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ABSTRACT

The oscillator of the 88-in. cyclotron which is being built in Berkeley is tunable from 5.3 to 16.5 Mc. It delivers a maximum c-w power of 300 kw. At the rated dee voltage of 75 kv the resonator stores 4.5 joules of electrical energy. The transients produced by this amount of energy, during sparking, place unusual requirements upon the design of the oscillator tube. The features of the RCA 6949 which make it particularly well-suited to this type of application are discussed in this paper. Other topics covered are the oscillator anode power supply, the hard-tube modulator, protective equipment, and oscillator instrumentation.

THE RCA 6949 AS A SELF-EXCITED CYCLOTRON OSCILLATOR*

Bob H. Smith

INTRODUCTION

At present there are five spiral-ridge cyclotrons under construction in the United States. Another half dozen or more have been proposed and will be built if funds are available. These machines represent the second generation of accelerators. The first generation were machines of fixed energy, each being built at successively higher energy in order to explore the properties of nuclear structure.

The first beams of charged particles came from natural radioactive sources, but as accelerators were developed their beams proved to be more convenient to use. About 1930, through work with energies of less than 1 Mev, it was found that nuclei of atoms could be split by artificially produced beams.[1,2] By 1939, accelerators had achieved beam energies of 20 Mev.

The experiments that were performed then had to do with the splitting of the nuclei of various atoms. Among the more interesting things found were the existence of neutrons within the nucleus, and in 1939, the fission of the uranium atom.

At the end of this period, the energy available from cyclotrons was limited by the relativistic mass increase of the accelerated particles. At large orbit radii, a lower rf frequency was required to maintain cyclotron resonance. Thus, the particle would be accelerated up to energies where it fell out of step with the rf, acceleration would cease, and deacceleration would occur. This problem was solved after World War II by frequency-modulating the dee voltage, thus giving birth to the synchrocyclotron.[3,4] This machine allowed the energy to be increased over an order of magnitude. At these energies, physicists found that the individual particles which made up the nucleus could be split, and that they broke down into a variety of particles including mesons.

Following the synchrocyclotron was the development of the synchrotron. This machine permitted extending the energy into the billions of electron volts. (Bev)

In 1955, at energies in excess of 5 Bev, anti-protons were literally created from energy.[5] This is another example of the birth of matter.

Recently two synchrotrons, one at Brookhaven and the other at Geneva, Switzerland, have been put in operation at an energy of 30 Bev. And in the Soviet Union a synchrotron of 70 Bev is under construction. What new secrets these machines will uncover awaits the immediate future.

In 1954, a second generation of cyclotrons started. At Livermore, Rochester, and Los Alamos, variable energy cyclotrons were built, so that physicists and chemists could study nuclear reactions in much more detail. These first machines covered the range from 1 to 15 Mev. The cyclotrons that are under construction at present are variable-energy machines for the range between 15 and 75 Mev. This is the range of energies where the relativistic increase in mass of protons is significant.

In 1938, L.H. Thomas proposed that the problems associated with the change in mass of protons could be solved by varying the magnetic field azimuthally in such a way that

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*This work was done under the auspices of the U.S. Atomic Energy Commission.

the cyclotron frequency would remain constant for all particle orbits.[6] At the same time, centering and focusing of the beam could be achieved. The Thomas theory was verified experimentally in 1951.[7] In these machines, the magnet poles contain wedge-shaped metal slabs which are called hills and valleys. Kerst showed that focusing could be improved and the iron and copper of the magnet used more efficiently if the hills were spiraled out radially.[8,9] These machines are called spiral-ridge cyclotrons.

In generating rf power for cyclotrons, there are two problems that do not exist in the communications industry or in other industrial uses of large amounts of rf power. The first is the problem of electron multipactoring between the high-voltage surfaces within the cyclotron; and the second and more serious problem concerns the transients produced by dee sparking.

Multipactoring is a resonant discharge that occurs when the rf voltage builds up to the value for which the transit time of an electron across a gap is half an rf period. The energy picked up by the electron must be sufficient to make the secondary-emission ratio exceed unity--about 150 electron volts. With each rf cycle there is an increase in the number of electrons traversing the gap, until the electron loading exceeds the power available from the oscillator. One method of avoiding this condition consists of providing a dc electric field to sweep the region free of electrons. This is the method being used in the Berkeley 88-in. cyclotron, of which a model is shown in Fig. 1.

The problem of dee sparking occurs because the space determining the electric gradient between dee and liner is also between the magnet poles. This is very expensive space indeed! When a cyclotron is first put into operation, the dee is permitted to spark hundreds of thousands of times, and the energy from the sparks vaporizes the spark-initiating foreign material from the high-voltage surfaces. After sufficient bake-in time the dee holds many times as much voltage without sparking as it did before the process started.

The resonator of the 88-in. cyclotron stores about 4.5 joules of electric energy. When a spark occurs, the dee voltage drops to almost zero. Part of the energy is dissipated in the spark, and part of it propagates throughout the rf system as a transient, causing sparks at many other points throughout the system. Occasionally the transient induces a spark within the oscillator tube, and once initiated, the anode power supply builds the discharge up into a pwer arc. If allowed to persist, this arc will destroy the oscillator tube. High-speed circuits must be used to remove the anode voltage quickly before serious damage occurs. This can be done with an ignitron crow bar, which short-circuits the anode supply, or by opening the circuit of the anode supply with a hard-tube modulator. The latter is the method being used in the 88-in. cyclotron.

The operating frequency range of the cyclotron oscillator is determined by the mass-to-charge ratio of the accelerated particles and the range of magnetic field that can be achieved, to meet the requirements of the orbit dynamics of the particle. The latter is determined by the properties of the steel in the magnet pole tip.

