# Permanent Magnet Quadrupoles for CESR Phase-III Upgrade *

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*Abstract*

The CESR Phase-III upgrade plan includes very strong permanent magnet quadrupoles in front of the cryostat for the superconducting quadrupoles and physically as close as possible to the interaction point. Together with the superconducting quadrupoles, they provide tighter vertical focusing at the interaction point. The quadrupoles are built with Neodymium Iron Boron (NdFeB) material and operate inside the 15 kG solenoid field. Requirements on the field quality and stability of these quadrupoles are discussed and test results are presented.

## 1 INTRODUCTION

The Cornell Electron Storage Ring (CESR) phase-III luminosity upgrade plan includes very high gradient, 27.6 cm long permanent magnet quadrupoles (PMQ's) followed by a pair of superconducting quadrupoles[1]. These permanent quadrupoles are located 33.7 cm away from the interaction point. This quadrupole scheme of the interaction region permits reduction of beta function at the interaction point $\beta_v^*$ to 1 cm or less and also helps to reduce the vertical beta function at the first parasitic interaction point which occurs 2.1 m from the IP, as well as the peak vertical beta which reduces aperture requirements and vertical chromaticity. By reducing the effects of parasitic crossings adjacent to the interaction point, it allows the operation with bunch spacing of 14 ns. The luminosity after the upgrade will be increased dramatically due to the extra beam current implied by 9 x 5 bunches made possible by reducing the bunch spacing and the tighter vertical focusing at the interaction point. Although it is designed for flat-beam crossing angle collision operation, the phase-III IR quadrupole scheme is compatible with the possible round beam configuration[2].

## 2 PERMANENT MAGNET QUADRUPOLE CONSTRUCTION

The permanent magnet quadrupole is made of three 9.2 cm long sections which are assembled individually, then bolted together for the full quad. The whole assembly is mounted to the drift chamber of the CLEO detector. The cross-section view of the quadrupole assembly sketch is shown in Fig. 1

The permanent magnet quadrupoles extend from 337 to 616 mm from the interaction point, have a constant inner radius of 3.35 cm and a two-step outer radius. The dimension of the quadrupole is designed in such a way that the strength of the PMQ is as strong as possible and physically as close as possible to the interaction point in the limited space available for the PMQs. They will operate inside the 15 kG solenoid field of the experimental detector. They are built with Neodymium Iron Boron (NdFeB) material because of its cheaper price, higher commercially available remnant field $B_r$ and intrinsic coercivity $H_{ci}$ comparing with Samarium Cobalt (SmCo) material. The quadrupoles are built with sixteen azimuthal segments.

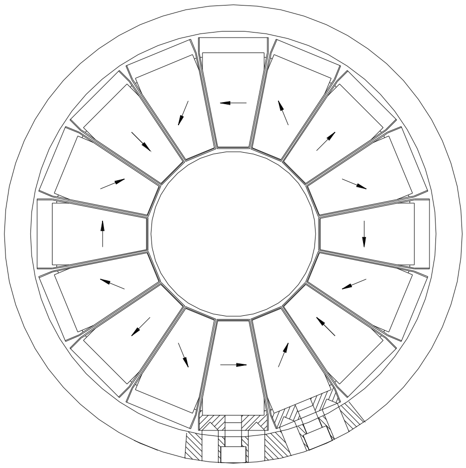

Figure 1: Phase-III Permanent Magnet Cross-section view.

Magnet pole-pieces were ordered with 3 easy-axis orientations (0,45, and $90^0$) and magnetized as shown in Fig. 1. The focusing strength of a permanent magnet quad is influenced by remnant field ($B_r$), inner "pole-tip" radius ($r_i$), and the ratio of outer to inner radius ($r_o/r_i$). This last parameter, $r_o/r_i$, must be limited to avoid subjecting parts of the magnetic material to excessive demagnetizing fields, which could seriously degrade field quality. According to the numerical analysis with the Pandira code and reverse magnetic field knock-down test with the magnet material, it is found that the $r_o/r_i$ of 2.1 is appropriate to the magnet material with $H_{ci}$ of 21 kOe and $B_r$ of 12 kG.

