# A 4-Mev Spiral-Ridge Cyclotron

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Our machine is a 22-in. proton cyclotron; it started, at least the magnet did, as a 1/5-scale model for the 110-in. cyclotron at Harwell. As some of you may know, we wished to convert this synchrocyclotron from its present energy of 175 Mev to the region of 240 Mev so as to bring us into the meson business. The current we get at present is about 1.5$\mu$a as a synchrocyclotron, and after conversion we were modestly hoping to get of the order of 100 $\mu$a and so put everyone else at this energy out of business. Well, it has not turned out to be quite as easy as was originally supposed.

To achieve this energy the mean field at the outside has to be as high as 19 kilogauss; that immediately limits the flutter that we can use to something of the order of 0.2. That would mean going from 23 kilogauss down to 15, and, to get the required focusing at 240 Mev, we would have to use quite a tight spiral with this value of flutter. Theoretical considerations have shown that with the 3-ridge machine we are likely to strike the $\pi$-mode resonance at an energy of 190 Mev, whereas with N = 4 there is some hope that we might be able to achieve our target. These factors immediately set our design to a 4-ridge machine, with a maximum delta value of 0.2.

We chose a simple Archimedean spiral, to make the fabrication of the poles easy. We also set our minimum gap equal to 6 in., this being the smallest gap in which we thought we could conveniently get the dee system.

The proton model I shall now tell you about is designed to simulate the central region of the proposed conversion. It has a spiral R equal to 0.15 $\theta$, R in inches, and $\theta$ in degrees; the gap is 4 in. at the minimum. We originally were going to use the same gap as the full-scale conversion, 6 in., but this gave too low a value of the mean field.

Figure 76 shows the magnet with the pole pieces, coils, and part of the field measuring equipment which I will describe later. On the left are a series of water-cooled resistors, to vary the current in the poleface windings.

In a close-up of the gap with the measuring gear inside, (Fig. 77), you can just discern the spiralled valley and ridge. Because of the rather large ratio of gap to radius, the Rose shims we have used on the outside are large. The pole pieces were made by machining four sectors and bolting them to a circular base plate. The required contour is then machined on these sectors to give the right mean field to form the valleys. You then take another set of sectors of greater depth and bolt them on to become the ridges. These are likewise machined to the required ridge contour. We had a requirement that the sectors would fit together so that the gap between them was nowhere greater than 0.005", and we wanted the spiral law to be accurate to within 0.002". We have had some trouble with the system used in machining the contours, and we don't quite get the accuracy that we would like. We hope by modifications that next time we will get the accuracy of the contour to about 0.001". At present it is within 0.001" over most of the region, but where there is a change of gradient an error up to about 0.005" can occur.

