Preliminary Design of the R-F System for ORIC

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The Oak Ridge Relativistic Isochronous Cyclotron* is being designed to accelerate protons, deuterons, alphas, and the heavy particles over a continuous energy range. The maximum energy is to be 75 Mev for protons, and the maximum beam current is to be as high as one milliampere. The magnet has a pole base 76-in. in diameter and a maximum orbit radius of about 31.5 in. Threshold r-f voltage cannot be specified at this time, but a value of 400 kv/turn was selected as a design goal.

The frequency range required of the r-f system in a variable-energy machine is a function of the dee angular width. For example, if we use either one or two 180° dees, then acceleration is possible only when the ratio of r-f to ion frequency (the harmonic) is an odd number. To get continuous frequency coverage, it would be necessary for the r-f system to tune over a 3:1 range. In ORIC, the r-f system would operate from 22.5 to 7.5 Mc/s to accelerate particles having ion rotation frequencies of 22.5 to 7.5, 7.5 to 2.5, and 4.5 to 1.5 Mc/s. Table 5 lists the maximum voltage gain possible with various dee sizes and for various harmonics.

Table 5. Voltage gain per dee as a function of dee angular width and harmonic.

	Voltage Gain per Dee				
Harmonic → / Dee Width ↓	1	2	3	4	5
180°	$2V_o$	0	$2V_o$	0	$2V_o$
120°	$1.73V_o$	$1.73V_o$	0	$1.73V_o$	$1.73V_o$
90°	$1.41V_o$	$2V_o$	$1.41V_o$	0	$1.41V_o$
60°	V_o	$1.73V_o$	$2V_o$	$1.73V_o$	V_o

V_o = peak dee-to-ground voltage.

By using two dees with an angular spread less than 180°, acceleration of particles may be possible on the second and other even harmonics. Therefore, the total frequency range required of the r-f system may be only 2:1 rather than the 3:1 ratio required for the usual 180° dees.

Unfortunately, a design for a given voltage gain/turn may be hampered by other factors. Since in ORIC the electrodes cannot go in the valleys, and since magnetic gap is so precious in any AVF cyclotron, there is a limitation on the maximum dee-to-ground voltage. By the selection of a dee-to-liner spacing, we fix this maximum dee voltage. By cutting back the dees from 180°, we lose voltage gain/turn for particles accelerated on the first harmonic, where the voltage is needed most.

Based on experience with out cyclotrons, and others, we have taken 1.5 in. dee-to-liner spacing as the minimum to hold 100-kv peak. Our r-f system must fit in a gap

*ORNL - 2648. The Oak Ridge Relativistic Isochronous Cyclotron.

with the 1.5-in. spacing out to a 40-in. radius. Beyond that point, a maximum gap of 16 in. is available. Out beyond the edge of the coils at a radius of about 75 in. the vacuum tank and liner are free to flare out even farther.

At one time or another we have considered all of the resonant systems listed in Table 6.

Table 6. Conceivable Resonators for ORIC.

Electrical Length of Resonant Sys.	Dees (No.)	Dee Width (deg)	Method of Tuning (Variation of)
1. $\lambda/4$	2	180, 90, 60	ℓ_s, Z_{os}, $Z_{os} + \ell_s$
			$Z_{os} + \ell_s + C_D$
2. $\lambda/2$	2	180, 90, 60	$\ell_s + C_D$
3. $\lambda/2$	2	180, 90, 60	C_T
4. $3\lambda/4$	2	180, 90, 60	C_T, L_T
5. Two Coupled-Circuit Resonators	2	180, 90, 60	M, C_T
6. $\lambda/4$	1	180	$\ell_s + Z_{os} + C_D$

One of our early goals was to avoid sliding contacts. That is, we would, if possible, have no movable spider. This consideration led to the so-called "barn-door" system in which the turning is accomplished by variation of the characteristic impedance of the dee stems. Within the limitations imposed by our geometry, the dee capacity, and stem space, we could not get the necessary frequency range without a movable spider in addition to variation of Z .

