Model Magnet Work at NRDL

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I will talk about certain saturation effects in the ridges of these cyclotrons, and look into possible uses of the saturation effects themselves. We, at NRDL, are starting from the rather optimistic point of view that a cyclotron of the strong-focusing type can be made, and will work. What I would like to investigate are possible alternative methods of making a good variable-energy machine.

As you have heard, in the talks of Allen and Dols, as the magnet excitation is varied for variable-energy operation of a cyclotron, one of the striking problems is that of saturation of the iron. As I see it, three basic problems have been indicated in previous talks. The first is in the effect of the fringing field at outer radii. You remember that on all curves of radial magnetic profile that we have seen, at high magnet excitation the field fell off at larger radii due to the increased saturation of the fringing field in the pole piece. Second, there is the problem of termination of the ridges at the center. Depending on the geometry of the ridges at the center, one can obtain a relative magnetic hump, or valley, as the magnet excitation is increased. Finally, there is a change in average magnetic field radial contour necessary for isochronism for the particle being accelerated at a particular energy. It seems to me that one should be able to control these saturation effects so that they will work for you instead of against you. I thought I would start investigating the effects of sub-surface voids in the ridges. They would be designed so that, as the magnet excitation is increased, one would relatively lower the average magnetic field at smaller radii, with the possibility that one can so tailor this change in the average magnetic field that the appropriate radial profile may be maintained.

I will make the assumption that the change in the average magnetic field due to saturation effects will be determined by the saturation of the ridges, and that the valley iron will remain essentially unsaturated and at an equimagnetic potential. Because we are just trying to get a feel of what is going on, the experiments we are doing first are in rectangular coordinates. With two rectangular iron plates, one fixed to the top and the other to the bottom of the pole piece of our magnet, thus simulating the ridge system of a cyclotron, we measured the average magnetic field along the median plane. Measurements were taken on one side of the plane of symmetry for an equal distance in high and low magnetic field regions corresponding simply to a ridge configuration with equal areas of ridge and valley. Then for the same weak field we compared average fields for configurations of this sort with varying amounts of voids placed underneath the surface of the ridge.

The measurements were taken point-by-point with a standard Rawson rotating coil flux meter - 100 points in all. Then the values of the field were averaged and the mean-squared deviation was taken so that we could get an idea of the flutter one would achieve with various void geometries.

Figure 108 is the magnet we are using, the 6-1/2 ton magnet and the 70-kw rectifier power supply. In the background, not shown too clearly, is our Rawson flux meter and the digital voltmeter on which the data were logged. The results from the digital voltmeter are punched out on paper tape. I present this picture of the magnet and power supply because I thought that it might be of interest to some people here. It was bought commercially from the MevA Corporation in Los

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Angeles; they are using it as the basis of a cyclotron they are building, which I believe will be of the Thomas type.

The insert in Figure 109 illustrates the geometry of our ridge-and-void system. Here is presented a family of curves which describe the reduction in average magnetic field due to the void in the ridge. It was measured by comparing the average field for the solid ridge against the average field for the ridge with the void for the case when the weak field, or field in the valley, is the same. The horizontal axis represents the maximum field for the solid ridge configuration because it is this quantity which most nearly determines the saturation effects. We have indicated along the horizontal axis the average field for the solid-ridge configuration, which is obviously a non-linear function of the maximum field.

Well, as you can see, for the various amounts of undercut we can get varying amounts of reduction in the average field. All of our curves seem to show a slight preliminary hump at 12 kilogauss rising to a maximum at about 20 kilogauss and quickly dropping down to zero at higher fields. This peak at 20 kilogauss can be interpreted as complete saturation of the iron in the ridge. Thus, for fields above this value, there is less and less difference between the solid ridge configuration and that with the sub-surface void.

Figure 110 presents our results for the case in which our voids are reversed and put on the outside. I might say that the gaps are identical with the gaps we saw in Figure 109, and if the two curves are compared they look very much the same, showing that it makes little difference whether the voids are at the outside or concealed in the center.

