

# Lawrence Berkeley National Laboratory

## LBL Publications

### Title

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

### Permalink

<https://escholarship.org/uc/item/65r0v9j0>

### Author

Smith, Bob H

### Publication Date

1959-04-01

UNIVERSITY OF  
CALIFORNIA

*Ernest O. Lawrence*

*Radiation  
Laboratory*

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy  
which may be borrowed for two weeks.  
For a personal retention copy, call  
Tech. Info. Division, Ext. 5545*

BERKELEY, CALIFORNIA

## **DISCLAIMER**

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

UCRL-8711

UNIVERSITY OF CALIFORNIA  
Lawrence Radiation Laboratory  
Berkeley, California  
Contract No. W-7405-eng-48

A SURVEY OF R. F. TECHNIQUES  
APPLICABLE TO VARIABLE-ENERGY CYCLOTRONS

Bob H. Smith

April 1, 1959

**A SURVEY OF R. F. TECHNIQUES  
APPLICABLE TO VARIABLE-ENERGY CYCLOTRONS**

**Bob H. Smith**

**Lawrence Radiation Laboratory  
University of California  
Berkeley, California**

**April 1, 1959**

**ABSTRACT**

The 88-inch cyclotron is a variable-energy spiral-ridge machine intended primarily for the acceleration of deuterons to energies as high as 60 Mev. The resonator tunes continuously from 4.2 to 12.6 Mc, by means of movable panels which determine the inductance of the dee stem. The rf system of this cyclotron is described. A number of rf techniques that are applicable to variable-frequency cyclotrons and which have worked out well on existing machines are described.

**A SURVEY OF R. F. TECHNIQUES  
APPLICABLE TO VARIABLE-ENERGY CYCLOTRONS**

**Bob H. Smith**

**Lawrence Radiation Laboratory  
University of California  
Berkeley, California**

**April 1, 1959**

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 rf 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 rf problems.

I have gathered together a number of rf techniques from various cyclotrons which would appear to be useful in the solution of the rf problems of the new machines. First, however, I will describe the rf system of the 88-inch 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 rf 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 rf 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, 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 Figs. 1 and 2. The dee, as shown in Fig. 1, is rectangular. It is 98 inches wide and 70 inches long. The dee stem is ridged in order to increase the periphery and reduce the current density. This saves 70 kw of rf power at the high-frequency end of the range. The dee stem is 51 inches wide and 8 inches thick.

Figure 2 is a side view of the resonator. The movable panels which determine the dee-stem inductance are shown in the high-frequency position by the solid line and in the low-frequency position by the broken line. The dee-to-liner spacing is  $1\frac{1}{2}$  inches.

Note the ridges on the dee stem shown in Fig. 3.

Figure 4 is a picture of the quarter-scale rf model. In order 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. Radiofrequency 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-inch 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 5 shows the resonator voltage distribution, and Fig. 6 the current distribution. The rf skin power is 145 kw for a dee voltage of 70 kv. The 5-kv voltage drop which occurs near 70 inches at 12.6 Mc 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 Fig. 4, 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-inch 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.

If a transmission line has to be used, it probably will require some type of tuning device in order 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.

Figure 7 is the result of a study of rf hinges by one of our mechanical engineers, Ken Merck. For an rf heating power of 9.3 watts per sq. in. (this corresponds to 100 amp per linear inch at 12.6 Mc), it shows the relationship of temperature rise and bending stress to hinge length and thickness. A suitable hinge might be one which is 2 inches long and 3 mils thick. It would operate with a maximum bending stress of 20,000 psi and at a temperature rise of  $160^{\circ}$ . The ends of such a hinge would be attached to a water cooled block which would operate at a temperature of about  $20^{\circ}$ . Thus, the temperature of the center of the hinge would be about  $180^{\circ}$ . 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-inch cyclotron, are in use in the 184-inch cyclotron. These are shown in Figs. 8 and 9. The panels are of a light-weight, riveted type of construction, similar to that used on airplanes.

One of the more important rf 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 resonance. An effective technique consists of 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-inch 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 10 is a cross-sectional view of the 184-inch cyclotron and Fig. 11 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 Fig. 10, in the same manner as they can for the desired mode associated 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 Fig. 12.

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 13 is a picture of the dee-stem tank and dee of the 90-inch 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 a copper-plated-wooden 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 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-inch cyclotron tunes from 4 to 9.5 Mc 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 inches at the high end and 3/4 inch 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 rf power.

Radiofrequency people tend to avoid shorting fingers because of failures occurring in the early machines. Experience with these fingers on the 90-inch cyclotron indicates that such fears are not justified. During the period of operation of this cyclotron--four years -- the shorting fingers have failed only once, and then only because they were not properly seated. A cross-sectional drawing of these fingers is shown in Fig. 14. The maximum current density is 70 amp per inch at 9.3 Mc.

I have discussed the operation of the shorting fingers with the cyclotron crew in order to find what improvements 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-inch cyclotron uses a driven type of rf 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 rf circuitry of a driven rf 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 rf 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 rf techniques in the 680-Mev synchrocyclotron in Moscow which may be applicable to variable-energy spiral-ridge machines. Figure 15 is a cross-sectional view of this cyclotron. Note that the oscillator is capacitively coupled to the resonator. One plate of the coupling capacitor is mounting on the rotor of the rotating 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 16 shows the results.

Another feature of this machine which is interesting is the oscillator circuit shown in Fig. 17. This is a two-terminal oscillator--the grid signal is obtained from the 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 interelectrode 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.

Legends

- Fig. 1. The 88-inch cyclotron resonator, top view. The dee is of rectangular shape, (98 by 70 inches). The dee stem is 110 inches long, 51 inches wide, and 8 inches thick.
- Fig. 2. The 88-inch cyclotron resonator, side view. The frequency is determined by the position of the movable panels which determine the dee-stem inductance. They are shown in the high-frequency position (12.6 Mc) by the solid lines and the low-frequency position (4.2 Mc) by the broken lines.
- Fig. 3. The dee and stem of the quarter-scale rf model. The ridges on the dee stem reduce the current density at the high-frequency end of the range.
- Fig. 4. The quarter-scale rf model is of light-weight, wood-and-copper construction and lends itself well to experimental modification.
- Fig. 5. Resonator voltage distribution.
- Fig. 6. Resonator current distribution.
- Fig. 7. Mechanical bending stress and temperature rise in rf hinges. For adequate life, the thickness and length of rf hinges must be rather carefully selected. A suitable hinge might be one which is 2 inches long and 3 mils thick. It would operate with a bending stress of 20,000 psi and a temperature rise of  $160^{\circ}$ .
- Fig. 8. The movable panels of the 184-inch cyclotron are of light-weight, riveted construction.
- Fig. 9. The upper panel is shown in the low-frequency position; the lower panel is in the high-frequency position.
- Fig. 10. The 184-inch cyclotron resonator, cross-sectional view. The reduced dee-to-liner spacing near the voltage node extends the tuning range of this resonator.
- Fig. 11. The 184-inch cyclotron resonator with the liner removed. The equivalent circuits in the longitudinal and lateral directions are shown. The voltage distribution in the longitudinal direction is that of the main mode. The voltage distributions in the lateral directions are those of the undesired cross-modes. Their resonant frequencies were displaced from that of the main mode by suitable selection of the separation between the reeds.

