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THE PEP MAIN RING MAGNET SYSTEM*

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Summary

The PEP main ring magnet system consists of 192 bending magnets, 216 quadrupoles, 206 sextupoles and numerous other correction elements. The main ring bend magnets are laminated "C" frame dipoles having a very uniform flat field meeting a new criterion of symmetry called the residual asymmetry factor (RAF $\leq 10^{-5}$). The main ring quadrupoles consist of 216 laminated magnets of three differing lengths having a bore of 100 mm diam. The multipole content of these magnets as measured is $\leq 10^{-3}$. The present status of both magnets is that production has begun and completion is scheduled for early 1979.

Introduction

PEP is an 18 GeV electron-positron storage ring presently under construction at the Stanford Linear Accelerator Center (SLAC). It is a joint project of a team of scientists from both SLAC and the University of California Lawrence Berkeley Laboratories (LBL). The scheduled completion date is fall of 1979. The purpose of this paper is to describe PEP's main ring magnet system and present its current status.

The PEP ring is comprised of 6 interaction areas or experimental areas separated by 6 curved arcs. The main ring magnet system is made up of those magnetic elements required to constrain the beam to desired beam path. These elements are all located in the six curved arc sections. A typical arc section is shown in Fig. 1. The ring is of separated function design. Each arc section consists of a number of flat field bending magnets whose function is to bend the beam along its curved path. These magnets are separated by quadrupoles whose function is to focus the particles in the machine. Each arc contains 32 bend magnets and 36 quadrupoles giving a total of 192 bending magnets and 216 quadrupoles for the ring.

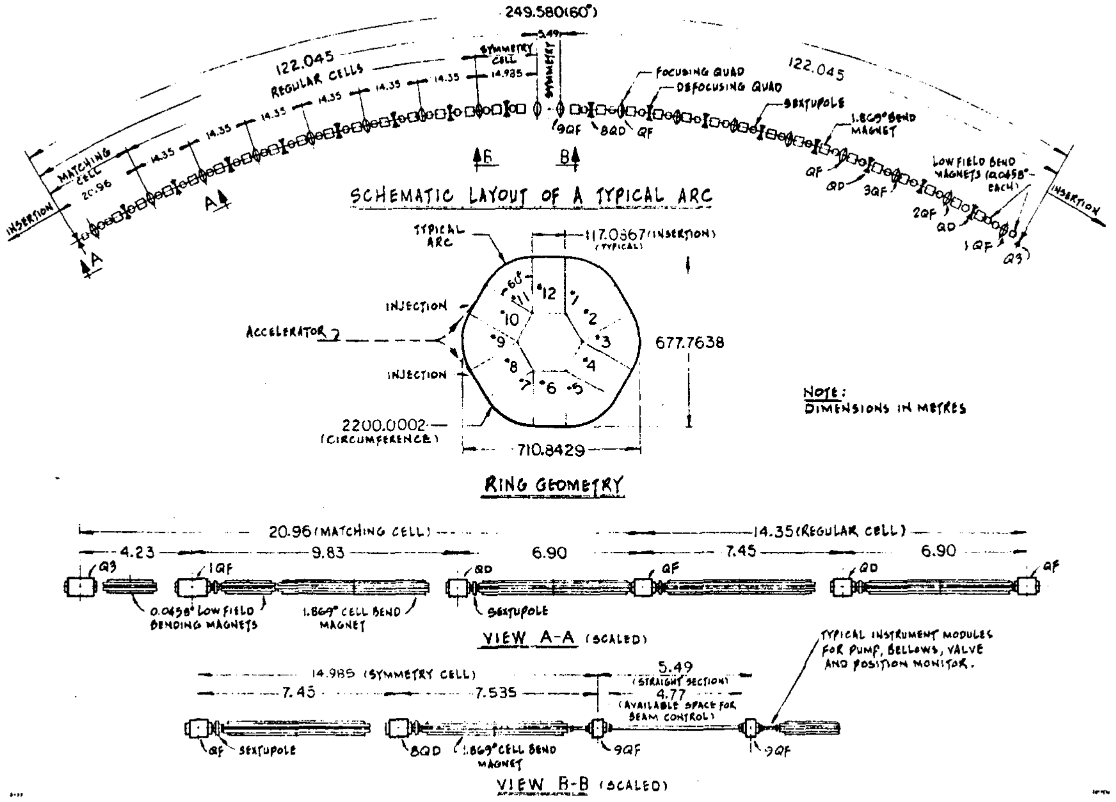

Fig. 1. PEP general layout.

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In addition, there are some 206 sextupoles, 24 interaction area quadrupoles and numerous other magnetic correction elements.

