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HARMONIC STRENGTHS OF PEP DIPOLES
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The harmonic content of magnets such as the standard PEP bend is (among other things) a function of excitation current, the way the current is set and even the magnetization history. For instance, harmonic strengths generally vary not only with the magnitude of the current but the direction and rate at which the current is approached and set. The field distribution resulting from different procedures can vary markedly depending on both the mechanical and magnetic design and the degree to which eddy current effects are emphasized. Variations among magnets of the same design result from variations in the iron (e.g., its chemistry, lamination fabrication and treatment procedures, etc.) as well as overall magnet fabrication procedures (e.g., from unobtainable tolerances on important assembly steps). Because the field distribution may also depend on the previous history of a magnet, all PEP dipoles were subjected to what are called "magnetization" and "standardization" cycles before measurement--the latter depending on the former and intended to set the initial conditions of the magnet to a reproducible standard.¹ The primary goal of the magnetic measurements was then to determine the dipole strength as a function of current for

each magnet based on a practical setting algorithm. The main constraints on the algorithm were reproducibility of the integrated field ($\int B_y dx$), speed, power and reduction of higher harmonics. Quadrupole and sextupole strengths were also measured on about one-half of the magnets at one current ($I = 1250A/E = 17.43$ GeV). This note presents the data and discusses it from the viewpoint of subsequent measurements with stored beams. The most important (and obvious) conclusion is that inability to fully distribute laminations according to heat number and/or strike number results in "magnetic personalities" among the magnets which are quite difficult to deal with afterwards although one can distribute "non-standard" magnets to minimize orbit distortions.

Bend Magnet Description

Figure 1 shows a schematic of the bottom half of a PEP bend, sliced through the median plane relative to the central design trajectory. Each magnet is formed from 16 gauge (1.59 mm thick), annealed and decarburized steel laminations (carbon content <0.008%). The magnet has a rectangular pole with a nominal gap height of $G = 70$ mm and a mechanical design gradient across the gap of $\frac{dB}{dx} = +0.53 \pm 0.05$ mT--intended to compensate the longer flux path through the lamination iron with decreasing values of x .

This is illustrated in Fig. 2 which shows the upper half of the magnet cross section, sliced through the x - y plane, as generated² with POISSON. Since the magnet is rectangular and long in the x -direction ($L/G > 76$), such 2-dimensional calculations should provide a good representation for a magnet whose steel conforms to the assumed permeability table except for residual field effects related to the coercive force

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(H_c) of the steel,³ eddy current effects associated with setting the magnet and mechanical distortions such as those associated with the mutual attraction of the poles or from the support members. Such distortion effects can easily nullify the predictions of the magnetic design calculations. While H-type magnets would have been preferable on the above points as well as their lower power and capital costs, the C-magnet allowed better vacuum chamber access and therefore installation schedule flexibility.

A total of 194 of these magnets were mechanically and magnetically measured prior to installation. Based on the measurements, the 192 magnets installed in the ring were divided into 3 classes containing 120, 48 and 24 magnets depending on whether their trim windings were to be excited and whether they were also near the vertical steering magnets in cells 4 and 8.

Bend Measurement Techniques

The magnetic induction integral, $\int \langle B_y(x,y,z) \rangle_{\text{coil}} dz$, was measured along lines parallel to the mechanical centerline of the magnet (shown as the straight dashed line in Fig. 1 and $x = y = 0$ in Fig. 2) using a rotating, long, pancake-coil (10-turns) having a rotation rate of $\sim 2\text{Hz}$ and a wire radius of 2.352 cm about the rotation axis. Because three magnets were measured simultaneously, the different coils were cross-calibrated against one another in the same magnet and field as well as against a point-by-point integral obtained using a Hall-probe and NMR on a calibrated lead-screw. An ideal measurement coil of this form is sensitive to only the symmetry-allowed harmonics of a bend, e.g., the dipole, sextupole and successive even n ($2n + 2$ number of physical poles)

harmonics. For a sufficiently long coil in a field having no variation of $B_y(x,y,z)$ with x (the direction parallel to the rectangular pole edge) and symmetry about the median plane ($y = 0$) it follows that the coil measures only

$$\int B_y(x,y,z)dz = \int B_y(0,0,z)dz \quad (1)$$

Thus, assuming the magnet is magnetically well designed and doesn't distort pathologically, one expects to measure only the integral of the vertical dipole component along the rotation axis of the coil⁴ whenever it is near the mechanical centerline. The accuracy of measurements for any one magnet and the rms variation over all magnets depends on many factors, however, none were found to be $>1:30,000$ for the final measuring system used to measure all magnets. Probably the best test was to remeasure bend #15 after 10 months of measuring more than 140 additional magnets (up to bend #156) with essentially the same results over the excitation range from 5.0 - 26.0 GeV of $(\Delta B/B)_1 < 1:10,000$ for all measurements ¹.