The magnet pole-pieces were supplied by Magnet Sales and Manufacturing Inc. The material is Shin-Etsu 36SH Neodymium Iron Boron. The typical magnetic and mechanical characteristics of this material is listed in Table. 1

The mechanical assembly of the quadrupole is similar to the existing REC quads operating in the storage ring [3, 4, 5]. The permanent magnet pole-pieces are affixed to a

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| | |
|---|---|
| Remnant Field $B_r$ | 12.2 kG |
| Coercive Force $H_c$ | 11.7 kOe |
| Intrinsic Coercive Force $H_{ci}$ | 23 kOe |
| Maximum Energy | 36 MGOe |
| Recoil Permeability | 1.05 |
| Density | 7.5 g/cm$^3$ |
| Electric Resistivity | $2.0 \times 10^{-4} \Omega \cdot cm$ |
| Temp coefficient of $B_r$ | $-0.1\ \%/^0C$ |
| Curie Temperature | $310\ ^0C$ |

Table 1: Typical characteristic for NdFeB 36SH.

| | $r_i$ cm | $r_o$ cm | Pole Field kG | k m$^{-2}$ |
|---|---|---|---|---|
| Front Section | 3.35 | 6.40 | 9.7 | 1.64 |
| Outer Section | 3.35 | 7.04 | 10.7 | 1.81 |

Table 2: Quadrupole magnetic strength.

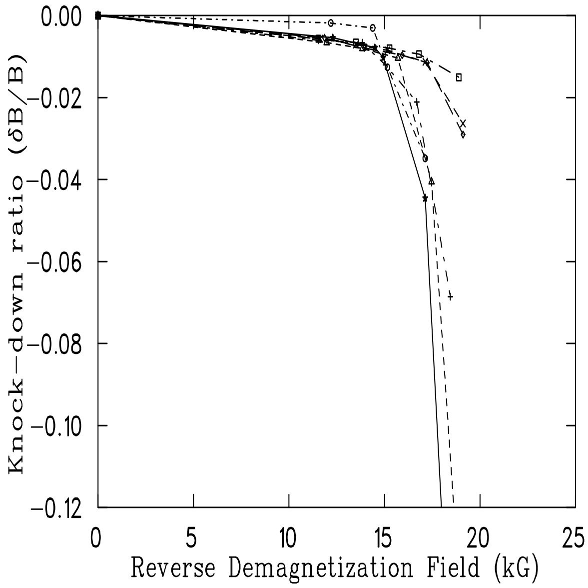


Figure 2: Knock-down ratio vs the applied external reversal field for several magnet pieces.

stainless backing plate using high temperature adhesive and covered by a stainless steel skin spot welded to the backing plate for extra protection. The backing plate with magnet was then screwed fast to the support shell. The weight of each quadrupole assembly is about 100 pounds. At 5.289 GeV, the predicted quadrupole strength is listed in Table. 2.

## 3 FIELD QUALITY AND STABILITY

The interaction region quadrupole requires extremely precise control of magnetic field so the magnet field quality and stability requirements are especially severe. The permanent magnet must maintain a constant flux output over a long period of time during the operation. Many factors can affect the magnet and tend to alter the magnet flux which would change the field quality and quadrupole strength in our application. These influences have been studied and the flux change of the magnet have been predicted. The change of the magnetization of the magnet during the operation could be minimized by exposing the magnet to influence in advance and rendering the magnet insensitive to subsequent change in service.

### *3.1 Resistance to the Irreversible Demagnetization*

The permanent magnet maintains its magnet flux because there are lots of small magnet domains aligned by crystal anisotropy. A very high external magnetic field tends to disturb the domain alignment. When the magnet pole-pieces are assembled into the quadrupole, some regions of the magnet material operate in a very strong anti-parallel magnet field. For the case of our design, it is found that this anti-parallel magnet field could be as high as 13 kG according the Pandira simulation. Several different magnet samples were tested for the knock-down ratio of the remnant field $B_r$ with the applied reverse external field. The knock-down ratio was defined as the ratio of the magnetization change before and after the exposure of the external field over its original magnetization. It was found that the intrinsic coercivity of 21 kOe was sufficient to limit the amount of demagnetization to a few percent with 13 kG reverse external field. Fig.2 shows the the amount of demagnetization vs the reverse external field for the NdFeB 36SH material we used. It was found that the material we are using could sustain to 15 kG of the reversal external field.