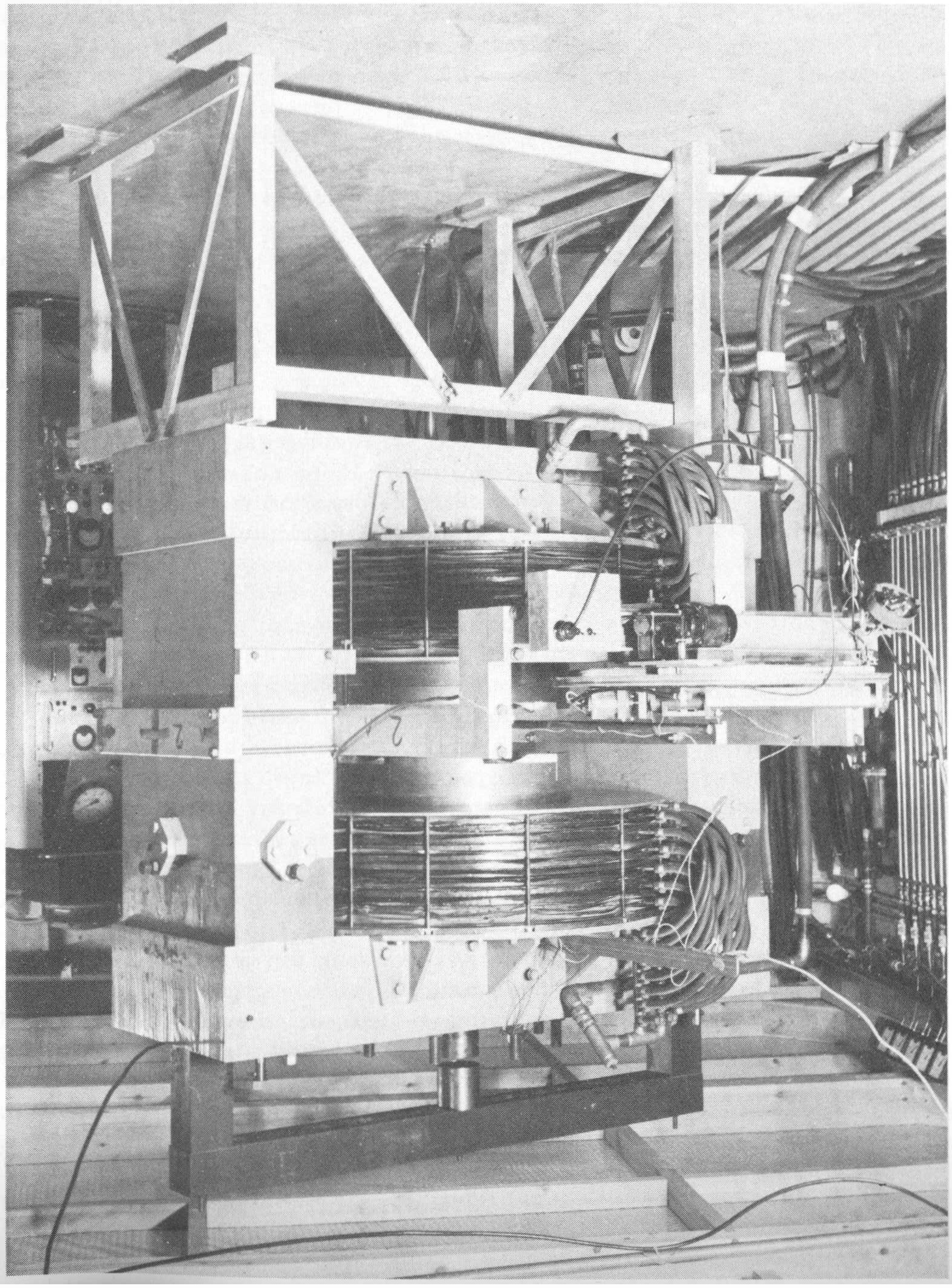


**Fig. 76. The magnet assembly.**

If we wish to change the contours then all we have to do is take the 4 ridges off, remachine the valleys, put the ridges back, and remachine them. What we had in mind was a fairly flexible system so that if we wish to change to 3 ridges instead of 4 it will not be too difficult.

We have a series of three concentric coils; each in a single turn of water-cooled copper pipe, 0.2 in. OD. They are set at radii of 1, 4.5, and 8 inches. We have a concentric feed supplying the power so that we don't get any disturbances at the ends. With a maximum current of 400 amp fed to all the coils in series we can get