The 88-in. cyclotron operates within the frequency range from 5.3 to 16.5 Mc and requires 300 kw of oscillator power. One can appreciate the problem of rf shielding and the dangers of interference with essential communications facilities. With previous machines we have been able to reduce the stray radiation to less than 10 μv per meter at a distance of 1 mile.

In a self-excited cyclotron oscillator, the resonator is the frequency-determining element. An oscillator consists of the dc components necessary to make the vacuum tube operate efficiently: the coupling system--to couple the vacuum tube to the resonator-and the resonator itself.

THE RESONATOR OF THE 88-IN. CYCLOTRON

A quarter-wave resonator operating in the T.E.M. mode was selected for the 88-in. cyclotron. Tuning is accomplished by varying the characteristic impedance of the inductive portion of the resonator--that is, the region surrounding the dee stem. The resonator is shown in Fig. 2. The movable panels provide a change in volume of about 80 to 1. The dee stem has a series of longitudinal corrugations which increases the perimeter and reduces the rf current density. This saves about 70 kw of rf power.

The voltage and current distribution of the resonator are shown in Fig. 3. From the rf current distribution and the geometry of the resonator, the rf skin losses were computed to be 121 kw for a dee voltage of 70 kv.

In addition to the skin losses, rf power is consumed in a number of ways. The stray-ion loss in the center of the machine is about 30 kw. At the maximum particle energy, 60 Mev, a 1-ma beam will produce 60 kw of beam power. The miscellaneous losses such as those associated with the transmission line and the components in the oscillator anode circuit are about 10 kw. The total of all these losses is 221 kw. Experience with cyclotrons indicates that one needs to provide an operating margin, so 300 kw of rf power is being provided.

Figure 4 shows the equivalent circuit, so far as rf is concerned, of the 6949, the anode-coupling system, the resonator, and the grid-coupling system. The rf circuit is complex, involving many poles and zeros. These are called higher modes in the accelerator art and have to be studied very carefully. There are two main problems. The first is parasitic oscillation, which may occur if a higher mode in the anode circuit is sufficiently close in the frequency domain to one in the grid circuit. Although the large physical size and wide tuning range of cyclotron resonators intensify this problem, it is not basically different from parasitics in other industrial rf applications.

The second problem concerns the excitation of higher modes by harmonics. Since the oscillator tube operates in class C, the plate current contains essentially all harmonics. So long as the impedance in the anode circuit is negligible at the frequency of a harmonic, the harmonic voltage, and therefore the harmonic power, developed is negligible. The difficulty is that the frequencies of the higher modes vary as the cyclotron is tuned. The way these frequencies vary must be studied carefully and the critical components suitably adjusted so that there is no place within the operating-frequency range of the cyclotron that a mode lines up with a harmonic (Fig. 5). This condition cannot be achieved for an infinite number of modes and an infinite number of harmonics. Fortunately, the magnitude of the harmonic current decreases roughly as $1/n$, where n is the order of the harmonic, so that only the lower-ordered harmonics involve enough power to cause damage.

The modes were studied on a quarter-scale rf model of the 88-in.-cyclotron resonator (Figs. 6 and 7). The way in which the value of each of the components shown in Fig. 3 varies in frequency was measured; the frequencies of the modes were computed and compared with those observed in the model. It was possible to avoid mode excitation by the second and third harmonics within the operating range of the machine.

There are two reasons why excitations of higher modes by harmonics have to be avoided. First, standing-wave patterns associated with the harmonic may provide destructively high voltages at delicate components such as the vacuum insulator. Second, high harmonic voltage may occur at the anode of the oscillator tube and make the oscillator inefficient, thus reducing the power available to excite the resonator at the fundamental frequency.

Visualized as transmission lines, the anode and grid circuits are designed to operate with very high standing-wave ratios. Such lines have the property that the phase of the voltage between the input and any other point on the line is either zero or pi. By using this property, the rf system was designed to provide a grid voltage 180 deg out of phase with the anode voltage throughout the operating range. The price one pays for this property of transmission lines is a negligible reduction in efficiency. The short length of the lines and the low current densities makes the losses less than 1% of the transmitted power.

The grid transmission line operates in a foreshortened half-wave mode to provide the phase reversal necessary for oscillation. Fringing panels attached to the main tuning panels of the resonator vary the coupling of the resonator to the grid line in such a way that the grid voltage remains essentially constant through the operating range of frequencies. This was worked out experimentally on the 1/4-scale rf model. The voltage and current distribution of the grid line is shown in Fig. 8

THE OSCILLATOR ELECTRONICS OF THE 88-IN. CYCLOTRON

The oscillator circuit is shown in Fig. 9. The operating characteristics of the 6949 as determined from the constant current characteristics are shown in Table I.

One of the problems with oscillator tubes results from the high amount of energy available from the resonator during sparking. With conventional tubes having squirrel-cage grids of very light wire, the spark will often blast through the grid structure. The mechanical damage often causes a grid-to-cathode short.

For accelerator applications, a tube should have a sufficiently heavy grid to absorb several joules of energy in an area determined by the cross section of the spark. The 6949 as shown in the cross-sectional drawing of Fig. 10,has such a grid. Also, the grid is shielded from anode sparks by the shield tees, which are massive copper structures almost immune to spark damage.

Another feature that is desirable in an oscillator tube is high power sensitivity. This reduces the size of the grid line and simplifies the problem of coupling the grid to the resonator. Also it makes it feasible to use a large safety factor in the design of the grid vacuum insulator.

