Selection of Magnet Configuration for the ORIC

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I would like to describe how the magnet configuration was chosen for the Oak Ridge cyclotron. This is the work of Blosser and myself on the theoretical considerations, of Hudson and Lord on the model magnet work, and of other people too numerous to mention. For reasons that we don't have time to go into now, it turned out that the variables which we had at our disposal were the number of sectors, the amount of spiral, and the hill gap. The things we want to get out of this are radial stability and axial stability, or vertical focusing.

For the number of sectors and the spiral, these conditions go in opposite directions. You need a lot of sectors and a small spiral for radial stability, whereas for axial stability you need a small number of sectors because this gives the maximum flutter, and you need a large spiral which, of course, gives more focusing. Our procedure was to let the radial stability determine the minimum number of sectors and the maximum amount of spiral we could get away with, and then reduce the hill gap until axial stability was achieved.

The first problem was to get model magnet data for the stability calculations, which Gordon will talk about later. We found we could have either a 3-sector weak spiral or a 4-sector tight spiral; these are the smallest number of sectors and the largest amount of spiral that are consistent with radial stability. By "weak spiral" I mean practically none, i.e., nearly a Thomas machine; and by "tight spiral" I mean the spiral that maximizes the axial focusing, which is the Stahelin spiral.

Now, for focusing there are critical places, at the maximum radius and at small radii. The average field must increase with radius as $1 + Kr^2$ to maintain isochronism, so that the $(r/H)(dH/dr)$ term gives its maximum defocusing at the maximum radius; the flutter term must thus be at a maximum there to compensate for it. The difficulty at small radii is that the $(r/H)(dH/dr)$ defocusing term builds up as r^N, where N is the number of sectors, so that the latter is smaller at a small enough radius.

The only adjustable parameter we have is the gap; we can decrease the gap until we get focusing at the large radii, but at small radii it isn't that simple, as shown for a 4-sector tight spiral machine in Figure 10. The defocusing term is the $(r/H)(dH/dr)$ term obtained if the average field is to give isochronism. The other curves are the focusing term given by the flutter for various gaps. Obviously, decreasing the gap does not do the job at small radius. It helps some; it gives a smaller defocusing region, but you just can't get focusing in this region. The net axial force is shown at the top of Figure 10; and for each case, the total defocusing impulse, defined as defocusing force times number of terms, is shown. To give us a feeling for what sort of value we wanted for this defocusing impulse, its value for the Oak Ridge 86-inch Cyclotron, which is a very poor machine from the focusing standpoint, is shown in Figure 10. Even with the smallest gaps we were interested in, which were about 7 in., we could not do any better than the 86-in. cyclotron.

The only thing left to do was to give up isochronism. The isochronous field is as curve A of Figure 11; something must be done to this isochronous field to get focusing at the small radii. There are two ways to get it, by electric focusing and by

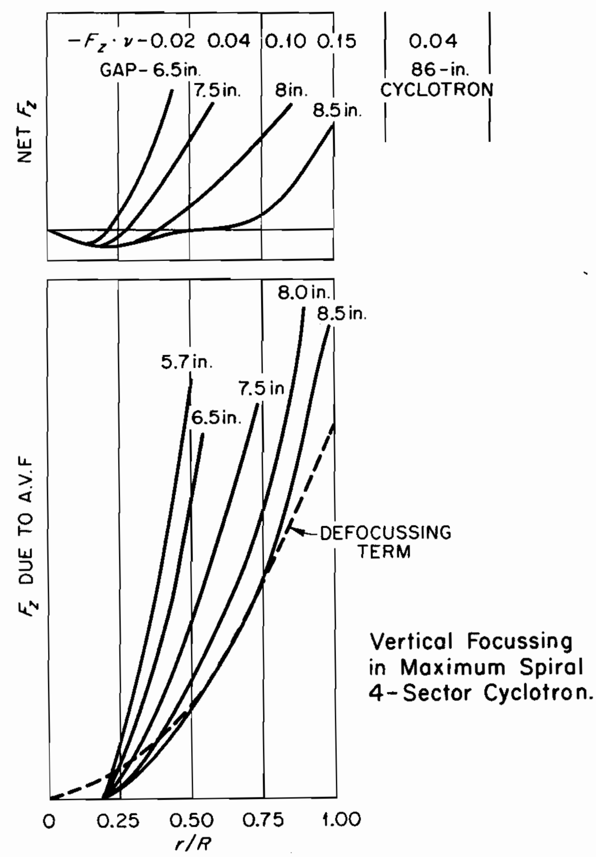

Fig. 10. Axial focusing.

the (r/H) (dH/dr) term. The first is done by decreasing the average field at the center below the isochronous value. It must, of course, in time come up to the isochronous value, so that the average field looks like curve B. This results in a focusing electric phase, but also results in more magnetic defocusing at larger radii. It turned out that for every case anywhere near interesting we got more extra magnetic defocusing; the method didn't work.

