# DESIGN OF THE PEP-II LOW-ENERGY RING ARC MAGNETS*

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We describe the PEP-II Low-Energy Ring (LER) arc quadrupole and dipole magnets, being designed and built by a Lawrence Berkeley Laboratory (LBL) and Institute of High Energy Physics (IHEP) collaboration. The LER requires 292 "standard" 43-cm long, 10-cm bore aperture laminated quadrupoles. A 2-piece construction was chosen to reduce the influence of assembly tolerances on field quality. Laminations with an optimized pole profile are punched from 1 m x 2 m x 0.5 mm steel sheet, a standard product in China. The chosen design is patterned after that of the Advanced Light Source (ALS) booster quadrupole. As some of the quadrupoles are run in long strings and others in short strings, two coil types (15-turn and 58-turn, each with several cooling-circuit topologies) are being fabricated. The majority of coils are aluminum but a few quadrupoles require copper coils due to their high excitation. Fabrication, assembly, magnetic measurements and fiducialization will be carried out at IHEP. Dipoles will be fabricated similarly. We require 192 dipoles, 45-cm long, with a magnetic radius of 13.75 m and a good-field aperture of 90 mm; the pole shape is optimized for field levels up to 3.5 GeV beam energy. Coils are an aluminum pancake configuration designed to keep power consumption moderate.

## I. COLLABORATION

The construction of PEP-II is a joint collaboration of scientists, engineers, and technicians at three institutions in the U. S. (SLAC, LBL, and LLNL). An international collaboration has been established with IHEP in the P. R. of China to develop and produce some of the LER arc magnets (Fig. 1). Scientists and engineers from IHEP visited LBL in the summer of 1994 to review magnet requirements and to participate in the development of the designs for both the quadrupole and dipole magnets required for the PEP-II LER. Discussions extended to methods of magnetic measurements and fiducialization of the magnets. Arrangements for the construction of magnet prototypes, the production quantities, and measurement and fiducialization of the magnets were formalized in two agreements signed by representatives of IHEP, LBL, and SLAC in November, 1994 and March, 1995. The schedule calls for the completion of the quadrupole prototype by July, 1995, the dipole prototype by November, 1995 and fabrication of the production quantities of magnets through February, 1997.

## II. MAGNET REQUIREMENTS

The LER is designed to operate for positron energies which range between 2.4 to 3.5 GeV. The multipole values listed below are normalized to the fundamental at the indicated radius.

### *A. Quadrupoles*

| | |
|---|---|
| No. Required: | 292 |
| Bore Radius: | 50 mm |
| Effective Length: | 430 mm |
| Excitation Range: | $0.67 \le B' \le 19.21$ T/m |
| String Magnet Excitation: | 4.5 T/m @ 3.1 GeV |
| Magnet-to-Magnet Reproducibility: | $\le 1\text{x}10^{-3}$ |
| Line-Integral Field Quality | |
| Systematic Multipoles: | $\le 1\text{x}10^{-3}$ at 50 mm radius |
| Random Multipoles: | $\le 5\text{x}10^{-4}$ at 50 mm radius |

### *B. Dipoles*

| | |
|---|---|
| No. Required: | 192 + 8 for Wiggler Chicanes |
| Magnet Gap: | 63.5 mm |
| Effective Length: | 450 mm |
| Central Field: | 0.75 T @ 3.1 GeV |
| Magnet-to-Magnet Reproducibility: | $\le 1\text{x}10^{-3}$ |
| Line-Integral Field Quality | |
| Uniformity: | $\le 1\text{x}10^{-3}$ for $-45 \le x \le 45$ mm |
| Sextupole Content: | $\le 1\text{x}10^{-4}$ at 30 mm radius |

Figure 1: Tom Henderson (LBL) and Jiang Yan Ling (IHEP) with punch from quadrupole lamination die set.

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## III. QUADRUPOLE DESIGN

The majority of the quadrupoles are divided among two families which are connected in two long power supply strings. Other quadrupoles control the dispersion, the tune, and shape the beam in the wiggler and interaction regions of the lattice and are connected in short power supply strings. Because of these varied applications, and since the LER lattice is designed to operate over a range of energies (2.4 to 3.5 GeV) a common magnet design was needed to satisfy a wide range of excitation. Detailed design of the PEP-II LER quadrupoles, including a summary of two-dimensional magnetostatic calculations, electrical parameters and water flow and cooling calculations, is included in reference [1].

### *A. Yoke design*

A yoke design (Fig. 2) was chosen and analyzed to satisfy the demanding field-quality requirements for the quadrupoles over a wide range of excitation. This same yoke design is shared among all the quadrupoles in the LER except for selected magnets in the interaction region.

