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Spiral Ridge Studies at the University of Florida

N. M. King

The chief purpose of my talk today is to recommend the use of the Harwell report, AERE A/R 2514, by P. F. Smith. It represents an attempt to make available for ridge design purposes certain rather general experimental results obtained by the magnet group at Harwell.

As I'm sure you all know, one almost immediately comes up against discrepancies between the kinds of field configuration desirable for theoretical purposes and what one can actually get in practice. To help overcome this, the Harwell group has exploited a very useful analogy, using what I am going to call a "rectangular-ridge structure". This just consists of sets of long rectangular bars, spaced a certain distance apart, and set along the flat polefaces of an ordinary magnet (Fig. 13).

Now let's compare this with the kind of spiral-ridge structure we might want to use in a cyclotron. Suppose we are interested in one particular radius, which I will call r_1. If we unwind the circle r_1 into a straight line and plot azimuth, θ, against the vertical co-ordinate, z, we find that we have an unwound cross-sectional view of the periodic ridge structure (Fig. 14).

As you can see from this kind of picture, we immediately obtain all but one of the geometrical parameters associated with our ridge structure. We have the minimum gap, g, and the slot depth, d; we have a pitch, p, associated with the ridge, and a wavelength, λ, for the periodic structure. I will say more about λ in a moment.

In order to completely describe the system at this radius, we are going to need two further parameters. One will be a spiral angle, and here I have selected α, which is the smaller of the two possible angles; (it is the complement of the one Cohen and the other speakers have been using this morning). Besides that, we should specify the mean field at which we are operating, since saturation effects will change the properties of the system at different field levels. In general, to achieve an economical design we must proceed to fairly high field levels where these effects will be important; in particular, with variable-energy machines, we would like to have some way of estimating the focusing properties at different levels.

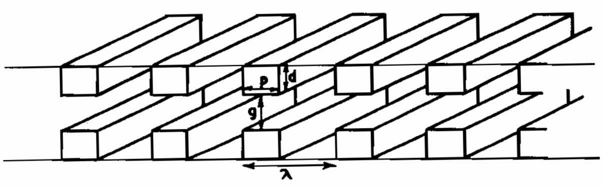

Fig. 13. Rectangular-ridge system

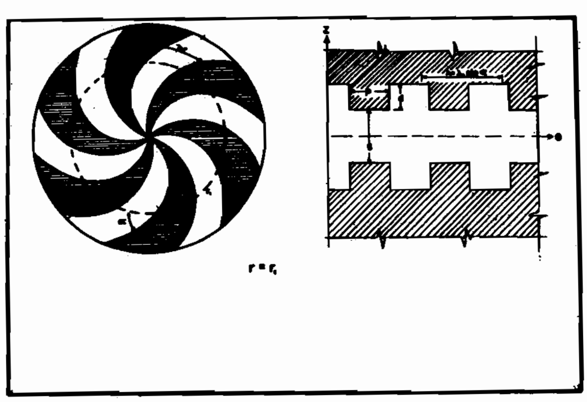

Fig. 14. "Unwound" spiral-ridge system

The Harwell measurements were, therefore, made by setting up an analogy between this kind of "unwound spiral ridge" picture and an actual mechanical ridge structure, such as I described at the beginning. They were made at 2 kilogauss intervals everywhere between

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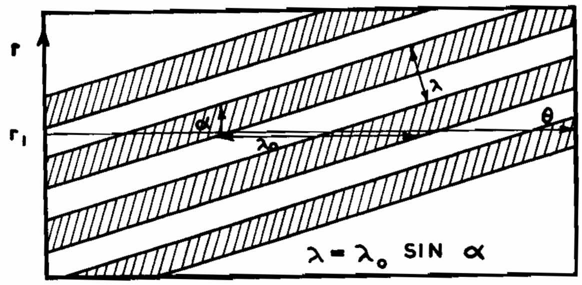

Fig. 15. Ridge wavelength

6 and 20 kilogauss, thus providing an estimate of the effects of saturation, and covering almost every circumstance to be met within spiral-ridge cyclotron design.

The spiral angle is brought in by what might seem at first sight to be a rather childish approximation. Instead of using the wavelength, λ_0, which we would get from dividing the circumference, $2\pi r_1$, by the number of ridges, N, we simply transform the structure to a different wavelength, λ, given by $\lambda_0 \sin \alpha$. In practice, this approximation is surprisingly accurate. We can see intuitively how it takes account of the spiral (Fig. 15); if we again straighten our circle r_1 into a straight line and illustrate our ridge edges in the nighbourhood of r_1 in our "straightened-out (r, θ) plane", they will slope across at the angle α. Then, provided that the radial field gradient is sufficiently small, the "equivalent rectangular-ridge system" will obviously be the one with wavelength λ rather than λ_0. The approximation involved is found in practice to be accurate enough for cyclotron design.