Fig. 12. The cross modes of the 184-inch cyclotron tune with the main mode in such a way that they remain separated, and hence, are not excited by the main mode.

Fig. 13. The notched shape of the dee of the 90-inch cyclotron was selected to reduce the voltage taper along the dee edge. The voltage taper is about 2%.

Fig. 14. Cross-section of the shorting fingers of the 90-inch cyclotron. The above cross-section was milled from a block 32 inches long, and the individual finger width of 1/8 inch produced by suitable saw cuts. The material is copper-plated steel. They operate at a maximum density of 70 amp per inch (50 amp r. m. s. ).

Fig. 15. The resonator of the 680-Mev synchrocyclotron near Moscow. The oscillator is capacitively coupled to the resonator. One plate of the coupling capacitor is mounted on the rotor of the rotating capacitor. Because of the contour of the plates of the coupling capacitor, the coupling ratio varies with rotor position in such a way that the dee voltage is substantially independent of frequency.

Fig. 16. The success of the novel coupling technique is illustrated by the dee voltage-vs-frequency curve shown above.

Fig. 17. The circuit of the two-terminal oscillator of the 680-Mev machine (USSR). Because of judicious selection of the poles and zeroes of the transfer function of the feedback circuit, the phase of the feedback voltage is correct for oscillation throughout the pass band in which the machine operates, but degenerative outside of this band.

