CEAL- 1034

NEW RADIAL SURVEY OF THE RING OF 48 MAGNETS and CONSEQUENT RADIAL DISTORTIONS OF THE EQUILIBRIUM ORBIT

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CAMBRIDGE ELECTRON ACCELERATOR

CAMBRIDGE 38, MASSACHUSETTS

DISCLAIMER

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SUMMARY

After a five-year interval, the radial positions of the 48 magnets of the Cambridge Electron Accelerator have been resurveyed. The rms error in radial position was found to be about 0.025 inch. Calculations show that the magnitudes and phases (locations) of the errors were such as to produce distortions of 0.2 to 0.4 inches in the equilibrium orbit. See Fig. 1.

The magnet positions were then readjusted. Spot checks suggest that, as far as the important harmonics are concerned, the magnets now lie within perhaps 0.005 inch of a true circle.

The computer program required has been rewritten for the IBM 7094 computer, and is being extended to show not only the errors in magnet position but also the consequent distortions of the equilibrium orbit.

We expect that it will suffice to make radial surveys only every five years.

INTRODUCTION

The most recent of the full radial surveys of the CEA magnet ring was made in November 1961 -- more than five years ago. Immediately after that survey was made, the positions of all 48 magnets were readjusted, and tests then indicated that, as expected, the residual errors in radial and azimuthal positions were of the order of 0.005 inch (5 mils).

In the intervening five-year period occasional partial surveys were made, but the radial errors were found to be increasing at such a low rate (about ½ mil per month, rms) that it was decided that no complete survey and no readjustments of magnet positions were then needed.

However, during the course of 1966 the Operations Division reported that there were radial distortions of the order of 0.3 inch in the equilibrium orbit. They found it necessary to make special readjustments of positions of targets, damping magnets, etc., to allow for the distortions.

Accordingly, a new full survey of radial positions, azimuthal positions, and orientations was called for. This survey, and its consequences, are described below.

(No measurements of magnet height will be discussed here. Magnet heights have been measured and readjusted almost every year, and a height survey made on 11/11/66 showed the variability in height to be about 4 mils rms, which is well within acceptable limits.)

SURVEY PROCEDURE

The procedure followed was the same as that used in previous radial surveys; see Chapter 5 of Report CEAL-1000. Four large fixture plates, with appropriate stations for target and telescope, were employed -- on four adjacent magnets treated at one time. Each plate is bolted to the front guide rails of the appropriate magnet, and the positions of the second and third magnets are determined with respect to the first and fourth. Azimuthal positions are determined with the aid of a precision tape maintained under constant tension. A 75% overlap of successive groups of magnets is provided; thus 48 set-ups of the set of fixture plates are required in all.

We are indebted to Mr. R. D. Hay for prolonged and reliable help in the performance of the survey, and to the Operations Division for clearing various obstructions (quadrupole magnets, collimators, etc.) from the path of the surveyors.

The survey data obtained are on file in Rm. 411, in a notebook called "Radial Survey #5".

PROCESSING THE DATA

The survey data were processed by the IBM 7094 computer of the Harvard Computation Center. The basic program was worked out by one of us (K.W.R.) six years ago, for use on a Bendix G-15 computer; as explained in Appendix 1 the most difficult part of the task was to derive the appropriate Green's function. The program was rewritten by one of us (M.R.) for execution on the IBM 7094.

Execution of the program took about one minute.

The print-out sheets present data indicating the radial error, or displacement, of each end of each magnet, and also the azimuthal error.

To make sure that the new program was correct, we made a preliminary run on the data obtained in the survey made five years ago, and made sure that the output data agreed (to five significant figures) with the output data obtained five years ago from the Bendix G-15 computer.

RESULTS

The rms value of radial displacement of one end of a magnet was found to be 31 mils. Figure 1 shows the complete set of radial displacements.

The rms value of radial displacement of the <u>center</u> of a magnet was about 25 mils.

The rms value of the azimuthal displacement of a magnet was 27 mils.

The greatest radial displacement of a magnet was 66 mils, and the greatest azimuthal displacement was 62 mils.

