PERFORMANCE OF THE PEP-II LOW-ENERGY RING QUADRUPOLES*

N. Li, J. Osborn, J. Tanabe, D. Yee, R. Yourd, M.S. Zisman, *Lawrence Berkeley National Laboratory, Berkeley, CA, USA 94720,* and Z. Cao, R. Hou, Y. Sun, *Institute for High Energy Physics, Beijing, P. R. C.*

Abstract

Production quantities of quadrupoles for the PEP-II Low-Energy Ring (LER) have been fabricated and measured in China in collaboration with IHEP (Beijing). The LER design specification calls for short quadrupoles (L_{eff} = 430 mm) with a bore radius of 50 mm. End effect corrections, using a chamfer geometry originally developed for the ALS quadrupoles at LBNL, were verified in a prototype magnet prior to release of the design for production of the 320 quadrupoles (including spares) required for the LER. Rotating coil measurements were carried out at IHEP yielding multipole error spectra, magnetic center distribution and transfer function behavior for the full production quantity of magnets. Separate measurements were made to determine the reproducibility of magnets connected together in a series string by measuring the individual magnets against a reference magnet using a bucking magnet. Measurement results of all the magnets indicate that the error multipole spectra satisfy the field quality requirements, reproducibility requirements for magnets in a power supply string are satisfied and the spatial distribution of the magnetic center with respect to the mechanical magnet center falls within a radius which is substantially smaller than the transverse alignment tolerance specified for the quadrupoles.

1 INTRODUCTION

LER ring quadrupoles are divided among four different designs. 150 have coils wound with 15 turns of aluminum conductor per pole. These are connected in two power supply strings QF and QD. In addition to requirements for field quality, they must satisfy reproducibility requirements. The balance of the magnets are connected singly, in pairs, or in series strings which contain four magnets. These magnets are wound with 58 and 52 turns of either aluminum or copper conductor.

Details of the core and coil designs and operating parameters are reviewed in previously published papers[1,2]. The LER will operate at a positron energy of 3.1 GeV. However, the magnet design parameters and performance requirements are specified for energies ranging from 2.4 to 3.5 GeV.

No. Required:	316
Bore Radius:	50 mm
Effective Length:	430 mm
Excitation Range:	$0.67 \le B' \le 13.91$ T/m
String Magnet Excitation:	4.5 T/m @ 3.1 GeV
Reproducibility:	$\le 1\text{x}10^{-3}$
Systematic Multipoles:	$\le 1\text{x}10^{-3}$ •B2 @50 mm r
Random Multipoles:	$\le 5\text{x}10^{-4}$ •B2 @50 mm r

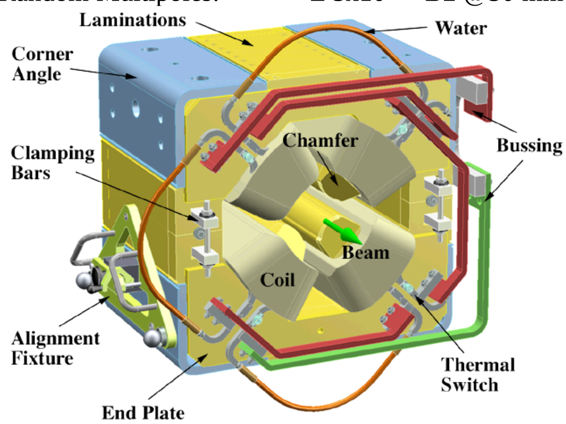

Fig. 1. PEP II LER Quadrupole.

At the writing of this paper, all the 15 turn magnets and most of the 58 turn aluminum conductor magnets have been manufactured, measured and received at LBNL. This paper summarizes the performance of some of the quadrupoles received from IHEP.

2 MAGNETIC MEASUREMENTS

A compensated line integral coil was designed at IHEP. Three coils were fabricated by a vendor in China selected by IHEP. A MetroLab® Integrator and a PC based computer were purchased and a data acquisition system was designed and assembled at IHEP. Two of the coils were retained at IHEP and the third was delivered to LBNL so that measurements can be verified.

