OPTIMIZATION OF THE PEP-II LOW-ENERGY RING DIPOLES

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Abstract

The PEP-II Project [1], a collaboration of SLAC, LBNL, and LLNL, began construction in January 1994. Dipoles for the PEP-II Low-Energy Ring (LER) are being fabricated in China in collaboration with the Institute of High Energy Physics (IHEP) in Beijing. The LER design calls for short dipoles (l_{eff} = 450 mm) with a 63.5 mm gap. As a result, magnetic properties are dominated by end effects and a proper end chamfer must be developed. Magnetic measurements using both integral coil and rotating coil techniques were carried out at LBNL on an early dipole prototype to determine the sensitivity of various allowed multipoles to the end chamfer shape. Dynamic aperture studies were carried out in parallel to explore the sensitivity of the lattice to these multipoles. By interpreting the measurement results in terms of differences from the baseline chamfer, a prescription was developed to “transfer” the results to another prototype dipole more representative of the production magnets. The optimized end chamfer shape was validated with a pre-production dipole and full production is under way.

1. INTRODUCTION

The design for the LER arc dipoles was developed [2] in collaboration with IHEP and these magnets are now being fabricated in Shanghai, China. Main parameters for the dipole are given in Table I. Although the LER circumference is 2200 m, the desire for enhanced radiation damping led to the use of short, high-field dipoles (see Fig. 1). For a short dipole having a large gap, the magnetic properties are heavily influenced by the end fields.

Table I. PEP-II LER dipole parameters.

Nominal energy [GeV]	3.1
Energy range [GeV]	2.4–3.5
Effective length [m]	0.45
Bend radius [m]	13.75
Gap [mm]	63.5
Nominal field [T]	0.752
Core length [m]	0.382
Nominal current [A]	580
Magnet power [kW]	4.5
RMS strength variation, $\Delta B/B$	0.001
Allowed multipoles, b_n/b_1@ 30 mm	$\leq 1 \times 10^{-4}$

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Fig. 1. LER dipole being measured at IHEP.

Measurements of two early prototypes (the first with removable end chamfer inserts) indicated that the multipole content was somewhat too high; this was confirmed by tracking studies of the LER dynamic aperture. Dipole field optimization required development of a chamfer to reduce these unwanted field components, particularly the sextupole (n=3) contribution. Though we did carry out some 3-D magnetic analyses [3], the development work consisted mainly of shimming the end chamfers to determine empirically the changes in multipole content of the first prototype magnet. Measured differences were then applied as adjustments to the second magnet. We were guided in the shimming by Halbach’s analytical approach [4], which permits exploring the problem of canceling more than one multipole with the end chamfer.

2. PROTOTYPE RESULTS

Integral-coil measurements made at LBNL on the first prototype dipole (Fig. 2), fabricated by an initial industrial partner of IHEP, showed marginally satisfactory multipole content with the baseline chamfer obtained from 3-D calculations with the AMPERES code [5].

After IHEP transferred dipole production activities to Kelin Company, an industrial partner in Shanghai, a second prototype was produced, measured at IHEP, and sent to LBNL for verification. Though the second magnet was nominally identical to the first, it showed (Fig. 3) more pronounced field dependence and higher multipole content. Laminations for the two dipoles were from the same batch, and were punched with the same die, so the

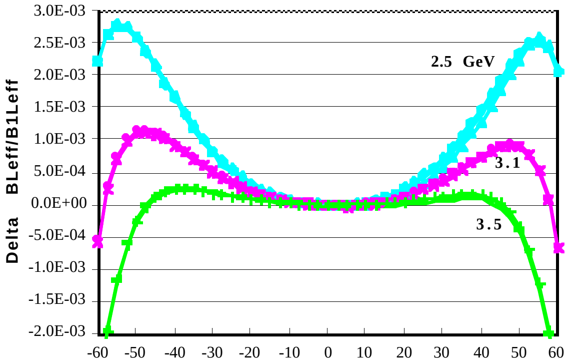

Fig. 2. Prototype 1 integral-coil results.