One $\lambda/2$ system was copied from the University of Michigan proposal*. This system has identical dee stems extending from both sides of the cyclotron so that the dee capacity is split in half. Thus, a given dee voltage can be obtained with about half the power required for a $\lambda/4$ system. Also, excellent mechanical support for the dees is possible. The big disadvantage of this system, which caused us to drop consideration of it, is that it nearly blocks access to the machine.

A second $\lambda/2$ system would have the dee on one end of a $\lambda/2$ line and a tuning capacitor on the other end. The principal disadvantage of this system was the necessity of supporting the structure on insulators or high impedance stubs, which lead to very complicated and poor mechanical construction.

The last $\lambda/2$ system is nearly a $3\lambda/4$ system, like that used for synchrocyclotrons. There a 3:1 tuning range is accomplished, but once again the problem of mechanical support arises. The support is equivalent to an inductance coupling the two parts of the circuit together. And because of the equivalence of the two circuits,

*A Proposal to the USAEC for the Construction of an 83" Spiral-Pole Cyclotron by Department of Physics, University of Michigan. January, 1958.

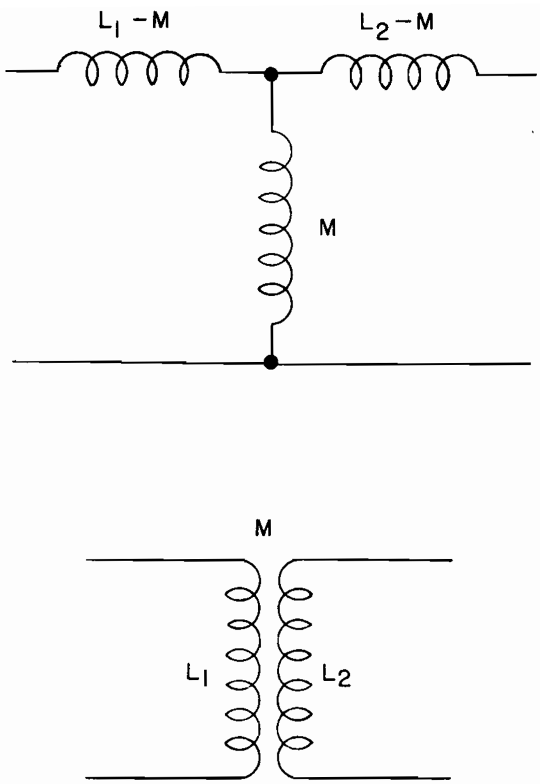

Fig. 134. Equivalent representation of an inductively coupled circuit.

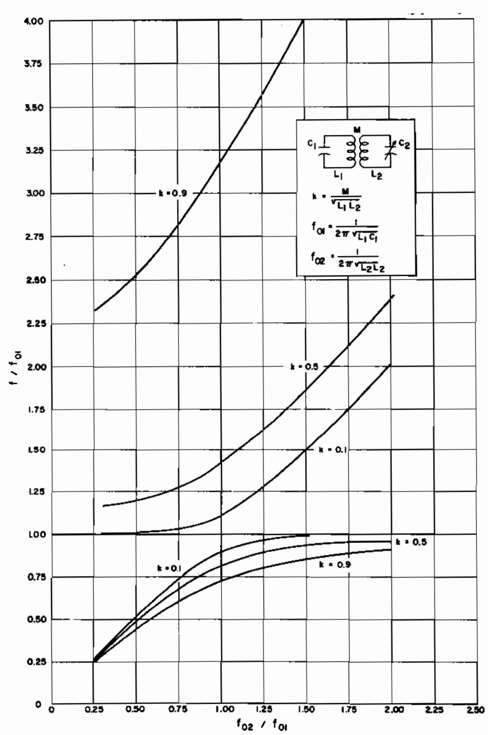

Fig. 135. Properties of two coupled lumped circuits.

shown in Figure 134, we may arrive at another possible resonator, the two coupled circuit resonator.