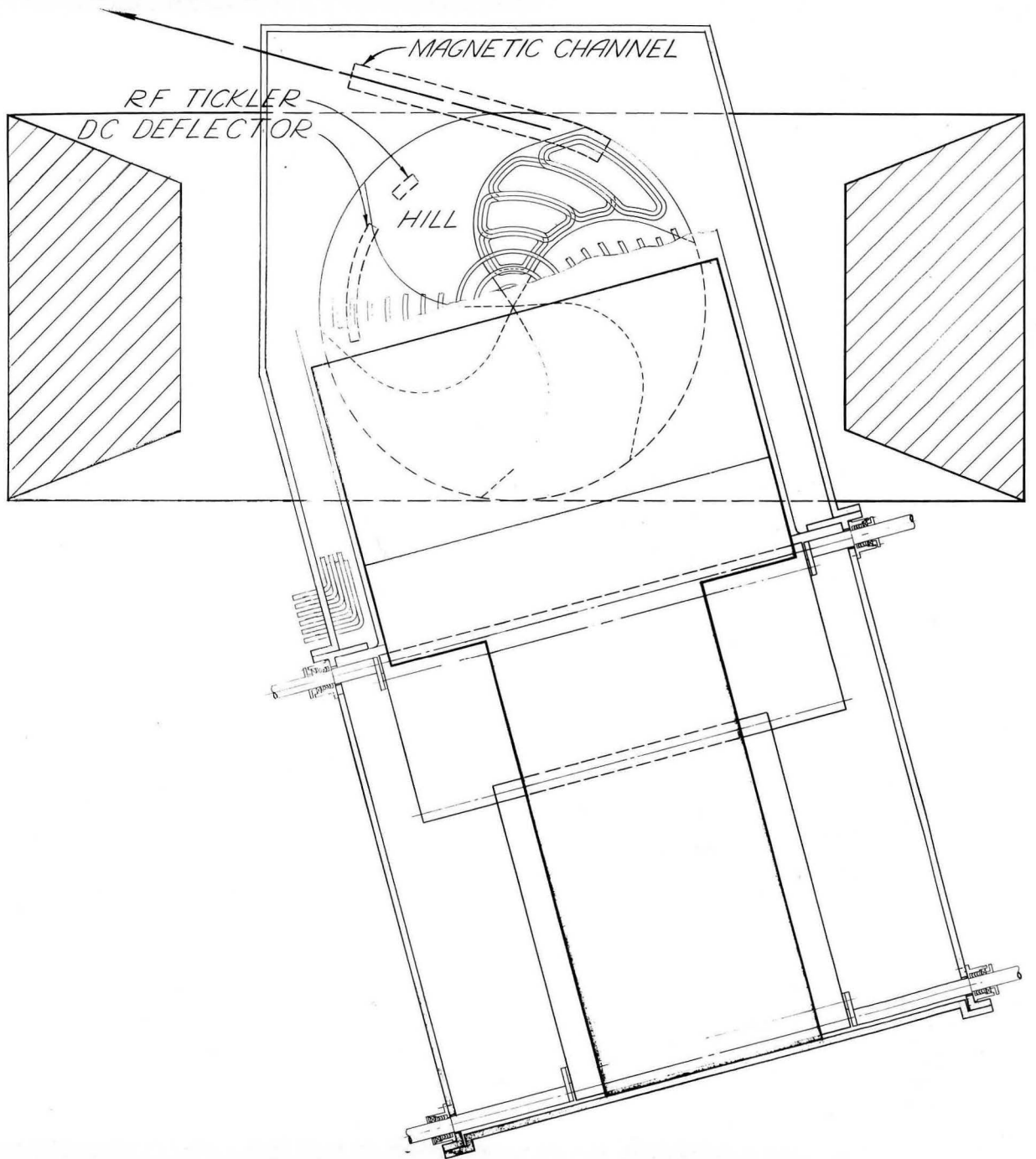


Fig. 1

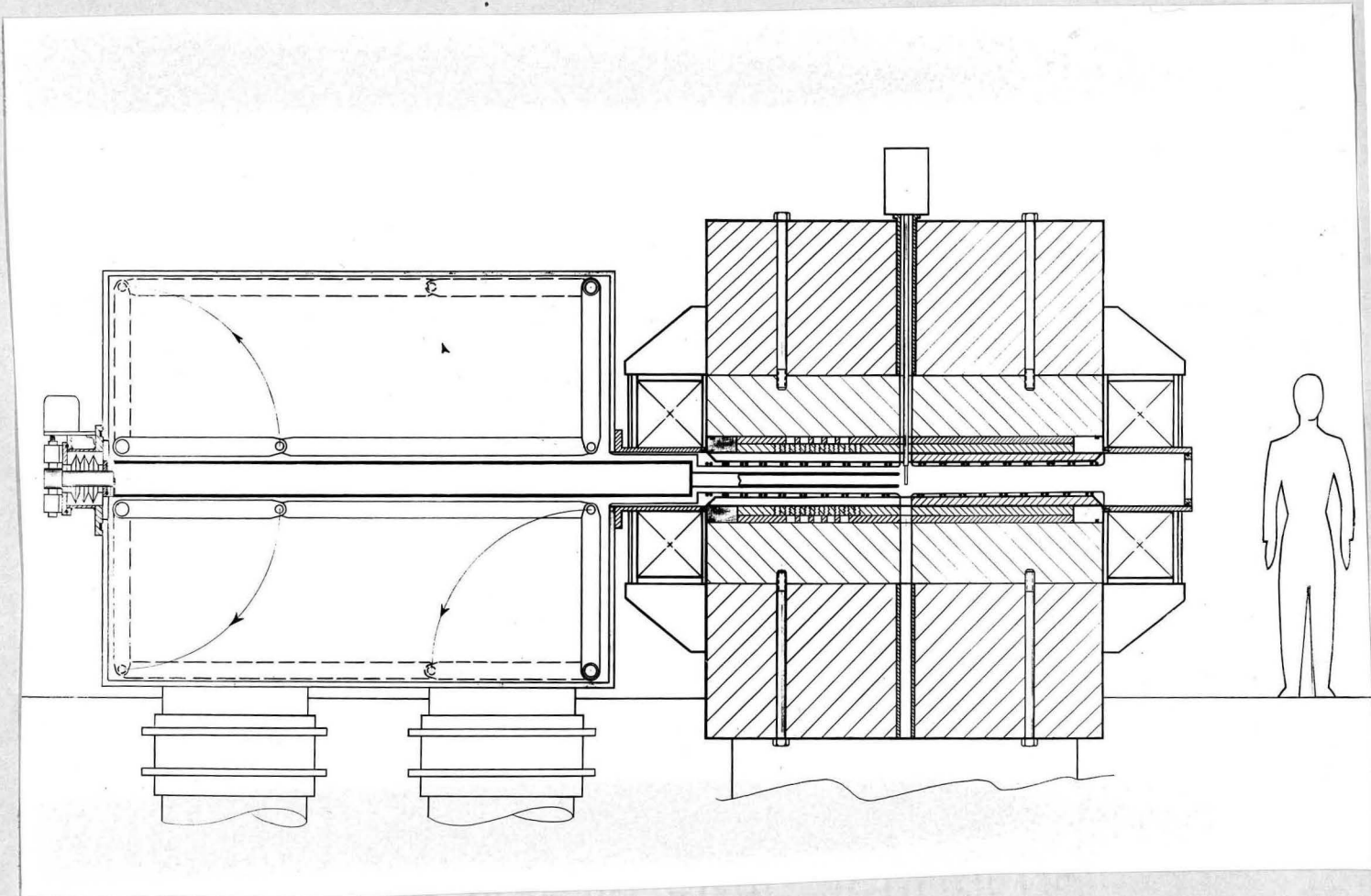


Fig. 2



