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MEASUREMENTS AND CORRECTION OF THE PEP INTERACTION REGION QUADRUPOLE MAGNETS

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Abstract

Lenses for the intersection regions of PEP must be pure quadrupole over the entire magnet aperture to within 1:10^4. Correction of the magnet and its end fringe regions to this accuracy requires measurement of the field quality (relative field harmonic component amplitudes at the pole radius) to 1:10^5 through the 30th harmonic. Equipment developed for these measurements and the techniques used for field correction are described.

Introduction

The PEP insertion quadrupoles[1] consist of two identical halves, which are mated using precision ground dowels that fit into "V" grooves punched into the core laminations. Although precise by normal standards, neither the pole geometry nor the assembly are adequate to produce the required field homogeneity, $\int \Delta B\,dz / \int B(2)\,dz \lesssim 10^{-4}$ at the steel radius.

The pole contour in the magnet interior (designed by the computer program MIRT) is adequate to reduce the "allowed" (four-fold symmetrical) harmonic amplitudes to about $2\times10^{-4}\times B(2)$. Errors in stacking the laminations modify these somewhat but, more importantly, such errors can result in a misplacement of the top half of the magnet with respect to the bottom.

The dowels, which position the upper half with respect to the lower half of the magnet, rest on the "high" laminations and, as a result, the top half can be rotated, or translated either vertically or horizontally, with respect to the bottom. The former results in odd harmonics, predominantly the sextupole, and the latter in even, predominantly the octupole. To achieve the required field quality the magnet halves must be located to within 0.01mm. wheras the stacking and assembly is not better than 0.05mm.

Inherent to the sharp cut-off of the poles at the magnet ends are large "allowed" harmonics which, when averaged over the entire magnet, contribute field errors on the order of $.002\times B(2)$ at the pole radius. Furthermore, positioning of the coils, coil leads, hose fittings, etc., at the lead end of the magnet cannot be maintained to assure reproducible field distribution to the required accuracy. These lead-end errors require that each magnet be corrected individually.

Studies of the beam trajectories in these long focal-length magnets indicate that the local field errors existant in the as-made magnet are tolerable, as long as their integral through the magnet sums to zero. Thus, errors due to improper top-bottom positioning, although not uniformly distributed through the magnet, can be corrected by gross adjustment of the magnet halves, and "allowed" harmonic components in the magnet interior can be cancelled at the ends.

Magnetic Field Measurements

We used the coil system shown in Figure 1. In order to be able to measure both fringe field regions as well as the center part of the quadrupole, the system is moved axially to the appropriate location. (See Fig. 2).

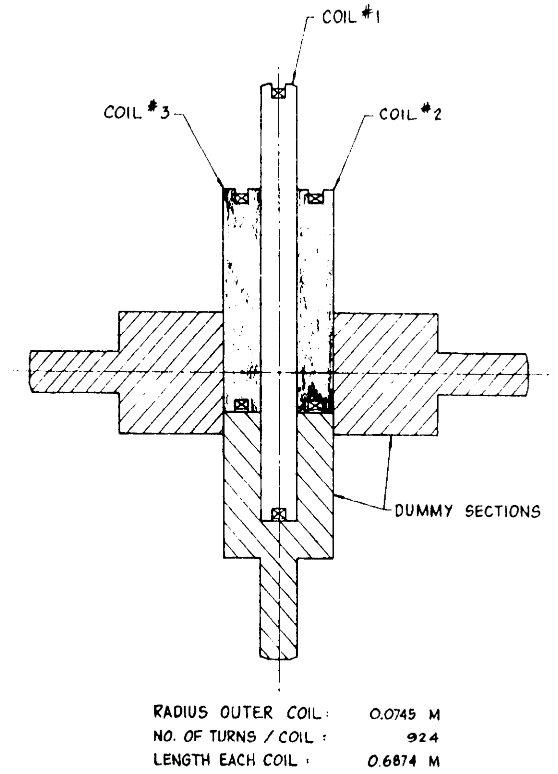

Figure 1: Measuring Coil

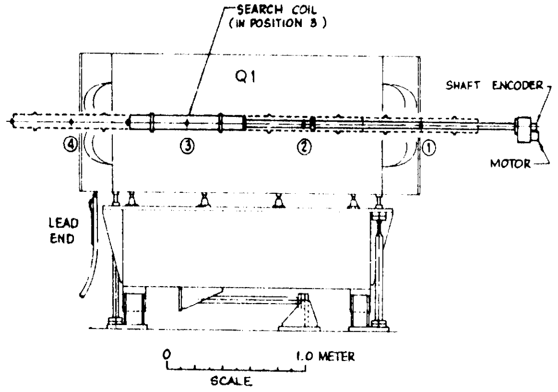

Figure 2: Search Coil Positioned in Magnet

The signals induced in coils 2 and 3 are electrically subtracted from the signal induced in coil 1 with weighing factors that are adjustable over a narrow range. The resulting signal is fed into a voltage to frequency converter that, together with a following counter, acts as an integrator. The counter is read at 128 equal increment azumithal steps as the coil is rotated through 360°. From the Fourier analysis of this information, the strengths of the harmonics are then computed.