Dipole Effects

The primary purpose of the PEP bend measurements was to determine the dipole integral of each magnet on a fixed mesh of currents⁵ which would allow setting the ring to any energy for injection or ramping a stored beam up or down in energy. Errors in the dipole integral for individual magnets are understood as deviations from the mean value. Representative results are given in Table 1 and shown in Fig. 3. Whereas the relative current stability of the power supply improved with increasing currents the field integral spread between magnets increases as the

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permeability begins to decrease above 1000A. An attempt was made to assign magnets into Class 1 in such a way as to minimize its rms spread since these magnets would not have supplies for exciting their backing correction trims.

Assuming no significant saturation or deformation of the steel with excitation current, one would expect the distribution of Fig. 3 to follow the distribution of mechanical gap heights, measured at zero excitation, so long as the steel was uniform and the lengths were the same because

$$\int B_y(x,0,z) dz = \frac{L_{eff}}{\langle G \rangle} [-(4\pi/10^3)NI + \int_{iron(x)} (H_c - B_L/\mu) dl] \quad (2)$$

where units are Gaussian (e.g., Gauss and Oersted) except for lengths and current which are MKS. The integral in the iron follows a flux tube whose shape depends on the x-value in the median plane as seen from Fig. 2. H_c varies throughout the magnet and depends on both the steel⁶ and the distribution of maximum field seen by the iron,¹ i.e., on the magnetization current, I_{max} .

At zero excitation, measurement of the residual field integral determines the coercive term,

$$\frac{L_{eff}}{\langle G \rangle} \cdot \mathcal{H}_c = \frac{L_{eff}}{\langle G \rangle} \int_{x=0} H_c dl \approx -85.0 \text{ G-m} \quad , \quad (3)$$

ignoring variations between magnets.⁷ Thus, at low inductions ($B_L < \mu$), the dipole strength is dominated by the current driving term, followed by the coercive force which contributes 1.6% at 350A (equivalent to 5 GeV).

Figure 4 shows the predicted relative strengths of Fig. 3 based solely on the measured gap heights. The mechanical length of the magnet

was the most easily controlled variable in Eq. 2 and is considered constant since an error of one lam only leads to an error $\Delta k_D \approx 10$ rad. While there is a rough correlation with the data of Fig. 3, it is clear⁶ that *quality control over production of large numbers of such magnets based on Eq. 2 requires distribution or "shuffling" of laminations--the extent and parameters of the distribution depending on the range and quality of fields required. This is so important and incontrovertible that it will be called Golden Rule #1.*

To complete this section, a brief tabulation of some possible corrections and other effects that might influence normal ring operation is given insofar as they relate to dipole effects. These include such things as fringing field effects, earth's field, proximity to other magnets and various hysteresis effects.

- 1) Conversion of the long-coil measurements, taken along the dashed line in Fig. 1, to the design orbit shown as solid is given by the multiplicative constant:

$$C_1 = \frac{L_{\text{Design}}}{L_{\text{measure}}} = \frac{(\phi/2)}{\sin(\phi/2)} \approx 1 + \frac{1}{6} \left(\frac{\phi}{2} \right)^2 = 1.0000443. \quad (4)$$

This correction to all measurements was not made by the magnet group.

- 2) The special vertical steering magnets (cells 4 and 8) are in the coil-dominated region of their adjacent bends so they act to shield the beam trajectory from a positive vertical field. The effect is essentially independent of current so that Class 3 magnets (which are next to vertical steering magnets) were corrected by the multiplicative constant:

$$C_2 = 1.0000477 \pm 0.000018. \quad (5)$$

Fig. 5 of PEP-Note-345 implies proximity to other magnets is not a problem.

- 3) The magnets tend to shield the earth's field from the measurement coils except near the ends so no correction was made for this although the mean value measured by the three coils was found to be⁹

$$\langle B_{\text{earth}} \rangle_{\text{coil}} = 0.554 \pm 0.089 \text{ G}. \quad (6)$$

The earth's field complicates measurement of any zero excitation offset but since field integrals as low as $0.1 \pm 0.1 \text{ G-m}$ were measured for virgin magnets, no correction appeared necessary.

- 4) The effect of an extended fringing field¹⁰ as compared to the equivalent sharp-cutoff approximation shown in Fig. 1 is to displace the real orbit parallel to the assumed one in the field free region if they coincide in the constant field region. There is no change in strength (k_D) but only an alignment error of

$$\frac{\Delta x}{G} \lesssim (G/\rho)/\cos^2(\phi/2) = 0.000423, \quad (7)$$

so this is irrelevant for a pure dipole field and is also negligible compared to the alignment errors and variations between the magnetic and mechanical center lines in these magnets ($\Delta x/G > 0.02$).

- 5) Trim current hysteresis is shown in Fig. 5 when the magnet has $I = 1250\text{A}$, i.e., the same as for Fig. 3. The 19-turn (10 gauge) winding can produce up to 0.033 T-m ($\sim 61 \text{ G}$) which is more than sufficient to correct its own magnet's error but this can also lead to as much as 0.0034 T-m (0.18%) ambiguity which is a significant

error compared to either the spreads in Fig. 3 or the injection sensitivity observed for some configurations.