With this analogy, it is relatively simple to set up a number of rectangular ridge systems and to vary the dimensions of the iron bars. The cross-section of a bar represents slot depth by pitch, d x p, and the vertical distance between bars corresponds to our gap, g. Varying the horizontal distance between bars corresponds to varying the ratio p/λ. Smith has recorded field measurements made in a wide variety of such systems, covering wide ranges of the parameters p/λ, g/λ, d/p, and $\overline{B}$.

Measuring the field for a given system,

$$B = \overline{B} \left[1 + \sum_j \delta_j \cos(2\pi j\ x/\lambda)\right] ,$$

Smith analyses it in terms of its Fourier component amplitudes, δ_j. He then defines the square of the total flutter, δ, to be the sum of the squares on all these harmonic amplitudes,

$$\delta^2 = \sum_j \delta_j^2 .$$

(I believe this is twice the quantity F^2 quoted in the Oak Ridge work). He also records the "mean gap parameter", G, defined as the vertical gap between two parallel poles to give the same mean field as the given ridge structure. The recorded quantities δ and G are sufficient for most purposes of ridge design.

In using the results for ridge design purposes, the general philosophy is to begin by considering the conditions at the maximum orbit radius. Most of the parameters at this radius will be determined or restricted by other considerations which I do not propose to discuss in detail. For example, the number of ridges and the mean field will have been chosen at this state; the total air gap available and the minimum gap, g, will have been decided by considerations of overall magnet design and space requirements for rf, vacuum gear, trimming coils, etc. Hence, the choice of g and d is generally fairly restricted. Similarly, the choice of p/λ will be suggested in individual cases by the proposed method of achieving the correct mean field law and the type of n/f system envisaged; this may become clearer at a later stage. The procedure from here on will differ from different cases, but typically, we might select the amount of axial focusing considered necessary. Then, by considering different values of the spiral parameter, sin α, we might use Smith's results to obtain the corresponding flutters, hence getting an estimate of ν_z; on this basis we might select the value of sin α at the perimeter. Obviously, a certain amount of trial and error is involved in all this. However, having decided on the parameter. Smith's results will also give an estimate of the mean gap value, G.

Now, since G varies closely as $\overline{B}^{-1}$; we may use the approximate relation

$$G \sim [\,1 - (r/r_1)^2\,]^{1/2}$$

(assuming the isochronous field to be that for a machine without ridges), to proceed to smaller radii, and have a look at what's going to happen there. That is, we use Smith's results in an inverse fashion, working back from G to the corresponding geometrical parameters g/λ and d/p. Again using our discretion in the choice of sin α, we get different values of λ and obtain the corresponding flutters. Hence, we may work out ν_z according to whichever theory we currently employ. The general idea is to begin using simplified expressions for ν_z and $\overline{B}$, obtain an estimate of the flutter as a function of radius, and iterate the procedure using more sophisticated expressions, including, for example, the flutter gradient terms in ν_z and $\overline{B}$.

Having considered several radii in the machine in this fashion, we may fix the spiral law and proceed to examine the whole cyclotron in more detail. We may get into a little bother at the center because the results have to be extrapolated; it is usually fairly easy to tell how they should be extrapolated, but things may get a little critical. Conditions also tend to be critical at the maximum orbit radius, where small changes in flutter have a large effect on ν_z; this may not be serious, since it should be correspondingly simple to adjust δ in practice. Nevertheless, this point should be borne in mind.

Recently we have started to use this type of design method at Florida, where we have been thinking in terms of a 400-Mev machine. The discussion of 400 Mev may be somewhat out of place here, but I believe the following slides will illustrate methods very generally applicable to design at all energies.

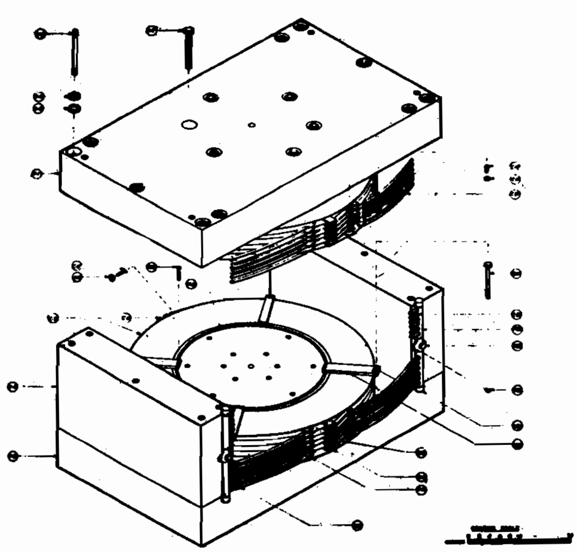

Fig. 16. The 24-in. model magnet

The ridge design is to be applied in the first instance to a 24-in. model magnet, Figure 16, designed for the project by McKenzie and Wright, (MEVA Corporation). It will have flat polefaces on which we intend to bolt various ridge structures for field measurement.

