

Survey of R-F Techniques
Applicable to Variable-Energy Cyclotrons

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Since 1954 a number of highly successful variable-energy cyclotrons have been built. The ability to tune the energy through a wide range has proven to be of such value that there is not a single machine, proposed or under construction, at the present time, which does not include this feature. These new machines are all of the spiral-ridge type and require less dee voltage than the conventional type. This alters the r-f problem materially. The dee-to-liner spacing does not have to be as large, so less magnet gap--the most costly item--is required. This results in an increase in dee capacitance, hence a reduction in shunt impedance and incidentally, more challenging r-f problems.

I have gathered together a number of r-f techniques from various cyclotrons which would appear to be useful in the solution of the r-f problems of the new machines. First, however, I will describe the r-f system of the 88-in. cyclotron which is being built in Berkeley.

Basically, the problems associated with this machine are the usual ones: it has a 3:1 frequency range, and the higher-order resonances must be so adjusted that they do not line up with the harmonics produced by the oscillator. Also, care must be taken with the higher-order resonances to avoid parasitic oscillations. An additional difficulty is the fact that it is a deuteron machine, so the r-f wavelength is twice as long as for protons. This means that if one minimizes the dee capacitance in order to reduce the charging currents, and hence the r-f power, as is customary with proton machines, the size of the dee-stem tank becomes impracticably large. The largest tank which seemed practical was selected and then the dee capacitance was increased until the low-frequency limit, 4 Mc/s, could be met. The resonator requirements are quite different at the two ends of the frequency spectrum. For example, for the low end one would like to use a long dee stem of small periphery. At the high end one would like to use a short dee stem of large periphery. The final solution must be the result of compromises between competing requirements at the ends of the frequency range.

In some respects the lower frequencies associated with deuterons help. The skin resistance is reduced by about 30%. For a given dee charging current one can tolerate twice as much dee capacitance.

This machine is going to get very radioactive. Deuterons are bad in this respect; the machine is being built for chemists rather than physicists, and they always want large beam currents. The best estimates indicate that the background level of the magnet room will be about 10,000 roentgens per hour. Because of this high radiation level we decided to have nothing in the magnet gap that is not easily removable, and that, in general as few things as possible in the vacuum system would be movable. We have attempted to keep the resonator construction as simple as possible.

The general scheme of the resonator is shown in Figures 144 and 145. The dee is rectangular, 98 in. wide and 70 in. long. The dee stem is ridged to increase the periphery and reduce the current density. This saves 70 kw of r-f power at the high-frequency end of the range. The dee stem is 110 in. long, 51 in. wide, and 8 in. thick.

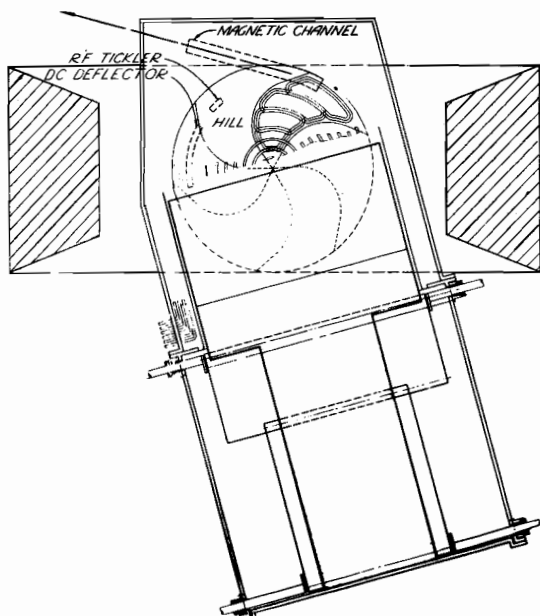


Fig. 144. The 88-in. cyclotron resonator, top view.