THE OSCILLATOR POWER SUPPLY

The oscillator requires an anode supply voltage adjustable from 0 to 20 kv at currents up to 25 amp. Voltage control is achieved by a tap-changing transformer in the three-phase ac lines ahead of the rectifier transformer. The rectifier is a three-phase, full-wave, silicon-diode stack. Vacuum switches connected in the three-phase, 16.6 kv ac lines feeding the rectifier are used as a relatively high-speed disconnect for overcurrent protection. In the event of a fault, they open within 10 msec plus the time to the first current zero. The vacuum switches were included so that an ignitron crowbar could be employed if necessary.

Following the rectifier is a Federal type D-50 triode operating as a hard-tube modulator. It has two functions. First, it is a device used to regulate the rf dee voltage, removing such perturbations as rectifier ripple, noise from the ion source, and changes in beam loading. Its second function is as a high-speed disconnect to protect the 6949 from power arcs. In this service it will open the anode circuit within 10 μsec of a fault.

The dc anode-supply cable is terminated in its characteristic impedance at the power supply so that resonances will not occur and produce high rf voltages or currents within the components of the power supply.

PROTECTIVE EQUIPMENT

The fault detector contains a number of inputs, each sensing a particular type of fault. First there is the rf-dc interlock. Periodically, in normal operation, the dee will spark. When this occurs the rf maintains an arc which reduces the dee voltage to about zero. The oscillator must be turned off until the vacuum system has had time to remove the products of the discharge. Then the rf can be turned on again. The required off-time is only about 1 sec. The rf-dc interlock compares the dee voltage with the amount of oscillator anode dc. If the ratio is too low, indicating the presence of an arc, the fault detector opens the anode circuit and recycles, approximately 1 sec later, bringing the machine back into operation.

The signal from the rf-dc interlock is slowed down by an RC circuit, so that the discharge will persist for about a millisecond. This is long enough to vaporize the foreign material which initiated the spark. If the circuit is made too fast, it takes too long to bake the resonators in. If it is made too slow, the spark damage to the dee and linear surfaces will be excessive. Experience indicates that 1 msec is about the right delay. High-speed circuits sense overcurrents in either the anode or grid circuits of the oscillator tube and send their signals to the fault detector which opens the hard-tube modulator with the minimum possible delay. The circuit operates within about 10 μsec.

The high-speed circuitry introduces transients into the power supply. Resistance-capacitance surge networks are used to suppress these transients. A wye-connected network connected across the rectifier transformer is mounted in the rectifier tank. A second RC network, also located in the rectifier tank, is connected across the dc-output terminals of the rectifier.

INSTRUMENTATION

The movable resonator panels are used as the coarse frequency adjustment. A servo-operated trimming capacitor provides fine adjustment. The trimmer is part of an automatic-frequency-control system designed to regulated the frequency to an accuracy of 10 parts per million.

Provision is being made with the hard-tube modulator to regulate the rf dee voltage to 0.1%. Dee voltage is measured by means of a pick-up loop located in the resonator.

CONCLUSION

The three most important differences between cyclotron rf problems and industrial rf problems are (a) the fact that a cyclotron resonator is a sparking load capable of delivering relatively large amounts of energy within each spark to the various electronic components; (b) the multipactoring problem, common in the field of particle accelerators, rarely occurs in other industrial applications; (c) rarely in industrial applications is it required to tune so much rf power continuously over such a wide band of frequencies.

The first difference above complicates the design of the oscillator and power supplies and leads to elaborate and expensive high-speed protective circuitry. It calls for an oscillator tube of unusually rugged internal construction. The massive grid bars hidden from the anode by even more massive shield tees makes the 6949 particularly well-suited to this application. The third difference intensifies the parasitic and harmonic problems.

The problem of stray rf radiation common to all industrial rf applications is automatically relieved somewhat by the fact that the resonator has to be vacuum-tight, automatically making it rf-tight. While the oscillator tube and other electronic components are outside the vacuum system, the rf currents and voltages here are relatively low compared with those within the resonator.

REFERENCES

1. "Disintegration of Lithium by Swift Protons," J.D. Cockcroft and E.T.S. Walton. Nature, vol. 129, 1932, p. 649.

2. "The Production of High Speed Light Ions without the Use of High Voltage," E.O. Lawrence and M.S. Livingston. Phys. Rev., vol. 40, 1932, p. 19.

3. "The Synchrotron - A Proposed High Energy Particle Accelerator," E.M. McMillan. Phys. Rev., vol. 68, 1945, pp. 143-144.

4. "Frequency Modulated Cyclotron," J.R. Richardson, K.R. MacKenzie, E.J. Lofgren, and B.T. Wright. Phys. Rev., vol. 69, 1946, p. 669.

5. "Observation of Antiprotons," O. Chamberlain, E. Segré, C. Wiegand, T. Ypsilantis. Phys. Rev., vol. 100, 1955, pp. 947-950.

6. "The Paths of Ions in the Cyclotron," L.H. Thomas. Phys. Rev., vol. 54, Oct. 1938, pp. 580-598.

7. "Two Electron Models of a Constant-Frequency Relativistic Cyclotron," E.L. Kelly, R.V. Pyle, R.L. Thornton, J.R. Richardson, and B.T. Wright. Rev. Sci. Instr. Vol. 27, July 1956, pp. 493-503.

8. "Constant-Frequency Cyclotrons with Spirally Ridged Poles," D.W. Kerst. Midwestern Universities Research Association Report, MURA 64, March 29, 1955.

9. "Fixed-Field Alternating-Gradient Particle Accelerators," K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett, and K.M. Terwilliger. Phys. Rev., vol. 103, no. 6, Sept. 1956, pp. 1837-1859.