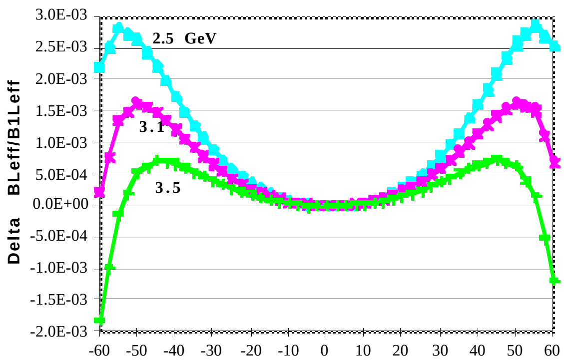

Fig. 3. Prototype 2 integral-coil results.

difference between magnets could only be attributable to the solid steel end plates.

Comparing Figs. 2 and 3, it appears that the original magnet shows saturation effects. Subsequent investigation showed that the steel used in the end plates of the original prototype had lower magnetic quality than that used in the second magnet, consistent with our observations.

Although the first magnet was built with removable inserts for the end chamfer—which proved invaluable in the optimization work described below—the second and subsequent dipoles had a fixed chamfer. For this reason, we made many of the measurements with modified chamfers only on the original prototype.

3. MEASUREMENT APPROACH

Measurements on both prototypes were initially carried out at IHEP using a long coil to measure ∫Bdl across the mid-plane of the dipole. After air shipment to LBNL, equivalent measurements were repeated with a finer grid. Both sets of measurements gave consistent results. Multipole coefficients were extracted from the long coil results by fitting a polynomial to the data. (Though this is straightforward in principle, care was taken to avoid numerical problems that appeared in several fitting routines we tried.) Unfortunately, it is difficult in practice to reliably measure a sextupole coefficient of $b_3/b_1 \leq 1 \times 10^{-4}$ by this technique, as the changes in integral field close to the magnetic axis (x=0) are very small.

To determine the multipole content of the magnet reliably, we resorted to a technique not commonly applied to dipoles—rotating coil measurements. A bucked "quadrupole" measurement coil with a length of 0.75 m and a radius of 25 mm was employed. The data reduction routine was suitably modified to produce coefficients normalized to the dipole, rather than the quadrupole, term.

Because the coil was slightly too short to give a reliable integral measurement, all measurements were performed by inserting the coil from each end of the dipole to the longitudinal center and then combining the results vectorially. It was observed that there was a significant difference in the harmonic content of the magnet at the lead end and the non-lead end. We have not studied this aspect in detail, but there is some evidence that the longitudinal asymmetry is due to different coupling between core and coil associated with the coil crossover geometry.

As a verification of our rotating coil measurements, the multipoles so obtained were used to reconstruct the integral coil measurements by means of Eq. (1).

$$\frac{\Delta B_y l_{eff}}{B_1 l_{eff}} = \sum_{n=3}^{\infty} \left(\frac{b_n}{b_1}\right)_{r_0} \left(\frac{x}{r_0}\right)^{n-1} \qquad (1)$$

The comparison clearly demonstrated that the two techniques produce equivalent results, giving us confidence that we are accurately determining the low-order multipoles with the rotating coil.

4. MEASUREMENT RESULTS

Based on the rotating-coil data, we proceeded to modify the chamfer to reduce the multipole content. In view of the strong field dependence visible in Fig. 3, our focus was on the intermediate case of 580 A, corresponding to nominal 3.1 GeV operation of the LER. It is clear from inspection of Fig. 3 that the original chamfer was too deep in the center, so magnetic material had to be added in this region. To determine the sensitivity, thin steel shims of different thickness were glued in turn to the end plate chamfers and measurements made with the rotating coil to see the effects on the n=3,5,7 components. We verified experimentally that identical shims on the two dipoles modified the allowed multipoles (n=3,5,7) in a similar fashion, that is, the *change* in, say, the n=3 multipole was the same when the same shims were added to either dipole, though the starting points were different in the two cases. Thus, we predicted multipoles for the second prototype from Eq. (2)

$$\left(\frac{b_n}{b_1}\right)_{2,\mathrm{mod}} = \left(\frac{b_n}{b_1}\right)_{2,\mathrm{nom}} + \left(\frac{b_n}{b_1}\right)_{1,\mathrm{mod}} - \left(\frac{b_n}{b_1}\right)_{1,\mathrm{nom}} \qquad (2)$$

where the subscripts 1 and 2 denote the first and second prototype, respectively, “nom” denotes the nominal baseline chamfer, and “mod” denotes a modified chamfer, either shimmed or machined.