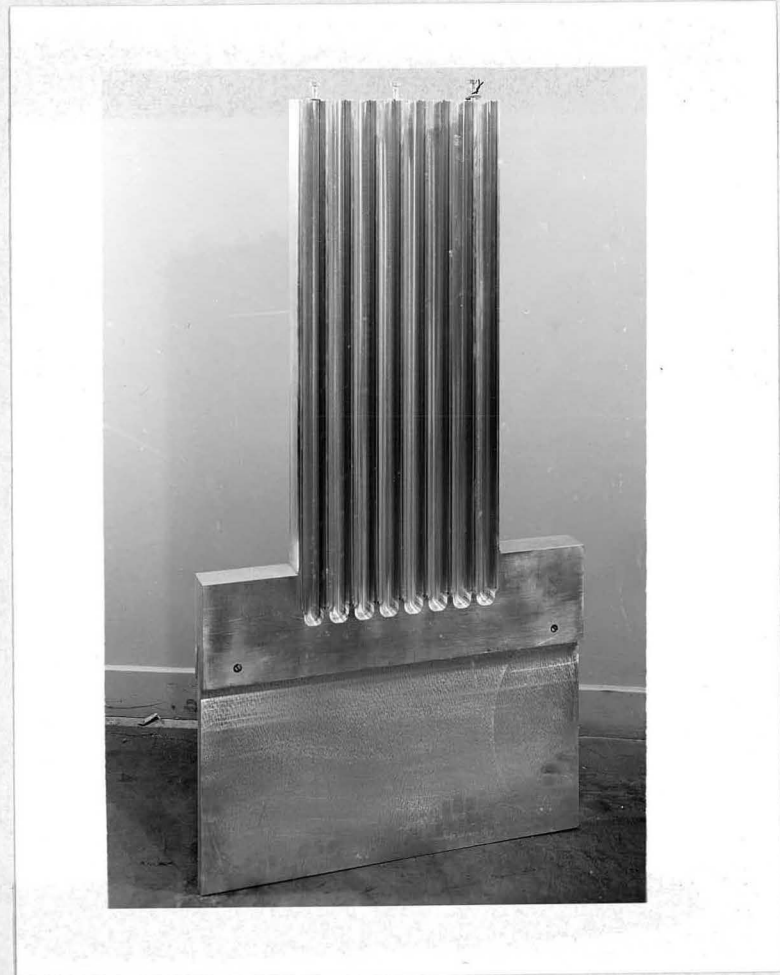


Fig. 3



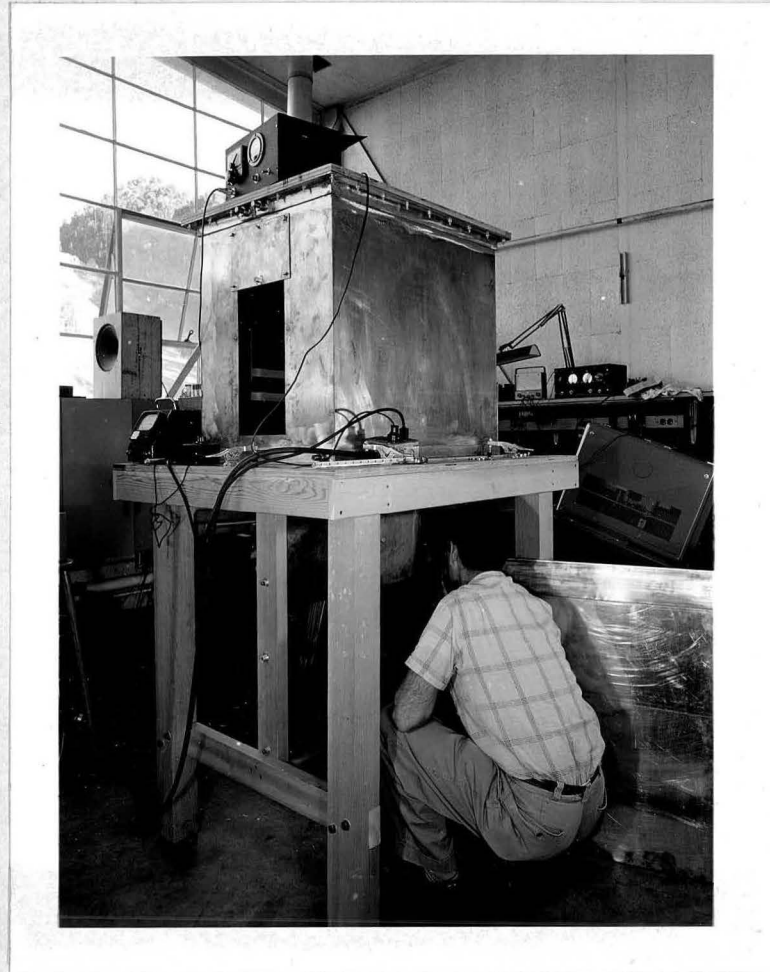


Fig. 4.

