MEASUREMENT AND SHAPING OF THE FRINGING FIELDS OF THE PRINCETON-PENNSYLVANIA ACCELERATOR MAGNETS

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Summary. The fringing fields must be included in the determination of the effective length and field index of the P.P.A. weak focusing magnets. For this purpose, a null method was used to compare the magnetic field inside the gap with the fringing field integrated along a line perpendicular to the magnet end.

$B_z(r,t)$, the field component normal to the median plane varied between 0.26 and 13.9 Kgauss, at 20 cps.

The measuring technique consisted in placing a short line dipole coil in the known and essentially two dimensional field (e.g.- sufficiently far from the end) and a long dipole coil through the fringing field free region. See Figure 1.

The outputs of the two coils were summed into an electronic integrator. The output of the integrator was set to zero at a preselected phase of the magnet's field. Then, the azimuthal position of the coil pair was adjusted so that the output at this phase remained equal to zero when the coils were simultaneously inverted. This procedure was followed for different radial positions. Then another phase was selected.

These measurements gave the effective length of the fringing fields to $\pm 5 \times 10^{-3}$ in., at B minimum, and $\pm 5 \times 10^{-4}$ in., at B maximum. The results were used to analyze and guide the design of correcting end pole pieces which produced the desired effective length and average field index. This work was performed on the P.P.A. full scale prototyped magnet. The excellence of the actual magnets was checked with the proton beam.

Introduction. The P.P.A. has sixteen magnets and therefore the contribution of their thirty-two fringing fields must be taken into account in establishing the physical lengths of the individual magnets and in adjusting the first effective value of "n".

Theory of the Measurements. Two line dipole coils were placed end to end, with their magnetic planes parallel to each other on a common axis free to turn through 180° (see Figures 1 and 2). Each of these coils was one half of an ideal line quadrupole[1]; one of them being short, the other long. The short coil and one end of the long coil were in a part of the magnet where the field was essentially free of end effects. The other end of the long coil was in an essentially field free region. Since the coils were rotated around their common axis and the magnetic field was time dependent, the output of each coil was

$$d\,e(\text{output})/dt = k\,N\,d(AB)/dt$$

where N = number of turns of a coil
A = average area of one turn; it is a function of time during the invertion operation
$B = B(t, r_o\theta) = B_{DC} - B_{AC}\cos\omega t$
B_{DC} = DC component of the magnetic field; it is a function of radius and azimuth.
B_{AC} = AC component of the magnetic field; it is a function of radius and azimuth.
k = the appropriate constant
r_o = orbital radius at which the measurement is being made
θ = azimuth
$\omega = 2\pi f$, f = frequency of the synchrotron magnets $\simeq$ 19 c.p.s.
$T = 1/f$

and the output of the integrator is

$$\Delta e = kN\int_{t=t_o}^{t=t_o+nT}[d(\mathring{A}B)/dt]\,dt = kN[AB]_{t=t_o}^{t=t_o+nT}$$
$$= kN\,AB(t_o) - (-A)B(t_o) = 2kN\,AB(t_o) \qquad (1)$$

The integrator had been reset to zero at time t_o. n cycles later, after the inversion, the output was examined at that particular phase. Note that the vector area A, has been reverse, and that $B(t_o + nT) = B(t_o)$

If the coils are connected differentially as shown in Figure 3, then the output of the integrator may be made to show no output at a given time (field) in the cycle if the position of the coils is varied azimuthally while the coils are being flipped backand forth. At the null then,

$$B_{ref}(t_o)W_sN_sL_{es}R_s^{-1} = R_L^{-1}W_LN_L\int B(t_o, r_o\theta)\,d\theta$$
$$= R_L^{-1}W_LN_LL_{eL}B_{ref}(t_o) \qquad (2)$$

where $B_{ref}(t_o)$ is the magnetic field in the uniform region of the magnet at a given phase angle. W, N, L_e and R are the widths, number of turns, effective lengths and total resistance of the two coils and θ the azimuthal angle.