The properties of two coupled lumped circuits are shown in Figure 135; the circuits have two natural modes of oscillation. In one case the currents are in phase, and in the second case they are opposite in phase. Thus, considering the effect of the second circuit back on the first, it is seen that in one mode the inductive reactance is increased, lowering the frequency from the value when the two circuits are isolated, and in the other mode the opposite situation occurs. The frequency of resonance is plotted with the ratio of the separate natural frequencies as variable and k, the coefficient of coupling, as a parameter.

The physical dimensions (dee size and stem length) of the ORIC are such that the dee and stems can form one circuit with a resonant frequency of about 10 Mc/s.

Two variations of this circuit were considered. The first has a fixed mutual inductance between the two circuits as shown in Figure 136. The disadvantages of this circuit are that wide tuning range is required of the tuned circuit and that it is impossible to tune to frequencies close to the natural frequency of the fixed (dee) circuit. Thus, since the dee-circuit frequency is within the required frequency range, a dead band would occur. A greater disadvantage is that to obtain maximum frequency range, the inductance as well as capacity must be variable; this required a movable shorting bar as shown in the modification of Figure 137. The current density required at the shorting clamp exceeds that of present designs by a factor of two to three.

The second variation of the two-coupled circuit scheme involves variable mutual inductance, as shown in Figure 138, along with variable frequency of the

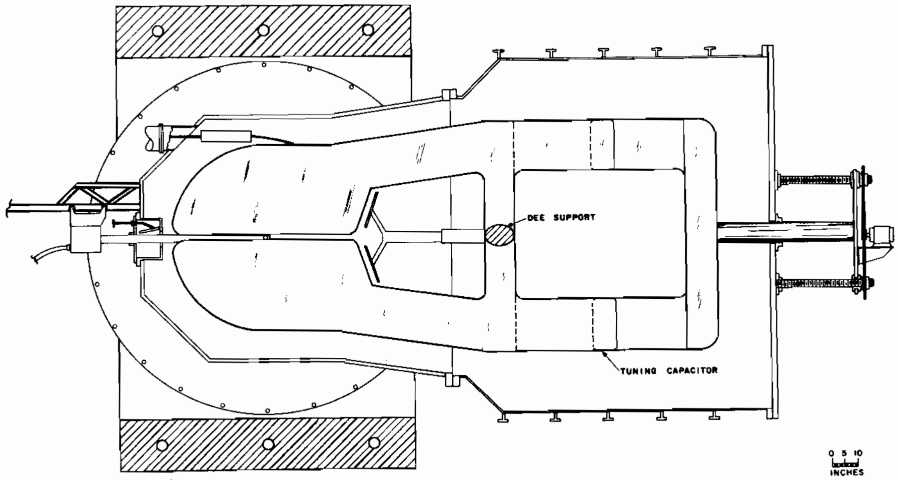

Fig. 136. Resonant system with fixed mutual inductance.

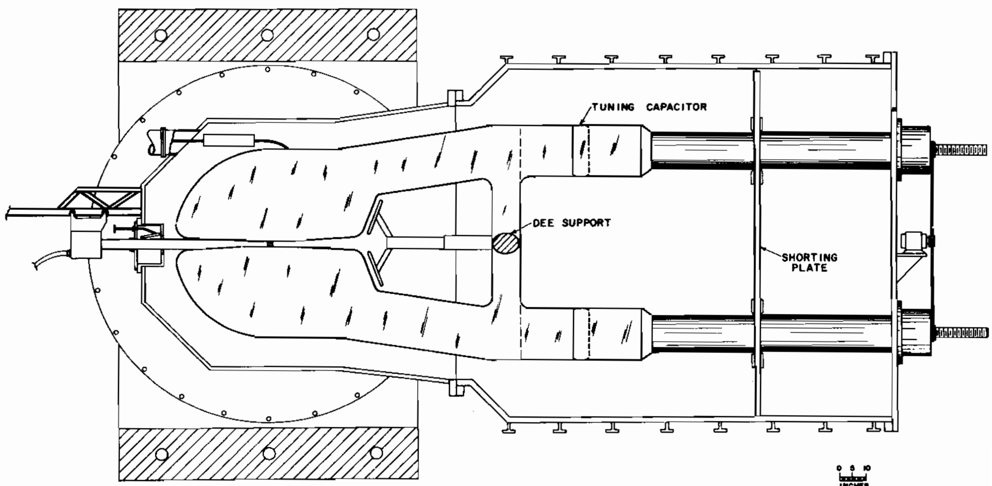

Fig. 137. Resonant system with movable shorting bar.

