Construction and Measurement of Large Permanent Magnet Quadrupoles*

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Introduction

As part of a luminosity upgrade program at the Cornell Electron Storage Ring we have built four rare earth cobalt (REC) permanent magnet quadrupoles with 10.5 cm diameter bore, 28 cm outer diameter, 122 cm length, and mass about 450 kg (including 280 kg of Co_5Sm). The pole-tip field is 7.8 kG and field errors are less than 0.1% of the quadrupole field at 75% of pole-tip radius.

The quadrupoles are mounted with their inner faces only 65 cm from the interaction points in CESR and two of the quadrupoles are embedded in the 10 kG solenoidal field of the CLEO experimental detector.

This places especially strict requirements on the stability of the REC magnet material, and much of our effort has been devoted to measurements of stability of the quadrupole fields. We describe the construction and the magnetic measurement and tuning procedures used to achieve the required field quality and stability.

Construction

The quadrupoles are built with sixteen azimuthal segments (fig. 1) with the direction of magnetization following Halbach's prescription.[1] For ideal magnets, with magnetization uniform and correctly aligned, the next lowest multipole field allowed by symmetry is n=18 (where n=2 is quadrupole). In practice the important defects are lower order multipoles caused by the permeability, piece to piece variations in magnetization, and errors in positioning of the magnets. These field errors may be reduced by matching magnets with similar properties and by a tuning procedure in which small displacements of the magnets are made so as to cancel measured errors.[2]
The mechanical structure of our magnets was designed to facilitate this tuning operation.

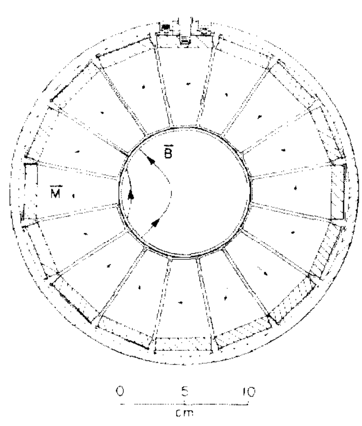

Fig. 1 Schematic of quadrupole module showing directions of magnetization and representative field lines. The shaded material is stainless steel.

Each quadrupole is built from eight 15 cm long modules, permitting most of the magnetic measurements and tuning to be performed on the individual modules before final assembly. A completed module is shown in fig. 2. The basic support structure is a machined stainless steel shell with wall thickness 1.14 cm and outside diameter 27.2 cm. Sixteen sets of holes for mounting the magnets are spaced around the shell, and sixteen screw holes at the end of the module are used

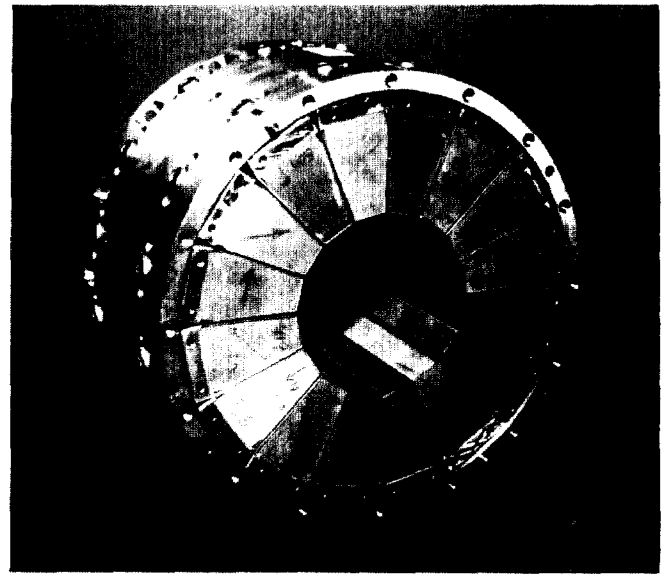

Fig. 2 Completed Module.

to fasten it to its neighbor, with alignment between modules provided by dowel pins.

The REC magnet material is brittle so that direct use of fasteners such as screws is not practical. We instead mounted each 15 cm long magnet on a stainless steel backing plate, and a formed 0.4 mm stainless steel skin was tensioned over the magnet with a force of about 5000 Newtons and spot welded to the backing plate (fig. 3).