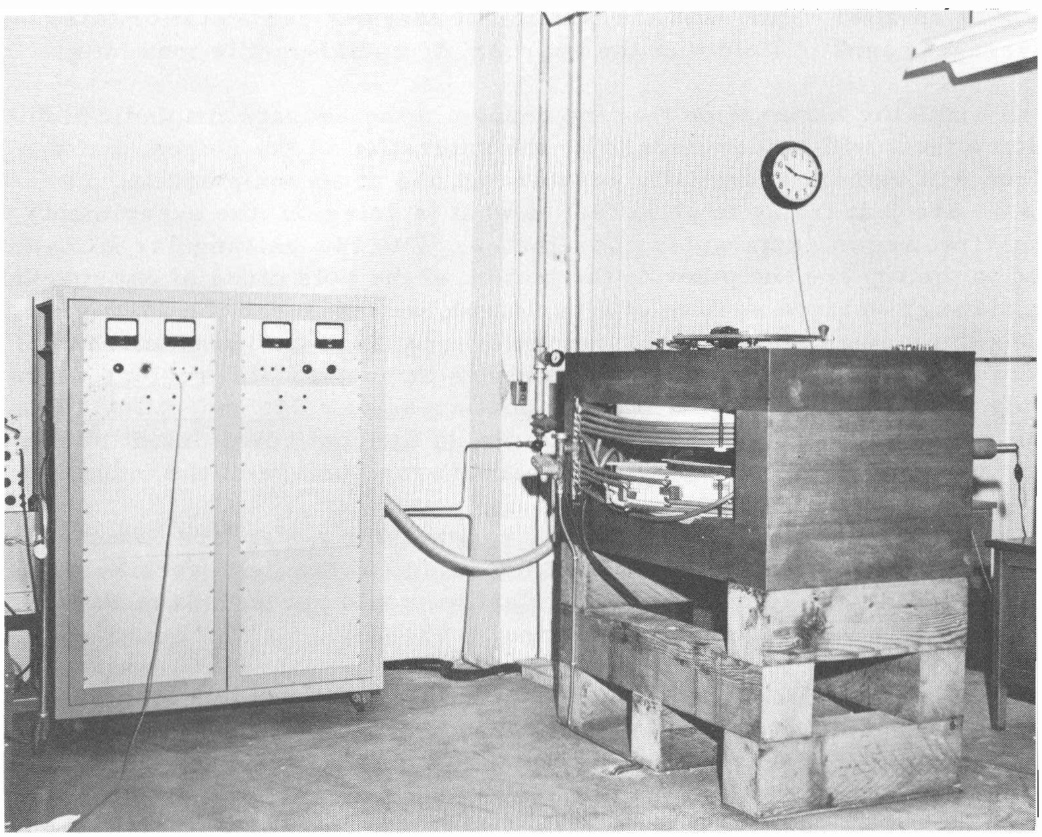

Fig. 108. USNRDL 24-Inch Model Magnet and Rectifier Power Supply.

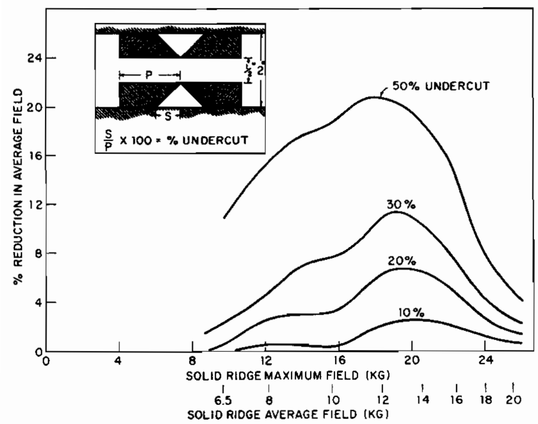

Fig. 109. The percentage reduction in average magnetic field due to various amounts of sub-surface voids is shown as a function of magnet excitation. This geometry corresponds to a very large flutter factor.