Table I. Maximum operating conditions for the RCA 6949 for the 88-in. cyclotron

Plate voltage, D.C.	15 kv
Plate current, D.C.	25 amps
Grid current, D.C.	1.4 amps
Grid bias, D.C.	-700 volts
Grid bias resistance	500 ohms
Driving power	3 kw
Rf plate voltage	14 kv peak
Rf plate current	130 amps peak
Rf grid voltage	2 kv peak
Power output	319 kw

FIGURE LEGENDS

Fig. 1. A twenty-fourth scale model of the 88-in. cyclotron. This variable-energy, spiral-ridge cyclotron will provide beams of deuterons, protons, alpha particles, and numerous heavy ions such as oxygen, carbon nitrogen, and neon.

Fig. 2. Cross-sectional views of the 88-in. cyclotron. The resonant frequency is adjusted by varying the characteristic impedance of the dee stem with the movable panels. It tunes from 5.3 to 16 Mc.

Fig. 3. The Voltage and Current Distribution of the Resonator.

Fig. 4. The equivalent circuit of the rf system.

Fig. 5. The higher modes (resonant frequencies) in the anode circuit of the rf system. The circuit elements of the rf system were adjusted so that the first two higher modes would not be excited by an oscillator harmonic.

Fig. 6. The quarter-scale rf model. This model was used to determine the values of many of the components of the rf system.

Fig. 7. The dee and stem of the quarter-scale rf model. The corrugated dee stem reduces the current density at high frequencies. The anode drive loop and coupling-adjustment capacitor are shown on the right side of the dee stem. The structure on top is the grid transmission-line.

Fig. 8. Voltage and current distribution of the grid transmission-line.

Fig. 9. The oscillator circuit.

Fig. 10. Cross-sectional views of the RCA 6949 (courtesy of R.C.A.) (A) Cut-away view of the 6949. (B) Simplified cross section. Note the spiral grooves in the anode to improve the water cooling. Also, note the massive shield tees which shield the grid from anode sparks. (C) Cross section of one of the 48 triode units. The grid and shield tees form an electron optical system that provides very high power gain.