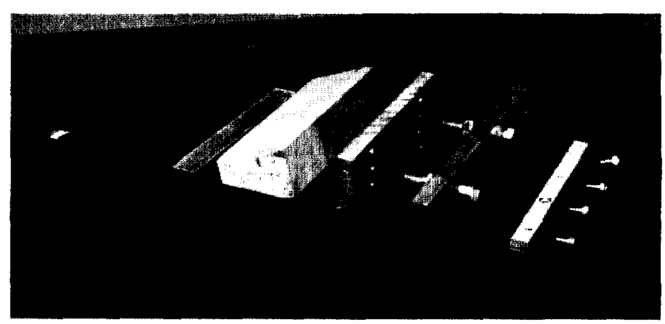

Fig. 3 Exploded view of magnet, backplate, and skin.

The backing plate (with magnet) was then screwed fast to the support shell. The position is determined by four set screws whose tips sit in conical holes in the backing plate, and which permit about +- 1mm of adjustment to the radial position of the magnet, as well as some adjustment of the tilt. Thus all mechanical support is provided by the outer shell and adjustment of magnet positions does not require access to the inside of the assembly.

Acceptance Measurements

Magnets were ordered with 3 easy axis orientations (0,45,and 90°), magnetized as shown in fig. 1. Each magnet was approximately 5.2 cm x 3.5 cm x 15 cm long with mass 2.2 kg. Because of the difficulty of producing large blocks of Co_5Sm with good magnetic properties each magnet was a glued assembly of 2 or 3 shorter pieces. The magnets were supplied by Vacuumschmelze GmbH in Hanau, FRG, and use their proprietary VACOMAX 170 material.

All magnets received (about 600 pieces) were tested for net dipole moment and dipole orientation using a Helmholtz coil attached to an integrator (magnetization is dipole moment/volume). The specifications were $\mu_0 M>8.8$ kG and $|\Delta\theta|<3^{\circ}$. The magnetization of all pieces passed and the angle errors were almost all less than 1°.

In the assembled quadrupoles some regions of the magnetic material operate close to B=0. We have previously tested the stability of several Co_5Sm based magnet materials and find that for exposure to B=0 the typical drop in magnetization is several percent, and occasional pieces fall much more.[3] We therefore included a specification that the magnetization of each piece fall by less than 6% on exposure to B=0.

Coercivity of each magnet was measured by applying an external field to give an average value of $\mu_0 H$ in the magnet of -9 kG (or B=0) and afterwards repeating the Helmholtz coil measurement. Several percent of the magnets failed this test and were returned to the factory. Significant batch to batch variations were observed.

Magnetic Measurements and Tuning

Measurements on each module were performed with a vertical rotating coil assembly. Two coplanar coils were connected in series so that both dipole and quadrupole signals were cancelled, enhancing sensitivity to the higher multipoles.[5] The coils rotated at 1 Hz and an optical shaft encoder provided a clock signal to a transient digitizer which recorded the amplified voltage signal and transferred the data for several turns to a computer. The coils were much longer than the 15 cm quadrupoles so that they integrated over the fringe field. Sensitivity was less than 1 Gauss per multipole at 4 cm (the radius of the outer arm of the measurement coil), compared to the quadrupole field of 6000 Gauss.

Using results of the Fourier transform multipole analysis the computer calculated radial motions for the 16 magnets which would cancel unwanted multipole content. The sixteen degrees of freedom can be used to independently adjust sixteen moments, in particular n=2 even (quadrupole), n=3-9 even and odd, and n=10 even. All other moments are then dependent variables, for example, the sextupole and dipole cannot be independently adjusted. In practice for each iteration a set of magnet movements was calculated which would zero moments n=3 through 10 even. Because the adjustments were performed in a somewhat casual fashion with an Allen wrench, several iterations were required to reduce the moments to < 1 Gauss/multipole at the 4 cm radius. Typical magnet motions were 0.1-0.4 mm for first iteration and 0.0-0.05 mm for the final. Some use was also made of the ability to tilt the magnets, for example by tilting all 16 magnets the direction of the quadrupole field can be rotated with respect to the support shell. The initial tuning operation required one to two hours per module. One consequence of this method of tuning is that the initial positioning of the magnets need not be extremely precise (it was not).