Figure 17 illustrates our first effort. It is a conservative design and may in fact turn out to be uneconomical. The 6-sector magnet is about 20 beet in diameter and has a mean field of 10 kilogauss at the maximum orbit radius, where the gap, g, is 6 inches. This gap was

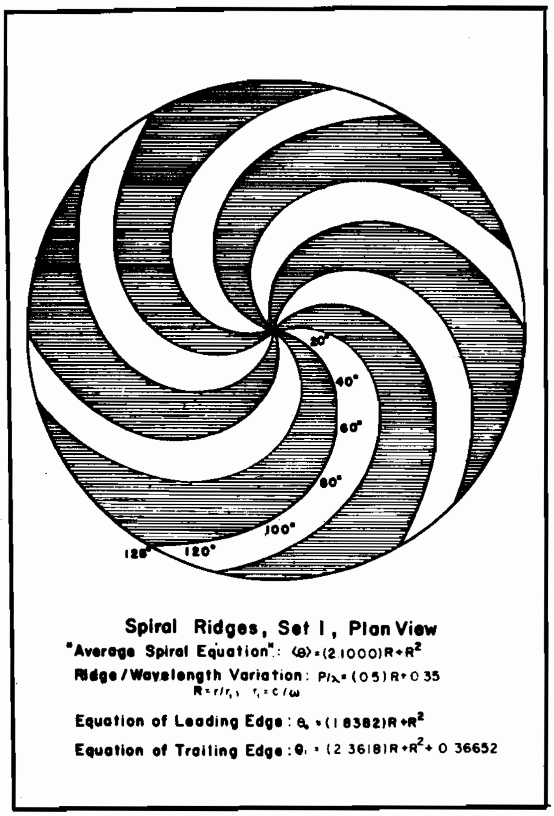

Fig. 17. Plan view of "low-field" poleface

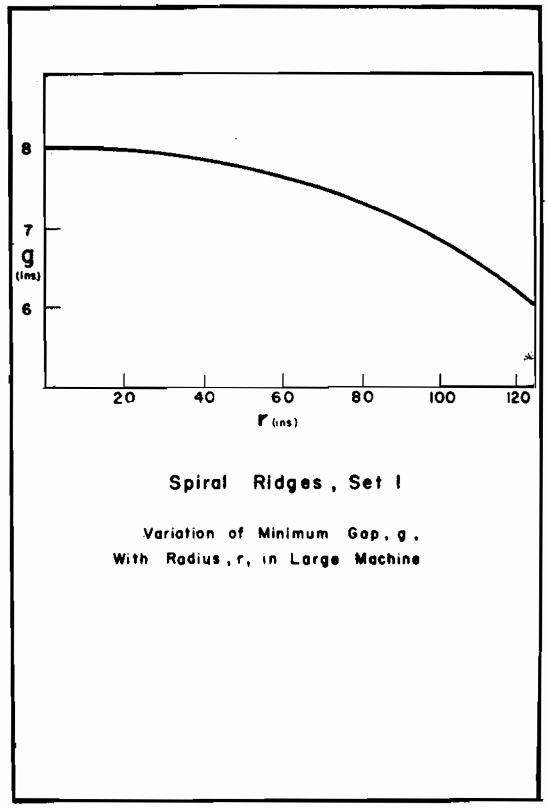

Fig. 18. Variations in minimum gap with radius

was chosen to leave just enough space to accommodate a conventional dee system. You can see that the mean field change is partly produced by allowing the p/λ ratio to increase from center to outside; the ridges flare out. I think p/λ is about 0.35 close to the center and varies to 0.7 at the outside.

Figure 18 shows the corresponding variation of minimum gap, g, required to fulfil the simultaneous requirements of isochronous mean field law and reasonable axial focusing. You can see that g would vary from about 8 in. at the center to 6 in. at the outside. If we did not allow the ridges to flare, the value at the center would go way up to about three times the value at the outside; the flutter in the central region would then be drastically reduced and we would have axial-defocusing conditions for a long way out.

Figure 19 shows the flutter as a function of radius, as predicted for this structure. The corresponding ν_z goes up to about 0.3 fairly rapidly and drops off to about 0.22 at the outside.