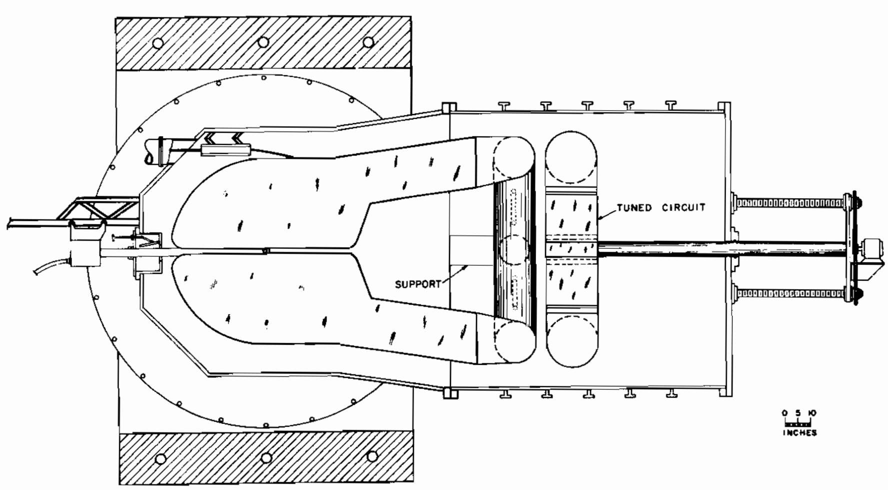

Fig. 138. Resonant system with variable mutual inductance.

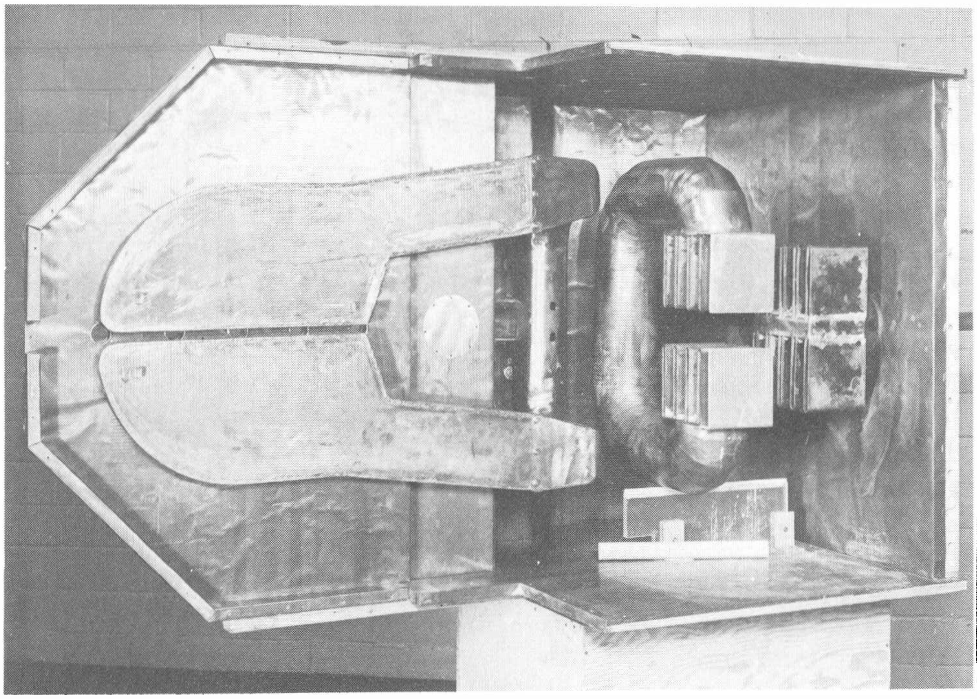

Fig. 139. Model-I resonator.

tuned circuit. This arrangement requires that the dee circuit be driven if the system is to be tuned to all frequencies in the band specified since the mutual inductance must go to zero. A model was constructed to measure the properties of this system.