Our main goal was to reduce the sextupole component to $b_3/b_1 \approx -0.5 \times 10^{-4}$. The preference for a slightly negative b_3 coefficient comes from the tracking results [6]. It is related to the fact that, in the nominal lattice, the SD sextupole families are stronger than the SF families. A positive b_3 in the dipoles further increases the required strength of the SD families and reduces the dynamic aperture margin. A negative b_3 produces the opposite effect and results in a larger dynamic aperture.

With regard to the n=5 and 7 components, we found that the chamfer depth had little effect on either. Using Halbach’s approach, we used “split” shims (two shims on each end plate with a gap between, see Fig. 4) to attack the two higher terms. We found that we were able to affect the n=5 and 7 terms independently of the sextupole term, but the shims essentially traded n=5 for n=7. We could interchange the two strengths, or find shims that made both terms the same. Because tracking results [6] showed no strong sensitivity to any of the configurations, we ultimately chose to avoid the complication of the split shim configuration for the production magnets.

We took advantage of the removable end chamfers on the first dipole to confirm the results from the shims by fabricating new inserts on an NC milling machine. A comparison of the original and modified profile are shown in Fig. 5. Note that the change in the chamfer depth to give the desired result was only about 0.5 mm.

5. PRODUCTION STATUS

Dipole magnet production is in full swing, at a rate of 30 magnets per month. Each dipole is characterized magnetically at IHEP prior to shipment to LBNL. To date, coil fabrication is completed and about 150 dipoles have been produced, of which 67 have been received at LBNL, another 40 have been measured at IHEP and await shipment, and the remainder are awaiting measurement. To fully characterize their multipole content, some of the magnets are being remeasured at LBNL with the rotating coil system. Thus far, the measured b_3 coefficient is small and slightly negative, as desired.

The integrated strength of each dipole with respect to an arbitrarily chosen “reference” magnet is also measured

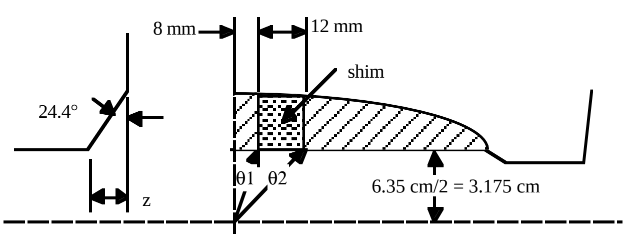

Fig. 4. Dipole chamfer geometry for the split shim case.

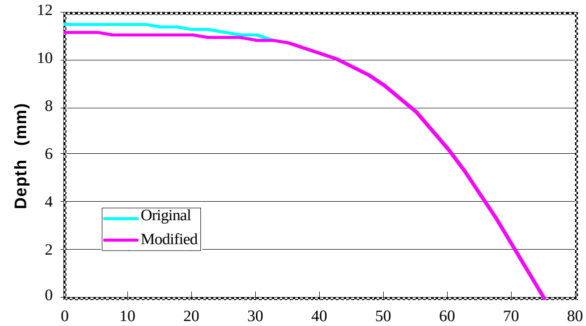

Fig. 5. Depth of original chamfer and modified version adopted for production dipoles.

at IHEP. With half of the dipoles measured, almost all magnets are within the strength tolerance specified in Table I. For the magnets on the extremes of the distribution, a sorting procedure has been defined to minimize the resultant orbit distortion. A few magnets have been determined to be beyond tolerance, and these will be reshimmed at IHEP to adjust their gap to bring the strength within specification.

6. ACKNOWLEDGMENTS

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