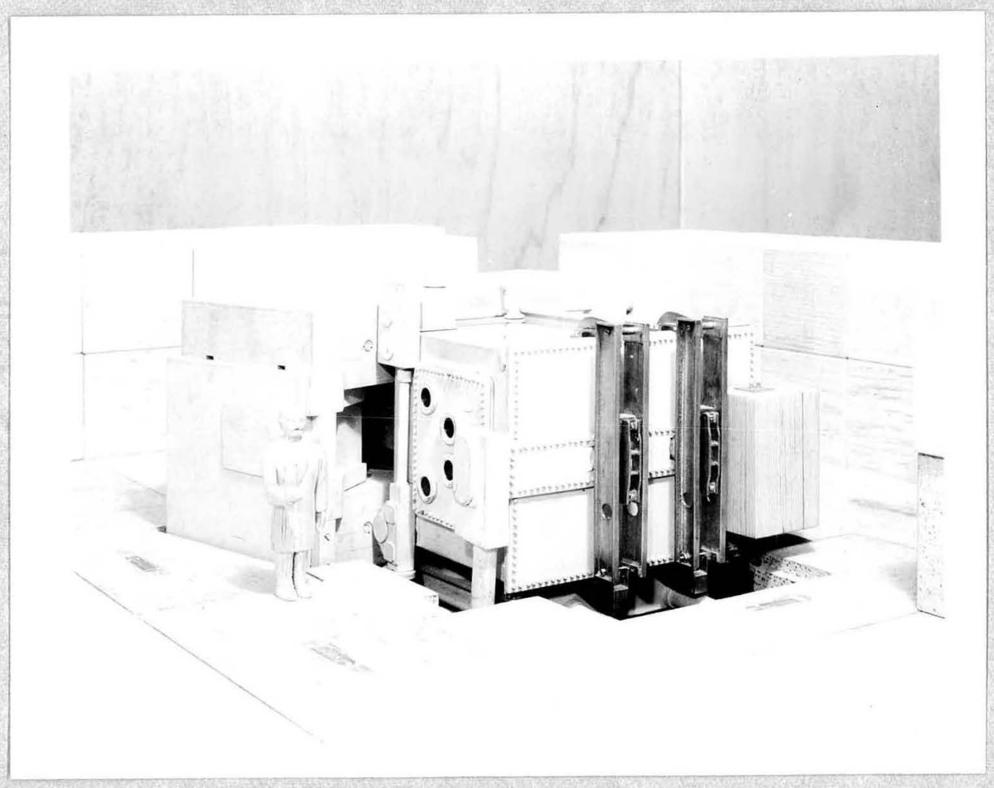

Fig 1

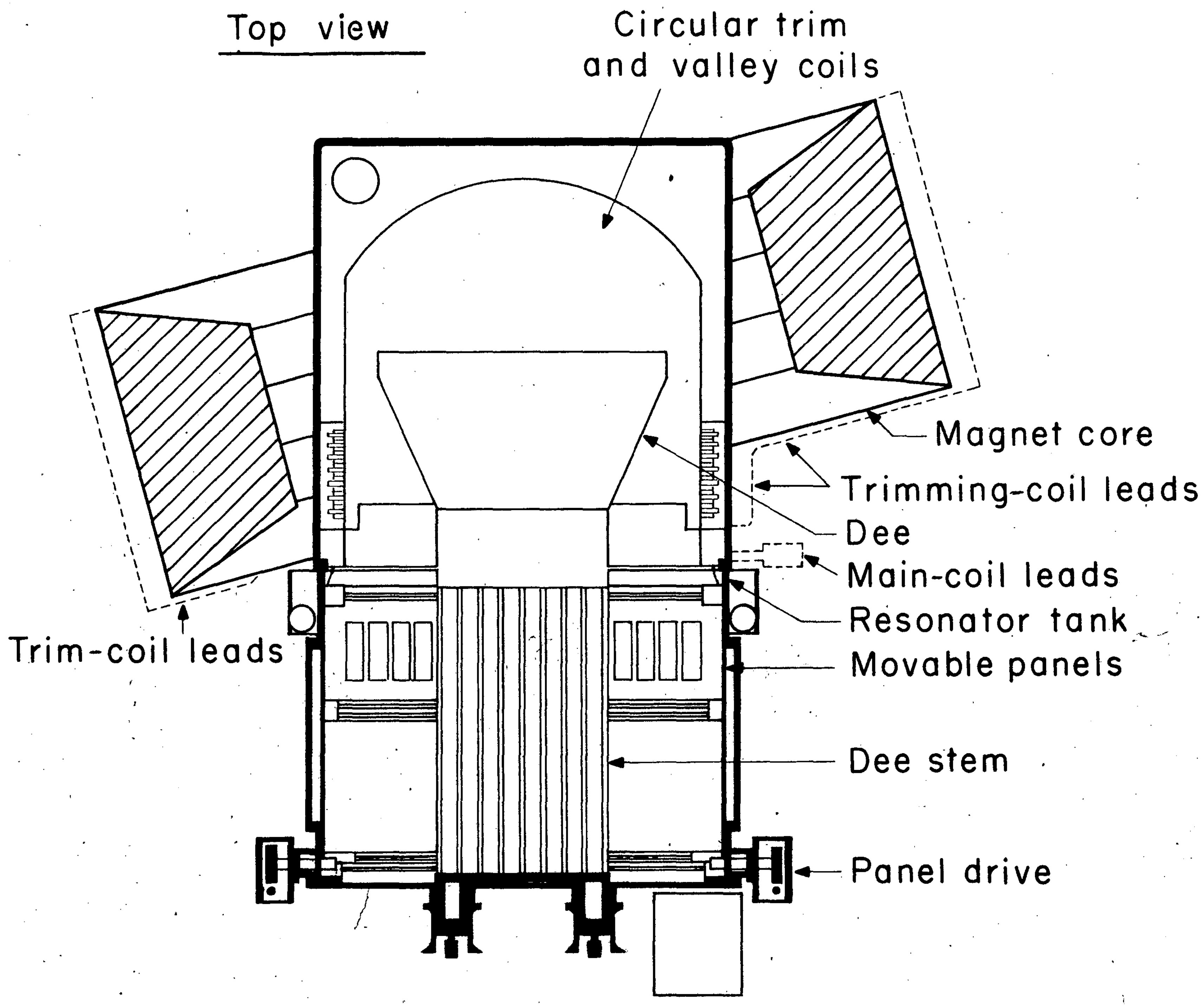

Fig 2a

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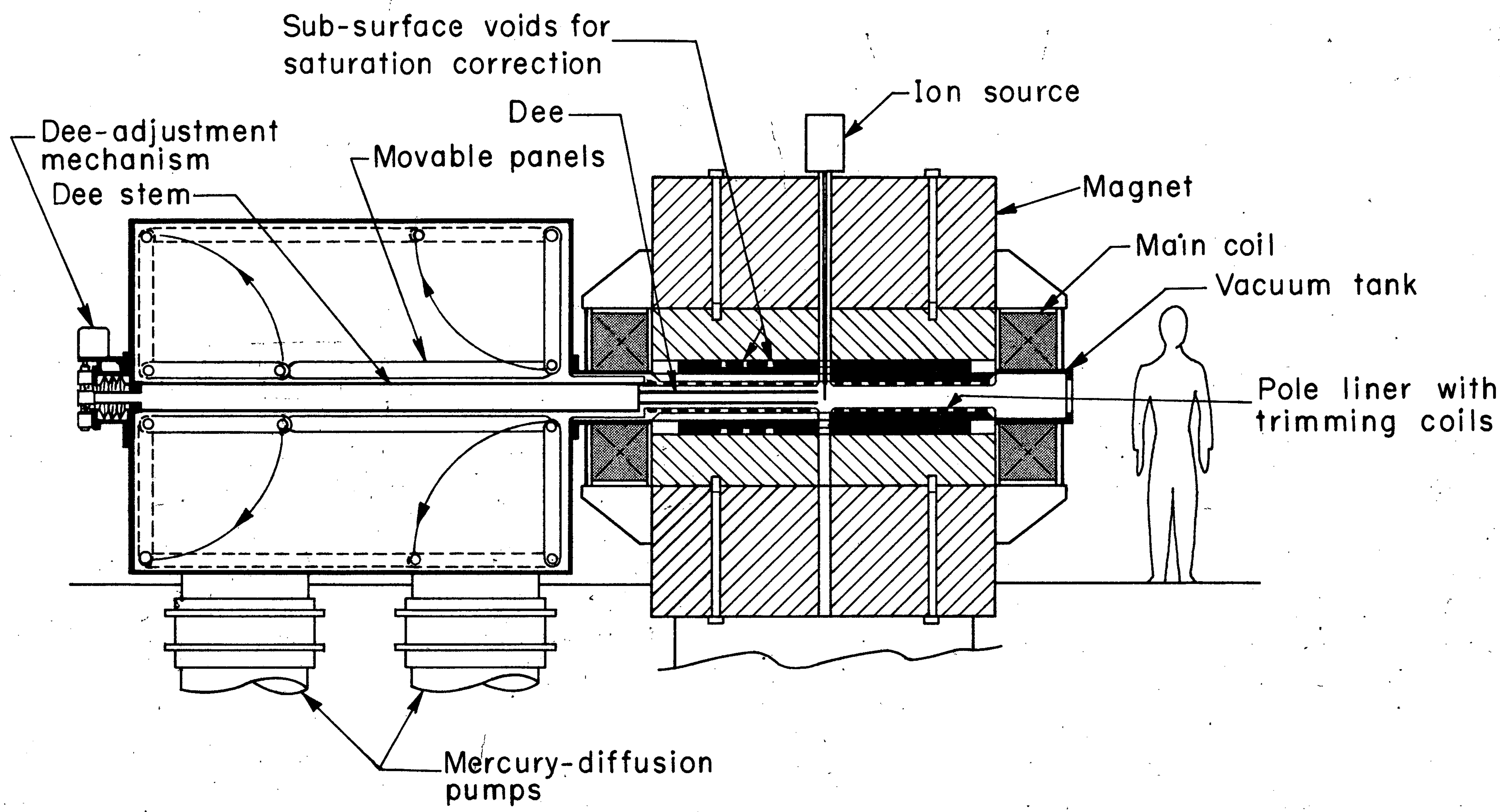
Side view