- 6) Hysteresis effects associated with exciting the primary windings are shown in Fig. 6. Considering only the dipole effect ($x \approx 0$), it is clear that the strength varies with the rate and direction of setting as well as the number of cycles. The potential for unrepeatability from such effects leads to Golden Rule #2 even when Golden Rule #1 has been followed:

To achieve optimal repeatability and uniformity, magnets should undergo a precondition or magnetization cycle which must not be achievable by any means during normal in situ operation. Further, all fields should be able to be set based on the same standardization algorithm (rate and cycle procedure) used during the magnetic measurements.

Although this is most relevant for magnets which can't be "fully" saturated, it also applies to solid core magnets (e.g., spectrometer magnets) because these are generally of multi-piece construction. Although it is obvious, it is stated as a golden rule because it seems to be "followed in the breach rather than the observance." Furthermore, since one expects to see greater use of combined function magnets¹¹ such effects will become of increasing interest in magnet design^{3,12} until eventually one will be able to calculate the optimal procedure rather than fashion it empirically. Figure 7 shows a typical set of magnetic measurements and how the magnetization cycle influences the results as a function of current.

Quadrupole Effects

Looking at Fig. 1 again, it is clear that the rectangular pole contour of the magnet leads to so-called "shim" angles (α, β) at entrance and exit of the magnet with $\alpha = \beta = -\phi/2$ which are equivalent to horizontally defocusing quadrupoles of strength

$$k_Q^0 = - \frac{\tan(\phi/2)}{\rho} = - 9.9 \times 10^{-5} \text{ m}^{-1} . \quad (8)$$

These are constant in strength and since they are an optical effect, resulting from the geometry of the magnets, rather than magnetic, they are not relevant here except to give an idea of what could be an important magnitude for the distributed quadrupole component of the magnet. Of course, one is interested in this for its effect on the tunes of the machine.

Returning to Fig. 6, one finds a good puzzle in that the more one studies it, the more confused one is likely to become. Both the sign and magnitude of the quadrupole strength may depend on whether the current is set from above or below as well as the rate of approach. For instance, the quadrupole components associated with the top and bottom curves (open circles) are nearly equal in magnitude but opposite in sign. Furthermore, the "brownout" data show that the magnitude depends on the final current. Finally, when the quadrupole component is unfolded, one is left with what can be called a transverse "umbrella" in the lower curves and a "dish" in the upper one--effects which are certainly related to the quadrupole variations as well as the previously mentioned dipole effects.¹³

The strength of harmonics in such a magnet can be written,¹⁴ using Eq. 1, as

$$\int B_y(x,0,z)dz = (B_0) \sum_n k_n x^n, \quad (9)$$

where we have already used $k_0 = k_D$ and $k_1 = k_Q^D$ in the discussion above. The distributed quadrupole strength can be written as

$$k_Q = \left(\frac{\partial k_D}{\partial x} \right)_{x=y=0}, \quad (10)$$

regardless of its equivalent optical strength which may differ. As indicated in the discussion of Eq. 1, the sensitivity of the quadrupole measurement depends only on the step size from the centerline, which was chosen large enough to encompass the full beam spread ($4\sigma_{x\text{tot}}$) over its trajectory through the magnet (Fig. 1) but small enough to ignore harmonics higher than three. Using Eq. 2 one then has

$$k_Q = - \frac{k_D}{\langle G \rangle} \left(\frac{\partial \langle G \rangle}{\partial x} \right)_{x=0} + \frac{k_D}{B_D \langle G \rangle} \left[\frac{\partial \mathcal{H}_c}{\partial x} - \frac{\partial \mathcal{H}_\mu}{\partial x} \right]_{x=0}, \quad (11)$$

where B_D is the effective, sharp-cutoff induction field.

With good steel, design and construction, the first term can be assumed zero, otherwise, the design constraint for a separated function, "dipole" magnet is

$$\frac{\partial \langle G \rangle}{\partial x} = \frac{1}{B_D} \left[\frac{\partial \mathcal{H}_c}{\partial x} - \frac{\partial \mathcal{H}_\mu}{\partial x} \right], \quad (12)$$

assuming no mechanical gradient increase with excitation.¹⁵ Thus, one desires cancellation between coercive and permeability terms somewhere toward the middle of the operating range.

Figure 8 shows the distribution of mechanical gradients, measured at zero excitation, which have a mean and rms:

$$\left(\frac{1}{N} \langle G \rangle \right) = 0.355 \pm 0.167 \text{ mr.} \quad (13)$$

Similarly, the mean and rms of the distribution of average gap heights, $\langle G \rangle$, shown in Fig. 4 is:

$$\langle\langle G \rangle\rangle = 70.122 \pm 0.040 \text{ mm.} \quad (14)$$

With Eq. 11 defined as $\bar{k}_Q = \bar{k}_Q^G + \bar{k}_Q^C + \bar{k}_Q^V$, one has:

$$\bar{k}_Q^G \approx - (1.65 \pm 0.77) \times 10^{-4} \text{ m}^{-1}, \quad (15)$$

which is considerably larger than the optical, edge contribution, Eq. 7.