CALCULATIONS AS TO THE CONSEQUENT RADIAL EXCURSIONS OF THE EQUILIBRIUM ORBIT

Using the results referred to above, one of us (T.L.C.) worked out a computer program for calculating the consequent radial excursions of the equilibrium orbit at the centers of the straight sections. Appendix 2 indicates the basis for this computer program.

The computer program was then executed. Figure 1 presents the results. The indicated orbit distortions have a large content of 6'th harmonic, or 6'th and 7'th harmonics, as would be expected of an accelerator the ν-value of which is 6.4. The largest distortion occurs in (or near) Straight Section 25; at this straight section the distortion is about 0.4 inch. The distortions in Straight Sections 4 - 11 are small -- less than 0.1 inch.

Comparison of the two curves indicates that the rms excursion of the equilibrium orbit is about 4 times that of the magnets.

READJUSTMENT OF MAGNET POSITIONS

Immediately following completion of the survey and the processing of the data, each end of each magnet was moved in such manner that the radial displacements were reduced to 2 mils or less and the azimuthal displacements were reduced to 5 mils or less. The control screws were then locked.

SPOT CHECKS ON NEW POSITIONS

Several sets of four magnets were than resurveyed to provide assurance that the survey had been performed correctly, the computer program was valid, and the readjustments had been made properly. The radial displacements of six magnets (18, 19, 20, 21, 22, 23) relative to neighboring magnets were measured by means of the usual fixtures, telescope, and target, and the relative displacements (after correction for the fact that the present regimen is for all open magnets to be 0.310 inch farther in than closed magnets) were found to be 0, -1, 2, 0, -9, 5 mils. The rms value is slightly less than 5 mils, which is acceptably small.

DISCUSSION

The fact that before the magnet positions were revised the rms value of magnet radial displacement was about 25 mils and the rms value of orbit displacement at a straight section was about four times as great indicates that there was indeed an appreciable need for re-survey and readjustment. The accelerator had continued to run well despite the distortions, but crucial items in certain straight sections (targets, damping magnets) sometimes had to be positioned by time-consuming trial-and-error processes relative to adjacent magnets, and the resulting positions were sometimes of the order of 0.2 inch from the nominal positions. Also there was some suspicion that a certain bilateral scraper (not positioned by trial and error) was affecting the beam in asymmetric and harmful manner. General confidence in the positioning of special equipment was diminishing.

The new survey and readjustments appear to have reduced the rms error in magnet radial position by a factor of about 5.

Errors in azimuth and orientation were, no doubt, reduced also; but those errors already were sufficiently small to be of little or no consequence.

Because the orbit distortions in the portion of the ring that contains most of the machine targets were small, the geometry of the emerging beams probably remained practically unchanged when the magnet positions were revised.

The computer program is being extended so as to provide, in a single operation, not only the magnet-end displacement data but also the consequent orbit distortion data.

It appears that the magnet radial and azimuthal positions change by about ½ mil per month, and that resurvey and readjustment about every five years should be frequent enough. To make surveys much more frequently than this would be burdensome -- not because the surveying proper takes much time (it requires only 40 man hours) but because of the inconvenience of having to clear away quadrupole magnets, collimators, etc., that are situated within a few feet of the magnet ring and hence block the surveyor's line-of-sight. Restoring such equipment to its exact original location may be difficult.