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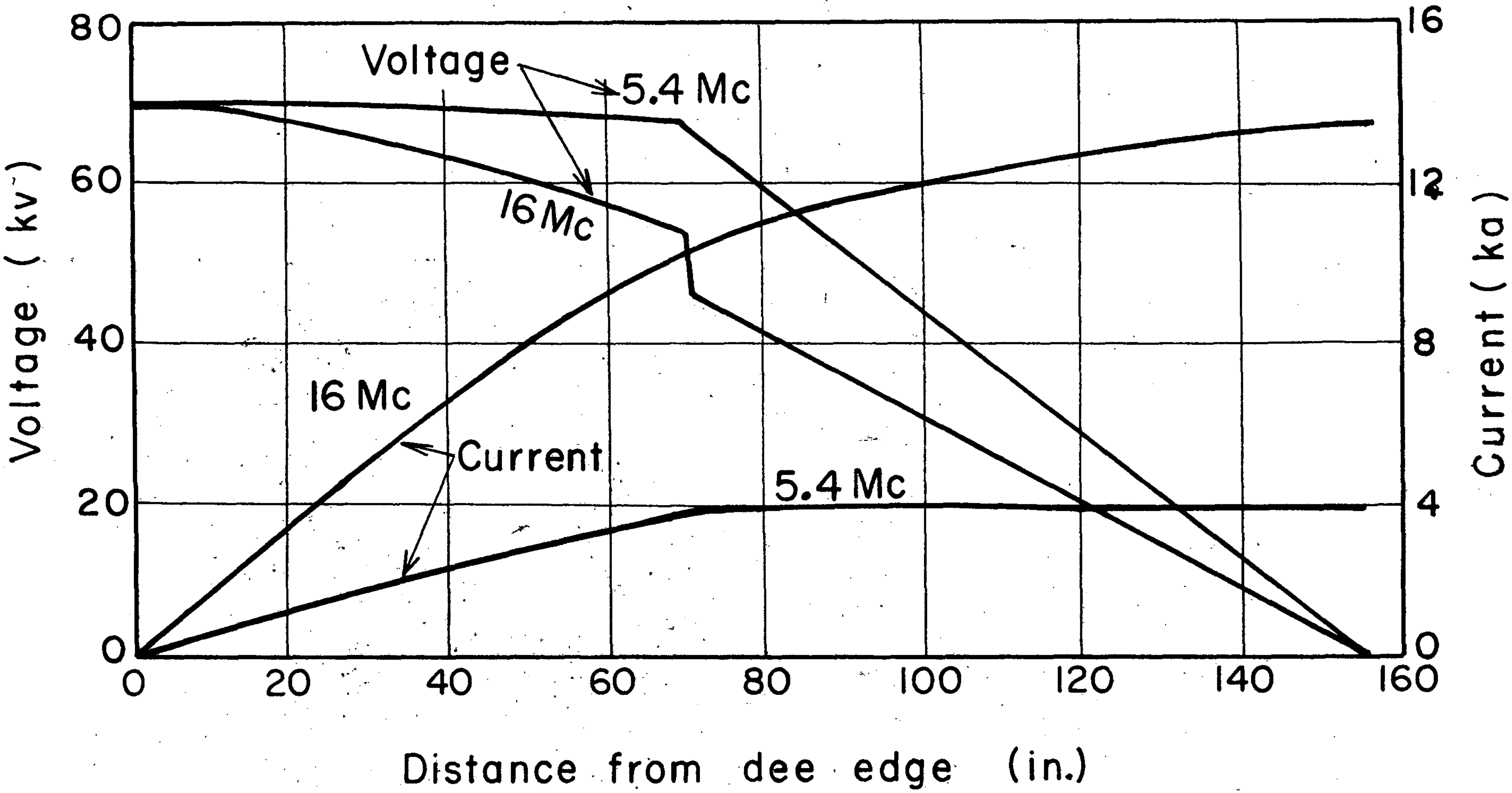