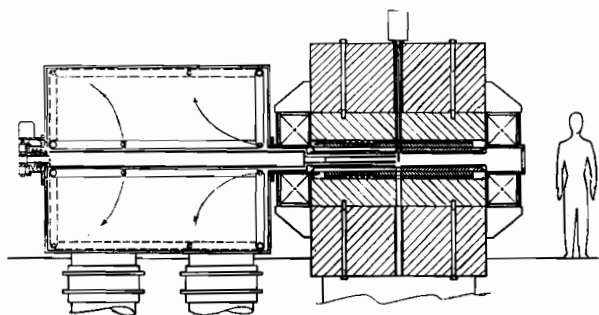


Fig. 145. The 88-in. cyclotron resonator, side view.

Figure 145 is a side view of the resonator. The movable panels which determine the dee-stem inductance are shown in the high-frequency position (12.6 Mc/s) by the solid line and in the low-frequency position (4.2 Mc/s) by the broken line. The dee-to-liner spacing is 1.5 inches. Note the ridges on the dee stem shown in Figure 146..

Figure 147 is a picture of the quarter-scale r-f model. To simplify construction of the model it was built vertically. The actual machine has a horizontal dee. The mechanical engineers and physicists like horizontal machines better than vertical ones because they provide better access to the magnet gap. Radio-frequency men usually prefer vertical machines because of their better voltage-holding ability which results from the greater cleanliness of the dee and liner surfaces. Vertical machines accumulate fewer finger prints on the high-voltage surfaces, and are not bothered so much by accidents like water leaks.

One time the ion source in the 184-in. cyclotron sprung a leak, and the pole tip filled up with water like a lake. In spite of removing as much water as possible with rags, and baking it out with heat lamps and fans, it was quite a long time before the water was all out of the cracks between the magnet shims, and the machine would hold voltage again. Of course, water leaks do not occur very often, but when they do it is a real mess in a horizontal machine.

Figure 148 shows the resonator voltage distribution, and Figure 149 the current distribution. The r-f skin power is 145 kw for a dee voltage of 70 kv. The 5-kv voltage drop which occurs near 70 in. at 12.6 Mc/s is a result of the inductance of the forward panel.

There is an interesting feature of this resonator which I am attempting to exploit at the present time. Notice, in Figure 147, that in order to produce the same dee voltage at the two ends of the frequency range, the same voltage, 15 kv, is required at the 160-in. point on the dee stem. It appears that the vacuum tube can be connected at this point and will produce essentially the same dee voltage throughout the frequency range of the cyclotron, for a given plate voltage.

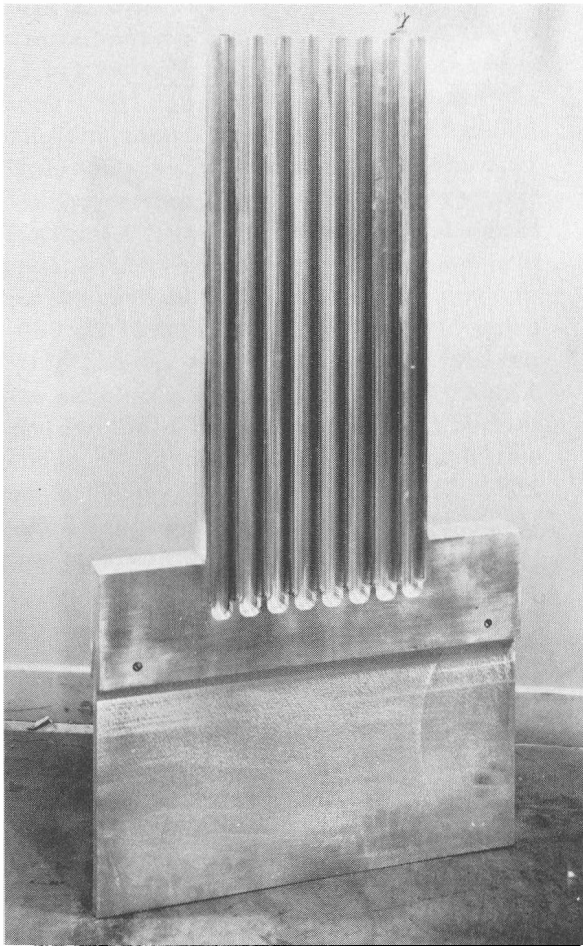


Fig. 146. The dee and stem of the 1/4-scale r-f model. The ridges on the dee stem reduce the current density at the high-frequency end of the range.