The Bend Magnet System

C-magnets were selected for use as the main ring bend magnets because they afford easy access to the vacuum chamber for infield repair and also allow the construction and installation of the magnet system to proceed independently of that of the vacuum system.

The gap or vertical aperture of the magnet was determined by the vertical beam stay clear with some allowance for vacuum chamber clearance. The horizontal aperture was determined from the required horizontal good field region plus a provision of 20 mm for magnet misalignments and sagitta of the curved beam orbit over the 5.4 m length.

Originally the criterion adopted for horizontal good field region was the area over which $\Delta B/B_0 \leq 10^{-4}$. This resulted in a pole width of 194 mm. Computer analysis by R. Servranckx(1) has shown that that criterion was not sufficient to guarantee good machine performance. Instead, a new criterion, the residual asymmetry factor (RAF), defined as

$$\mathrm{RAF} = \left| \int_0^d \frac{\Delta By(x,0) - \Delta By(-x,0)}{B_0}\, dx \right| \leq 10^{-5}$$

where quadrupolar and sextupolar terms are omitted, was adopted. In order to meet this new criterion, the pole width had to be increased from 194 mm to its present 214 mm. Detailed pole shaping was done using the computer program Poisson(2). By proper shimming the theoretical RAF was reduced to 5×10^{-6}.

The coil slot was determined by minimizing the installed system cost plus operating expenses for 10 years. Using a technique similar to that proposed by Brianti and Gabriel(3). The optimum current density was determined for both copper and aluminum coiled magnets. The aluminum coiled magnets; however, presented the minimum system costs. Figure 2 presents these results which are similar to thos found earlier by Green(4). Here the magnets system costs are plotted vs. current density. The minimum occurs around 0.5 A/mm^2 however it is highly dependent upon the assumed cost of electrical energy. The minimum installed cost, the magnets system cost less the operational costs, is around 1 A/mm^2. The latter was used as a design criterion for 18 GeV operation. It is interesting to note that the minimum copper coiled magnet system cost was about 2000 dollars higher and occurred at a current density of twice that of the same aluminum coiled system.

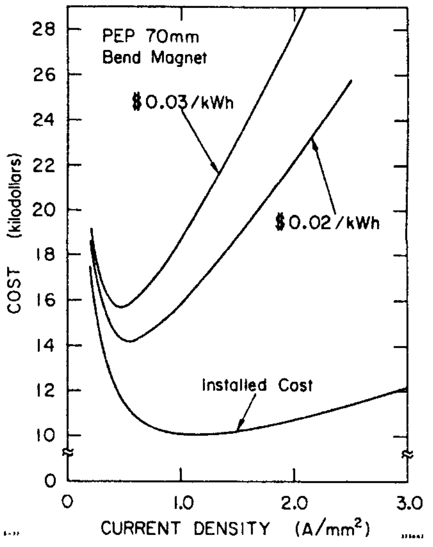

Fig. 2. Bend magnet system cost vs. current density.

A full size engineering model of the resulting design was constructed. Table 1 lists the major design information. A laminated construction technique with shuffled laminations was employed in order to reduce costs and to insure uniformity magnet to magnet. The 5.4 m long model contains approximately 3500 laminations sandwiched between two thick end plates held in place by welding plates to both the end plates and the laminations. The mechanical tolerances on twist and straightness in a storage ring are very stringent. Twisting causes coupling of the horizontal and vertical betatron motions whereas straightness affects the overall RAF of the magnets. Great care had to be exercised during the welding process to insure against undesirable welding distortions. The average twist over a bend magnet's length must be less than 1 mrad. Further the magnet support system must be capable of supporting the magnet such that any residual twist is symmetric about the magnet's center of length. The straightness of the magnets is controlled to 2 mm. Figure 3 is a drawing of the magnet. Figure 4 shows its magnetic performance. As can be seen there is a significant gradient in the magnet which is caused by gap opening during the one step punching process. Internal residual stresses present in the steel sheet due to rolling are the cause of this opening. Subsequent stampings with a similar though softer steel did not exhibit this property. Computer runs were made with the program Poisson with the gap as built. Figure 4 shows that those results compare favorably with the measured values. The magnet, as built, ignoring gradient, more than meets the required RAF of $\leq 10^{-5}$.

Quadrupoles

In preliminary PEP designs, the bore of the quadrupoles was determined by the size of the 2 chamber vacuum tank passing through it. In order to enhance the high energy performance of magnet system, reduce power consumption, and reduce capital costs, a change was made to a three chamber vacuum tank

Table 1. PEP main ring bend parameters.