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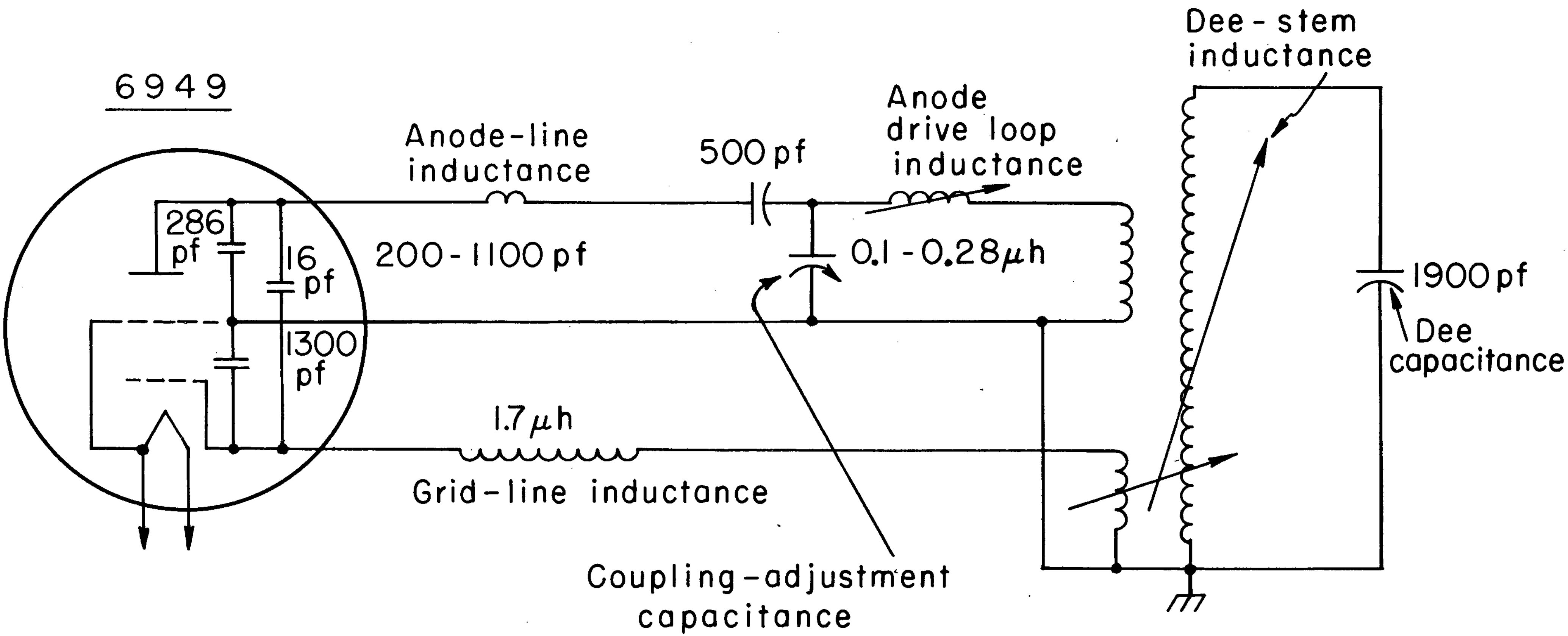

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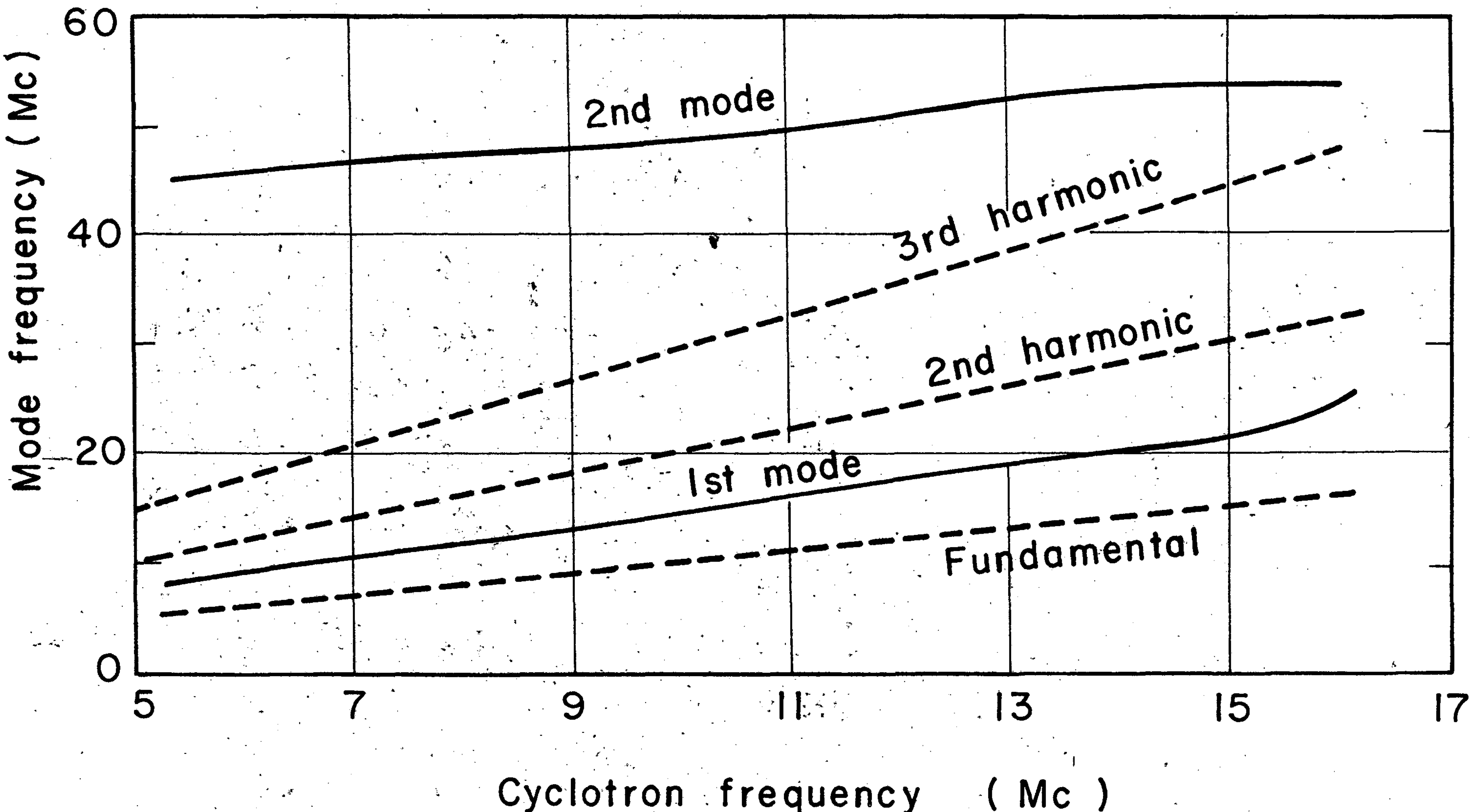

