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 Co5Sm). The pole-tip field is 7.0 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 m=18 (where m=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.

The mechanical structure of our magnets was designed to facilitate this tuning operation.

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 Co5Sm with good magnetic properties each magnet was a glued assembly of 2 or 3 shorter
The magnets were supplied by Vacuum Schmelze 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 itself). The coils were made of $\mu_0$ 8.8 kG and $|\Delta R|(<3\%)$. The magnetization of all pieces passed and the angle errors were almost all less than $1^\circ$.

In the assembled quadrupoles some regions of the magnetic material operate close to $B=0$. We have previously tested the stability of several Ce-$Gd$ 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. We therefore included a specification that the magnetization of each piece fall by less than 6% on exposure to $B=0$.

Using results of the Fourier transform multipole analysis the computer calculated radial motions for the magnets which would cancel unwanted multipole content. The sixteen degrees of freedom can be used to independently adjust sixteen moments, in particular $m_2$ even (quadrupole), $m_2$ odd, and $m_{10}$ 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 $m_3$ through 10 even. Because the adjustments were performed somewhat sequentially rather than simultaneously, several iterations were required to reduce the moments to less than 1 Gauss/multipole at 4 cm (the radius of the inner radius of the measurement coil), compared to the quadrupole field of 800y Gauss.

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 fields of $+16.5$ kG were chosen for each magnet, 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%.

Two of the four completed quadrupoles operate in the 10 kG field of the CERN detector. Modules with higher average coercivity were chosen for these quadrupoles. They were subjected for about a minute to a field of $-15.5$ kG which caused each magnet, 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%.

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The measured radial magnetic field at 4 cm radius for module #10 after subtraction of dipole and quadripole 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, re-heating, 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 odd.

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 CLEO detector. 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 290 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 tooling 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 competitive. One should also note the small outer diameter compared to iron quadrupoles of similar strength.

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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
4. K. Halbach, PEP NOTE #208, 1976, (LBL,SLAC Technical notes)