The other method was to get focusing by an average field falloff at the center, making the field look like curve C of Figure 11. Here there is magnetic focusing at small radii, but extra defocusing at larger radii; you hope to postpone this extra defocusing out to a radius where the flutter focusing can compensate it. This is a job for numerical calculations.

First, we assume a field shape and then calculate the phase as a function of term number. It is essentially a turn-by-turn calculation, but it turned out that about five turns could be done at a time. If the phase does not stay within 90°, the field shape is changed until it does. Once you find a field where the phase is satisfactory, then you calculate the electric focusing (which, of course, is defocusing), the average field falloff focusing, the flutter focusing, and the flutter gradient focusing. This again is a numerical turn-by-turn calculation. It turned out that a field shape as in curve C is beneficial up to a certain point, but not very far. As long as the phase shift wasn't more than about 30° we got an improvement. In fact, we could get a net focusing all the way except for about the first 3 or 4 turns, where we have electric defocusing which we can never get rid of if we have our field falling off. But still the defocusing impulse was very much improved. If this early field falloff is carried too far the situation rapidly deteriorates until you get more defocusing than in the isochronous case. This, then, gives a limitation on the maximum gap. The gap, of course, determines how soon the flutter focusing comes in, and you have to get it to come in early enough so that you don't have to do too much phase shifting by this method.

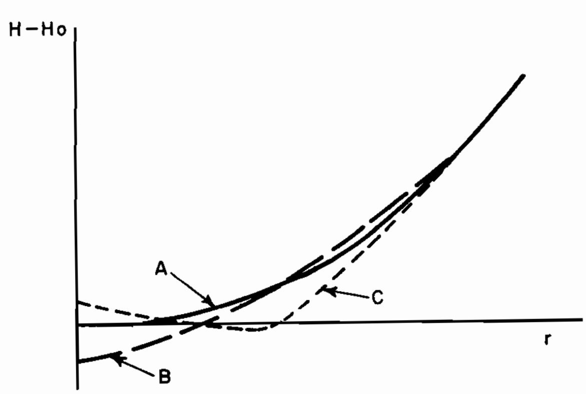

Fig. 11. The Isochronous field.

Figure 12 shows the results of all these calculations. For focusing at

MAXIMUM MAGNETIC GAPS (IN INCHES)
(VALUES IN PARENTHESES ARE WITH 500-KW VALLEY COILS)

	3-SECTOR LOW SPIRAL	4-SECTOR HIGH SPIRAL	4-SECTOR LOW SPIRAL
FOCUSSING AT SMALL RADII	9.0	7.0 (7.7)	6.5 (7.2)
FOCUSSING AT LARGE RADII	5.8 (7.5)	9.5	4.3 (6.5)

MINIMUM NON-USABLE GAP REQUIREMENTS

R.F. VOLTAGE BREAKDOWN GAP	2 3/4 IN.
POLE-FACE WINDINGS	1 IN.
DEE-LINER STRUCTURE	1 3/4 IN.
	5 1/2 IN.

Fig. 12. Maximum magnetic gap.

small radii with a 4-sector high spiral we could get away with a gap as large as 7 in.; if we were willing to put valley coils in, it was 7.7 inches. (The possibility of using valley coils was one other variable at our disposal).

For 3-sector low spiral, small radii were no problem at all. Of course, at large radii the tight spiral does help in focusing. We are able to get away with a gap as large as 9.5 inches with a 4-sector high spiral, but with the 3-sector low-spiral we had to use valley coils to get anywhere near the required gap. So, according to Figure 12, either the three-sector low spiral or the four-sector high spiral would allow us to have a gap of something like 7.5 in., which is what we wanted.

Incidentally, we wanted a gap of 7.5 in. because 5.5 in. were used as shown in the lower part of Figure 12, and we wanted about 2 in. left for the beam.

There are one or two other things to worry about in shaping the field, as in curve C of Figure 11. There is a radial resonance where the field is a minimum, which is not too bad; there is a little axial defocusing in the first few turns. It turns out that with a 3-sector low spiral and a 7.5-in. gap there is practically no defocusing at all. In fact, you can use an isochronous field without getting appreciable defocusing.

At this point we felt that we could either use the three-sector low spiral or the four-sector high spirals. We would avoid the difficult field shaping with the three-sector low spiral, and that is the one we chose partly for that reason and partly because we thought it would be better for deflection purposes.

CHAIRMAN JUDD: Thank you. Is the big difference in emphasis on this central region problem between your point of view and that of Richardson entirely due to the difference between 7.5 and 3 inches?

COHEN: Yes, if you have a 3-in. gap you have no problem.