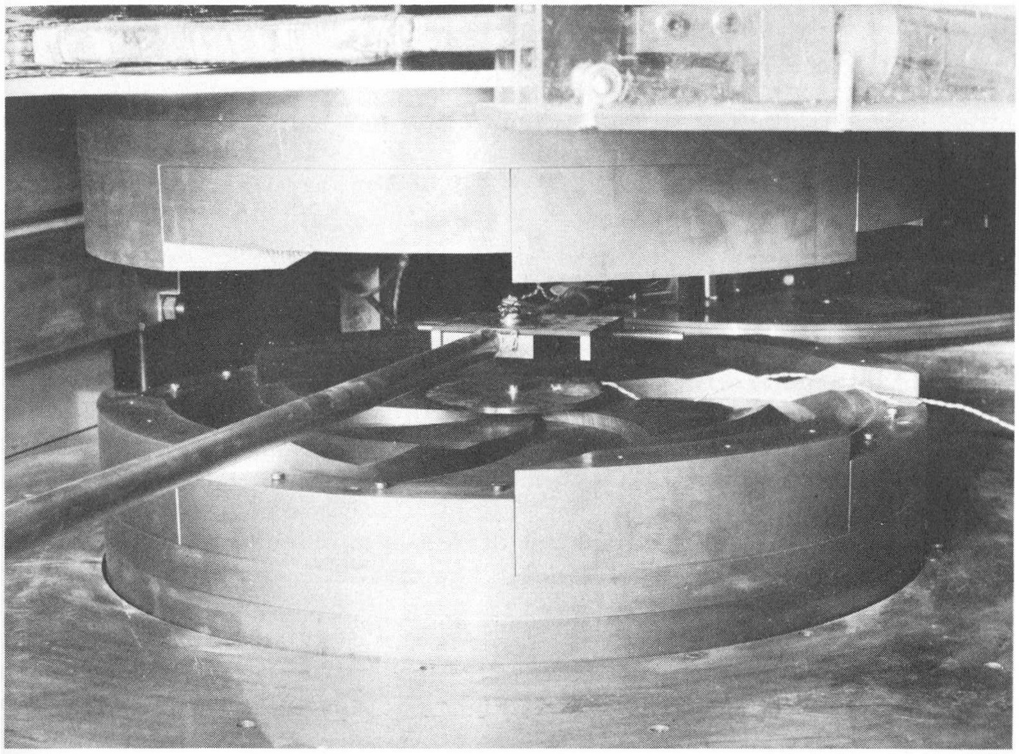

Fig. 77. The magnet gap.

a fairly smooth gradient of 15 gauss in. extending out to about 8.5-in. radius. By reversing the current in any of the coils we can alter the shape of the correcting field.

For the method of measuring the magnetic field we followed the system used by Cioffi[1] in which the EMF picked up in the moving search coil is cancelled by the voltage developed in a mutual inductance, a galvanometer being used to register any difference in these voltages. Compensation is then obtained through a double photocell and associated amplification circuit. With this system we are able to feed the output onto a pen recorder, which has been modified to increase its sensitivity so that 10 spans of the chart indicate a 100-mv signal. We can read to an accuracy of about 1 part in 3,000, and the linearity is better than 1 part in 5,000 over the range that we are using.

The system of moving the search coil is as follows. On either side of the magnet gap we have two disks which are driven together by means of a wire around their peripheries. Each disk has an arm and there is a connecting rod in between at the centre of which a search coil, which has a volume roughly of 1 $cm^3$, is mounted. We can set the radius accurately and by driving one of the disks with a motor the search coil will then move around the required circle. The output is fed to a pen recorder on which we also have marker pips every $10^\circ$ for reference. The radius can be measured to 0.001", and the angle of rotation to 3 minutes of arc. We take readings every 1 in. of radius.

From the results we compute the harmonic content up to the 8th harmonic. I am sorry I haven't slides of the results but these typical figures were handed to me just when I left the laboratory. At a radius of 4 in. the first harmonic has an

[1]Rev. Sci. Inst. 21, 624, (1950).

amplitude of 0.6 gauss; the second, 2.2; the third, 1.1; the fourth 378.2; the fifth, 0.5; the sixth 0.2; the seventh 0.1; and the eighth, 8.0.

We took considerable precaution in the design to keep the first harmonic down to less than 1 part in $10^4$. The mean field at the center is 13 kilogauss; at a radius of 4 in. we are well within tolerance. At a radius of 8 in. the first harmonic has come up to 0.7 gauss, at 9 in. to 3.4 gauss.

These measurements give the variation of field with azimuth, and what we have to do then is a field plot along the peak of the spiral to tie all the curves together. This is done by moving the search coil out radially over the maxima of each azimuthal plot. In this case reference marks occur at inch intervals of radius. I should have mentioned that in addition to giving the amplitude of the various harmonics, the computation will also give the phase of each harmonic, and in particular of the 4 $\theta$ harmonic.

One interesting result that comes out of this—the magnetic spiral law differs from that machined on the steel polefaces. The magnetic spiral is a looser spiral and results presumably from the outward fringing of the magnetic field.

The state of the machine at the moment is that we have our required mean field law established to within about 10 gauss. Figure 78 shows the results superimposed on the CW field law and also on the field law required to give zero axial focusing at all radii. With the poleface windings we hope we can adjust the field to be sufficiently near to the CW law to be able to get some results.

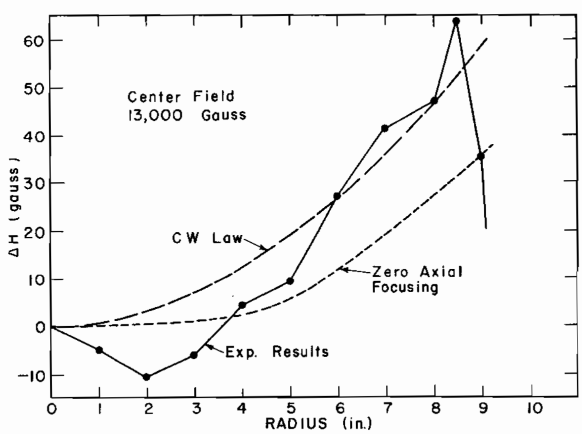


Fig. 78. Variation of mean magnetic field with radius.