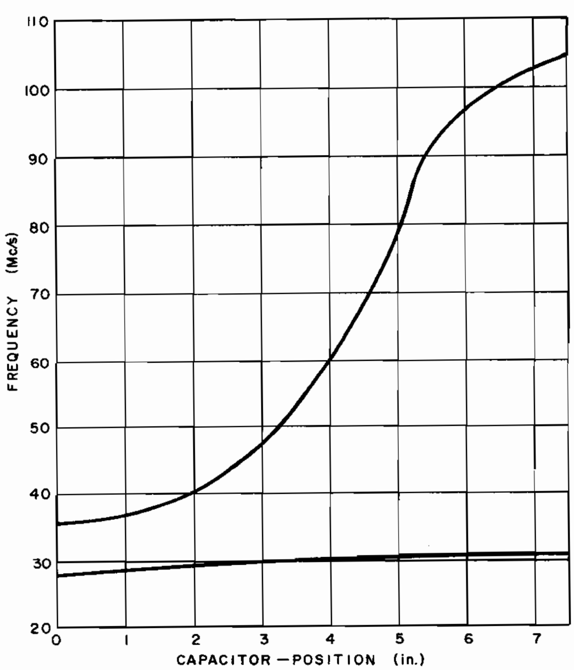

Fig. 140. Resonant frequency vs capacitor position, model I.

After consideration of the coupled circuit resonator in terms of voltage, current distribution, and power, a Model I was built as shown in Figure 139. This quarter-scale model was designed to tune over the range of 30 to 90 Mc/s. The items to be measured on this model were: (1) the tuning range; (2) the coefficient of coupling; (3) the Q of the resonator; and (4) the power required to drive the circuit to 100-kv peak dee-to-liner voltage.

In Figure 140 is shown the resonant frequency plotted against the position of the tuning capacitor for a particular spacing between the dee and tuned circuits. The resonant frequency of the dee circuit is the frequency approached by the lower resonant-frequency curve as the tuned circuit is tuned to higher frequencies. From the graph, this value is seen to be about 30.4 Mc/s.

Consider two magnetically coupled inductances; with a capacitor across each winding as shown in Figure 135. The resonant frequencies of this network are given by

$$\omega^2 = \frac{\omega_{01}^2 + \omega_{02}^2 \pm \sqrt{(\omega_{01}^2 - \omega_{02}^2)^2 + 4k^2\, \omega_{01}^2\, \omega_{02}^2}}{2(1-k^2)}$$

where ω_{01} = the self-resonant frequency of circuit 1
ω_{02} = the self-resonant frequency of circuit 2
k = the coefficient of coupling between circuits 1 and 2.

Let $\omega_{01} = \omega_{02} = \omega_0$ and solve for k:

$$\pm k = \left(\frac{\omega_0}{\omega}\right)^2 - 1.$$

This equation may be used with the data plotted in Figure 140 to find the value of k for both the upper and the lower resonant frequencies. The coefficient of coupling obtained by this method is plotted, Figure 141, in terms of the spacing between dee and tuned circuits on the quarter-scale model. This treatment of the system as if it were composed of lumped elements is not very satisfactory; however, a more precise treatment handling the coupled section as pieces of transmission line, like the dee and uncoupled parts of the stems, was developed.

The Q was determined from the width of the resistive component of impedance looking into a loop on the side of the dee circuit. The values of Q thus found were about 1600 to 3250 over the 30 to 90 Mc/s range.

The voltage standing wave along the dee, stems, and tuning circuit was measured. We were particularly interested in measurements at 90 Mc/s because there the power is greatest. Along the dee-lip edge, the voltage varied from 70.7 at the tip to 56.6 volts at the end of the lip closest to the dee stem. A voltage null occurred on the dee stem about halfway between the dee and opening into the coupled line region.