Stabilization

Permanent magnets operating with H sufficiently negative are metastable, with magnetization decaying away roughly logarithmically with time. REC magnets are usually "stabilized" at the factory before shipping by heating them to a temperature considerably higher than they will experience in service. This is effectively an accelerated aging which moves the magnet to a lower magnetization with a slower rate of change.

For the quadrupoles described here the magnetic environment of each magnet changes radically when it is inserted into the quadrupole. Therefore the stabilization treatment is best performed after assembly. Each completed module, after tuning, was heated to 120° C for about one half day, cooled, and remeasured. Some quadrupoles showed almost no change in multipole content while others developed large defects corresponding to drops in magnetization for particular magnets. The offenders were all magnets with azimuthal direction of magnetization, in which material at the inner radius operates near B=0. The problem showed only partial correlation with the coercivity measurements made during the acceptance tests; one possibility is that there are significant variations in coercivity within the magnets and that the test measures the average value while the multipole content is especially sensitive to material at the inner radius. Several of these magnets were replaced and all modules were retuned to low multipole content. A second exposure of several modules to 120°C resulted in no additional change in multipole content.

Two of the four completed quadrupoles operate in the 10 kG field of the CLEO detector. Modules with higher average coercivity were chosen for these quadrupoles. They were subjected for about a minute to axial fields of +-15.5 kG in a large electromagnet, and were then remeasured and retuned. After about three iterations additional exposures resulted in no measurable change in the multipole content. The typical decrease in quadrupole field resulting from this treatment was 0.5% .

Figures 4a-e show a partial history of one of the modules during the tuning and stabilization sequence. The success of the tuning in eliminating multipole moments up to n=10 is evident.

The standard deviation in the quadrupole strength of the modules after these treatments was 1.4% and the full range was 5% . A narrower range could have been achieved by partially demagnetizing the strongest magnets using high temperatures or reverse fields.

Measurements on Completed Quadrupoles

After assembly of the 15 cm modules into pairs, with the pairing chosen to give partial cancellation of dipole moment, the multipole content of each pair was measured using the vertical coil apparatus. The measurements were consistent with linear addition of fields and no additional tuning was performed. Pairs were then assembled into half quadrupoles which were measured using a horizontal rotating coil with somewhat reduced sensitivity compared to the vertical apparatus, and the half quads were joined to yield the completed quadrupoles.

For measurements on the 122 cm quadrupoles in the horizontal position, coils were constructed on lengths of 60 mm glass tubing to minimize sag. A pair of coplanar coils was used for multipole measurements and a coil with eight symmetrically spaced turns was used for measurement of the quadrupole field. No evidence was observed for differences in the multipole content of the complete quadrupoles compared to the modules although the sensitivity of the measurement was somewhat lower because the outer radius of the measurement coil was three rather than four cm.

The eight turn coil was used to intercalibrate the quadrupole strengths of the four REC quadrupoles with our standard electrically powered arc and interaction region quadrupoles at the 0.1% level of accuracy. It was also used to measure the temperature coefficient of the REC quadrupole field; the result was $\Delta Q/Q$=0.05%+-0.01%/$^{\circ}$C, in agreement with the manufacturer's value of -0.04%/$^{\circ}$C for reversible change in magnetization with temperature for VACOMAX 170 . Another measurement placed a limit on the time rate of change of the quadrupole field. Measurements taken three weeks apart showed a fractional decrease in the quadrupole field of 0.01%+-0.01%.