Procedure. The integrator was clamped by means of a transistor switch (which could be disconnected from the integrator by a DPST mechanical switch), for some 20 µsec., at a certain phase angle of the magnet cycle. After releasing this clamp the coils would be turned back and forth through 180 degrees. If the flux through both coils was the appropriate one (as determined by the turns-area of the coils and their respective series resistors) the output of the integrator would show no difference in the output (a null) for all angles of rotations of the coil pair from 0 to 180° and from 180° to zero. If this was not the case, the integrator was clamped again and the coil system was

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moved azimuthally until a null was obtained.

To determine the extra length of the magnet, we must know the geometry of the coils and their total resistance as seen by the integrator. Both coils, in our case, had equal width and the effective length of the short coil was $L_{es} = 3.514$ in. Then, the length of the long coil which would give the same output as the short coil if immersed in the same magnetic field as the short coil, would be

$$L_{eL} = (R_L/R_S)(N_S/N_L)\ L_{es} = 6.290 \text{ inches} \qquad (3)$$

The R's include the resistance of the coils and the summing resistors.

After the system had been slid azimuthally until a null was obtained at a given phase angle of B(t) when flipping the coils, we know that the effective end of the magnet was 6.290 inches from the effective end of the long coil, at that particular radial position of the coil system. The coil had been positioned perpendicualrly to the physical end of the magnet.

The coil assembly was mounted in a system of three slides, so that one had three mutually independent and orthogonal motions readable to ±0.001 inches. See Figure 8.

The coils were 0.400 inch wide, the short coil had four layers (630 turns) and the long one a single layer (167 turns). Both coils were inserted in a long, precision ground glass tube to assure collinearity and rigidity. The long coil was approximately 30 inches long. The forms were made of fiberglass epoxy and were machined to ± 0.001 in. The mechanical stops were capable to limit the rotations of the coils to 180° ± 1°.

Since it was obvious that the job of aligning the planes of the two line dipoles was going to be very difficult, a third coil of about 30 turns-cm^2 was mounted at about 90° with respect to the other two. The output of this coil could then be added with the necessary amplitude and phase to the other two to make them essentially parallel. This adjustment could be made easily as follows: the coils would be rotated through 90° until the output of one of the two coils was zero, then the other coil and the compensating coil were connected and the output of the compensating coil was adjusted for a null.

The value of the integrating capacitors was chosen to match the drift of the amplifier due to remnant leakage current ($\pm 10^{-9}$ Amp) in the operational amplifier (Kintel 111BK).

The transistor switch was of the common back to back type. It was disconnected just before commencing to flip the coils.

It was necessary to check that at no time during the cycle the input to the integrator would drive it to saturation.

Results. In Figure 5, we see (dashed lines) the first measurement of the additional effective length of the magnet. The pole pieces used were slotted to reduce eddy currents but their ends were flat and in the proper radial direction. Then, an effort was made to control the shape of the fringing field in order to trim the effective "n" of the magnet. The second set of pole pieces with thickened (longer) ends is shown with solid lines. These pole pieces were adopted. Measurements off the median plane (.8 inches above it) showed essentially the same effective lengths as a function of B. On Figure 6, we see a plot of the additional effective lengths as a function of B, for the original (unmodified) end pole pieces and the final set of pole pieces. On Figure 7, we see the plot of the additional effective lengths with the first set of modified pole pieces - a) alone, b) with the beam sensing electrode short straight section in place, and c) with an R.F. station mock-up in place. These components showed unimportant effects and no special pole pieces were designed for different types of straight sections.

References

1. Laslett, L. Jackson. "Coil Systems For Measurements of Fields and Field Gradients In Two Dimensional Fields", BNL report LJL - 2, unpublished.