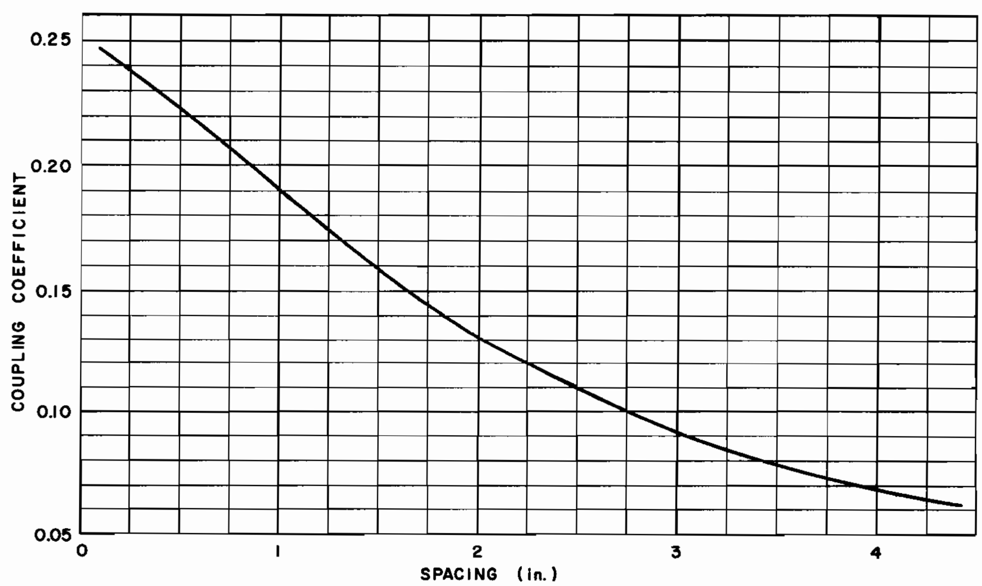

Fig. 141. Coefficient of coupling, model I.

The voltage at the end of the dee stem, and at the point at which the lines were coupled, was 230 volts. The corresponding point on the tuned circuit was measured at 755 volts with, I regret to say, not very high accuracy. The current along the lines was computed from the measured voltage and computed characteristic impedance. For the region in which the lines were coupled, it was necessary to solve the transmission line equations subject to the boundary conditions:

Line 1: (dee circuit) at $Z = 0 \quad V_1 = V_{01}$
$Z = \ell \quad V_1 = 0$

Line 2: at $Z = 0 \quad V_2 = V_{02}$
$Z = \ell \quad V_2 = 0$

Then,

$$V_1 = V_{01} \frac{\sin n(\ell - Z)}{\sin n\ell}$$

$$V_2 = V_{02} \frac{\sin n(\ell - Z)}{\sin n\ell}$$

$$I_1 = -j\left[\frac{V_{01}}{\sqrt{\frac{-L_{11}}{C_{11}}(1-k^2)}}\right] - \left[\frac{kV_{02}}{\sqrt{\frac{-L_{11}}{C_{22}}(1-k^2)}}\right] \frac{\cos n(\ell - Z)}{\sin n\ell}$$

$$I_2 = -j\left[\frac{V_{02}}{\sqrt{\frac{-L_{22}}{C_{22}}(1-k^2)}}\right] - \left[\frac{kV_0}{\sqrt{\frac{-L_{22}}{C_{11}}(1-k^2)}}\right] \frac{\cos n(\ell - Z)}{\sin n\ell}$$

where $n = \sqrt{L_{11}C_{11}(1-k^2)} = \sqrt{L_{22}C_{22}(1-k^2)}$

$$k = \frac{L_m}{\sqrt{L_{11}L_{22}}} = \frac{C_m}{\sqrt{C_{11}C_{22}}}$$

A value of k between 0.55 and 0.66 gives values which best fit the measured values of the voltage standing wave along the remaining part of the tuning circuit.