Magnet designation	71C5400	
Number of magnets	192	
Field at 18 GeV	0.3625	T
$\int B d\ell$ at 18 GeV	1.957	T-m
Pole width	0.214	m
Gap height	70.8	mm
Core length	5.33	m
Magnetic length	5.40	m
Width of useful field (0.1%)	120	mm
Turns per pole	8	
Current at 18 GeV	1316	A
Power at 18 GeV	9.6	kW

similar to that employed in Petra(5): the third chamber being cut away in the region of the quadrupoles and sextupoles. This allowed a bore reduction from 122 mm to 100 mm.

Economic studies similar to those done on the bend magnets resulted in curves similar to Fig. 2 and in optimum current densities for aluminum coiled quadrupoles of 0.5 to 1.2 A/mm^2 depending on the assumed cost of electricity. A value close to 1 A/mm^2 was used in order to reduce capital costs. Computer runs were made using Poisson to determine the optimum pole shape and width required to meet the design criterion of all multipoles other than 4 pole to be $\leq 10^{-3}$. Studies were also made to determine the necessary thickness of the back leg to achieve the required good field at 24 GeV. In order to achieve these energies pole tip fields of the order of 0.9 Tesla are required.

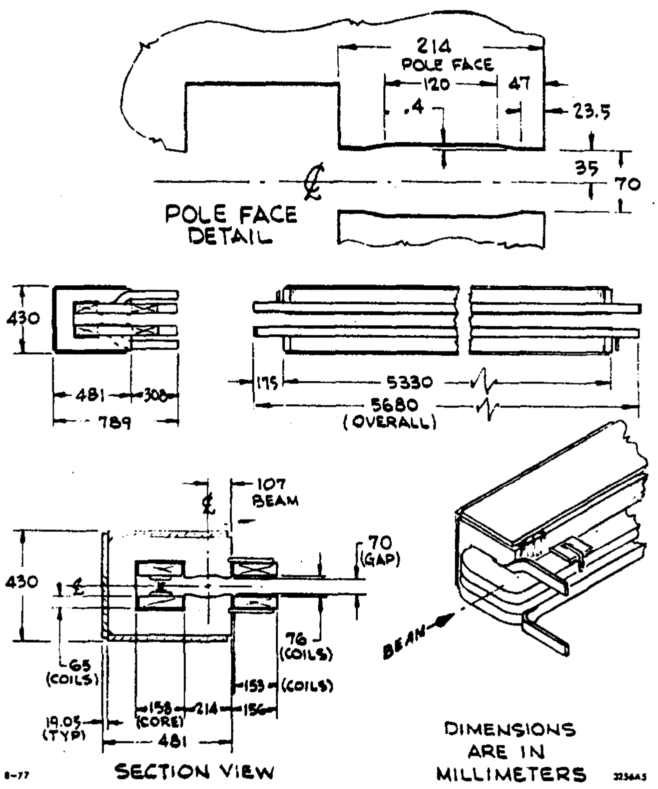

Fig. 3. Main ring bend magnet.

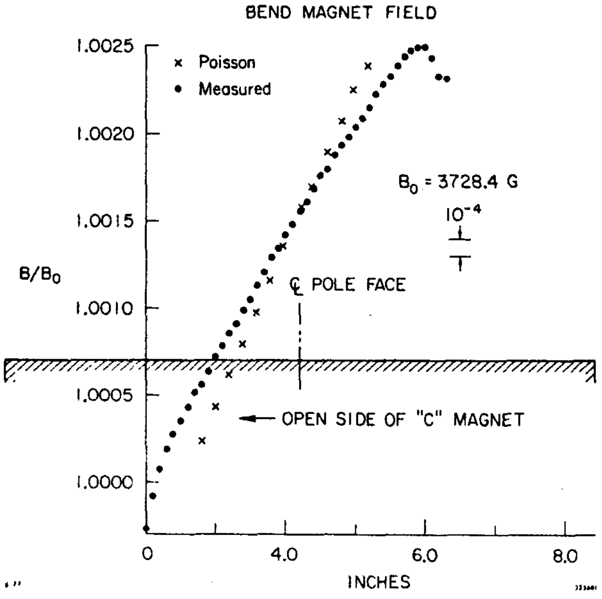

Fig. 4. Field vs. gap position.

The quadrupoles like the bends are also of laminated construction. Approximately 400 laminations are stacked between thick end plates, pressed and held together by means of an angle welded to the return yokes. Four such quadrants are put together to form a complete core. Indexing of the quadrants one to another is provided for by punching "V" grooves in the matting surfaces. Dowel pins placed in the grooves serve to properly align the quadrants. A tab is punched on one return leg. By properly flipping laminations in the stacking process and proper orientation of the quadrants, a series of slots are generated on the completed core into which bolts are slipped to hold the cores together. Quadrupoles of the same bore but of three different lengths are obtained by varying the numbers of laminations stacked. Table 2 lists the main magnet features.