88" CYCLOTRON  
RESONATOR VOLTAGE vs. DISTANCE

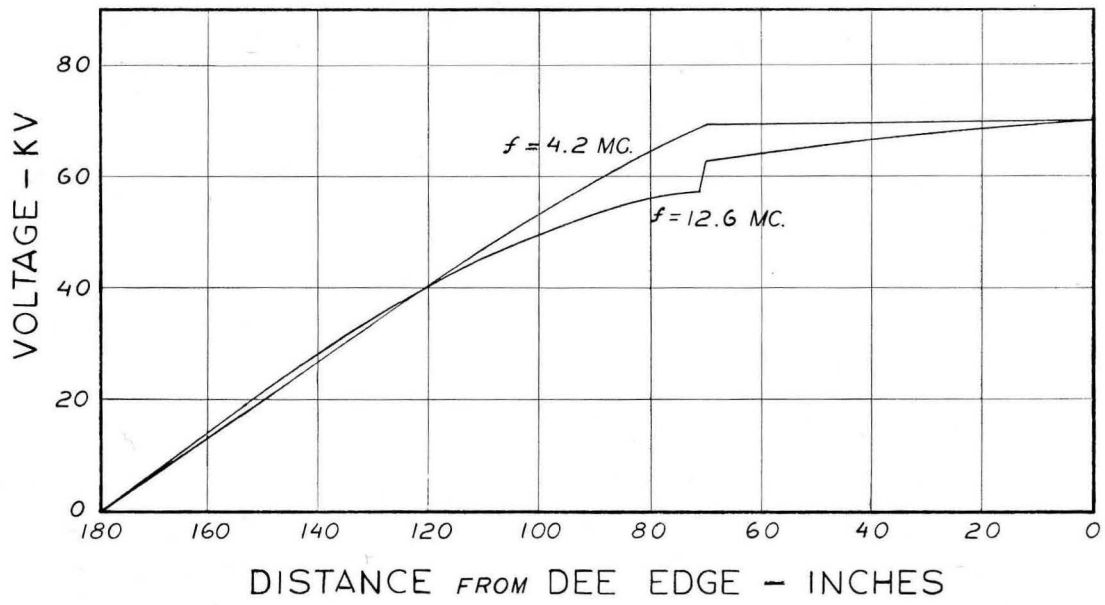


Fig. 5

### 88" CYCLOTRON RESONATOR CURRENT vs. DISTANCE

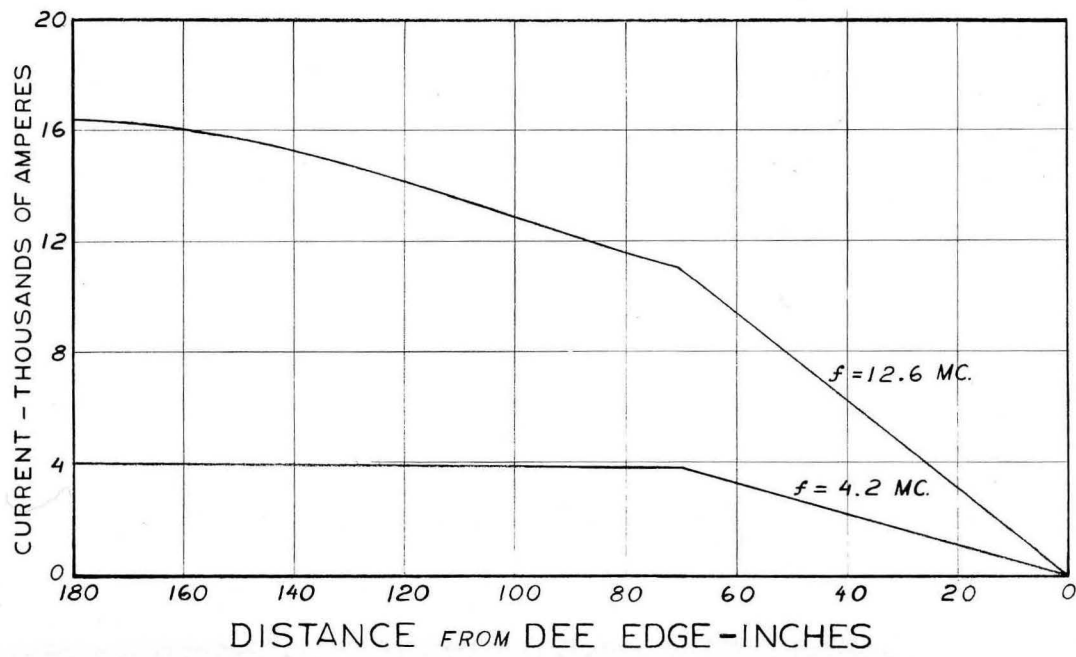