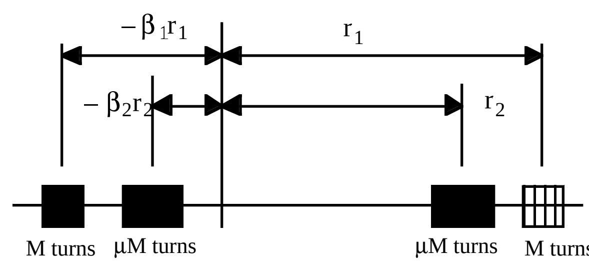

Fig. 2. Compensated coil schematic.

r_1=40.05 mm	$\beta_1 r_1$=30.05 mm
r_2=22.58 mm	$\beta_2 r_2$=12.63 mm
M=342/190 turns	μM=684/380 turns
Coil length	897 mm

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Magnetic Centers

The deviation of the magnetic center with respect to the axis of the coil is calculated using the dipole field measured by the rotating coil.

$$\Delta x = \left(\frac{b_1}{|B_2|}\right)_{@r_0} r_0 \quad \Delta y = \left(\frac{a_1}{|B_2|}\right)_{@r_0} r_0$$

This measured center is related to the mechanical center of the quadrupole since a cylinder with the exact diameter of the rotating coil housing is used to define the center axis of the quadrupole during fiducialization. Figure 2 illustrates the center distribution for 77 QF magnets. Distribution plots for the QD and the 58 turn magnets display similar patterns.

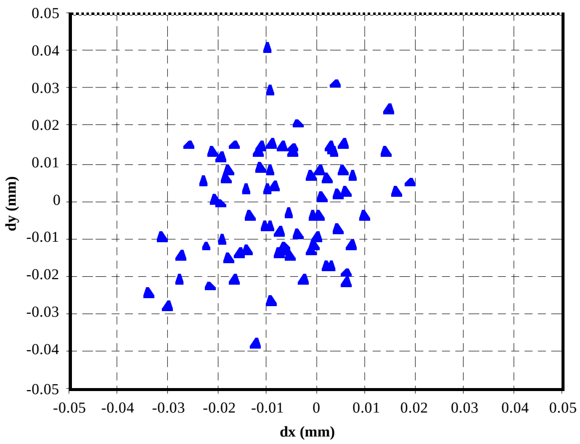


Fig. 3. Magnetic axis distribution for 77 QF quadrupoles.

Integrated error multipole data for all the magnets satisfy the reqirements. In Figs. 4 and 5 bar graphs are presented for five multipoles measured for a sample of 25 of the QF magnets thus far received. These spectra are typical of the spectra for the balance of the magnets. Two different bar graphs are presented.

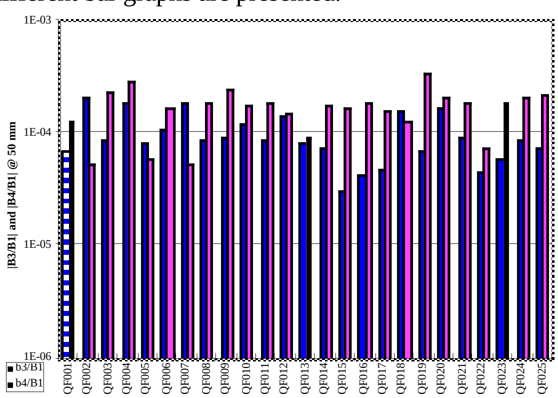


Fig. 4. Random multipoles for 25 QF quadrupoles.

The unallowed random multipoles (Fig. 4) result from small errors in core manufacture or assembly

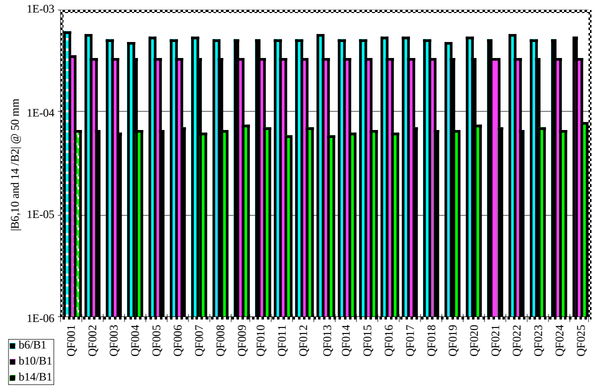


Fig.5. Systematic multipoles for 25 QF quadrupoles.