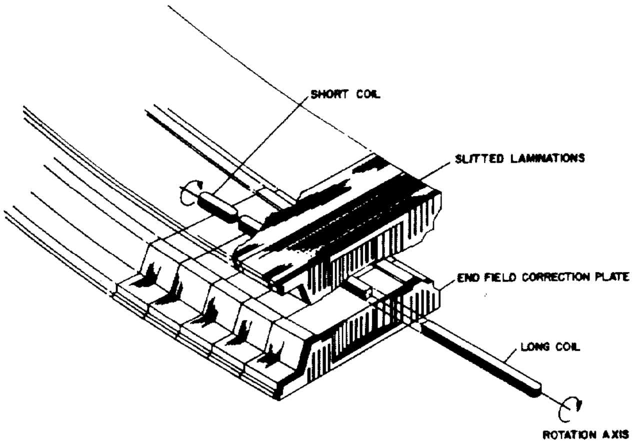

Fig. 1. Cut-out showing the location of the two line dipole coils at one end of the full-scale prototype magnet. The laminations are slitted to reduced eddy currents. The extra laminations near the front and rear shimms produced the changes shown in Fig. 5.

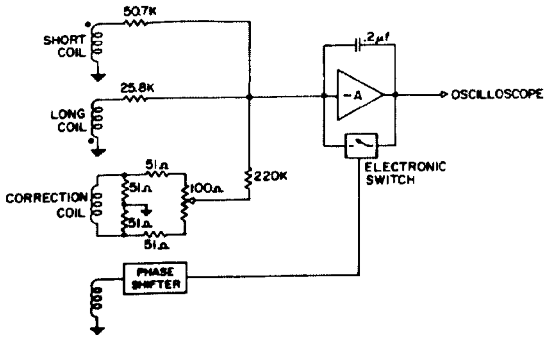

Fig. 2. Electronics used in the measurements described in the text.

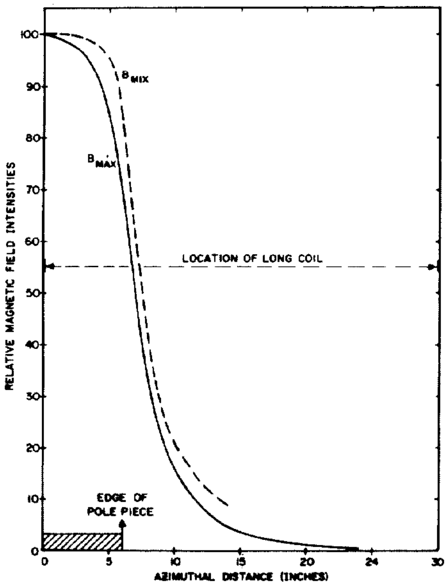

Fig. 3. Fringing fields of the end of the magnet taken along the mean stable orbit and normalized to 100 in the azimuthally uniform region of the magnet. The long coil was located as shown at $B = B_{min}$. At B_{max} it was about 5/8 inch further inside the magnet.

Fig. 4. Photograph of the coil system. On the right hand end the short coil is visible. On the handle of the coils, the mercury switch which was in series with the transistor switch is visible.

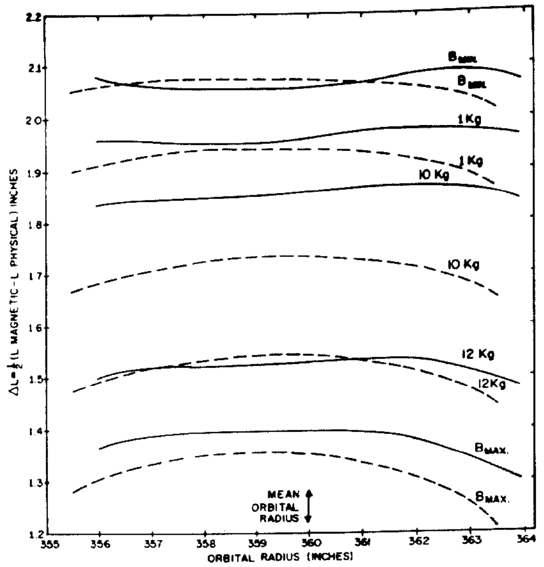

Fig. 5. Fringing fields with and without "bat-ears." The "bat-ears" are the extra laminations seen in Fig. 1, near the front and rear magnetic shims. The dashed lines show the magnetic field without corrections. The solid lines show the final field, e.g., with the second set of "bat-ears."