Prior to the change to the 100 mm bore quadrupole, an engineering model of the larger 122 mm bore quadrupole was produced. It is shown in Fig. 5. Its multipole coefficients as built are presented in Fig. 6. Also presented are the theoretical multipoles of the 100 mm bore quad. Since the construction technique and outside dimensions of the larger model are similar to the new small bore quad, and there

Table 2. PEP standard quadrupole parameters (18 GeV) (high-impedance design).

Magnet designation	100Q740	100Q1000	100Q550	
Number of magnets	72	36	108	
Nominal peak gradient	17.56	17.56	17.56	T/m
Operating gradient	10.90	10.90	10.90	T/m
Pole tip field at operating gradient	0.545	0.545	0.545	T
Gradient length product	8.07	10.90	5.99	T
Inscribed radius	50	50	50	mm
Minimum gap	37.0	37.0	37.0	mm
Core length	0.667	0.950	0.500	m
Magnetic length	0.740	1.00	0.550	m
Width of useful field	100	100	100	mm
Ampere turns per pole	10892	10892	10892	A-turns
Turns per pole	56	56	56	
Current	195	195	195	A
Power at 18 GeV	3.47	4.6	2.75	kW

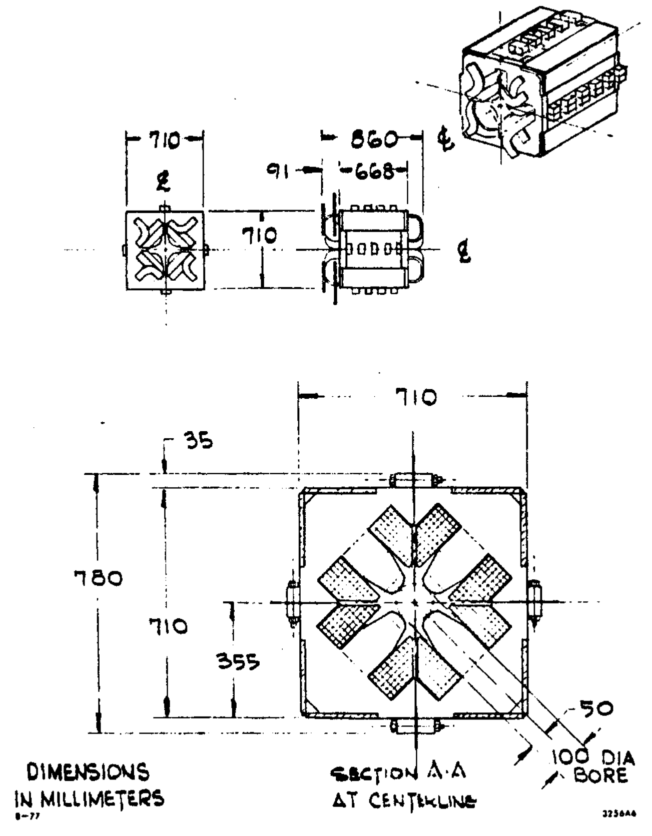

Fig. 5. Main ring quadrupole.

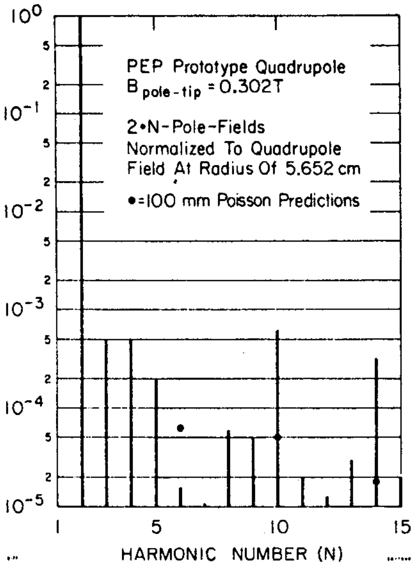

Fig. 6. Quadrupole harmonic content.

was good agreement of the theoretical Poisson data and the as-measured multipole coefficients, similar results are expected on the smaller bore version.

Magnet System Status

The present status of bend and quadrupole magnet system is as follows. The bend magnet coils are in production. The cores are out to bid. The quadrupole coils are in the bid cycle. The engineering model of the quad is presently under test. Upon successful completion of these tests the core package will be released for bid. The scheduled completion date of the entire production for both magnets is May, 1979.

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