The systematic "allowed" multipoles (Fig. 5) are primarily introduced in the magnet fringe fields. The magnitudes of the "unallowed" random multipole errors have a fairly wide variation from magnet to magnet. The "allowed" multipoles are reproducible within a narrow range for all the magnets. Measurements are collected for individual magnets at various levels of excitation. Although the individual magnet excitation required for 3.1 GeV LER operation is narrowly specified, measurements were made for a range of excitation broader than the required current. These measurements were made since the individual magnets in the LER ring vary over wide ranges in excitation and since performance at different LER energies (for future upgrades) must be anticipated. Typically, the magnet center varied ≤±10 μm and the individual multipoles varied $\leq \pm 3x10^{-6}$ from their average values over the range of current values for which the measurements were performed.

Transfer Functions

For the QF magnets, the power supply is cycled three times to 760 Amps (for conditioning) and ramped to the prescribed currents where the measurements are made with increasing current. A final measurement is made with the current reduced to 355 Amps. The change in the function at 355 Amps is due to the magnet operating on a different load line due to hysteresis in the iron.

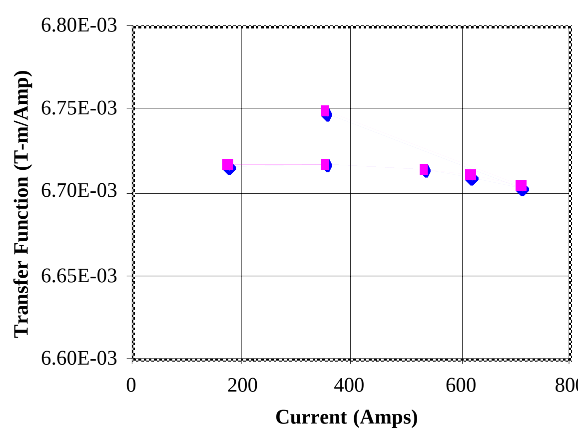
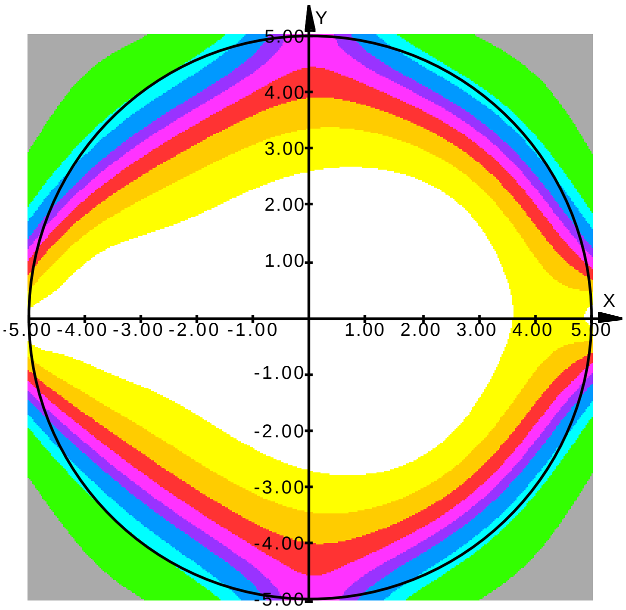


Fig. 6. Transfer function for QF01.

The transfer function data are not used to determine the reproducibility of the collection of magnets since the measurements are not sufficiently repeatable. Lack of stability of electronic components and environmental factors (temperature variations) contribute to errors in the measurement greater than the required precision to identify magnet repeatability to less than the specification ($\leq 1x10^{-3}$).

Magnetic Field Reconstruction



QF001 IHEP Measurement

Units: CM
Current: 355.00A

- Err ≤ 1.0E-04
- 1.0E-04 < Err ≤ 2.0E-04
- 2.0E-04 < Err ≤ 3.0E-04
- 3.0E-04 < Err ≤ 4.0E-04
- 4.0E-04 < Err ≤ 5.0E-04
- 5.0E-04 < Err ≤ 6.0E-04
- 6.0E-04 < Err ≤ 8.0E-04
- 8.0E-04 < Err ≤ 1.0E-03
- 1.0E-03 < Err ≤ 2.0E-03
- Err > 2.0E-03

Pole Radius: 5.00 | Ref. Radius: 5.00

N	BN/B2	PHI	N	BN/B2	PHI
3	6.28e-05	346.1	-	-	-
4	1.67e-04	176.9	-	-	-
5	5.54e-06	-3.8	-	-	-
6	6.35e-04	0.4	-	-	-
7	1.74e-06	152.0	-	-	-
8	5.51e-06	35.0	-	-	-
9	1.09e-05	151.3	-	-	-
10	3.53e-04	178.9	-	-	-
11	6.01e-06	170.9	-	-	-
12	5.19e-05	177.7	-	-	-
13	1.29e-05	296.0	-	-	-
14	6.51e-05	178.6	-	-	-

Fig. 7. Typical iso-error curve reconstructed from multipoles.