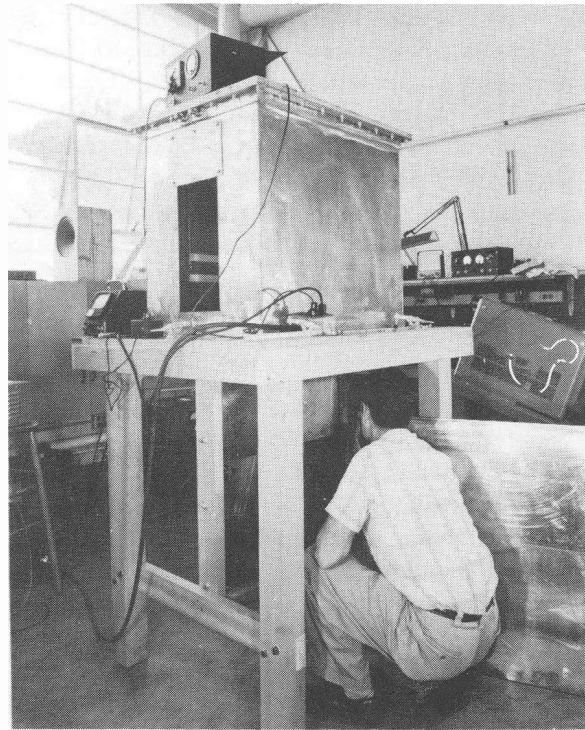


Fig. 147. The 1/4-scale 4-f model is of light-weight, wood-and-copper construction and lends itself well to experimental modification.

If a transmission line has to be used, it probably will require some type of tuning device to perform adequately over such a wide frequency range. If the oscillator can be coupled to the resonator without a transmission line, tuning will be appreciably simplified.

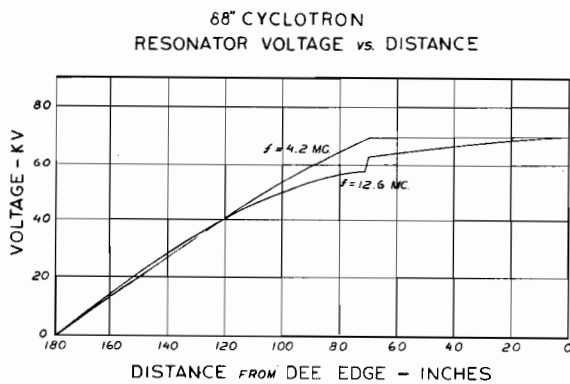


Fig. 148. Resonator voltage distribution.

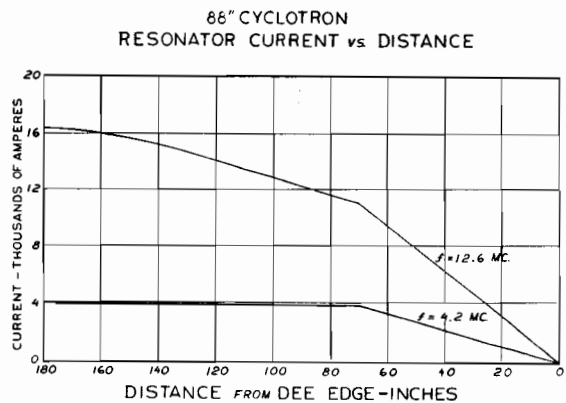


Fig. 149. Resonator current distribution.