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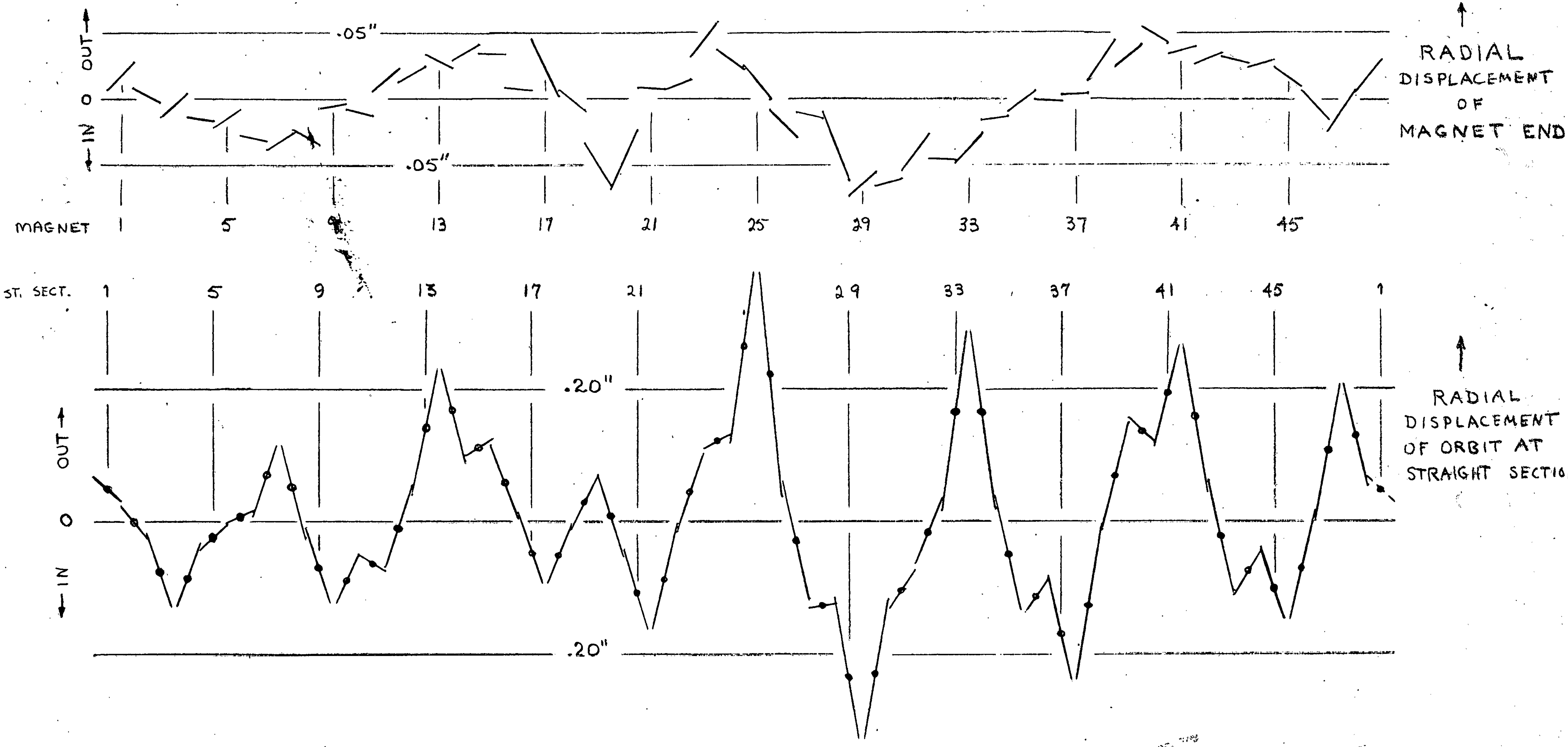
FIGURE 1

MAGNET POSITION ERRORS AND ORBIT DISTORTIONS DURING 5'th RADIAL SURVEY, DECEMBER 1966



T.L.C. Dec '66

APPENDIX 1

PROGRAM FOR CALCULATING THE ERRORS IN MAGNET POSITIONS

The radial survey data consist of three measurements for each of the 48 magnets. These are radial position and angle relative to the line-of-sight and azimuthal position relative to an adjacent magnet. From these data it is necessary to calculate the three errors of each magnet: the radial error at each end and the azimuthal error. For one magnet this is done by a Green's function which relates each error of the one magnet to all three measurements of all 48 magnets. This Green's function consists of 9 columns of 48 numbers each. To obtain each of the three errors of the one magnet 3 columns of the Green's function are multiplied by the appropriate measurements of the 48 magnets and the results are added together. Since the survey procedure is the same for all magnets, the same Green's function may be used for all magnets by appropriately precessing the numbers.

The Green's function was calculated by a harmonic analysis. There is no relation between the measurements and errors of different harmonics, and each harmonic may be treated individually. Since there are 48 magnets it is necessary to consider harmonics 0 to 24. Since there are three quantities of measurement and error and each quantity has two components in each harmonic for the two possible phase positions, there will be a 6 x 6 matrix relating the six measured components to the six error components for each harmonic.

The matrices relating measurements to errors were calculated for each harmonic, from geometrical considerations, then they were inverted and added together to obtain the total Green's function relating errors to measurements.