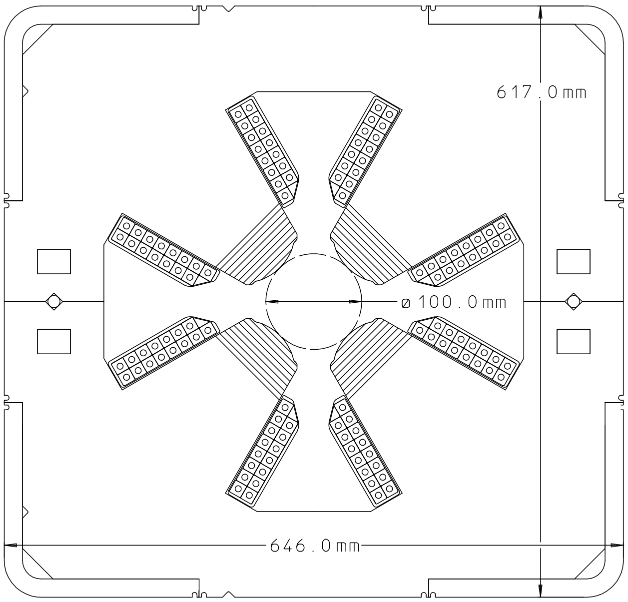

Figure 2: Quadrupole Layout with 15 turn per pole Coil.

The pole tip design is a scaled version of the optimized pole originally developed for the ALS (scaled from 32.5 mm to 50 mm pole radius). The original pole shape was shared among the ALS booster, storage ring, and beam transport quadrupoles and was developed with the goal of reducing the multipole errors allowed by the four-fold rotational symmetry (n=6, 10, 14, 18,...) to values $\leq 1\text{x}10^{-4}$ of the fundamental when measured at the pole radius. With this high quality for the two-dimensional field, the chamfer developed to minimize the multipoles due to the three dimensional fringe fields can be used for any magnet, independent of its magnetic length. This allowed us to scale both the chamfer and the pole shape for the PEP-II LER quadrupoles from the ALS design with full confidence that the field quality for the line integral of the magnet will meet the same good-field quality as achieved for the ALS.

The yoke is made in two pieces rather than four pieces to enhance its rigidity and simplify magnet assembly. This made it possible to reduce the potential assembly errors and the resulting random multipole errors. The advantages of this approach were first exploited during the fabrication of the PEP Insertion quadrupoles in 1979[2]. The ease of precisely shimming the halves of the two piece magnet with respect to each other allows the cancellation of selected multipole errors[3].

### *B. Coil design*

The two piece yoke design constrained the coil geometry. To install the coil, its width could be no wider than the space between adjacent poles. Reduction of the quadrupole power required reducing the current density by increasing the coil height. This resulted in a rather tall and narrow coil cross section and limited, somewhat, the choice of conductors that could be used to satisfy power supply and power distribution constraints. Moreover, since many of the old PEP magnets with aluminum coils are used in the High Energy Ring (HER), a further requirement for the LER magnet coils was to use aluminum conductor so that the water-cooling system could be shared.

The arc quadrupoles connected in long strings have coils with 15 turns per pole wound with 0.5 inch hollow square aluminum conductor. Other quadrupoles connected in short strings have 58 turn per pole coils wound with 0.25-inch hollow square conductor. All but a few of the 58-turn coils are made using aluminum conductor. The few magnets which utilize copper conductor are located in the interaction region of the PEP-II ring. These require higher currents and take advantage of the local water system provided in that area for other copper and stainless steel accelerator components. The 58-turn coil magnet water cooling circuits are arranged in a variety of different configurations, depending on the power dissipation for the particular magnet application. Parameters for two of the coil configurations are listed below.

| 58 Turn per pole aluminum coil: | 1 circuit |
|---|---|
| Resistance | 279.2 mΩ |
| Maximum Current | 46 A |
| Maximum Gradient | 2.68 T/m |
| Water Flow @ 130 psi | 0.075gpm |

| 58 Turn per pole aluminum coil: | 4 circuits |
|---|---|
| Resistance | 279.2 mΩ |
| Maximum Current | 139 A |
| Maximum Gradient | 8.10 T/m |
| Water Flow @ 130 psi | 0.682 gpm |

## IV. DIPOLE DESIGN

The arc dipoles in the LER are connected in two series power supply strings. Thus, they share, with the majority of the quadrupoles connected in series strings, very stringent magnet to magnet reproducibility requirements. Therefore, the manufacturing plan, developed by LBL and IHEP, includes careful shuffling of the steel and laminations required for the large number of magnets to ensure the distribution of any variations in iron magnetic properties and any systematic variation in laminations due to die wear. Detailed design of the PEP-II LER dipole, including summary of two and three dimensional magnetostatic calculations, electrical parameters and water flow and cooling calculations are included in reference [4].