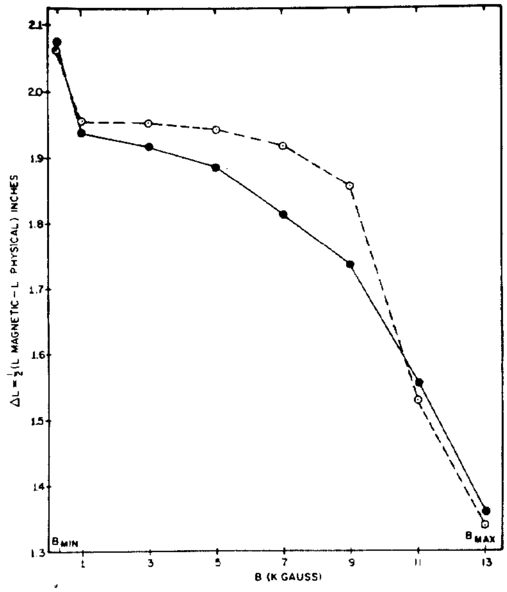

Fig. 6. Extra length [= (magnetic length - physical length)/2] of the fringing fields as a function of the magnetic field. The solid line represents the uncorrected end, the dashed line the final end.

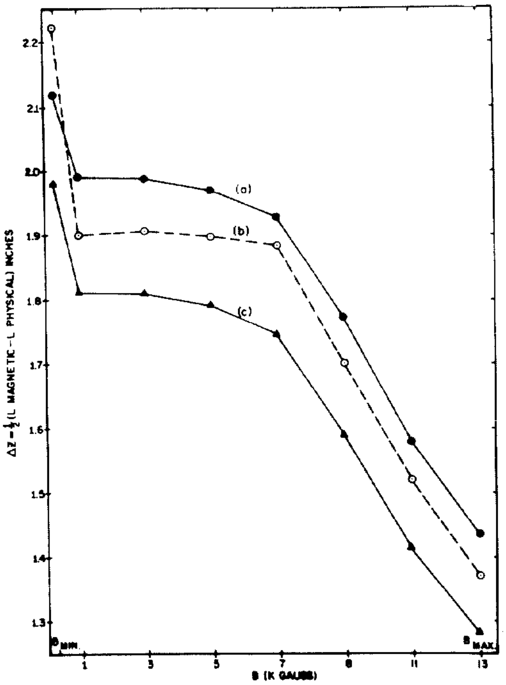

Fig. 7. Extra length of the fringing fields as a function of magnetic field. Curve (a), first set of "bat-ears;" curve (b), first set of "bat-ears" + stainless steel box for beam sensing electrodes; curve (c), first set of "bat-ears" + vacuum chamber + R.F. cavity mock-up.

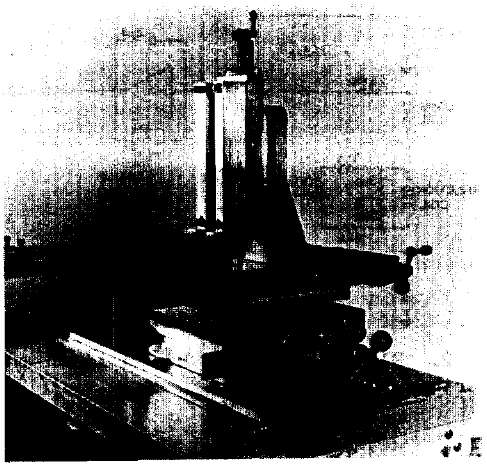

Fig. 8. Photograph of the slides used to support and locate the coil system.