The percentage flutter is plotted against radius in Figure 79a and reaches about 9% at 9-in. radius. In Figure 79b the actual contours of the ridges and valleys are illustrated, together with the positions of the orbit-correcting coils.

We are using a single dee system; in Figure 80 it is being tested in the vacuum tank. For convenience of operating this machine we decided to pulse it with a 1% cycle, 200 μs pulses occurring at 50 cycles per second. This reduces the power requirements, the cooling required on the dee, and also the background radiation so as to make it quite easy to do experiments. The dee system will allow us to get 38 kv.

One final word, the focusing does not reach right into the center, and we expect that we will have to introduce some falloff in field here. We made a rough calculation--or should I say a smooth approximation?—on the basis of which we can get the condition for $\nu_z = 0$. For the field law meeting this condition, we estimate that the phase slip will only be 17.5 degrees. It is worth noting that a larger gap would necessitate a greater falloff in field to restore axial focusing and this would result in increased phase slip. For instance if we put our gap up by 30%, then this phase slip will increase by a factor of 10 for the same dee voltage.

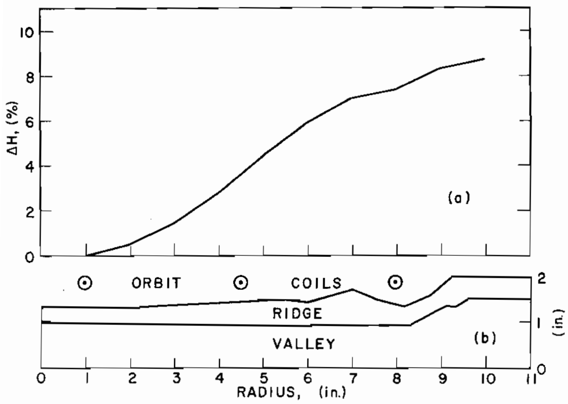


**Fig. 79.** (a) Modulation of magnetic field.
(b) Ridge and valley contours of pole pieces and positions of orbit coils.

CHAIRMAN KELLY: I would like to ask one question to start. These measurements were made with a 13-kilogauss average field; does this mean that you have to give up the 19?

SNOWDEN: No. The 19 was the field required at the maximum radius, and that would have corresponded to a center field of 15 kilogauss. We would have liked to have done this model work with 15 kilogauss center field but, as I explained, with the large gap we use it is difficult to achieve this. We felt that if we brought the gap down any more so that we could get 15 kilogauss then we would not have enough room for a reasonable dee system.

SYMON: I would just like to ask about the configuration of the correcting coil as it goes around over the valleys--the ridges.

SNOWDEN: The coils are mounted on a flat plate and lie within the hollow part of the pole pieces. Figure 79b illustrates this point.

JUDD: How do you arrive at those rather erratic curves you just drew, with both ups and downs? Is this by empiricism or by a calculation, or iteration, or by a smooth approximation?