### *A. Yoke design*

An "H-type" geometry (Fig. 3) was selected for the yoke so that a simple pancake coil can be utilized. The pole width was selected and the shape of the rectangular bumps at the edges of the pole was optimized in order to satisfy the field quality requirements for the magnet in the central two-dimensional region of the magnet. The pole edges were slightly tapered in order to minimize iron saturation at the pole root when operating at the high end of the required excitation range.

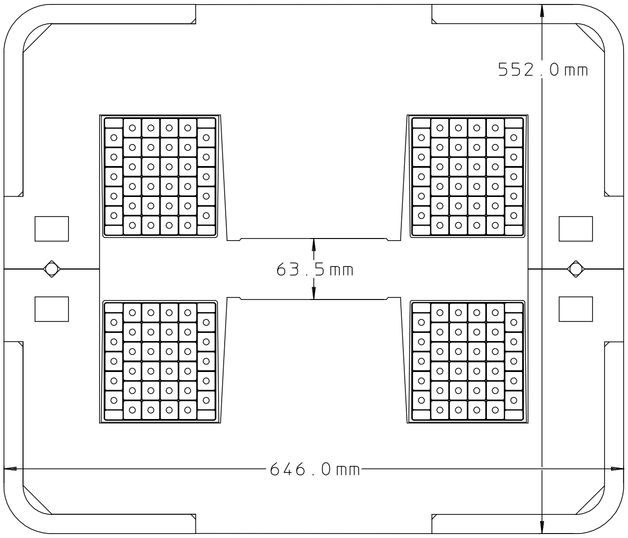

Figure 3: Dipole Layout.

Since the dipoles are relatively short, the variation of the fringe field at the end of the magnet is expected to dominate the line-integral field uniformity. Field distribution studies were made using Amperes© [5] (a three-dimensional magnetostatic code using the boundary element method) in order to estimate the shape of the chamfer (Fig. 4) which will satisfy the field-integral uniformity requirement for the dipole.

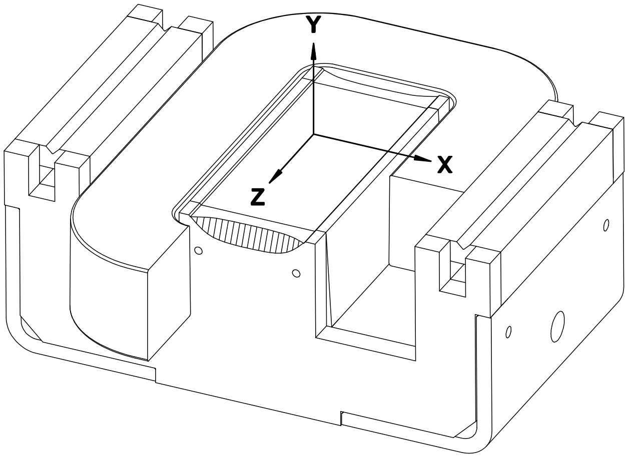

Figure 4: Dipole Chamfer.

### *B. Coil design*

The dipole coil has thirty-four turns of 0.715 inch square hollow aluminum conductor in order to satisfy power supply and power distribution constraints. The 34 turns are enclosed in a cross section sized for 36 conductors. Two turns were lost due to "soft" crossovers which allowed easy transitions between coil rows and layers.

34 Turn per pole aluminum coil - 1 water circuit

| | |
|---|---|
| Resistance | 10.97 mΩ |
| Current @ 3.1 GeV | 563 A |
| Field @ 3.1 GeV | 0.75 T |
| Water Flow @ 130 psi | 0.933 gpm |

## V. ACKNOWLEDGEMENTS

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## VI. REFERENCES

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

[2] R. T. Avery, T. Chan, K. Halbach, R. Main, J. T. Tanabe, "PEP Insertion Quadrupole Design Features", Proceedings of the IEEE Particle Accelerator Conference (PAC), San Francisco, CA, March, 1979, pp. 4033-4035.

[3] J. T. Tanabe, "ALS Storage Ring Quadrupole, Shimming Procedures", LBL Engineering Note M7156, December, 1990.

[4] J. Osborn, J. Tanabe, "Standard 45 cm Arc Dipole Engineering Design", LBL Mechanical Engineering Note M7512A, March, 1995.

[5] Amperes©, Integrated Engineering Software, 46-1313 Border Place, Winnipeg, Manitoba, Canada R3HOX4.