For use in storage rings very accurate knowledge of the direction of the quadrupole field with respect

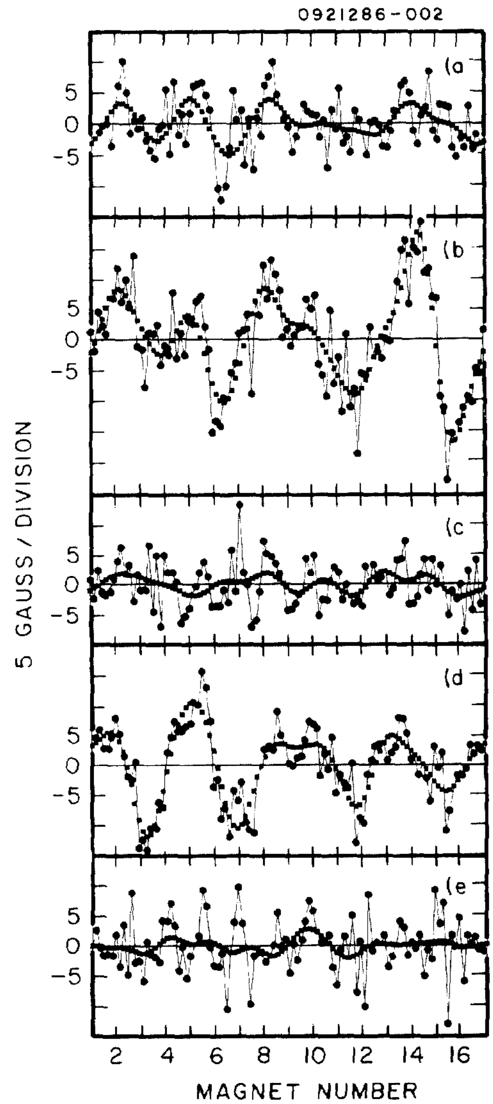

Fig. 4 Measured radial magnetic field at 4 cm radius for module #10 after subtraction of dipole and quadrupole terms, plotted vs. azimuth (magnet # 1-16). The conditions are: a) after initial tuning, b) after heating to 120°C, c) after replacing magnet #15, reheating, and retuning, d) after exposure to a 15.5 kG axial field, and e) after retuning and final exposure to 15.5 kG. (■) includes multipoles n=3 through n=10 even and (●) includes n=3 to n=50 .

to the mechanical structure is required. The vertical coil apparatus permitted comparison from one module to another at the level of 2 milliradians and this information was used to tune some modules closer to the average value and to sort modules so that those in a completed quadrupole would differ in orientation by only a few milliradians. The multi-turn coils were not suitable for measuring an absolute angle. This was done using a floating wire technique; two 25μ gold plated tungsten wires were strung through the quadrupole and followed oppositely curved trajectories when energized with current. These wires were observed with an optical survey instrument as the quadrupole was rotated to bring them vertical. The measured rotations between the mechanical and magnetic axes were between 0 and 4 mrad, with estimated uncertainty +-2 mrad.

A final set of measurements was made after the quadrupoles had been installed in the storage ring. The quadrupole field and the multipole content of one of the quadrupoles installed in the CLEO detector were measured with the detector solenoid off, and energized to fields up to 10 kG. The results, for solenoid at 10 kG, compared to 0 kG, are for the quadrupole field $\Delta Q/Q$= 0.01%+-0.01%, for the sextupole, ΔB= 0.5+-0.5 Gauss at 3 cm radius, and for higher multipoles $\Delta B <$ 0.5 Gauss at 3 cm radius. Thus the field quality remains good in the 10 kG field. This also implies that there is very little mechanical motion due to the torques on the magnets. During these tests several quenches of the superconducting solenoid were accidentally induced, with no observable effect on the multipole content.

Cost of the Quadrupoles

Cost was completely dominated by the REC magnets, about $75,000 for the 280 kg making up each quadrupole. The additional cost for machined stainless steel parts was about $8,000 per quadrupole and the labor costs for assembly and measurement, if accounted separately, about $10,000 . An alternative would have been to use iron-free superconducting quadrupoles. If superconducting quadrupoles of appropriate size had already been designed and tooled and if sufficient refrigeration power were readily available this would be the cheaper solution. Lacking these, and not requiring a magnet with variable strength, the REC solution is competetive. One should also note the small outer diameter compared to iron quadrupoles of similar strength.

Acknowledgements

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Footnotes

1. K. Halbach, Nucl. Instr. and Meth. 169, 1,1980
2. K. Halbach, Nucl. Instr. and Meth. 198, 213,1982
3. S.W. Herb, IEEE Trans. Nucl. Science NS-32, No. 5, 3578, 1985
4. K. Halbach, PEP NOTE #208,1976, (LBL,SLAC Technical notes)