each with three concentric magnetic elements. The first package called DSQ contains a dipole, sextupole and quadrupole. The second (OSQ) has an octupole, skew sextupole, and skew quadrupole (Figure 1).

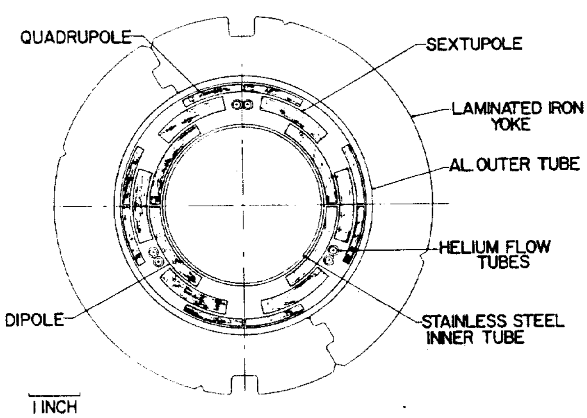


Figure 1 Cross Section of DSQ Correction Package

The DSQ comes with either a horizontal or vertical bending dipole so that there are all together three distinct packages. The specification for the various elements are as follows:

| Multipole | 2 Pole | 4 Pole | 6 Pole | Skew 6 Pole | 8 Pole |
|---|---|---|---|---|---|
| No. Turns | 2x572 | 4x273 | 3x606 | 3x495 | 4x367 |
| Inductance (mh) | 673 | 352 | 391 | 281 | 130 |
| $\int B\text{-}dl$ (kG-in.) | 183 | 66 | 53 | 42 | 32 |

$\int B\text{-}dl$ is the integral field strength at 1 inch radius at 50A current. The package length is 30 inches.

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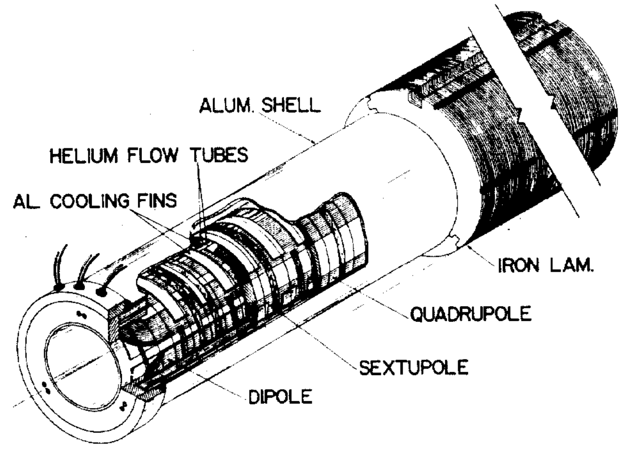


Figure 2 DSQ Assembly

The coil elements may be operated at different relative strength and polarity as required by the control system. Although it is likely that excursions of less than ±25A will be needed, the coils are designed to be stable to ±50A.

Magnetically the harmonic content of an individual coil element must be only a few percent of the strength of the principle multipole.

## DESIGN CONSIDERATIONS

Correction coil current leads penetrate the cryostat at each spool. With more than a thousand pairs of leads and a limited heat load budget, the coils must operate at low current. Much of the experience with high current (>1 kA) superconducting magnets is not applicable to low current magnet design. In particular large numbers of turns of small dimension wire must be properly placed, restrained, and cooled for reasonable stability. Good mechanical support is possible if the wires are in a regular array. In the thin saddle coils of this application the best that can be achieved is a random wire array of fairly uniform density. Unfortunately a randomly wound coil does not lend itself to effective external restraint. Tight banding causes non-uniform force distribution and can result in failure of the insulation and possibly the wire itself. Wire support in our case is achieved with epoxy impregnation. Highly filled epoxy is desirable for optimum thermal conductivity as well as improved crack resistance. The price of impregnation, of course, is the exclusion of helium and reduced stability.

During the evolution of the correction package a design was sought which would be very stable at the nominal operating current[1,2]. The earlier elements, operated alone, would train easily to 130A (80% of short sample). When the elements were subjected to the fields of the other elements, however, the resulting fields (and forces) at the conductors are of different magnitude and direction. When the three coil elements were operated at the same current but all relative polarities, the maximum stable current was only between 40 an 50A. When operated individually the magnets would



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train again to their old values.

This "hysteresis of training" requires that the coils be operated in a range below the onset of training (ie., where heat pulses from wire motion are below the quench threshold). To insure stable operation of the coils under all conditions of current and polarity, we enlarged the wire diameter (lowered the current density so that all the coils operate stably, well above the nominal operating current. At 50A each coil element is operating at about 25% of its own short sample limit.