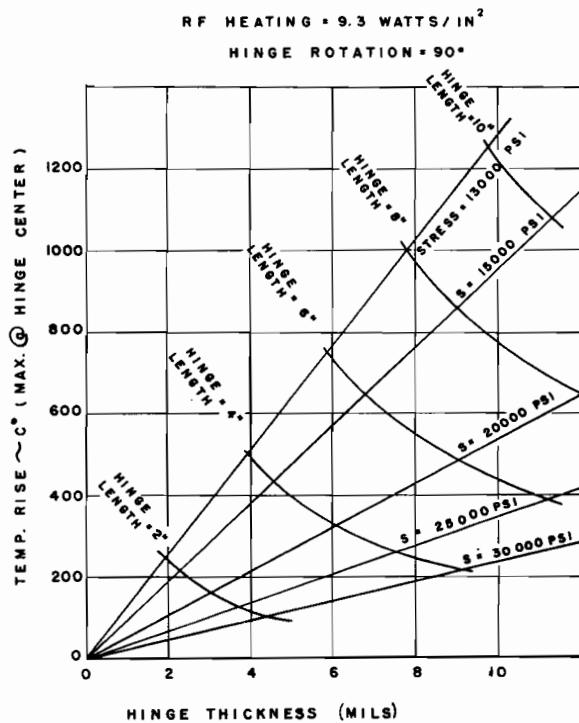


Fig. 150. Mechanical bending stress and temperature rise in r-f hinges. For adequate life, the thickness and length of r-f hinges must be rather carefully selected.

Figure 150 is the result of a study of r-f hinges by one of our mechanical engineers, Ken Merck. For an r-f heating power of 9.3 watts/in. (this corresponds to 100 amp per linear inch at 12.6 Mc/s), it shows the relationship of temperature rise and bending stress to hinge length and thickness. A suitable hinge might be one which is 2 in. long and 3 mils thick. It would operate with a maximum bending stress of 20,000 psi and at a temperature rise of 160°. The ends of such a hinge would be attached to a water-cooled block which would operate at a temperature of about 20°. Thus, the temperature of the center of the hinge would be about 180°. A test which we made indicates that such a hinge would have a life in excess of 100,000 operations.

Movable panels, similar to those which we will use in the 88-in. cyclotron, are in use in the 184-in. cyclotron. These are shown in Figures 151 and 152. The panels are of a light-weight, riveted type of construction, similar to that used in airplanes.

One of the more important r-f problems associated with variable-energy cyclotrons is that of control of the higher transmission-line resonances. Of course, these must not line up with harmonics of the oscillator. Often one faces the problem of finding a way of increasing the bandwidth between two resonances—say the quarter-wave and the three-quarter-wave resonances. An effective technique consists of

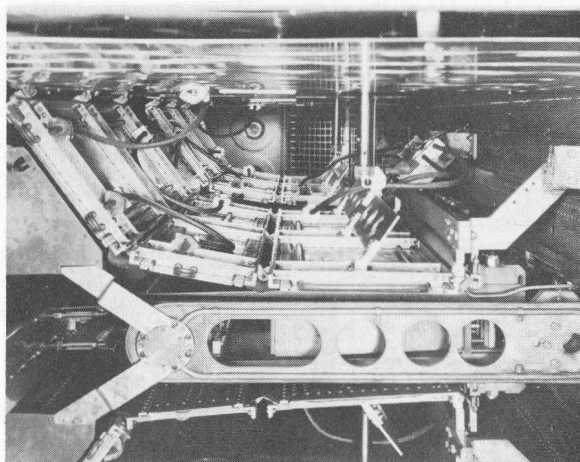


Fig. 151. The movable panels of the 184-in. cyclotron.

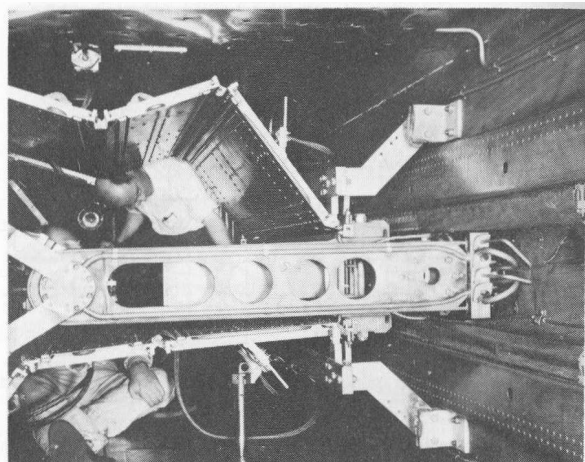


Fig. 152. The upper panel is shown in the low-frequency position; the lower panel is in the high-frequency position.