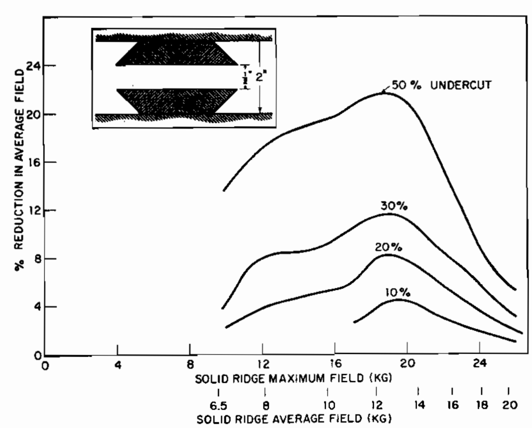

Fig. 110. Same as Fig. 109 except that the voids are shifted to the edge of the ridge.

Figure 111 is the case in which the flutter is not quite as severe. We have almost a one-to-two flutter now. The amount of control that we have for a 30% undercut, for example, is only 9% and this is considerably less than before as you might expect. We still get a somewhat peculiar preliminary hump, and again at 20 kilogauss the decrease in average magnet field tends to become less. In other words, we no longer are increasing the difference in the magnetic field averages above 20 kilogauss.

This is just a crude beginning, obviously, but what is hoped is that one can tailor the profile of the void so that one can think of going from one of these curves to another in arbitrary fashion, producing an arbitrary reduction in average magnetic field as a function of magnet excitation. In this way the proper average magnetic field might be maintained at each radius in the cyclotron so that isochronism would be maintained, let's say, to 1% or so. If this is at all possible then it will relieve the necessity of putting in such large, so-called trimming coils on the magnet pole pieces, and it seems to me that perhaps many more small coils could be put in the gap of the cyclotron and much finer trimming could be obtained.

For these various configurations, besides running average fields, we also computed the square of the flutter factor. This is $\overline{\Delta B^2} / \overline{B}^2$ and is presented in Figures 112 and 113 as a function of the magnetic field. Simply as a check for the solid-ridge configurations we obtained numbers that would compare pretty well with the Harwell report of Smith[1]. The flutter factor for our void configurations are somewhat below the solid-ridge configurations, but not much below. You will notice that all the flutter factors seem to approach one another at low fields and high fields, as might be expected.

[1] Smith, P. F., "Further Measurements of the Magnetic Field Produced by Ridged Pole Pieces," AERE A/R 2514. United Kingdom Atomic Energy Authority, AERE, Harwell, England (1959) Unclassified.

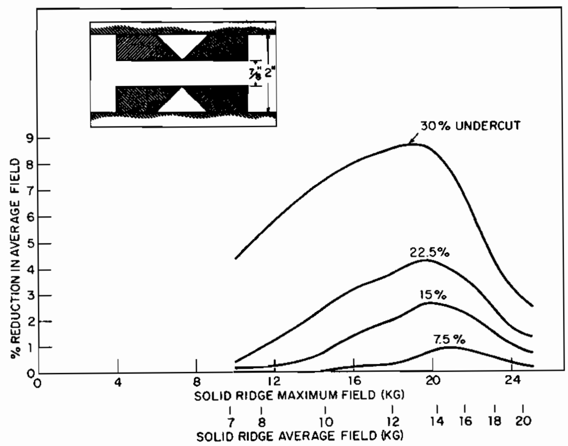

Fig. 111. Same as Fig. 109 except that the flutter has been reduced.

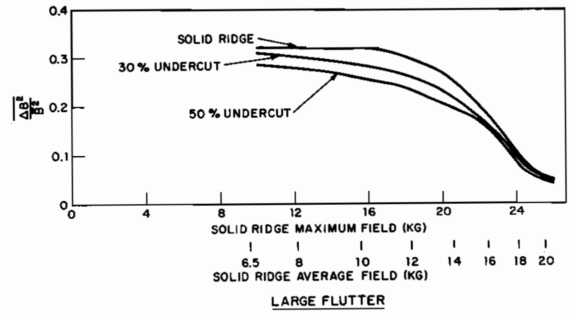

Fig. 112. The square of the flutter factor, $\overline{\Delta B^2} / \overline{B}^2 = \frac{1}{n} \sum^{n} (B_i - \overline{B})^2 / [\sum^{n} \frac{B_i}{n}]^2$, is presented for three void geometries of Fig. 109.