Fig. 6



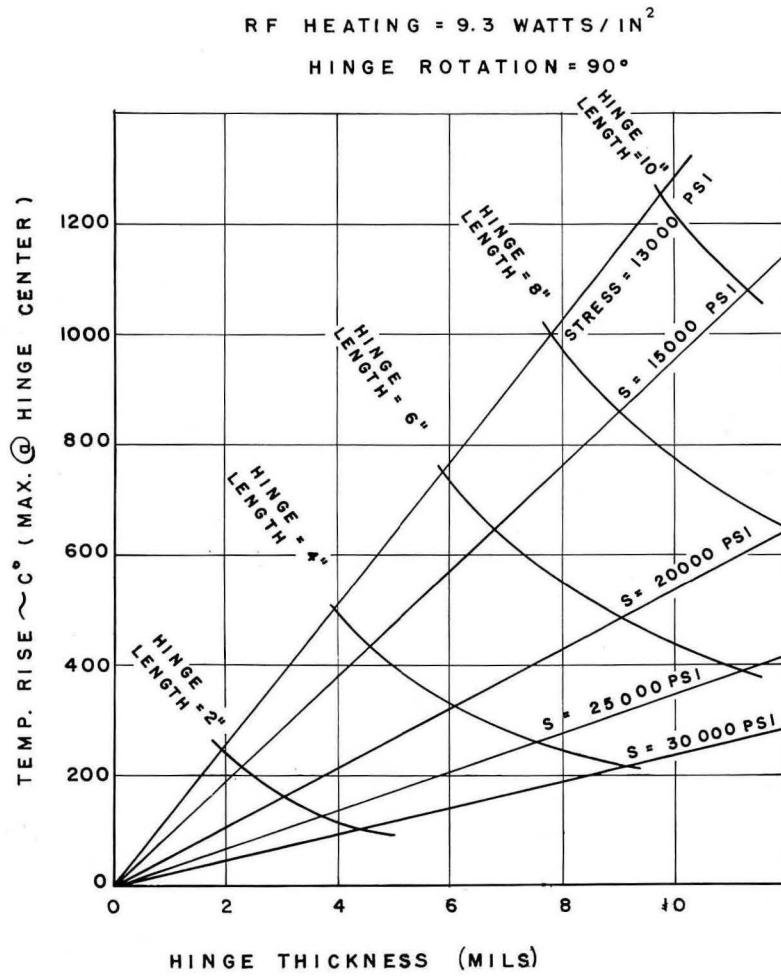


Fig. 7

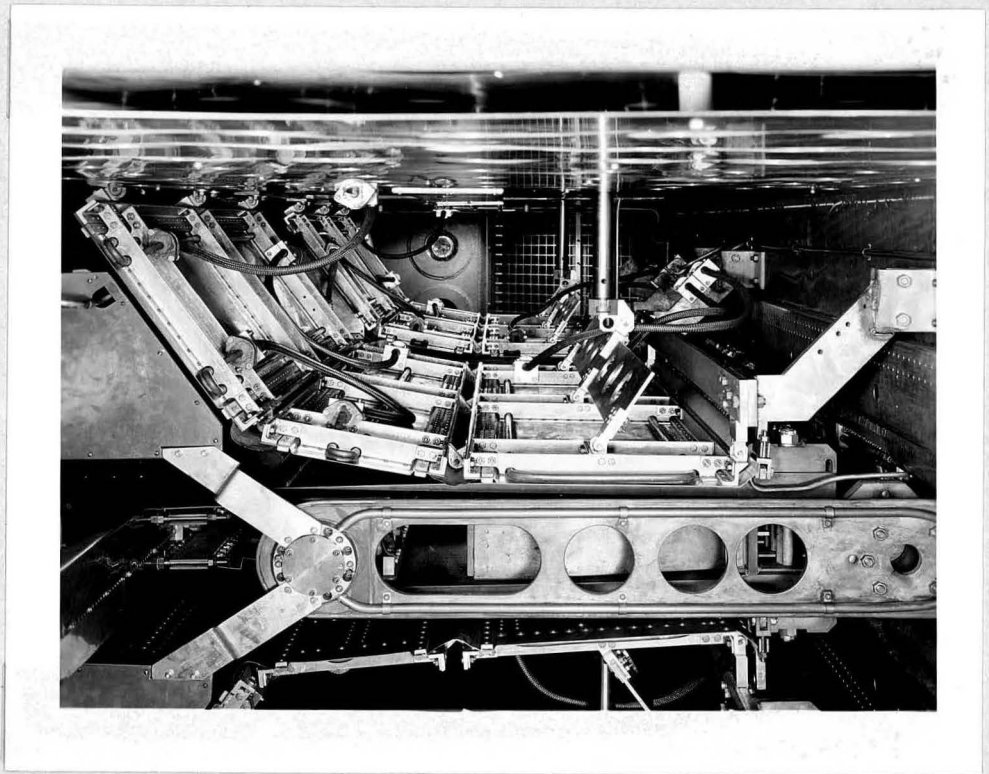


Fig. 8

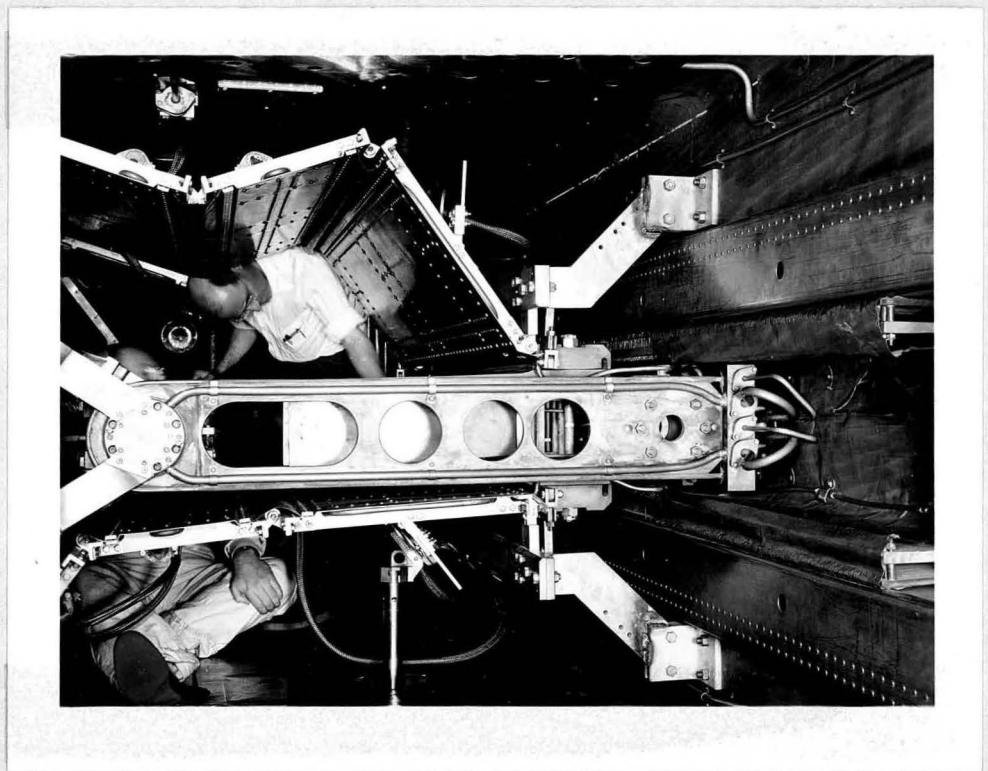


Fig. 9