It was necessary to treat three of the harmonics differently from this general procedure. The 24 harmonic contains only one phase position for each harmonic, and is therefore a 3 x 3 matrix. The first harmonic contains two linear combinations of errors which produce only a translation of all the magnets. These produce no measurable quantities, and must be subtracted from the error vector space before the matrix can be inverted. Therefore a 4 x 4 matrix is used for the first harmonic. In the zero harmonic only the angular measurements are included.

The same Green's function is used for both clockwise and counter-clockwise survey by appropriately inverting and precessing it.

The computer program consists of commands to do the necessary multiplication and summing the precession to obtain all the errors of the 48 magnets from the measurement data.

APPENDIX 2

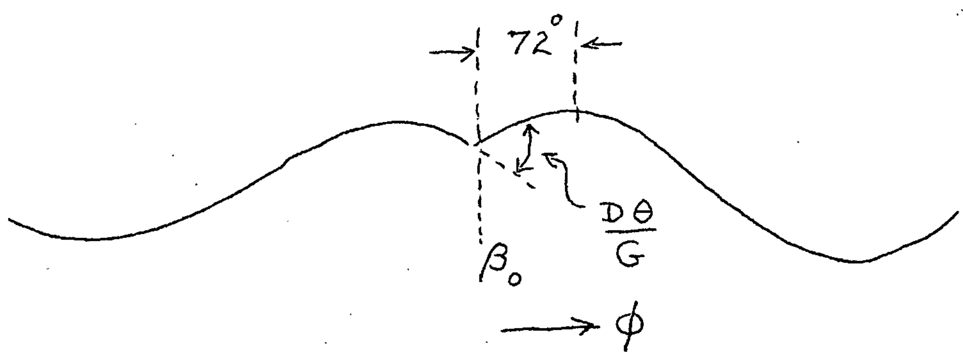
BASIS FOR COMPUTING THE ORBIT DISTORTIONS THAT RESULT FROM GIVEN ERRORS IN THE RADIAL POSITIONS OF THE 48 MAGNETS OF THE CEA

The orbit distortion at a particular point is the simple sum of the distortions at that point produced by each individual magnet. The first step is to express the form of the orbit distortion in a perfect machine with one magnet positioned incorrectly. Because we will choose points at the center of straight sections, we do not need the correct form inside the displaced magnet. The magnet position error is measured as a shift of its upstream and downstream ends which we will transform to displacement of the center and tilt. The displacement produces a cosine-like wave and the tilt a sine-like wave of the usual betatron oscillation form except that the orbit closes on itself by the action of the extra bending created by the magnet position error. It is the superposition of these waves - 96 in all - that produces the orbit distortion at a particular point, thus the final step is to insert the correct phase difference between the point and each magnet into the sine and cosine functions and sum to get the orbit distortion. This process is repeated for each straight section.

Let X_u and X_d be the upstream and downstream position errors, positive if radially outward. Then the displacement $D = \frac{1}{2}(X_u + X_d)$ and the tilt $T = (X_d - X_u)$.

For a closed (odd no.) magnet a positive D means a weaker field on the axis so that the beam is bent outward from its normal path; and a positive tilt means a stronger field at the upstream end, a weaker field at the downstream end given no net error in direction but an effective shift of the beam inward. An open (even no.) magnet will have effects of the apposite sign for positive D and T.

A displacement D is equivalent to superimposing a uniform field on top of the correct field. If the magnet normally bends beam thru an angle θ we will have an extra bending Dθ/G where G is the radial distance (11.38") in which the gradient would reduce the normal field to zero. We will worry about signs later. As is usual we consider that this bending takes place sharply at the magnet center as far as outside effects are concerned. The distorted orbit closes as shown



for $\nu = 6.4$ with the usual betatron form $\frac{\beta_0^{1/2}}{\beta^{1/2}} \cos(\phi - \phi_0)$.