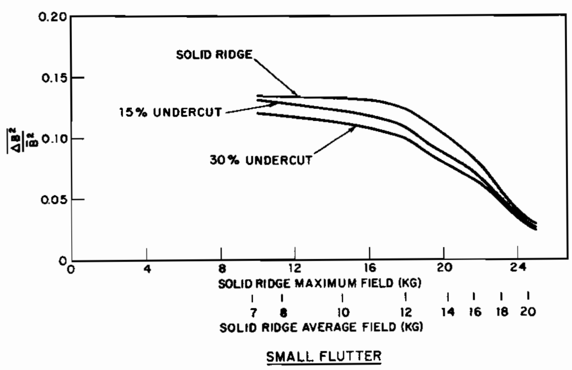

Fig. 113. The square of the flutter factor, $\overline{\Delta B^2} / \overline{B}^2$, is presented for three of the void geometries of Fig. 111.

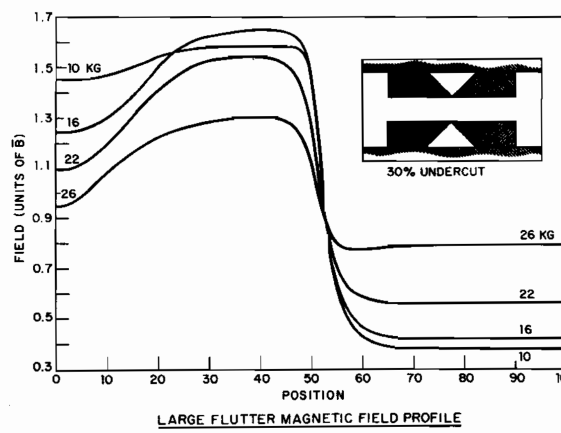

Fig. 114. The magnetic field profile in units of the average field, is shown as a function of position from the center of the ridge to a point an equal distance in the weak field region. The geometry is the same as that of Fig. 109 with 30% undercut and each curve is labeled according to the equivalent maximum field for the solid ridge configuration.

Because some cyclotrons are being designed with maximum magnetic fields of about 23 kilogauss, a large geometric flutter is necessary; Figure 112 illustrates how at lower magnet excitations the flutter factor will increase greatly and overfocusing in the axial direction must be avoided.

Figure 114 is an actual plot of the magnetic field for the case of a large flutter factor and a 30% undercut void in the center. Along the horizontal axis, position 0 to 50 represents measurements taken from the center to the edge of the shim, and 50 to 100 represents positions in the weak field. The vertical axis represents the magnetic field measurements normalized to the average magnetic field corresponding to that particular geometry. You will notice that we get the closest to the square wave at 10 kilogauss nominal field. Actually, the 16-kilogauss contour goes higher than the 10-kilogauss contours, which is rather interesting. You can also see the

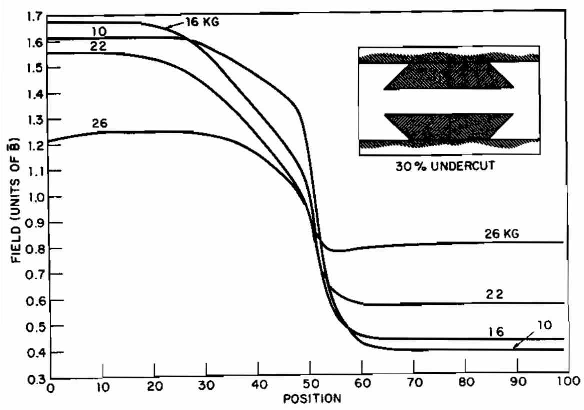

Fig. 115. The magnetic field profile is shown as in Fig. 114 for the case in which the voids appear at the edge of the ridge.

way the flutter decreases. The profile for the case where the voids are at the edge of the ridge is shown in Figure 115.

We are hoping that with results of this type perhaps a cyclotron could be designed in the following way. From the results of the Harwell magnet report by Smith a cyclotron solid-ridge system can be calculated for a given particle energy and magnet excitation. Then, deviations of the magnetic field from the isochronous condition for other magnet excitations may be corrected through the use of sub-surface voids.