The values of $\bar{k}_Q^C$ can be estimated using Fig. 2 and Eqs. 3 and 11 as:

$$\frac{\partial \mathcal{H}_c'}{\partial x} \approx \frac{\mathcal{H}_c'}{g_0} \frac{dg}{dx} = \langle H_c \rangle \frac{dg}{dx} \approx 1.65 \text{ Oe} \quad (16)$$

i.e.,

$$\bar{k}_Q^C \approx - 3.86 \times 10^{-3} / E(\text{GeV}) \text{ m}^{-1} \quad (17)$$

Similarly, the value of $\bar{k}_Q^V$ can be estimated, but with a little more care. For instance, some of the curves in Fig. 6 result from purposely inducing eddy current effects such as discussed by Halbach.¹⁶ While it is difficult to totally escape such effects, the standardization and setting procedure is supposed to minimize them so that we can approximate $\bar{k}_Q^V$ by

$$\bar{k}_Q^V \approx - \frac{k_D}{\langle G \rangle \cos \psi} (1/\nu) \frac{dg}{dx} \approx 0.79 \left(\frac{1}{\nu} \right) / \cos \psi \quad (18)$$

assuming no variation of μ with x . Using the measured, low field permeability, $\mu = 3000$, and assuming it doesn't change appreciably with current gives

$$\bar{k}_Q^\mu \gtrsim + 3.04 \times 10^{-4} \text{ m}^{-1} \quad (19)$$

Based on these assumptions, one expects the residual field integral or coercive term to exceed the permeability contribution below 12 GeV.

Figure 9 shows the measured quadrupole strengths for $I = 1250\text{A}$ (or $E = 17.43 \text{ GeV}$). At this current, the prediction, based on Eqs. 15, 17 and 19, is

$$\bar{k}_Q \gtrsim (-0.82 \pm 0.77 \times 10^{-4}) \text{ m}^{-1}, \quad (20)$$

i.e., $\bar{k}_Q$ should not be more negative, so long as there is no gap closure at this excitation. The mean and rms of the measurements¹⁷ are

$$\langle k_Q \rangle \approx (-0.42 \pm 0.44) \times 10^{-4} \text{ m}^{-1}. \quad (21)$$

Adjusting Eq. 19 for the lower permeability at 1250A can account for the difference¹⁸ between prediction and measurement. Below 1250A, one expects $\bar{k}_Q^\mu$ to decrease somewhat and $\bar{k}_Q^c$ to also decrease (i.e., become more negative) so that $\langle k_Q \rangle$ should become more negative (assuming no gap opening). This is not inconsistent with Fig. 6 since the so-called "brownout" data was actually taken at the same *constant* rate of change of current, i.e., the magnet was not truly standardized. Since the 800A data is comparable to 1250A data at the same rate, one might reason that it is possible to use eddy currents to compensate such a decrease of $\langle k_Q \rangle$ with energy.

The model for this (ignoring the laminar structure) can be written down by considering the induced eddy currents in the backleg perpendicular to the line A-B in Fig. 2:

$$J_z = -\frac{\sigma}{c} \langle \dot{B} \rangle \times . \quad (22)$$

This eddy current translates into a relative variation of μ across line A-B which in turn translates into an induced variation of the gradient across the gap which can be positive or negative depending on the sign of $\dot{B}$, i.e., whether one approaches from above or below.

We complete this section by summarizing some conclusions based solely on considering the quadrupole strength of such magnets:

- 1) There is a definite correlation between the mechanical gradient and quadrupole strength. In fact, the simple prediction of k_Q for individual magnets as well as $\bar{k}_Q$ is consistent, within the errors on $\bar{k}_Q^G$, with the measurement of $\langle k_Q \rangle$. The same can be said of k_D and $\bar{k}_D^G$.
- 2) A much smaller variation of $\bar{k}_Q^G$ would have resulted from distributing the laminations serially according to magnet number as they are produced from heats of steel ordered according to H_c , i.e., by following G. R. #1.
- 3) Comparison of the data in Fig. 6 obtained by ramping up at a constant rate of 100 A/s with that obtained by standardizing, i.e., following an exponential upward approach, shows the former is totally eddy-current dominated. This demonstrates how easy it is to change the character of the magnets and the optics of the ring by inconsistent setting or standardization procedures, i.e., by ignoring G. R. #2.

- 4) From the equations above, one wants H_c to have a small magnitude, one wants a high permeability, a small angle, ψ , and as high an operating field, B_D , as is compatible with a small variation of μ over the intended operating range. This last point also favors a small ψ which can be obtained by either making a higher pole segment or a more symmetric design, e.g., an H-magnet.
- 5) When one considers that a mechanical gap closure of 1 mil at the pole-edge causes a change of $\Delta k_Q^G = 1.2 \times 10^{-4} m^{-1}$ and, the additional fact, that the magnet, through lack of symmetry about the y-z plane, is more sensitive to eddy currents, one has Golden Rule #3:

Don't make magnets whose mechanical symmetry doesn't conform to the desired magnetic symmetry. Regardless, insure that the calculations comprehend the real magnet, e.g., its steel and construction.

I know of no application at SLAC where this should be broken, e.g., see SLAC Pub.'s 2279 and 2289 for synchrotron radiation magnets.