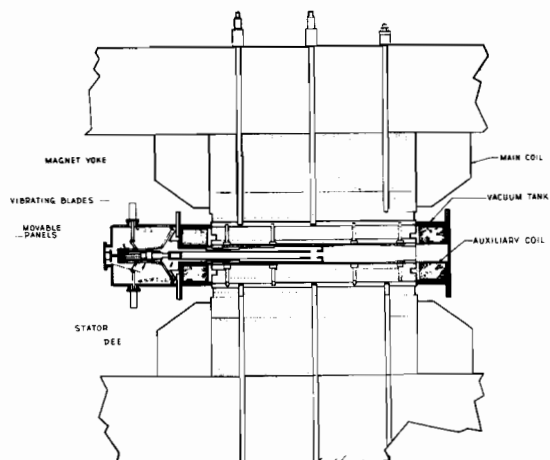


Fig. 153. The 184-in. cyclotron resonator, cross-sectional view. The reduced dee-to-liner spacing near the voltage node extends the tuning range.

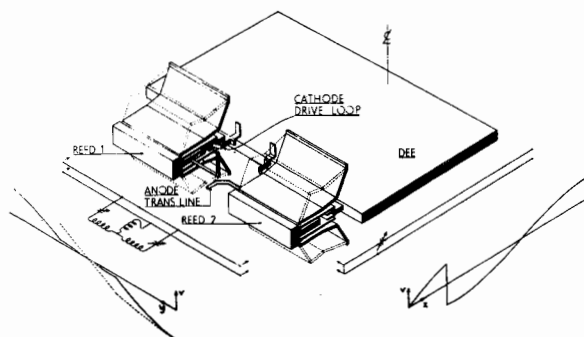


Fig. 154. The 184-in. cyclotron resonator with the liner removed. The equivalent circuits in the longitudinal and lateral directions are shown.

varying the characteristic impedance of the line along its length. For example, if the characteristic impedance is lowered near the voltage node of the three-quarter-wave resonance, its frequency will be changed very little. However, for the quarter-wave resonance this point on the line will be at a relatively high voltage, and the resonant frequency will be lowered appreciably. Thus, the bandwidth between the two resonances is materially increased.

Often, by suitable choice of resonator geometry, the frequency of an undesired mode can be made to move with the tuning of the desired mode in such a way that it does not cause trouble. This technique was employed in the 184-in. cyclotron resonator. Here, because the dee width was of the order of a half wavelength there were two cross-modes of comparable frequency to the main mode. Figure 153 is a cross-sectional view of the 184-in. cyclotron and Figure 154 is an isometric drawing showing most of the resonator, the equivalent circuits in the two directions, and the corresponding voltage distributions. Those shown in the y-direction are the two undesirable cross-modes. The voltage and current distribution of the cross modes can be computed from the equivalent circuit associated with the y-direction, in Figure 153, in the same manner as they can for the desired mode asso-

ciated with the x-direction. It is apparent from the equivalent circuit in the y-direction that the separation of the two sets of reeds and panels influences the frequencies of the cross-modes without affecting the frequency of the main mode. The geometry which was chosen produced the mode distribution shown in Figure 155.

While the medium-energy machines of current interest do not have the cross-mode problem, the technique of arranging the geometry so that an undesired mode tunes with the main mode in an appropriate way is effective and may be applicable.

Figure 156 is a picture of the dee-stem tank and dee of the 90-in. cyclotron at Livermore. The shape of the dee was chosen to reduce the voltage taper along the dee edge—note the notched shape of the upper end of the dee. This shape was worked out experimentally by the use of quarter-scale model. An approximate shape was designed on paper and made out of wood. It was then painted with conducting paint (Du Pont silver solution No. 4817) and copper plated. The voltage distribution along

