A Spiral-Ridge Electron Model Cyclotron

D. L. Lafferty

The electron model which I shall describe this morning is not intended to represent a scaled-down version of any actual or contemplated machine; the project was initiated about two years ago as a design problem. Furthermore, neither the chosen field variation nor the construction techniques represent a very realistic approach for proton machines. The field modulation is sinusoidal which means that, even though the field is mathematically simple in form, the required poleface contours are difficult to construct. The mosaic structure would be very expensive for a proton machine and would, moreover, lead to further practical problems at high fields. Our primary aim in constructing the model was to gain practical experience in handling the problems associated with the production and analysis of non-uniform fields. The construction work is all completed and we are now analyzing the magnetic field.

Figure 124 shows the lower poleface of the model. The iron surface is built up in a mosaic pattern from about 5,000 half-inch steel rods to form the four spiral sectors. The upper poleface is a mirror image of the one shown here and is supported by the four corner posts.

The calculation of the iron surfaces to gove a prescribed median-plane field is a difficult problem due to the uncertainties in the properties of iron. Furthermore, once the iron has been machined to a particular contour, corrective shimming is a tedious and uncertain proposition. The mosaic structure was adopted in an attempt to minimize these difficulties.

The gross parameters were determined, in general, by practical considerations; for example, the availability of a Channel 1 television transmitter resulted in the choice of frequency. Other general features of the model are listed in Figure 125.

In the region near the center of the cyclotron the maximum flutter which one can get from iron contours is insufficient to provide the required axial focusing. The maximum obtainable flutter is a function of the radius and depends on the minimum gap and the ridge wavelength at a given value of r. The possible values of field flutter are thus restricted by the considerations of magnet design. One desires to minimize the radial extent of the defocused-beam region, in which large amplitude oscillations arise, by having the flutter increase as rapidly as possible near the center. The flutter should thus increase radially at the maximum rate until a safe value is reached. This behavior is illustrated by the curves in Figure 126. The curve labeled C shows

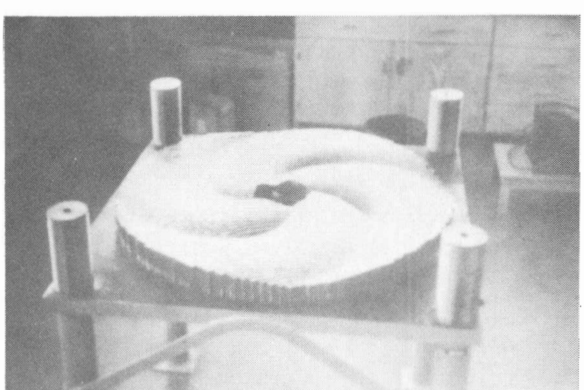
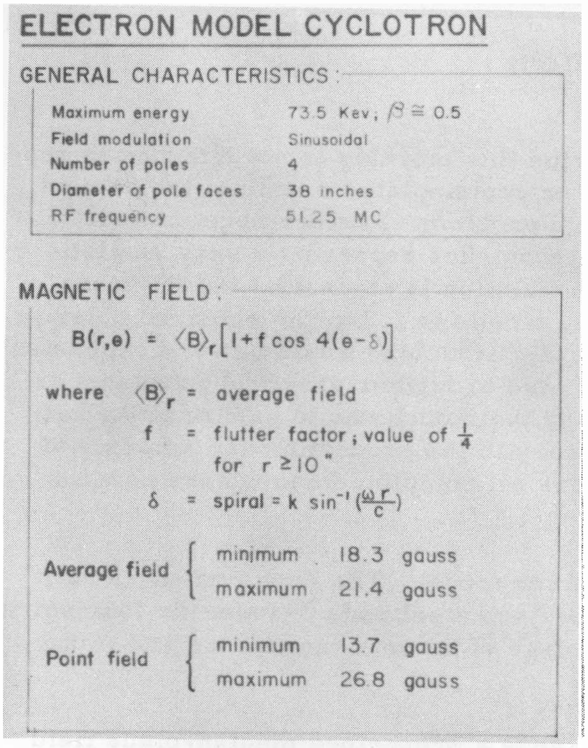


Fig. 124. Lower poleface of Florida model.



ELECTRON MODEL CYCLOTRON

GENERAL CHARACTERISTICS:

Maximum energy	73.5 Kev; $\beta \cong 0.5$
Field modulation	Sinusoidal
Number of poles	4
Diameter of pole faces	38 inches
RF frequency	51.25 MC

MAGNETIC FIELD:

$B(r,\theta) = \langle B\rangle_r \left[1 + f \cos 4(\theta - \delta)\right]$

where $\langle B\rangle_r$ = average field

f = flutter factor; value of $\frac{1}{4}$ for $r \geq 10''$

δ = spiral = $k \sin^{-1}\left(\frac{\omega r}{c}\right)$

Average field	minimum	18.3	gauss
	maximum	21.4	gauss
Point field	minimum	13.7	gauss
	maximum	26.8	gauss

Fig. 125. Characteristics of Florida model.