A table of multipole error amplitudes and their phases are difficult to interpret when evaluating the quality of a magnet. An analog method of reconstructing the field was developed which maps the field error in space and helps evaluate the quality of the magnetic field within the prescibed good field region. The algorithm for reconstructing the field error map is simple.

$$\left(\frac{\Delta B_{\substack{\text{azimuthal}\\ \text{radial}}}}{B_2}\right)_{r,\theta} = \sum_{n=3}^{n=14}\left(\frac{\Delta B}{B_2}\right)_{r_0}\left(\frac{r}{r_0}\right)^{n-2} \begin{matrix}\cos\\ \sin\end{matrix}\left(n\theta+\psi_n\right)$$

$$\left|\frac{\Delta B}{B_2}\right|_{x,y} = \sqrt{\left(\frac{\Delta B_{\text{azimuthal}}}{B_2}\right)_{x,y}^2 + \left(\frac{\Delta B_{\text{radial}}}{B_2}\right)_{x,y}^2}$$

Magnet Reproducibility

Magnet reproducibility was measured at IHEP by placing identical coils in a bucking magnet and the measured magnet connected in opposition and ramping the magnets connected in series. This null measurement was compared with the null measurement from a reference magnet. The figure compares the reproducibility data (trIangles) with mechanical length measurements of the quadrupoles (squares) which are ranked from shortest to longest. In general, the quadrupoles satisfy the requirement of magnet reproducibility $\leq \pm 1x10^{-3}$.

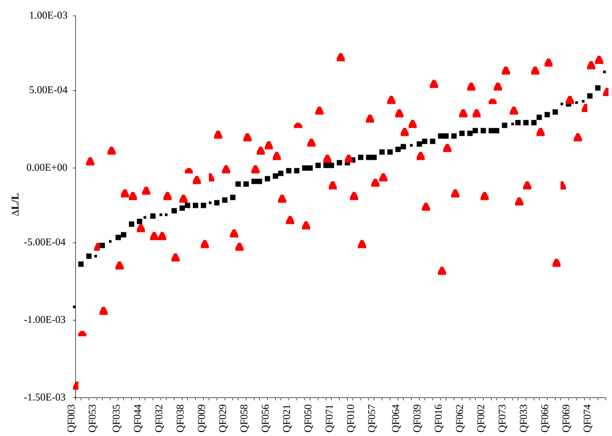


Fig. 8. QF magnet reproducibility.

3 STATUS

Quadrupole magnet production will be complete by the end of June, 1997. Magnetic measurement results have been routinely delivered to LBNL for evaluation from IHEP as magnets are delivered. All magnets thus far delivered have met or exceeded the performance specifications set forth at the beginning of the project.

4 ACKNOWLEDGMENTS

The PEP-II project is grateful for the hard work and professionalism of the team of scientists, engineers, and craftspersons at IHEP. Approximately 200 of the 316 quadrupoles required for installation in the LER have been received. Measurements have indicated that the excellent field quality demonstrated by the prototype has been maintained and that the craftsmanship evident in the early magnets continues. We would also like to thank the team of technicians and scientists working for Ms. R. Hou at IHEP for the thorough and careful measurements of all the magnets.

5 REFERENCES

[1] J. Tanabe, J. Osborn, N. Li, D. Yee, "Standard 43 cm Quadrupole Engineering Design", LBL Mechanical Engineering Note M7498A, October, 1994.

[2] T. Henderson, N. Li, J. Osborn, J. Tanabe, D. Yee and R. Yourd, "Design of the PEP-II Low Energy Ring Arc Magnets", Proceedings of the IEEE Particle Accelerator Conference (PAC), Dallas, TX, May 1995, pp. 1322-1324.