As an alternative to this low field machine we are examining two other approaches. The difficulty in reducing the radius and putting up the mean field is, of course, that the defocusing region at the center becomes relatively more serious. One method of getting over this is illustrated schematically in Figure 20. Here we have a composite

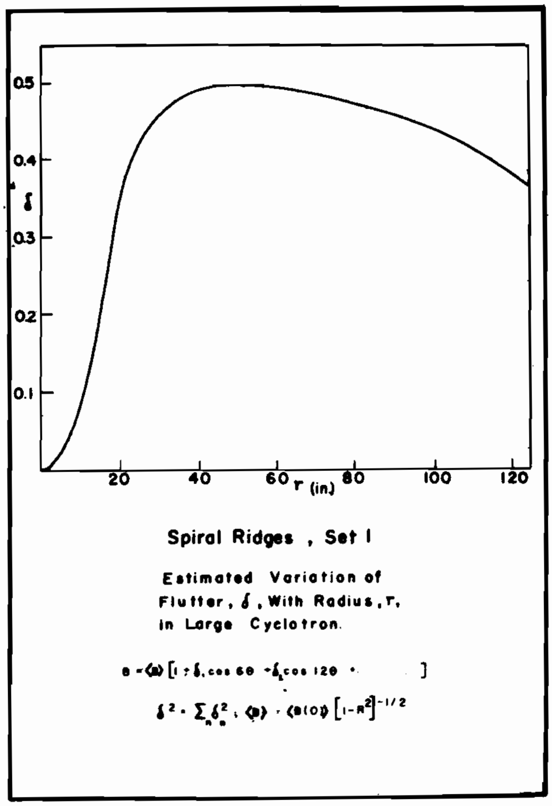

Fig. 19. Estimated flutter vs radius

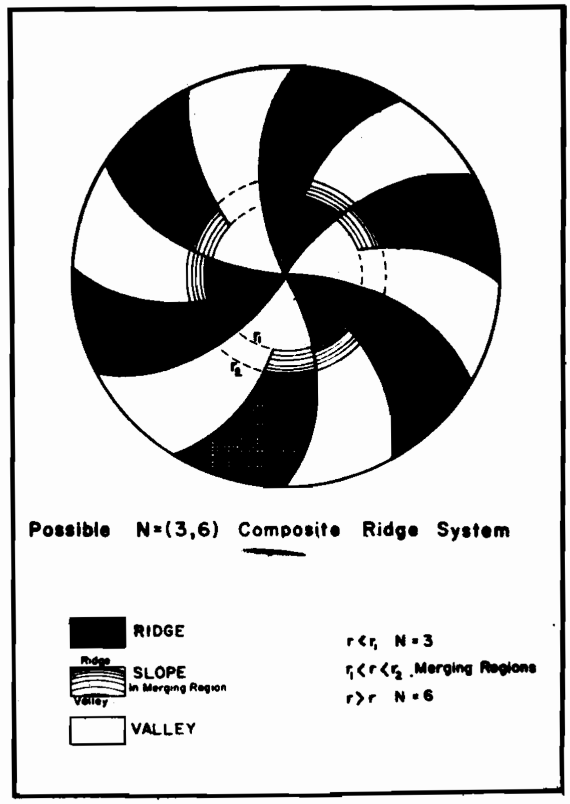

Fig. 20. Composite, (N=3-6) "high-field" design

machine, 3-sector at the center changing over to 6-sector at the outside. There is an intermediate merging region where half of each of the ridges slopes down to the new valley floor, and half of each of the valleys slopes up to form a new ridge. The transition region will occur well before the $\nu_r = 3/2$ resonance for 3 ridges, and we would try to get rid of the 3rd harmonic in the 6-ridge system before the error resonance at $\nu_r = 4/3$ sets in. We hope to try out this type of design on the magnet model.

Finally, we are examining a proposed method of achieving a small-radius design, (about 70 in.) without departing from the N = 6 condition. This would incorporate the r-f system under study at UCLA, where the accelerating electrodes are spiral shaped affairs located in the valleys and lying beneath the level reached by the top surfaces of the ridges. This scheme would allow us to reduce the minimum gap, g, to about 3 in. at the outside. One disadvantage is that we are restricted in the variation of p/λ we can allow, since there must always be enough valley to accommodate the electrodes. Here we have kept the p/λ ratio constant at 0.4 all the way. The mean field law is achieved by variations in g and d alone.

We are still having trouble getting enough focusing at the center, and at the moment ν_z is down to about 0.04 at the 11-in. radius. This is not too good, but we believe that by relaxing the design to some extent we may succeed. An encouraging feature is that the $\nu_r = 6/6$ resonance at the center should not be so serious as the corresponding cases with 3 and 4 ridges; it may even be possible to allow $\overline{B}$ to fall off at small radii and then come back up to the isochronous law.

In addition to studying the fields from the various ridge designs, the magnet model may also be used to look at extraction schemes. At the present time we are thinking, rather qualitatively, of using the $\nu_r = 3/2$ resonance, just below 400 Mev, to bring out the beam. All in all, the model programme promises to be an extremely interesting mixture of theory, experiment, and computation.