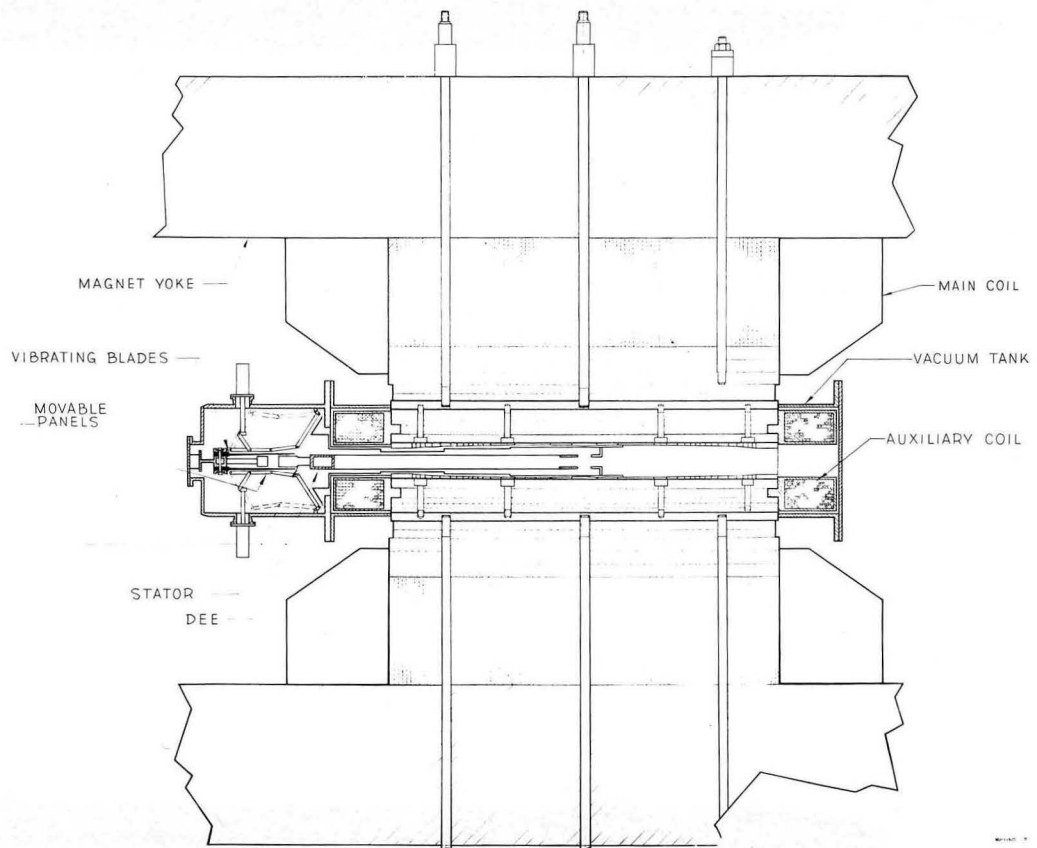


Fig. 10

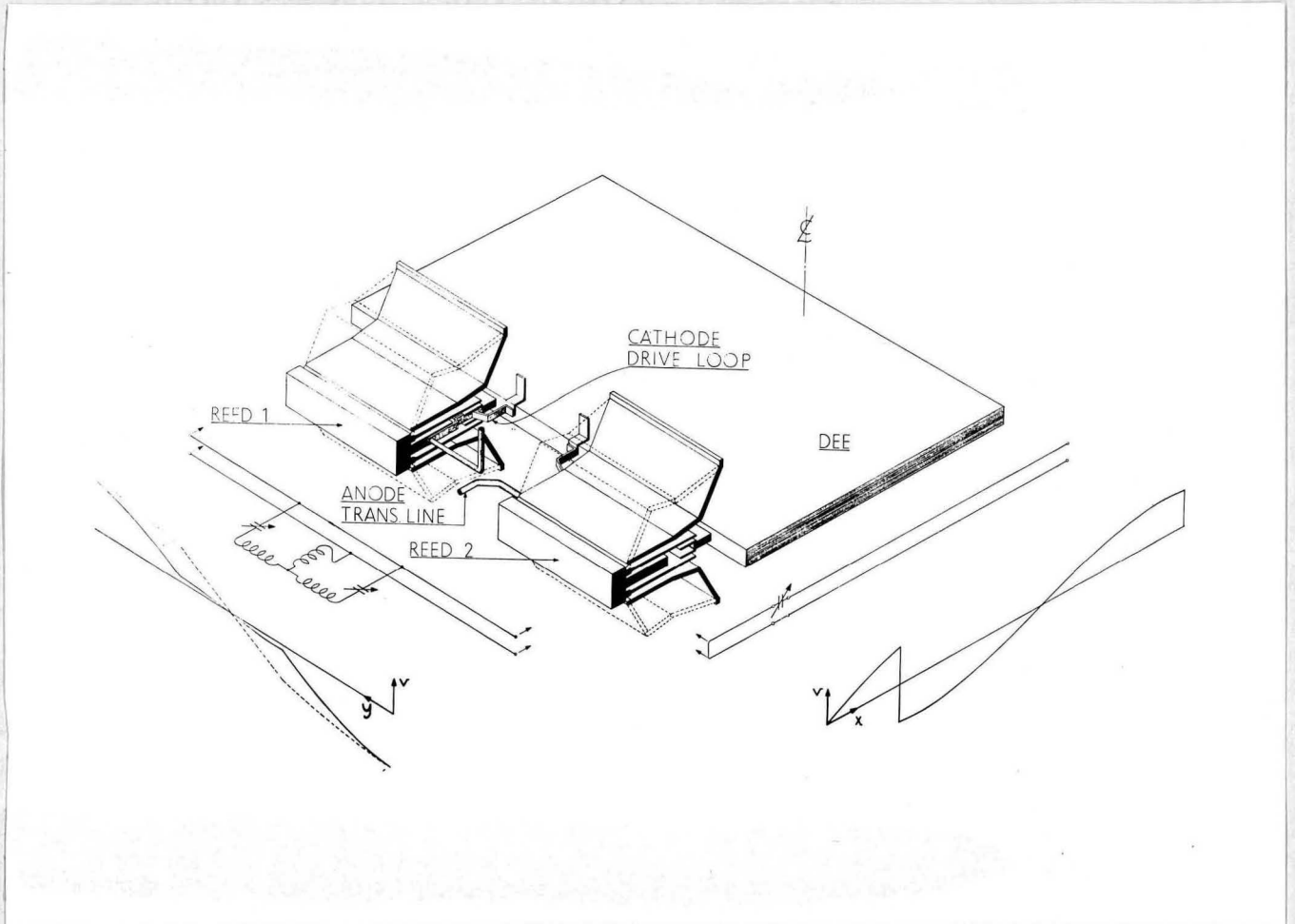


Fig. 11



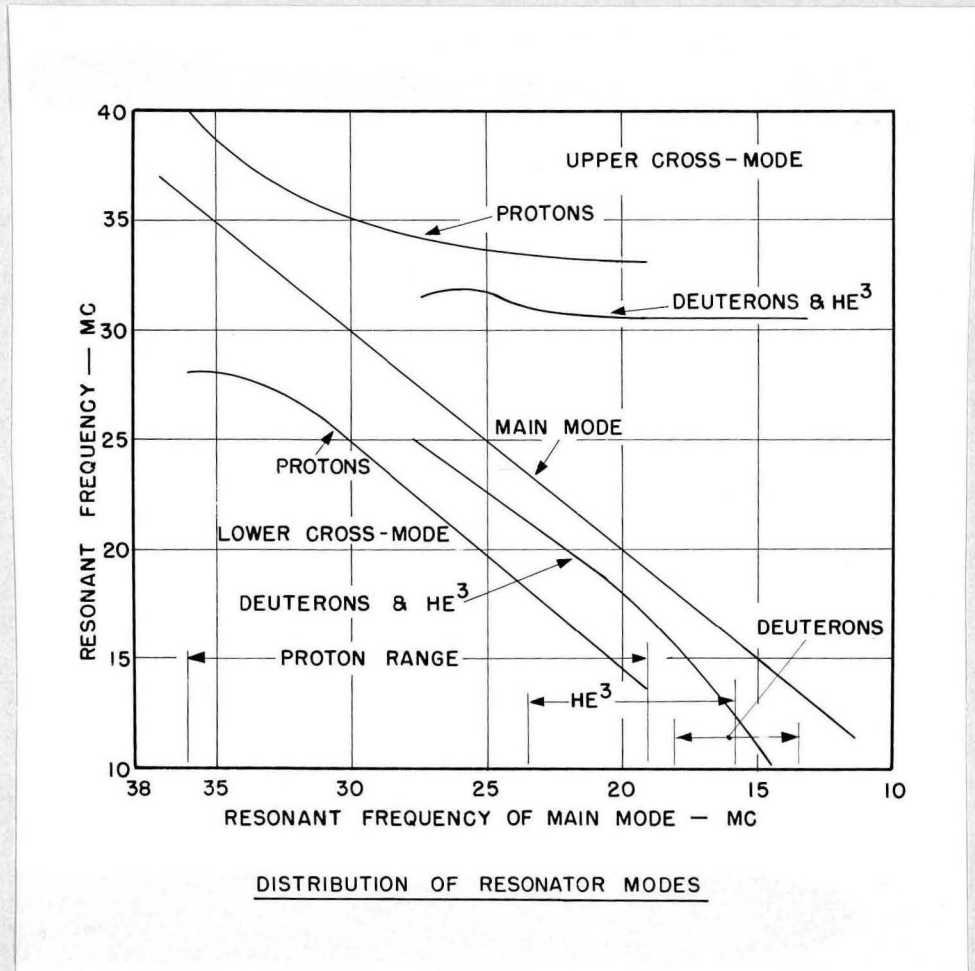


Fig. 12



Fig. 13

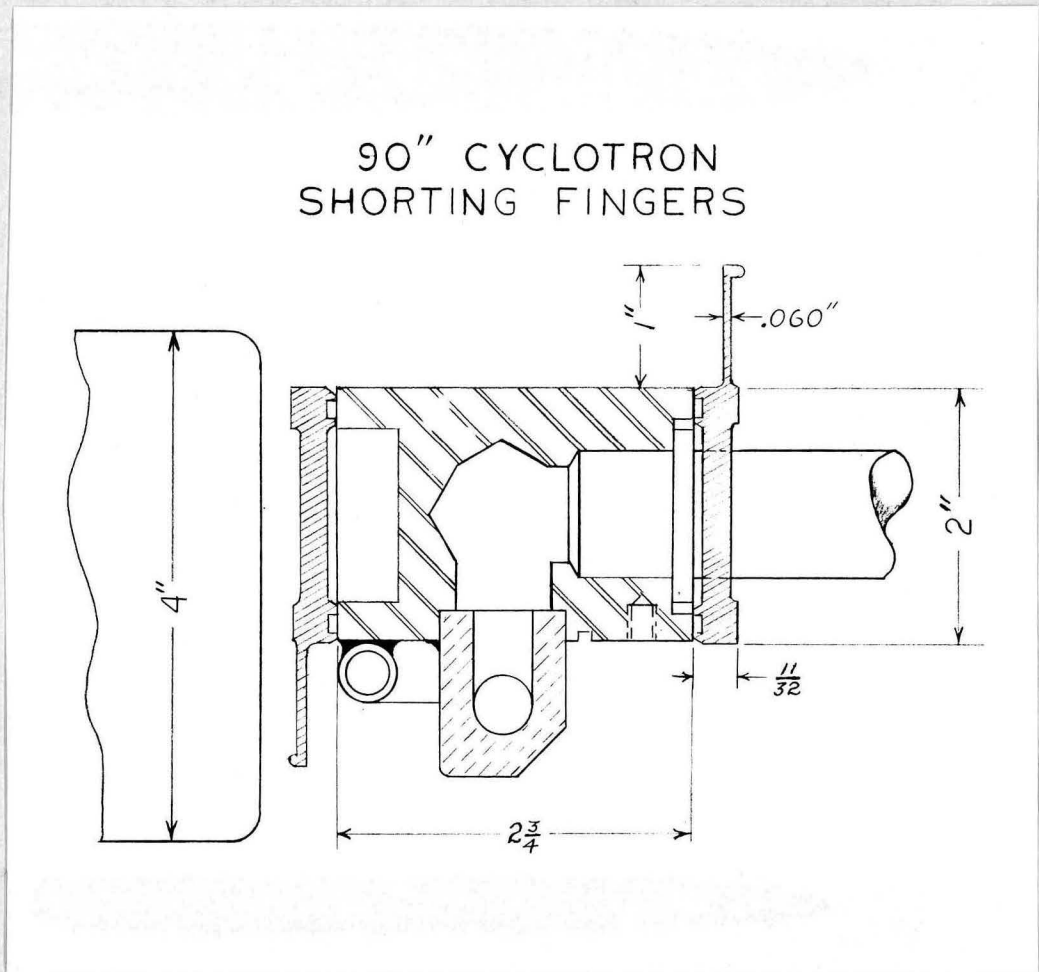