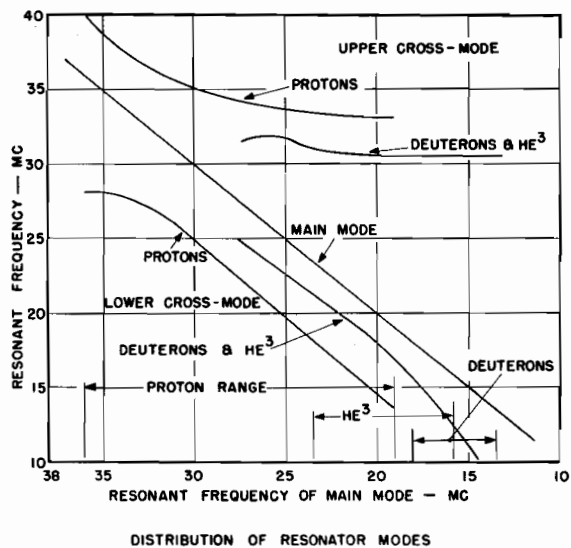


Fig. 155. The cross modes of the 184-in. cyclotron tune with the main mode in such a way that they remain separated, and hence, are not excited by the main mode.



Fig. 156. The notched shape of the dee of the 90-in. cyclotron reduces the voltage taper along the dee edge to about 2%.

the dee edge was measured and appropriate modifications were made to the dee with a saw. The exposed wood was then painted with conducting paint and a new set of voltage measurements taken. After several tries the best shape was found and the full-scale dee built accordingly.

The 90-in. cyclotron tunes from 4 to 9.5 Mc/s in two bands. A set of shorting fingers provides two dee-stem lengths--hence two bands. Within each band the frequency is tuned by movable liners. The dee-to-liner spacing is 2-5/8 in. at the high end and 3/4 in. at the low end of each band. The reduction in spacing is permissible as the frequency is lowered, because the threshold dee voltage decreases sufficiently to make the most severe sparking condition occur at the high end of the band. This is quite an efficient resonator but does not lend itself very well to the small magnet gaps used with spiral-ridge machines--the liners require too much space (2 inches).

By reducing the distance that the dee-stem currents have to flow at the higher frequencies, the shorting fingers produce a substantial saving of r-f power.

Radio-frequency people tend to avoid shorting fingers because of failures occurring in the early machines. Experience with these fingers on the 90-in. cyclotron indicates that such fears are not justified. During the period of operation of this cyclotron--four years--the shorting fingers failed only once, and then only because they were not properly seated. A cross-sectional drawing of these fingers is shown in Figure 157. The maximum current density is 70 amp/in. at 9.3 Mc.

I have discussed the operation of the shorting fingers with the cyclotron crew in order to find what improvements

90" CYCLOTRON
SHORTING FINGERS

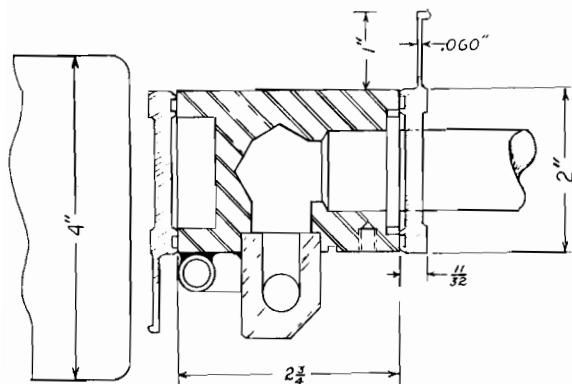


Fig. 157. Cross section of the shorting fingers of the 90-in. cyclotron. The structure was milled from a block of copper-plated steel 32 in. long; individual fingers 1/8 in. wide were produced by suitable saw cuts.

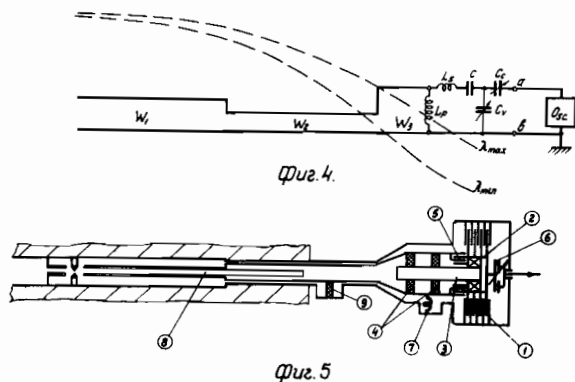


Fig. 158. The resonator of the 680-Mev synchrocyclotron near Moscow.

might be made in any future designs. In their opinion, the fingers themselves are quite adequate and need no modification, but the mechanism for moving the fingers could be improved. They feel that the mechanism should be driven by a power device such as an electric motor or an air cylinder and should be entirely automatic in operation. It should be protected by suitable interlocks. Sliding vacuum seals should be avoided; none of the mechanism need come through the vacuum wall.