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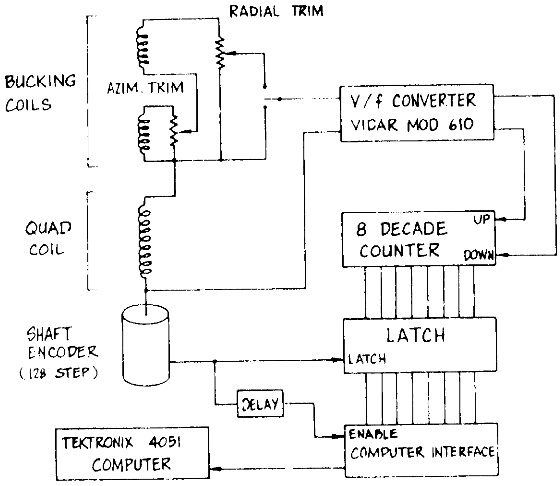

Figure 3: Circuit Diagram

The major considerations that went into the design of this system are the following:

A) The coil rotation speed is slow (1.5 RPM) to reduce vibration and the inertial forces that occur at high rotation speeds with even slightly mechanically unbalanced systems.

B) Integration of the coil output makes the system independent of variations of rotational speed.

C) Coil 1 is used to measure the absolute quad strength. The multicoil array, used for measurements of the higher components, is designed to have a vanishingly small sensitivity to both quadrupole and dipole fields.

    (1) The cancellation of the quadrupole signal is necessary to become independent of small power supply variations and angle encoder errors.[2]

    (2) The insensitivity to the dipole component is very important because small lateral displacement of the coil assembly during operation leads to induced signals that will be interpreted as harmonics that are, in fact, not present in the field. There can be many causes for such displacements, for instance: bearing tolerances, torques transmitted through the drive shaft, gravity forces acting on a mechanically asymmetric coil support structure. An analysis[3] shows that without compensation for the dipole component, displacements of the order 0.5 μm are sufficient to destroy the validity of our measurements.

    (3) The simplest coil system that is insensitive to dipole and quadrupole fields consists of two flat coplanar coils whose centers coincide. The system shown in Figure 1 evolved from such a system by splitting the smaller coil in two. This avoids some wire crossover problems at the ends, and gives two parameters instead of only one to electrically fine tune the nulling of the sensitivity to dipole and quadrupole fields. The relative size of the coils and their position relative to the axis of rotation have been optimized to maximize the array sensitivity to the sextupole, octupole and higher components.

    The support of the coils has been made mechanically symmetrical so that gravitational sag is constant during rotation of the system.

All of the errors associated with this type of measurement (power supply drift and ripple, stray AC fields, coil vibration, azimuthal indexing errors, and assymmetrical sag, etc.) result in modulation of the coil output, which, when analyzed, yield harmonic components not present in the field. Measurement to $1\mathrm{x}10^{-5}\mathrm{x}B(2)$ of the quadrupole require that the amplitude of such modulation be less than this value. To put the effect and importance of insensitivity to dipole and quadrupole fields into perspective, in such a system in an ideal quadrupole, the output signal is always zero, no matter how the system is rotated or displaced, i.e., <u>one performs a null measurement</u>.

Field Corrections

Although inadequate to produce the required field homogeneity, the precise fabrication of the magnet limits the error fields to the "allowed" harmonic components that are correctable by adjustment of the pole-tip contour, and to sextupole and octupole components due to misplacement of the two magnet halves with respect to each other. The effects of these latter gross movements of the structure have been studied[4] and described quantitatively. Knowledge of the amplitude ($\int B(N)dz$ through the magnet) and phase of these components is adequate to prescribe the motion of the magnet halves required for their elimination.

The "allowed" components are corrected by adjusting the contour of a 28mm long pole-tip insert in the magnet end-plate.[5] A plane chamfer at the insert end removes the gross fringe region errors,[7] and residual errors (including compensation for those existing in the magnet interior) are corrected by adjusting the insert tip contour. To produce the required field homogeneity, "allowed" components through N=26 (6,10,14,18,22,26) must be corrected, requiring six adjustable points on the contour. To provide an extended choice of component "mix", eight points were provided.

Since perturbation of any point on the contour will affect all components, a systematic method is required to adjust the components simultaneously. The insert contour consists of 14 chords, symmetric about the pole apex, with intersections at x_i,y_i and $-x_i,y_i$(see Fig.4). The x_i were chosen to provide maximum decoupling of the various components, and the contour modification is made by adjusting the various y_i.