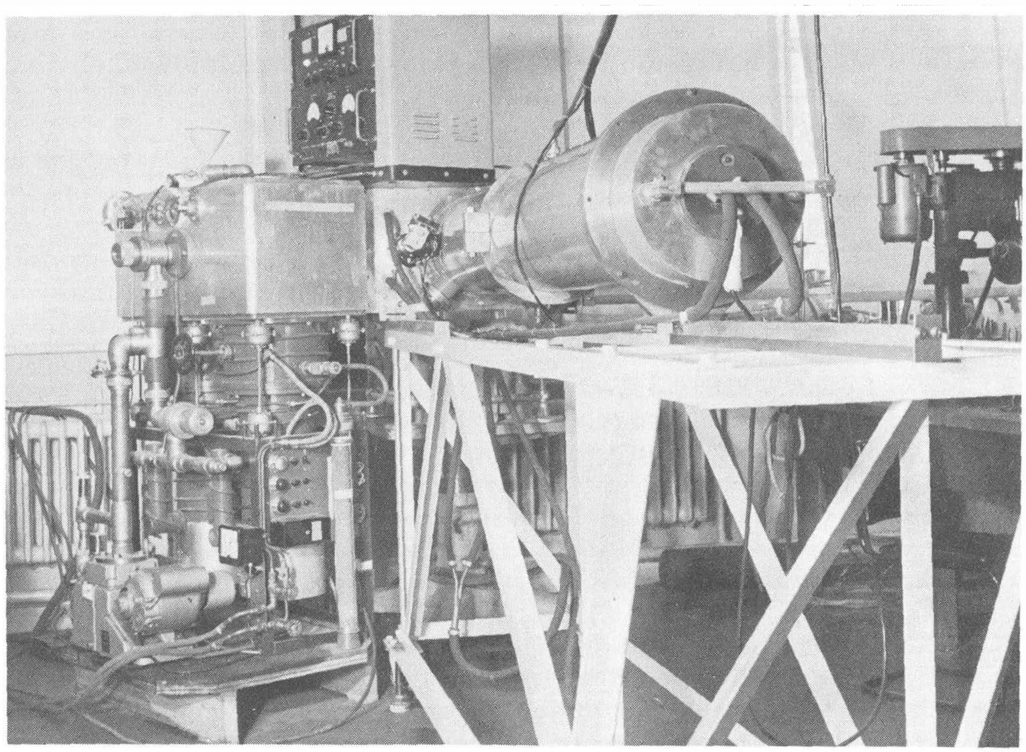

**Fig. 80.** Dee system being tested under vacuum.

SNOWDEN: Having measured the field we find out how far it differs from the required field that we wish to achieve at a chosen number of points. We have previously determined experimentally the effect on the field of a given size shim. Then we solve a series of simultaneous equations in order to find out the heights of shims to be added to give agreement with the required field at the chosen points.

JUDD: How many iterations of that procedure were involved?

SNOWDEN: To achieve this, two, but first a very approximate contour had been obtained empirically.

JUDD: Is there actually reversal as drawn in the hill?

SNOWDEN: Yes.

LIVINGOOD: Did I understand you to say that you get within 10 gauss of the desired shape without the use of any current in your coils, just by machining iron?

SNOWDEN: Yes.

LIVINGOOD: Very good!

SCHMIDT: What energy are you designing for on the converted machine?

SNOWDEN: It is still to early to say. There are other considerations that come in. The resonance phenomenon which has been studied by King and Walkinshaw[1] make it unlikely that we will be able to operate as a CW machine above about 180 Mev. From there on we would have to use frequency modulation; the amount required would be very small, only about 1%. It may, therefore, be possible to obtain a very high repetition rate, possibly using ferrite. Certainly a mechanical system will work at quite high repetition rates and there is then some hope of getting beam currents of 50 microamps.

HAVENS: There was one thing that bothered me. You had a 4-in. gap on your model, and it looked to be about 1/6 scale. Is that right?

SNOWDEN: No, the magnet itself was a 1/5 scale model, but the cyclotron is designed to represent the central 10 in. of the full-size machine and in theory should have the same gap as the full size, that is 6 inches.

WELTON: I don't want to detract from your very nice work, but it seems that for a conversion of this type, especially in view of the work reported earlier this afternoon, a combination of three sectors near the middle branching out to six at the outside would be a very good way of getting the relatively easy central region stability combined with the freedom from the resonance difficulties up to the highest energy that you are interested in. I presume this has been thought about. I am wondering what the arguments are against its adoption.

SNOWDEN: We have indeed thought about it. It was merely the complication of knowing what happened when you went from 3 to 6 ridges that made us choose this simpler method. We certainly would be interested in any computations that have been done for the region between 3 and 6 ridges.

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(1) Nuclear Inst. 2, 287-298 (1958).

WELTON: At Oak Ridge what we call Cyclotron Analogue II (a high-energy cyclotron electron model) has 8 sectors, at the outside. You cannot very well start a machine with 8 sectors, so it has 4 in the middle. John Martin has by this time a fairly good start on the detailed coil and magnetic field calculations for it.

MARTIN: There have been no radial stability tests across this transition from 4 to 8 sectors, but, although there is a slight anomaly in the focusing ridges, you do get good focusing across this region.

KING: I should say that it is over a year ago that we decided on the 4-ridge design. At that time we were very frightened. Now I don't think we would be so scared and we don't see very many theoretical difficulties. But I personally would like to see some computations done before launching out into hardware.