- 6) From Fig. 1 and the fact that $\langle k_Q \rangle \neq 0$, it follows that the effective dipole strength is modified because the central ray spends more time at positive than negative values of x , i.e., using

$$\delta k_D = \langle k_Q \rangle \langle \delta x \rangle \quad (23)$$

where

$$\langle \delta x \rangle = \rho \left[\frac{\sin(\phi/2)}{(\phi/2)} - \frac{1}{2} (1 + \cos(\phi/2)) \right] = + 3.67 \text{ mm}, \quad (24)$$

this is equivalent to effectively less bending; i.e., we would need a fractionally higher current by the amount:

$$-\left(\frac{dk_D}{k_D}\right)_F = 4.27 \cdot 10^{-6} \left(\frac{E(\text{GeV})}{17.43}\right) \quad (25)$$

This is equivalent to only 0.052 MeV at 14.5 GeV.

Sextupole Effects

The existence of "shim" angles ($\alpha, \beta = -\phi/2$) generally imply the equivalent of defocusing sextupoles ($k_S < 0$) at entrance and exit of strength: 14.20

$$k_S^0 = -\frac{1}{2\rho R} \sec^3(\phi/2) \approx -0.0032 \text{ m}^{-2}, \quad (26)$$

where $R_a = R_b = R > 0$ is the radius of the isoinduction lines at entrance and exit. If the magnet pole is wide enough ($W/G \gg 1$) and there is no significant saturation over the operating range, then a rectangular pole contour will have $R \rightarrow \infty$ --even at the ends where the third dimension enters. Because this would be an unaccustomed (if not unnecessary) extravagance one expects a small, negative sextupole strength at entrance and exit (because $W/G \approx 1.5$) which becomes increasingly negative with energy. One also expects the distributed sextupole strength to become increasingly negative with excitation.

Clearly, the upper curve in Fig. 6 has the "wrong" sign, i.e., it doesn't decrease as one goes away from center but increases. Where we understood the induced gradient from eddy currents to result from the lack of symmetry in the *backleg return yoke* of the C-magnet, the induced sextupole can be understood from the symmetric arrangement of the coils around the *pole* such that the induced eddy currents approach zero near the magnet centerline and reverse when $\dot{B}$ changes sign. This is essentially the "dish" effect that Halbach studied in Ref. 16. Comparing to the lower curves in Fig. 6, obtained by standardizing, we

see that the sextupole strength is significantly reduced and also has the expected sign ($k_S < 0$).

Figure 10 shows the distribution of sextupole strengths which were measured in the same way and at the same time the quadrupole data was obtained. One sees the same correlations with the magnet fabrication procedures as for the quadrupole data¹⁷ but with one significant difference--there is an apparent increase with time (or lamination number). Table II summarizes the results based on the previous partition of the data.¹⁷ There are several possible explanations, e.g., significant die wear at the "sharp" corners of the pole edge which became increasingly rounded--resulting in less saturation at 1250A. Unfortunately, there are no measurements at other excitations. The mean and rms are:

$$\langle k_S \rangle = (+3.38 \pm 10.9) \times 10^{-4} \text{ m}^{-2}, \quad (27)$$

where the rms is taken simply as the weighted average of the three groups.

The same kind of analysis as done for $\bar{k}_Q$ will not be done for $\bar{k}_S$ except to point out one result, i.e., imposition of a mechanical gradient (to optimize $\bar{k}_Q$) can modify $\bar{k}_S$ ²¹ and all higher orders. While this is not the explanation of Fig. 10, it provides further support for G. R. #3. The large spread in the data of Fig. 10 supports G. R. #1 and, as just discussed, the sextupole effects displayed in Fig. 6 support G. R. #2. The reason an analytic treatment of $\bar{k}_S$ is not done is because there are too many terms and too little information, i.e., a set of measurements similar to those of Fig. 7 should have been obtained as a function of both current and position (x), before and after the magnetization step was done. This brings us to another important point which will be called G. R. #4:

It is preferable to do a good, complete 2-D magnetic design calculation than a poor 3-D one, i.e., at least one full-scale prototype should be built which tests the proposed fabrication procedure's ability to produce a magnet which verifies the 2-D calculations and allows us to measure and modify 3-D effects such as end contributions may give.

This has a lot to say about how one designs magnets and is applicable to systems with only a few components such as spectrometers. For instance, a corollary is that one should *not* plan on shimming the end fields to correct errors observed in the central field (or vice-versa) because that should not be necessary! This also has something to say about how one designs optical systems, e.g., short, separated-function magnets should be avoided--especially since optics considerations generally prefer combined function systems anyway.^{11,22}

Discussion

The guaranteed operating range of the FEP bend magnets is from 200-1850A, i.e., from 2.8 - 25.6 GeV with a standardizing current of 1250A. From Tables I and II, the relative multipole strengths measured at 1250A are:

$$\begin{aligned}
 \langle k_D \rangle_{\text{class 1}} &= 0.032625 \pm 0.000018, \\
 \langle G \rangle \cdot \langle k_Q \rangle / \langle k_D \rangle_1 &= -0.000090 \pm 0.000094, \\
 \langle G \rangle^2 \cdot \langle k_S \rangle / \langle k_D \rangle_1 &= 0.000051 \pm 0.000162,
 \end{aligned}
 \tag{28}$$

with higher multipoles undetermined but convergent. One is interested in such results because the bend magnets are the largest class of magnets in the ring ($N = 192$).