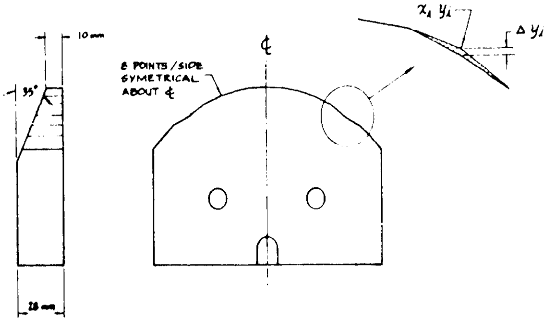

Figure 4: Pole Insert

The coefficients of the change in the component amplitudes $\Delta B(N) = \delta(\int B(N)dz/\delta y_i)$ (integral over the fringe region) were measured for the "allowed" components through N=30, by successively reducing each y_i starting at the apex. These coefficients, and measurement of the components through half of the magnet, provide eight linear equations of the form:

$$\sum_i \Delta B(N)\cdot \Delta y_i = -\int B(N)dz$$

(integral extends from the magnet center through the fringe region). These equations can be solved to provide y_i required to reduce the integral of the "allowed" components to zero.

Successive application of these corrections were used to develop "standard" sets of inserts for both ends of the first magnet. The standards were then used as initial cases for subsequent magnets, with only minor contour adjustment required to compensate for differences between magnets.

The computer was programmed to harmonically analyze the data from each of the four search-coil positions, sum each allowed component over half of the magnet, set up and solve the pole-tip correction equations for each end, and print out the contour data necessary for a tape-controlled milling machine to produce the two sets of corrected pole tips. The program also summed the sextupole and octupole components over the entire magnet, and calculated changes in the mating dowel-key size necessary to reposition the top and bottom magnet halves and reduce these components to acceptable amplitudes.

Conclusion:

Fourteen of the twenty-four PEP insertion quadrupoles have been measured and trimmed. Fig.6 is a typical result, showing the amplitudes of the various harmonic components, $\int B(N)dz / \int B(2)dz$, integrated over the entire magnet at the pole radius. Fig.7 shows iso-error contours $B/B(2)$=const., generated from these components. The homogeneity of the field is probably at a practical limit for the equipment and methods of correction used, and for the stability of the magnet structure.

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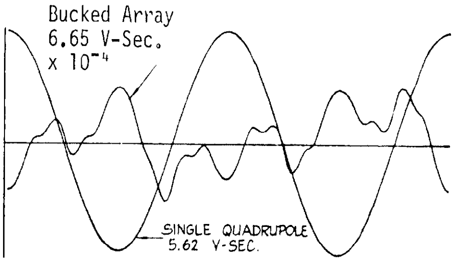

Figure 5: Raw Data

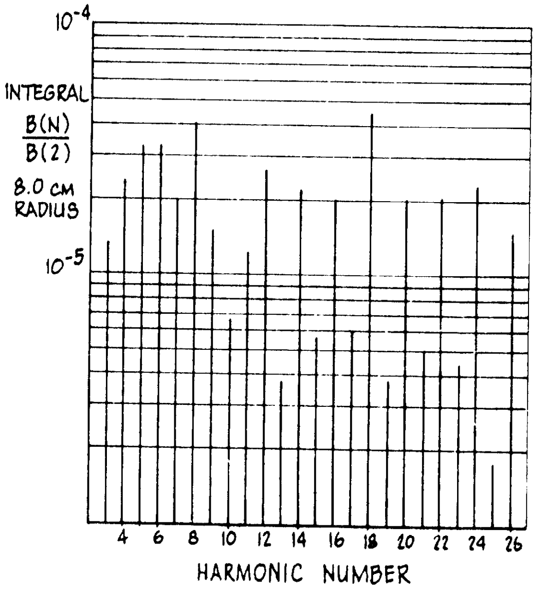

Figure 6: Multipole Amplitudes

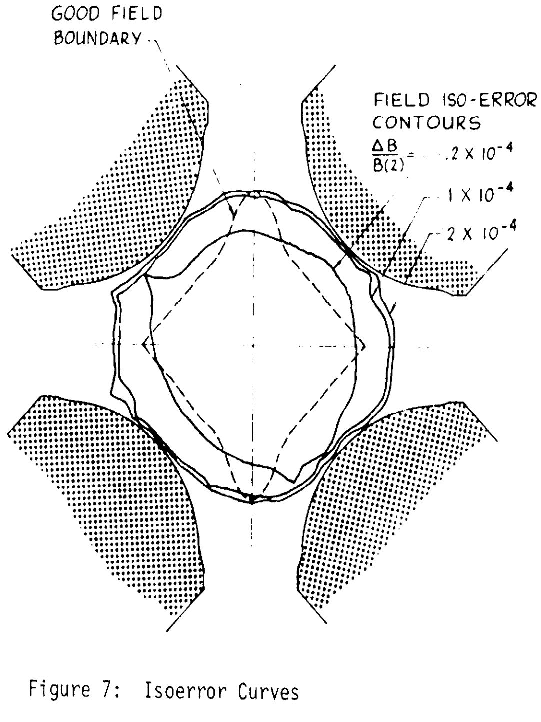

Figure 7: Isoerror Curves