The 90-in. cyclotron uses a driven type of r-f system. There are two advantages of this type of system over a self-excited one: (1) In the driven case the grid and anode circuits are coupled to different resonators so there is no feedback path for parasitic oscillations except through the grid-anode capacitance of the vacuum tube. This is an almost ideal capacitance in most modern tubes and is easily neutralized for a very wide range of frequencies. Thus, the driven system provides better discrimination against parasitic oscillations than the self-excited system. (2) All of the r-f circuitry of a driven system except that of the final amplifier anode can be developed and tested at a location remote from the cyclotron. This permits most of the r-f work to be done in parallel with the cyclotron construction rather than in series with it. In the other characteristics—performance, cost and reliability—there is very little difference between the two types of

system. My personal opinion is that either of the two types, when carefully designed, satisfy the requirements of a variable-energy cyclotron very well.

There are some interesting r-f techniques in the 680-Mev synchro-cyclotron in Moscow which may be applicable to variable-energy spiral-ridge machines. Figure 158 is a cross-sectional view of this cyclotron. Note that the oscillator is capacitively coupled to the resonator. One place of the coupling capacitor is mounting on the rotor of the capacitor. By contouring the plates of the coupling capacitor, it was possible to vary the coupling ratio with rotor position in such a way that the dee voltage is almost independent of frequency. Figure 159 shows the results.

Another interesting feature of this machine is the oscillator circuit shown in Figure 160. This is a two-terminal oscillator—the grid signal is obtained from the

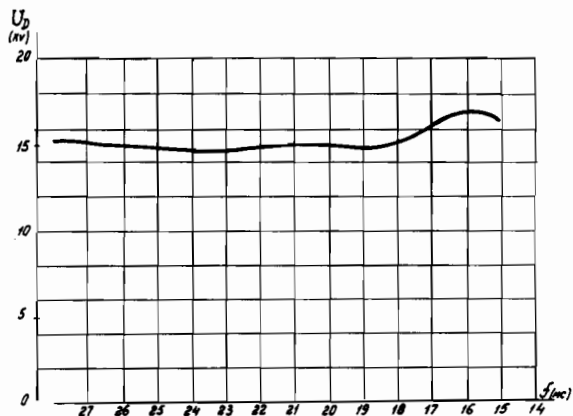


Fig. 159.

Figure 159. The success of the novel coupling technique in the 680-Mev machine is illustrated by the dee voltage-vs-frequency curve.

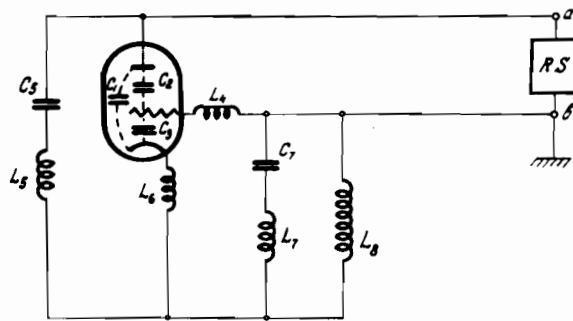


Fig. 160.

Fig. 160. The circuit of the two-terminal oscillator of the 680-Mev machine.

anode rather than the cyclotron resonator--which discriminates against parasitic oscillations outside of a designed pass band. This is really a very nice piece of classical engineering. They simply took the electrode inductances and the inter-electrode capacitances of the vacuum tube, added the necessary feedback circuitry to provide oscillation, and chose the poles and zeros of the feedback transfer function in such a way that the phase was right for oscillation through the desired pass band and wrong outside of this band. It seems as though this circuit should provide as good discrimination against parasitics as the conventional grounded-grid cyclotron oscillator, and it eliminates the relatively fragile cathode-line vacuum insulator.