An rms error in the bending strength of only 18 μ rad translates into a closed orbit error at any location, s , of:

$$\langle x_{c.o.}^2(s) \rangle^{\frac{1}{2}} \approx \frac{\sqrt{\langle B_x \rangle B(s)/8}}{|\sin \pi \nu|} \sqrt{N} \sigma_{k_D} = 0.43 \sqrt{B(n)} \quad \text{mm}, \quad (29)$$

where we have used the ring values given in Table III for configuration #31. Even a small rms error can therefore lead to significant orbit distortions! The question of the absolute calibration of the beam energy will be discussed in another PTH.²³

The tune shifts expected from a quadrupole strength such as given by Eq. 26 will be

$$\begin{aligned} \Delta \nu_x &\lesssim \frac{N}{4\pi} \langle k_Q \rangle \langle B_x \rangle = -0.0093 \\ \Delta \nu_y &\lesssim -\Delta \nu_x \langle B_y \rangle / \langle B_x \rangle = +0.0162 \end{aligned} \quad (30)$$

i.e., ν_x decreases and ν_y increases compared to a model which includes Eq. 8 but not Eq. 21. The inequalities should be valid below 17.4 GeV, i.e., one expects $\Delta \nu_y - \Delta \nu_x (\gtrsim 0.025)$ to increase with decreasing energy. Comparisons with ring measurements are complicated by the fact that the most sensitive quadrupoles in the ring are in series with the bends. This appears to be a relatively small but non-negligible effect.²⁴

The tune spread, which is a measure of the stopband widths, can also be calculated from Eq. 28 as:

$$\langle \Delta v_x^2 \rangle = \frac{N^2}{4\pi} \langle v_x \rangle^2 k_Q = 0.0007$$

$$\langle \Delta v_y^2 \rangle^{1/2} = 0.0012. \quad (31)$$

Similarly, using Courant and Snyder's formulae again,²⁵ one can write the corresponding beta mismatch as

$$\frac{\langle \Delta \beta_x^2 \rangle^{1/2}}{\beta_x(s)} \cdot \sqrt{2} \pi \frac{\langle \Delta v_x^2 \rangle^{1/2}}{|\sin 2\pi v_x|} = 0.0032$$

$$\frac{\langle \Delta \beta_y^2 \rangle^{1/2}}{\beta_y(s)} = 0.0053. \quad (32)$$

One-half percent or so would seem quite acceptable. If the damping partition numbers are $J_x = 1 - \mathcal{P}$ etc., then the change due to a distributed quadrupole or energy error ($\delta = \delta E/E$) will be:

$$\Delta \mathcal{P} \approx \frac{\langle \eta \rangle}{\langle k_D \rangle} \left| [2 \langle k_Q^0 \rangle - \langle k_D \rangle / \rho] \delta + 2 \langle k_Q^0 \rangle \right| \quad (33)$$

i.e., $\Delta \mathcal{P} \ll 1$ for the ring acceptance. Furthermore, imposing an energy perturbation which makes $\Delta \mathcal{P} = 0$ can cancel any tendency to antidamp from such a quadrupole contribution--a result compatible with simply shifting the beam in the dipoles as given by Eq. 23 (within the approximations used here).

Although the sextupole content in Eq. 28 is of higher-order, it can influence the tunes through residual orbit distortions such as Eq. 29, i.e.,

$$\Delta v_{x,y} \approx \frac{N}{4\pi} \left| \langle k_S^n \rangle \langle x_{c.o.} \rangle \langle L_{x,y} \rangle \right|_{\text{bend}} \quad (34)$$

which shows that orbit distortions of the magnitude of Eq. 29 can produce significantly large tune shifts ($\Delta\nu \approx 0.1$). For an otherwise perfect ring, a measurement of the tunes together with Eqs. 30 and 34 would allow determination of the distributed multipole components or knowing them,²⁴ one could infer how much of the observed discrepancy with the ring model comes from this source. From the results above and the new mini-beta insertions, one expects to see a much smaller discrepancy between tunes predicted by the model and the measurements. By direct analogy with the above, a vertical closed-orbit error in a region with $\eta_x \neq 0$ and $k_s \neq 0$ also introduces vertical dispersion $\langle \eta_y \rangle \neq 0$ modulated by B_y .

A summary of the magnet alignment tolerances which were requested is available as a PEP PTN.²⁶ Also, the magnetic measurements procedure used for these magnets as well as some sample output is available from the author. All of the above data is accessible from the SLAC computers.

ACKNOWLEDGEMENTS

It is important to thank all members of the PEP Magnet Group but especially Marty Anderson, Bob Bell and Gerry Fischer who had the task of making these magnets. I would also like to thank the SLAC Magnetic Measurements group, who were always available and built a superbly sturdy measurement system that resisted all attempts of man and nature to destroy it. Zorlab Vassilian was every bit as dependable and is the individual most responsible for the quality of the data presented here together with a great many Stanford students who helped with the measurements. I must also thank John Rees, who got me to automate the data "sooner than later," since this proved to be extremely helpful in assigning the magnets into classes. Finally, I thank Margie Barnes for her help and patience with this report.