The power input to the model was measured with a directional coupler and found to be about 10 to 12 watts for 70.7 rms dee voltage. Since the model is a quarter-scale one, the frequencies are all four times their full-scale values. Therefore, the skin depth is one-half as great in the model. The power per square in the model is, then, twice the value it would be in the full scale. And since we were striving for 70.7-kv rms dee voltage the full-scale, full-voltage machine would require 5 to 6 megawatts excitation power. Improvement of the coupling coefficient would reduce the excitation power. Calculations indicate that the power might be reduced to 1 megawatt if it were possible to obtain nearly unity coupling between the transmission line sections.

R-F Model II, Figure 142, which lived a rather short time and received only slight attention, consisted of two 90° dees inserted in the magnet from opposite sides. To prevent any first harmonic in the r-f accelerating voltage, the two

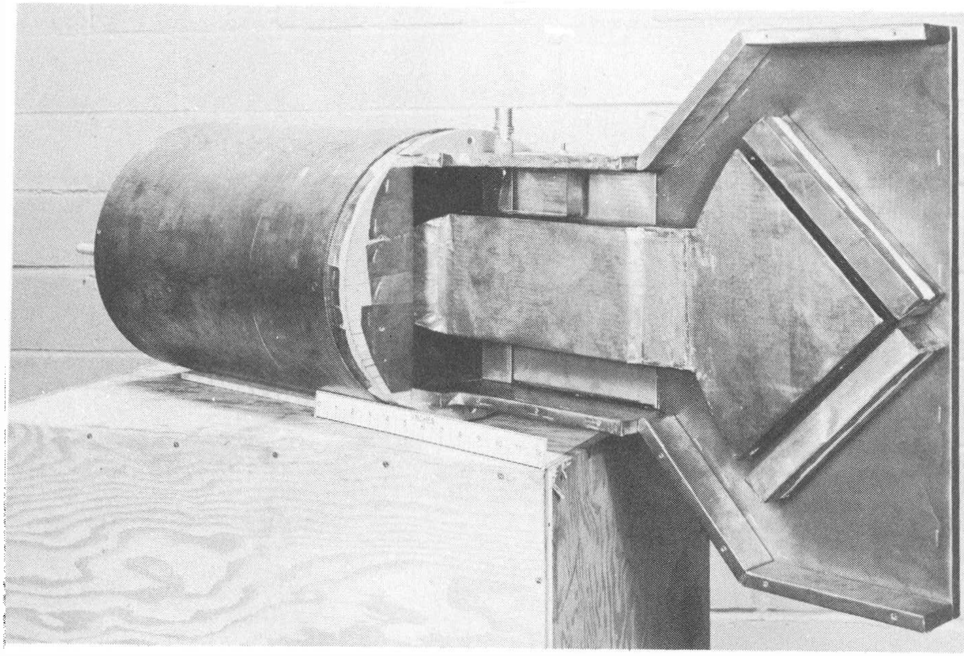

Fig. 142. R-F Model II.

electrodes would have to be driven with equal voltages either in-phase or 180^o out-of-phase, a problem that appears soluable but certainly desirable to avoid. An advantage of the 90^o system is that only a 2:1 frequency range would be required. But other disadvantages are that insertion of the eldctrodes in both sides of the magnet would use a large part of the space about the median plane, and if an electrostatic deflector is to be used along with a magnetic channel, there is no room left for them.

R-F Model III is a quarter-scale version of a single 180^o resonator tuned with a movable shorting plane, or spider. Medium fine and fine tuning may be obtained by using the variable characteristic impedance of the dee stem between the dee and the most forward position of the shorting plane, along with variable capacitor plates along the sides of the dee. The model, Figure 143, will tune the range from 92.5 to 27.4 Mc/s. Measurements of the Q and power loss are in progress.

The current density in the shorting plane will probably exceed 150 amp/in. (peak) at the highest frequency and at the maximum 100-kv dee-to-liner voltage. A special resonator is being built to test the properties of possible solutions to the problem of readily movable high-current contacts under conditions identical to those which would exist in the full-scale machine.