The effect of beam radiation heating on the stability of the correction coils is not known. It is also extremely difficult to test one of the correction packages under radiation conditions that would exist in the machine. The inner coil is likely to be the most sensitive to radiation heating as the heat paths are longest. To assist in the cooling of the inner layer, a series of tubes are imbeded in the package and run the length of the coil. Fins of high purity aluminum soldered to tubes surround the inner layer. This system of flow tubes is expected to improve the cooling of the inner coil by about a factor of ten.

## DETAILS OF FABRICATION

The 0.020 inch diameter conductor used in the correction coils has 500 Nb-Ti filaments and a copper to superconductor ratio of 1.45 to 1. The conductor has a short sample limit of 150A at 5T. The wire is insulated with heavy Omegaclad, a multiple pass coating of Polyester-Amide/Polyester-Imide.

Each coil is random wound on a rotating mandrel. The wire, under about 15 pounds tension, first passes through a bath of high temperature cure epoxy cut with five parts acetone. The bath leaves an epoxy layer a few tenths of a mil thick. Once the requisite number of turns is achieved, the exposed edges of the coil are compressed to give the necessary coil dimension. The assembly is then heated in an oven to cure the epoxy to produce a rigid, though completely porous coil. The coils are assembled on an inner stainless steel tube where each correction element is applied one layer at a time (see Figure 2). G-10 keys are used to locate and index the coils. Care is taken to make the assembly completely permeable to the impregnant. Once each layer (element) is finished, it is bound with shrink Mylar tape. The tape is heated to force that layer to the proper radial dimension. The tape is removed and replaced with a few turns of fiberglass roving to maintain the shape of the layer until the next layer is in place. The inner layer (the sextupole coil) is surrounded by 0.010 inch thick by 0.5 inch wide high purity aluminum strips soldered to a stainless steel tube that runs the length of the magnet. There are six flow tube assemblies per package.

The complete coil assembly is inserted into an aluminum tube. The stainless inner tube, aluminum outer tube, and two temporary end caps constitute the vacuum impregnation fixture. The assembly is evacuated and impregnated with Stycast 2850FT. During impregnation the resin and fixture are held at 50C to minimize viscosity. The package is cured at 120C for 3 hours using circulating oil in a jacket surrounding the package. Finally a laminated iron yoke is attached to the coil.

## PERFORMANCE

Each coil element within the package will train in a manner typical of potted magnets. After 5 to 10 quenches the coil will reach 80 to 85% of the short sample limit. The short sample limit is about 215A for each of the coils. When the coils are operated simultaneously, however, the operating current is sharly reduced.

The correction package as a whole is tested for maximum stable current by ramping each element up to the same current one after the other and then successively ramping them down. The polarity of one of the elements is reversed and the ramping sequence is repeated. All three relative polarities are tried. The current is stepped until the sequence cannot be repeated without quench. The current at which this stability occurs is typically limited to 60 or 70A. Occasional quenches occur during the test sequence but the limiting current is quickly reached and repetition of the sequence does not cause the package to "train" to increasingly higher current. The limiting current achieved in the packages tested so far, however, is comfortably above the requirement.

Magnetic performance is best illustrated by the harmonic content of a typical OSQ package. The numbers below are fractions of the principal multipole (normal/skew). The measurements are made with respect to the approximate center of the coils. The final center will be selected to minimize undesirable harmonics.

| Multipole n | Octupole | Skew Sextupole | Skew Quadrupole |
|---|---|---|---|
| 1 | -.006/-.030 | - | -.017/.020 |
| 2 | .029/.017 | .065/.032 | 0.0/1.0 |
| 3 | -.049/.056 | 0.0/1.0 | .003/.001 |
| 4 | 1.0/0.0 | .003/.001 | -.001/0.0 |

## DISCUSSION

A correction coil system has been developed for the Energy Saver which meets both stability and field quality requirements as they are understood at this time. Studies of the effects of superposed fields on training and stability will continue in order to improve the margin of reliability of the coils. The use of varing external fields on superconducting magnets may, in fact, prove to be a valuable tool in the understanding of the process of training especially in impregnated magnets where conditions for stability are not well understood.

The performance of the correction coils under beam conditions is not yet known. The effects of radiation heating on the stability of the coils is difficult to calculate. Tests of parts of the Saver in the main ring tunnel over the next several months should, however, resolve this question.

## REFERENCES


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