REFERENCES

1. Because of the comparatively low field desired in these magnets ($B \ll B_{sat}$), to keep the radiated power down, it is not possible to significantly saturate them. This is not a problem so long as the magnetizing current is never exceeded ($I_{max} = 2000A$).
2. R. Early and G. Fischer.
3. These become increasingly important with decreasing field strengths and are difficult to control. We will attempt to use the code PANDIRA to study them.
4. The coils were straight with lengths $l = 6219$ mm and $(l-L)/2C > 6$. The coil centerline had a range of travel of ± 4.5 cm about the mechanical centerline of the magnet. $\Delta B/B < 0.2\%$ over this range.
5. The dipole integral for each magnet was measured following standardization to $I = 1250A$, proceeding downwards to $50A$ in $150A$ steps and then upwards to $2000A$ with the same step size at a rate of $5 A/s$. Consequently, the ring ramping rate is $\leq 5A/s$ or ≤ 70 MeV/s. A rate in excess of this will result in an apparently low energy, i.e., more efficient steel when approaching currents from below.
6. One wants magnet steel to have a low coercive force (e.g., $|H_c| \leq 1$ Oe) since this reduces the area of the hysteresis loop, magnetic aging effects and variations between magnets.
7. The variations alone are larger than the earth's unshielded field because of variations between heats of steel which were $0.88 \leq |H_c| \leq 1.53$ Oe and difficulty in hand-mixing the available heats between magnets.

8. Significant anomalies such as the Class 2 magnet #087 were traceable to a longer length than its neighbors. Another typical example is Class 2 magnet #001 which is formed from only one heat of steel with an $H_c \approx -1.02$ Oe whereas the reference magnet was formed from 3 heats having a range $1.03 \leq |H_c| \leq 1.23$ Oe. The area of all hysteresis loops and residual fields (B_r) of the reference were greater than for #001 whereas the dipole integral per ampere of excitation was less for currents $100 \leq I \leq 1900$ A. The "high" field ($I \geq I_{\max}$) behavior can be attributed to the differing chemistry and treatment of the heats leading to a relative inversion of the high field permeabilities and/or "anomalous" enhancement of H_c .
9. This was encouraging considering the different locations of the coils in the measurement building since it verified that the accurate cross-calibration of the coils had been maintained over the course of the measurements (July 1978 to Sept. 1979).
10. H. A. Engle, Rev. Sci. Instr. 35 (1964) 278.
11. One generally deals with combined function magnets anyway, except that the higher harmonics are supposed to be weak enough to ignore.
12. The implications for quadrupole magnets will be discussed in another note on the PEP quads similar to this one.
13. Dipole variations associated with eddy currents were observed by Cobb and Harris, Int'l. Symp. on Magnet Tech. (Stanford) pg. 823 (1965).
14. K. L. Brown, SLAC Report No. 75.
15. The low fields required to reduce radiative energy loss simplify this problem but don't eliminate it because of the increasing importance of coercive contributions compared to the current driving terms.

16. K. Halbach, NIM 107, (1973) 529.
17. Because measurements were obtained on only half the magnets, the determination of the mean is based on a weighted average of two groups. One group was composed of magnets from #030 - 140 since, according to G. Fischer, a restrike operation began after #029 which included a mechanical gradient of 0.53 mr for the first time. From Fig. 8, it appears that this gradient was roughly obtained until after magnet #140 when "acrap" laminations had to be included which were made prior to #030.
18. The calculation is admittedly crude. It was intended primarily to show how different effects contribute and thereby justify the PANDIRA Calculations.
19. A full ray tracing calculation will be done to get the effective transfer matrix. In first order, the magnets should be partitioned into an odd number of lens, $n \geq 3$, e.g., triplets with the entrance and exit strengths modified from the value given in Eq. 8.
20. H. A. Engle, Focusing of Charged Particles, Academic Press (1967).
21. Imposition of a gradient (after magnet #029) can be expected to increase $\bar{k}_s$ as observed in Fig. 10. Comparing Figs. 9 and 10 implies that the imposed gradient was roughly twice as large as it should have been--at least at this excitation.
22. The argument here is not whether combined-function elements are preferred but rather on how to realize them. Golden Rules #3 and #4 certainly relate to this problem which will be discussed elsewhere (Collider Memo). When fabrication mistakes occur, such magnets are natural candidates to also serve as general purpose

correction magnets, e.g., by adding pole-face windings for various multipoles similar to the way magnets were selected to have their backleg dipole trims excited. In this way, one might require only about $2v$ such magnets ($N \gg 2v$), which determines the fabrication tolerance.

23. An energy error will be reflected everywhere, e.g., tunes, acceptance, damping partition, etc. The higher multipoles were shown to influence this but the magnitudes don't appear significant as long as the orbit distortions are controlled.
24. The model that has been formulated can be tested on the reference magnet.
25. Courant and Synder, *Annals of Physics* 3 (1958) 1 or Sands, SLAC Rpt. No. 121.
26. P. Morton and R. Helm, PEP PTM #163.