The quadrupole magnet will operate immersed in a 15 kG axial solenoid field (perpendicular to the NdFeB permanent magnet easy axes) of the experimental detector. Several magnet pole-piece were exposed to external 20 kG perpendicular field, no demagnetization was found after the exposure.

### *3.2 Temperature Stability*

The properties of the magnet material changes with temperature and time. The magnet can be stabilized by heating it to the temperature well above the operating temperature. This process speeds up the initial aging and slows down the rate of change thereafter.

All magnet pole-pieces were thermally stabilized for three hours at 100 $^0C$, which was the maximum temperature without the irreversible loss of coercive force. The losses of the magnetization during this procedure were measured to be less than 1% of the original magnet moment. Several thermal stabilized magnet sample pieces were remeasured after being stored on self for eight months and no magnetization changes were found.

It is also important that heat stabilization be performed when the magnets are in a field similar to that which they will see during operation. We will do the temperature stabilization process for the assembled quadrupole. Since the quadrupole is operated at the room temperature, it is reasonable to do the temperature stabilization process for the quadrupole assembly at 60-70 $^0C$ for one or two hours. The quadrupole strength will be decreased very slightly (less than $0.5\%$ since the magnet material has very high intrinsic coercivity and all the magnet pieces have been heat stabilized to 100 $^oC$.

Since the the Curie temperature of the NdFeB material is much lower than the SmCo material used in the CESR's present IR quads, the temperature coefficient of $B_r$ was measured to be almost three times higher. This means the quadrupole strength is also almost three times more sensitive to the temperature. Fortunately, the Phase III quads focal length is longer (weaker focusing) due to its shorter physical length and the beta functions are lower, making the machine optics much less sensitive to changes in quad strength. It was estimated that the quadrupole temperature should be controlled to within 0.2 $^oC$ to limit the storage ring vertical tune shift within 0.0005 integer. The temperature of the quadrupole will be controlled by running coolant through a 1/4 inch tubing on the out shell to remove heat from the silicon detector electronics.

### 3.3 Corrosion and Surface Oxidation

NdFeB material is more subject to oxidation and corrosion than the SmCo material. All surfaces of the magnet piece were coated with Cadmium Chromate coating for corrosion and oxidation resistance.

### 3.4 Radiation Damage

There are several reported studies about the radiation damage due to the neutrons and photons ($\gamma$ and X-rays)[6, 7, 8, 9]. Those data suggested that the integrated neutron fluences of $5 \times 10^{14}$ n/cm$^2$ and 50 MR of bremsstrahlung radiation is needed to show sizeable damage to the NdFeB material. The radiation level in the electron/positron storage rings is mainly due to the gamma bremsstrahlung and the synchrotron radiation. For CESR, it is estimated that the integrated dose of photons in the interaction region where the PMQs are located is a few MR for 5 years of operation. The present CESR neutron level is measured at about $2 \times 10^9$ n/cm$^2$ a year. Both neutron and photos radiation level for the 5 years of CESR phase-III operation are estimated much lower than the threshold level to show significant radiation damage. Several magnet sample pieces were exposed to a dose of 6 MR of gamma radiation in a Cobalt-60 chamber and no magnetization change were found after the exposure.

### 3.5 Field Quality

The effect of nonlinearities in the permanent magnet quadrupoles is evaluated by a tracking study. The dynamic aperture is computed for trajectories with initial energy offset 0, 5, and 10 $\sigma_E/E$ for both the error free machine and a machine with errors. It is found that a field error of less than $1 \times 10^{-3}$ at a radius 3 cm is required.

The multipole field could be caused by magnet piece to piece variations in magnetization, errors in positioning the magnet and the anti-parallel demagnetization by the local field observed by some of the magnet pieces when the magnet are assembled into the quadrupole.

The variation of $B_r$ and magnetization angle error of all the magnet pieces were measured. It was found the the $B_r$ variation is less than $\pm 2\%$ and the angle error of the easy axis is within $2^0$. The field error will be reduced by matching magnets with similar properties and a tuning procedure to adjust a small amount of radial motion of each magnet piece to cancel the measured multipole field. A rotating coil measurement system was built to measure the multipole field to the accuracy of 1 part in $10^4$ of quadrupole field at radius of 3 cm. It is expected that quadrupole with $5 \times 10^{-4}$ of multipole field error at 3 cm radius will be achieved.

## 4 ACKNOWLEDGMENTS

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