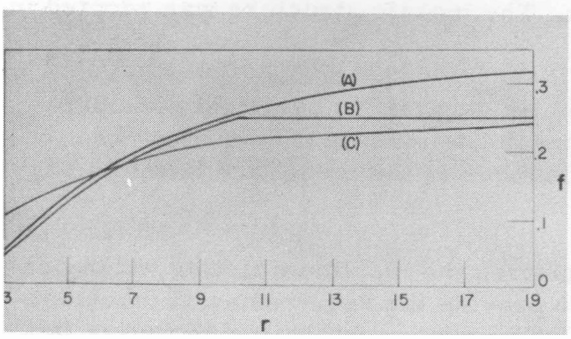


Fig. 126. Variation of flutter with radius.

the flutter required to overcome the axial defocusing arising from the radially increasing field. Curve A is the maximum flutter which we can obtain with a minimum gap of 2.5 inches. Curve B represents the actual flutter as a function of radius in the model; note that f increases at about the maximum rate out to 10 in. and then remains constant. The cross-over of the curves C and A means that one would expect no axial focusing under about six inches. With the fixed value of flutter chosen as 0.25 and with $\nu_2 = 0.18$, the equation for the spiral (from the smooth approximation) is a simple arc sin function as indicated in Figure 125. The ridges and valleys spiral through a total angle of about 122°.

Figure 127 shows the arrangement of the half-inch rods from which the polefaces are assembled. The base plates were laid out in rectangular coordinates and precision drilled with a jig. As can be seen from the figure, the rods build up in a hexagonal pattern. A clearance of five mils between centers was maintained during the drilling. The rods were turned out on a turret lathe in several groups. The lengths of the threaded portion was the same for all groups but the half-inch diameter sections varied in length from group to group. The plates were drilled through from one side and then countersunk and tapped from the other. A cross-sectional view is shown in Figure 128. A slot for an impact wrench is provided in the threaded end of each rod and adjustments in height are made by rotating the rod.

The surfaces of constant potential needed to produce a given median-plane field represents a solution of a three-dimensional Laplace equation; the surfaces in this case were obtained by solving the two-dimensional equation which results if one neglects the radial variation of the field. We infer from Smith's measurements[1] that this is a reasonable approximation. The x and y coordinates of the center of each rod were calculated by the computer and the spacing between upper and lower polefaces determined at each of these points. The vertical distances of

[1] P. F. Smith, AERE A/R 2514

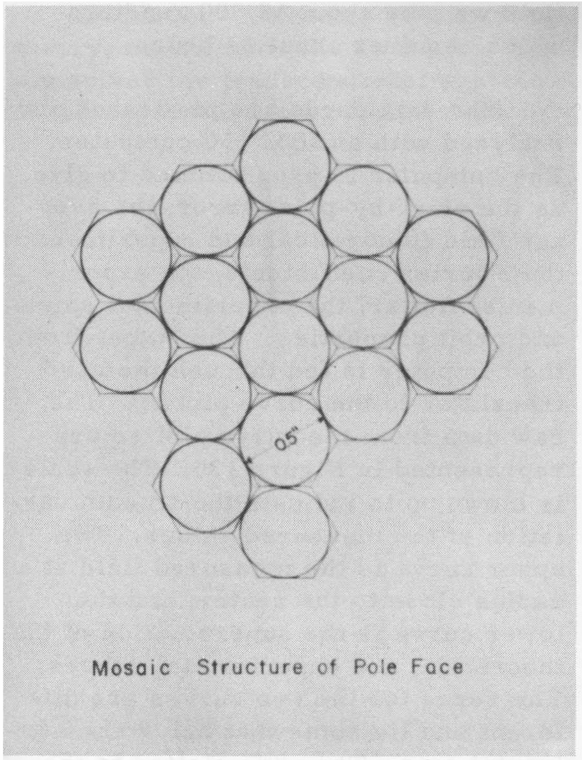


Fig. 127. Mosaic structure of poleface.

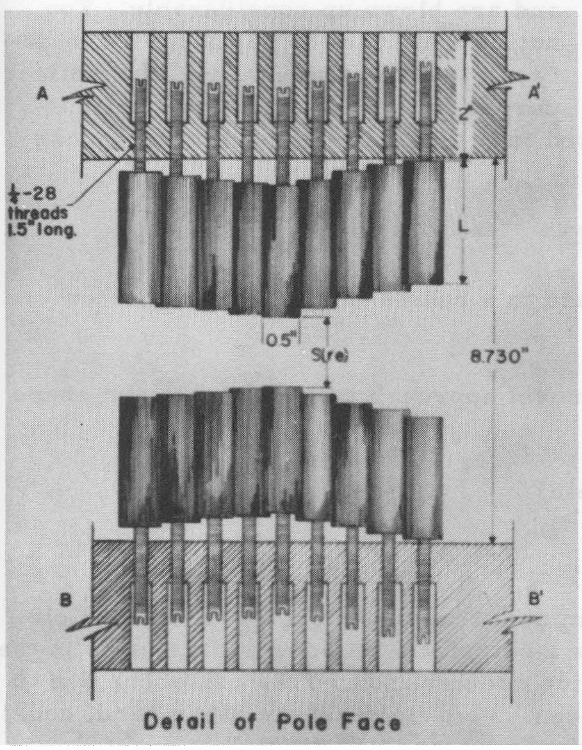


Fig. 128. Details of pole construction.

the rods from the median plane were printed out by rows; the polefaces were then assembled according to these calculated values.