TABLE I

Current [A]*	Class	#	$\langle \int B dz \rangle$	$\pm$	RMS [T-m]	$\langle \int B dz / (BL)_{ref} \rangle$	$\pm$	RMS
349.40	3	24	-0.53228	$\pm$	0.00048	0.99915	$\pm$	0.00085
	2	48	-0.53238		0.00043	0.99932		0.00074
	1	120	-0.53224		0.00026	0.99906		0.00049
	All	192	-0.53228		0.00035	0.99914		0.00062
799.70	3	24	-1.21832	$\pm$	0.00114	0.99907	$\pm$	0.00092
	2	48	-1.21856		0.00093	0.99926		0.00075
	1	120	-1.21823		0.00061	0.99902		0.00050
	All	192	-1.21832		0.00080	0.99909		0.00064
1249.90	3	24	-1.89722	$\pm$	0.00201	0.99769	$\pm$	0.00104
	2	48	-1.89791		0.00196	0.99804		0.00100
	1	120	-1.89709		0.00106	0.99765		0.00055
	All	192	-1.89731		0.00151	0.99775		0.00078
1700.00	3	24	-2.56692	$\pm$	0.00342	0.99642	$\pm$	0.00128
	2	48	-2.56823		0.00371	0.99691		0.00138
	1	120	-2.56664		0.00174	0.99634		0.00066
	All	192	-2.56707		0.00269	0.99649		0.00100

*The PEP "standard ampere" is defined by the transducers used for the magnetic measurements since the transducers and their electronics are used in the ring.

TABLE II

Magnet #	$\langle k_Q \rangle$	$\pm$	RMS [m^{-1}]	$\langle k_r \rangle$	$\pm$	RMS [m^{-2}]	Sample #
001-030	+0.000045	$\pm$	0.000046	-0.00194	$\pm$	0.00092	10
030-140	-0.000081	$\pm$	0.000046	+0.000407	$\pm$	0.00131	53
140-192	+0.000016	$\pm$	0.000040	+0.001505	$\pm$	0.00073	31

TABLE III

E	14.5		GeV
v_x	21.279		
v_y	18.253		
β_x^*	4.58		m
θ_y^*	0.31		m
$\langle \beta_x \rangle_{\text{bend}}$	14.65	$\pm$	2.52 m
$\langle \theta_y \rangle_{\text{bend}}$	25.26	$\pm$	3.33 m
$\langle n_x \rangle_{\text{bend}}$	0.89	$\pm$	0.31 m

Fig. 1: Schematic cross-sectional view through the median-plane of a standard FEP bend magnet (C-type) which was designed to have an effective magnetic length, $(1/B_0) \int B_z(s) ds$, along the circular design orbit between effective field boundaries, of 5.400 m. ϕ is the average bend angle per magnet in degrees i.e. the effective dipole strength. The maximum beam spreads expected in the dispersion plane in these magnets are $\sigma_{x\text{tot}} < 6 \text{ mm}$.

Fig. 2: POISSON plot of the upper half of the FEP standard bend magnet showing the coordinate convention (consistent with Helm, PEP PTH-207). z is the third coordinate of a right-handed system which coincides with the mechanical centerline of the magnet. The induction is negative and the dipole strength, k_0 , is positive. A linearly increasing negative field for positive x -values corresponds to a horizontally focusing quadrupole ($k_1 > 0$) and a quadratically increasing negative field corresponds to a horizontally focusing sextupole ($k_2 > 0$). The angle here is $\psi \approx 30^\circ$.

Fig. 6: Effects of current ramping rate and direction of approach on absolute field level and distribution in PEP bend magnet #001. The lowest curve was obtained by dumping the magnet from 1250A following a complete standardization cycle and then running up to 1250A at a constant rate of 100A/S. The highest curve resulted by then running the current up to 2000A and back down to 1250A at the same constant rate. All data is at 1250A except for that in boxes (□) which was at browout current (800A).

AVERAGE GAP HEIGHT

Fig. 4: Ratio of the measured, average gap opening of the reference magnet to all others. Error bars represent the uncertainty in this ratio from the rms spread in the beam gap opening.

1250 AMPERES BY CLASS

7-81

4136A8

Fig. 3: Ratio of $\int B_z ds$ to the simultaneously measured value for the reference bend for each class defined as (1) trims not excitable (total = 170), (2) trims excitable (46) and (3) trims excitable and near a vertical steering magnet (34). The average $\pm$ error on this data is typically less than or comparable to the size of the print symbol.

MECHANICAL GRADIENT

Fig. 8: Distribution of average, mechanical gradient measured across the gap, transversely to the longitudinal centerline for each magnet. The average error, resulting from the rms of the measurement data, is ± 0.31 mr.

Fig. 7. Field integrals measured before and after subjecting a virgin magnet to the preconditioning magnetization cycle.

SEXTUPOLE

Fig. 10: Sampled distribution of sextupole strengths measured in the PEP bend magnets following standardisation at 1330A.

QUADRUPOLE

Fig. 9: Sampled distribution of quadrupole strengths measured in the PEP bend magnets following standardization at 1250A.