For a closed magnet, a positive D gives outward bend as in diagram

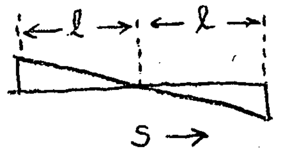
$$y = \frac{D\theta}{G} \; \frac{(\beta\beta_0)^{1/2}}{2\sin\pi\nu} \; \cos(\phi - 72^\circ)$$

$$= 2.48 \;\; D \cos(\phi - 72^\circ) \text{ at straight sections.}$$

For an open magnet

$y = -1.05\ D \cos(\phi - 72^{o})$ at straight sections.

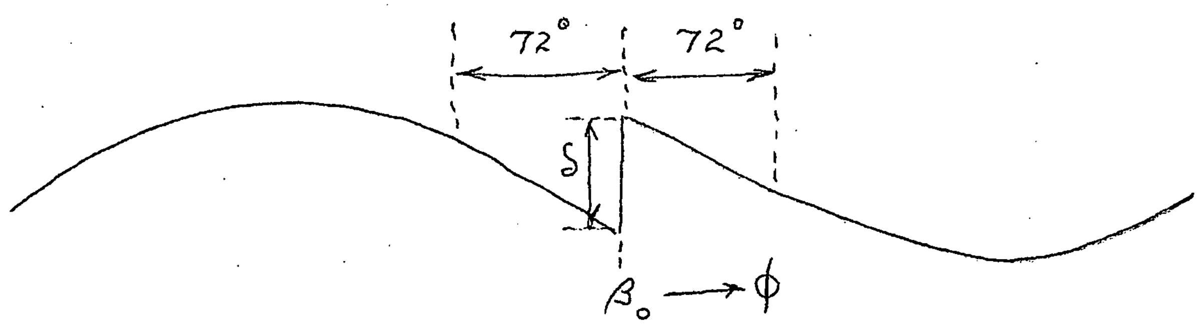
A tilt T superimposes a field of the form $\frac{T}{2\ell}\frac{S}{G}$ as shown (correct sign later).



So $\frac{d^2y}{ds^2} = \frac{TS}{2\ell G}\frac{1}{\rho}$ where ρ is the normal bending radius (1040"). Integrating twice between $-\ell$ and $+\ell$ (half magnet length) gives a displacement $\delta = \frac{T\ell^2}{6G\rho}$, and no change of direction. (A correction must be made because the actual field ends are 5" further out than the locating pins which are the "ends" referred to in the survey data.)

$\delta = \pm .072\ T$, minus sign for closed magnet.

The orbit closes as shown ($\nu = 6.4$)



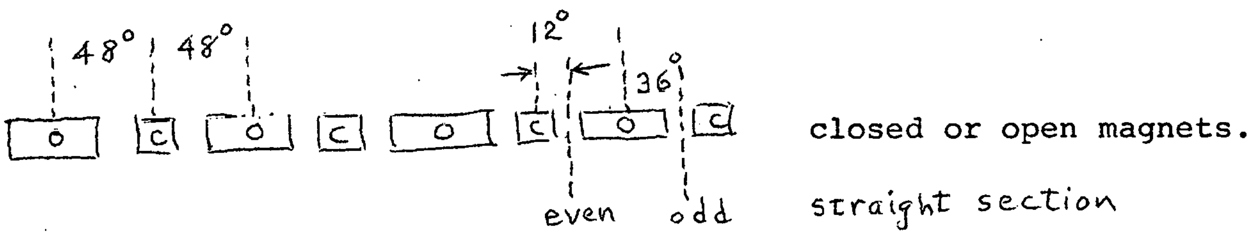
$$y = -\frac{\delta}{2\sin\pi\nu}\left(\frac{\beta}{\beta_o}\right)^{1/2}\sin(\phi - 72^{o})$$

$y = .0267\ T \sin(\phi - 72^{o})$ closed

$y = -.0628\ T \sin(\phi - 72^{o})$ open

Note that D & T are of the same order but the distortion from T is much smaller.

The angle ϕ between a magnet and a straight section is easily found from this diagram



The angle in the formulas is taken forward from the magnet (but not more than 1 turn), thus we count backwards from the st. section pt. If the st. section number is even, the first magnet back is 12° away; if the s.s. no. is odd, 36° away. Each succeeding magnet back adds 48°.

The orbit distortion at a straight section is computed by adding the distortions from the preceeding 48 magnets, using for each magnet its value of D & T, the open or closed formulas, and the phase angle between the magnet and the straight section.

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