A very careful analysis of the field is required if one is to have much success in trying to correlate the behavior of the beam with theoretical predictions. The importance of errors in the field makes it desirable to measure the field at a great many points with a high degree of accuracy. We have just begun our field analysis so that I will not be able to present the results of our computer programs. I would, however, like to describe the data reduction system and indicate the type of analysis we are doing.

The field is measured to an accuracy of 0.01% with a flux-gate type of magnetometer (Fig. 129). Measurements of the field are made at constant radius for each degree around the circle. The output from the magnetometer is applied to a digital voltmeter which in turn supplies appropriate pulses to a reproducing punch. The four-figure number representing the experimental field, along with the radius, the angle, the calibration constant of the magnetometer, the theoretical value of the field at the point, and the date, is punched on an IBM card. After the punching operation is complete, the punch actuates a relay which operates the drive motor and the probe arm is stepped, by means of reduction gears and a geneva mechanism, around to the next point. The probe remains stationary during the measuring period. The 360 accumulated cards are run back through the "read" side of the punch at the rate of fifty cards per minute. The measured values of the field are automatically plotted by a curve plotter through the intermediary of a card translator. The plotting of the field values requires little time and permits a visual check of the data. For a detailed scan of the

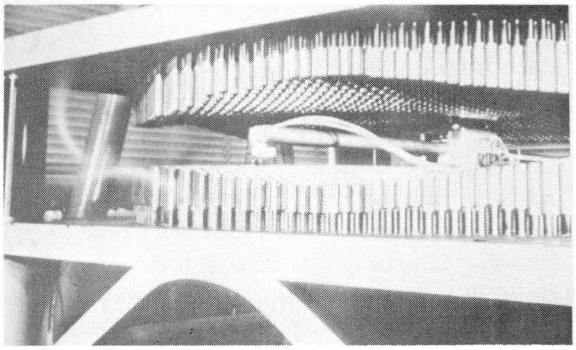


Fig. 129. Magnetometer in position.

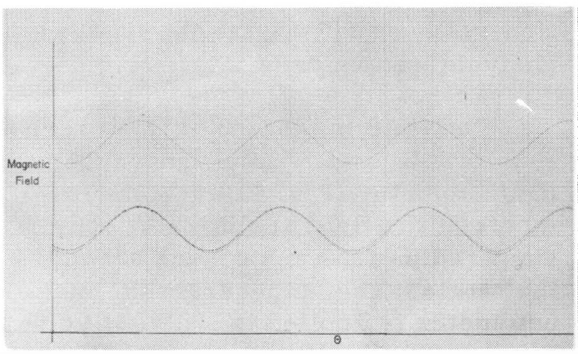


Fig. 130. Typical field plots.

field we take about 15,000 readings which requires about 24 hours.

The data cards are processed and analyzed with an IBM 650 computer. The computer is programmed to give us the point-by-point error, the average field (theoretical and experimental), the Fourier coefficients, the experimental flutter, the experimental spiral, and orbit properties. The output from the computer is fed through the card translator to the curve plotter. The raw data from the curve plotter are represented in Figure 130. The scale is blown up to indicate the smooth variation of the measured values. The upper curve is the measured field at a radius close to the center, and the lower curve is the superposition of the theoretical and experimental curves. The zeros for the two curves are different and lie somewhat below the horizontal axis. They are plotted to the same scale but are displaced vertically. These curves are presented to show the variation in angle at a given radius and are blown up considerably. You notice that there is some variation between the experimental and theoretical curves in the valleys; however, it is exaggerated in this plot. The curve is plotted to 0.1%. From preliminary checks the errors appear to be about 0.5%.

SYMON: Is this plot for a flutter of 0.25?

LAFFERTY: No, this curve corresponds to a radius in close to the center where the flutter is somewhat less.

CHAIRMAN KELLY: It is certainly a novel approach to getting the iron shape that one wants.

SCHMIDT: Is this a true sinusoidal field?

LAFFERTY: It is intended to be.

SCHMIDT: It may be interesting to comment that last night Dr. Lind, of Colorado, pointed out that if anyone ever invents a polarized ion source the flutter in the field will probably depolarize the beam during acceleration. This can occur due to the harmonics in the many fields we have seen. This field, on the other hand, could be so designed as to avoid any depolarization during acceleration.

GORDON: The setup of the spacing was based strictly on the two-dimensional theory, as it seems the simplest form, with the correction for the spiral. One simply solves the transcendental equation for the potential surface to obtain the value of the separation at a point; I think it is quite remarkable that it turns out so well.