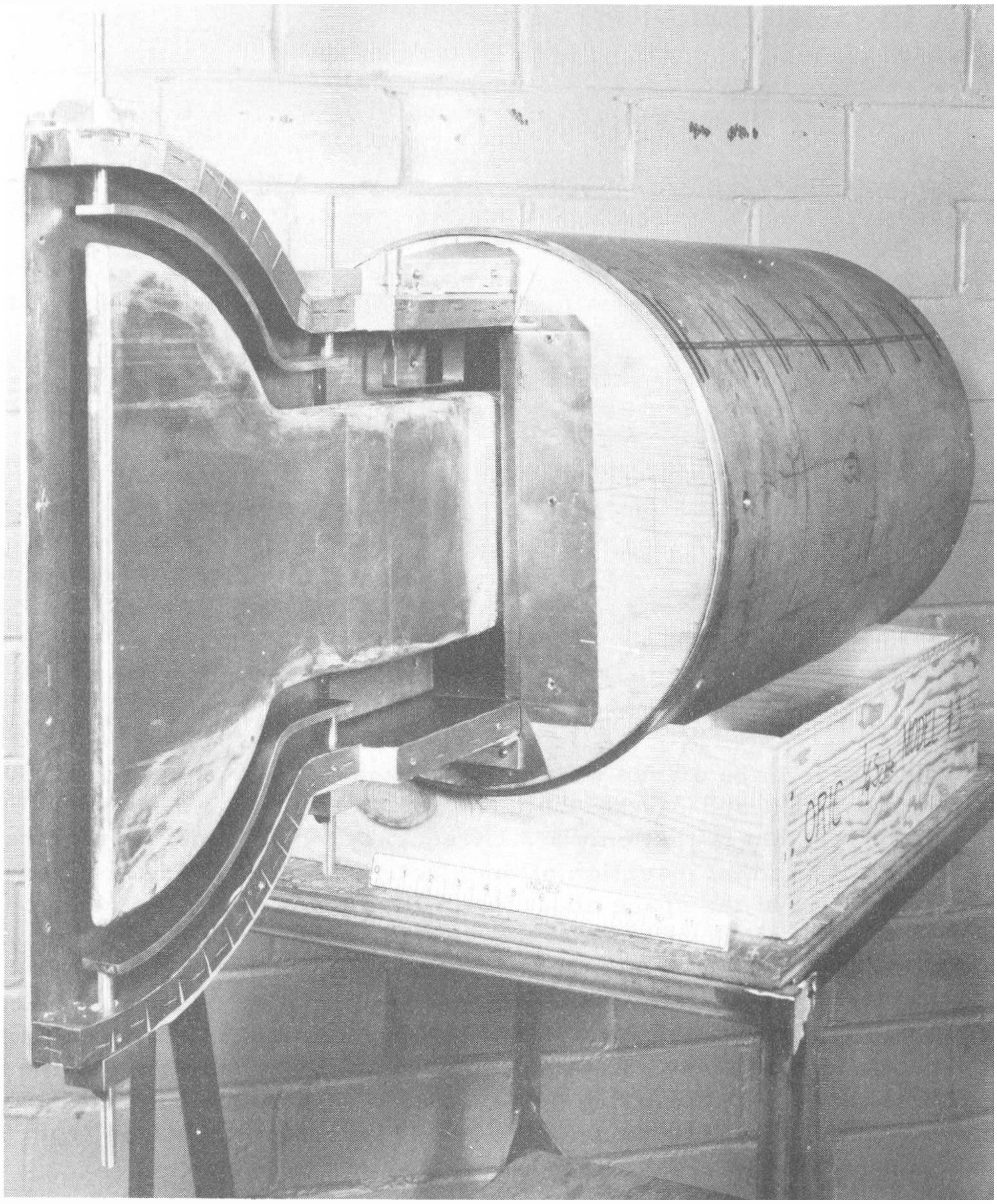

Fig. 143. R-F model III.