Fig. 14



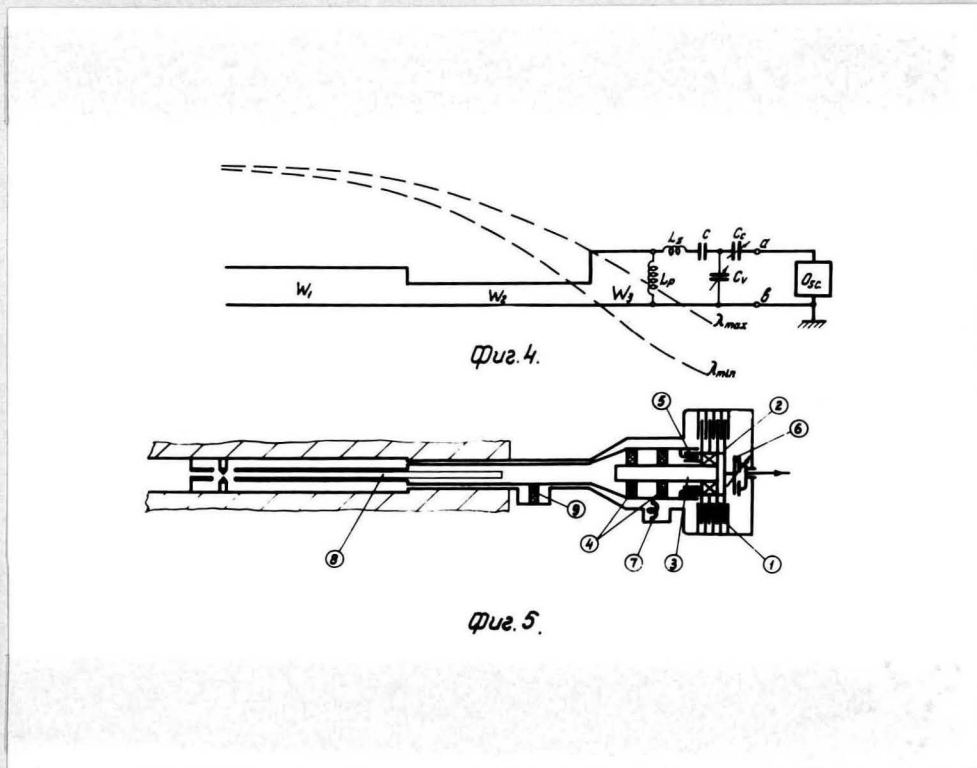
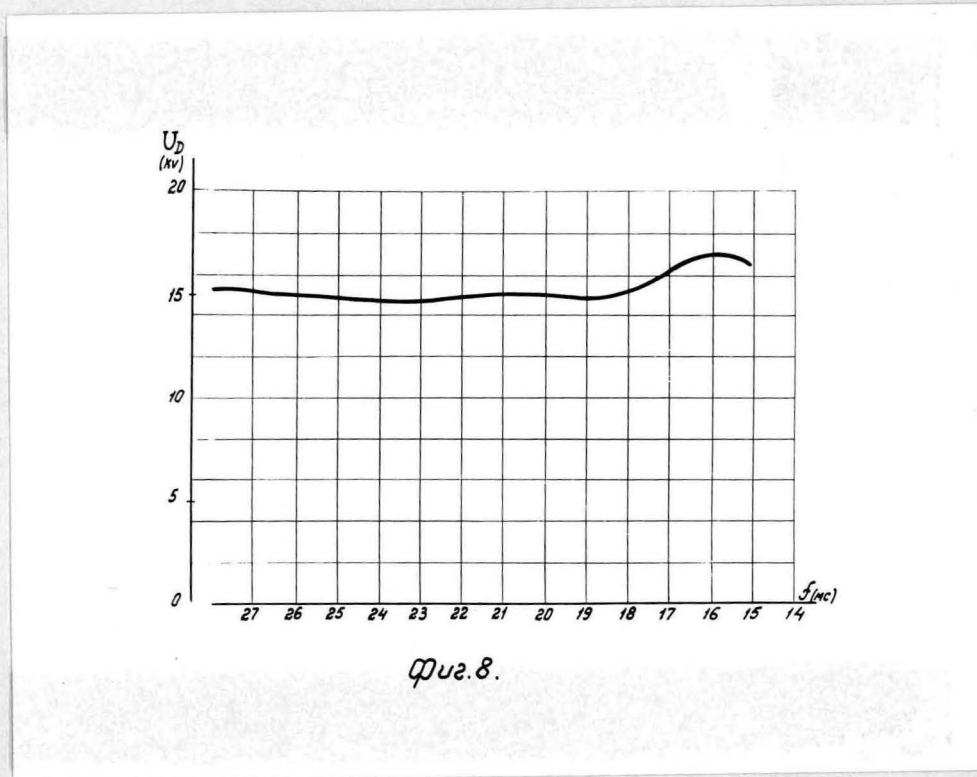
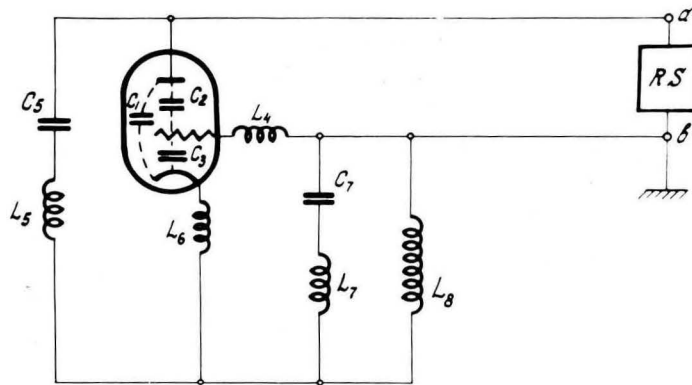


Fig. 15



Фиг. 8.

Fig. 16



Фиг. 3.

Fig. 17