2nd mode
3rd harmonic
2nd harmonic
1st mode
Fundamental
Mode frequency (Mc)
60
40
20
0
5
7
9
11
13
15
17
Cyclotron frequency (Mc)

Fig 5

58511-1

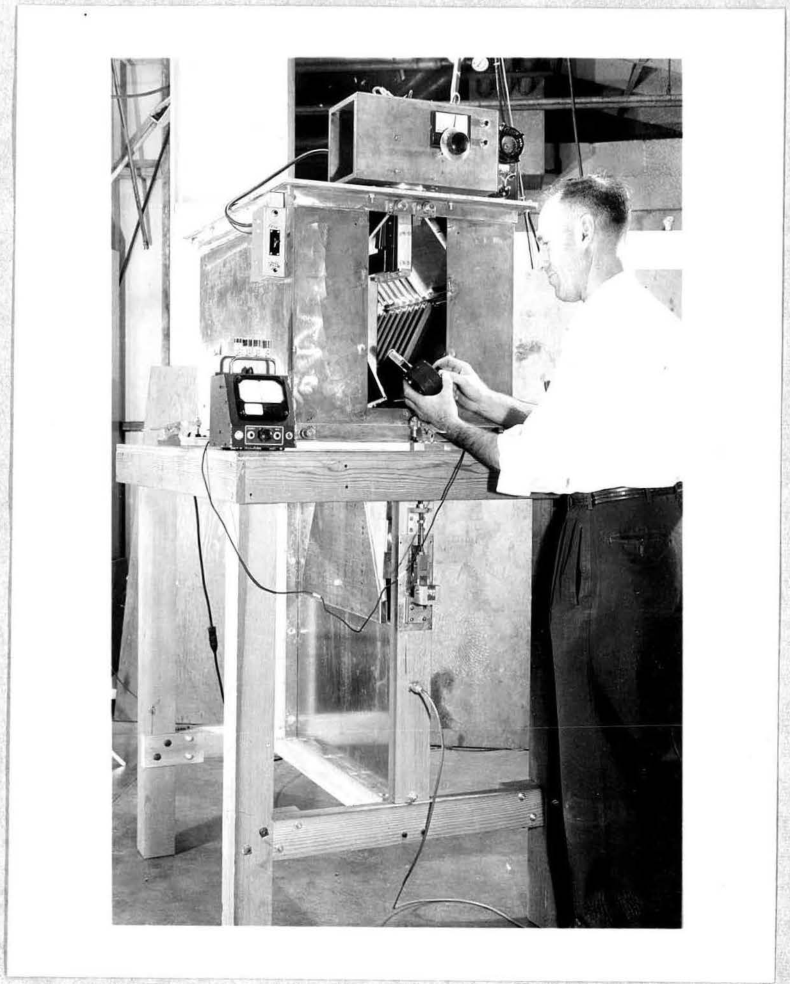


Fig 6

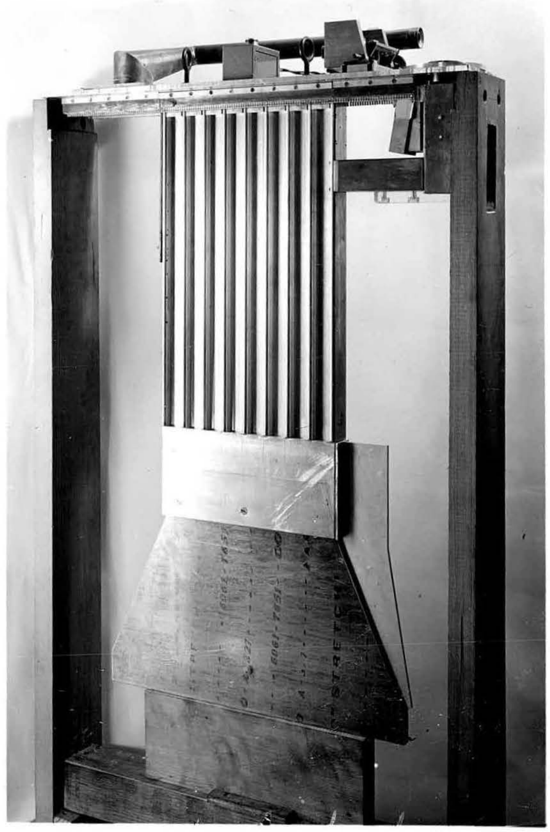
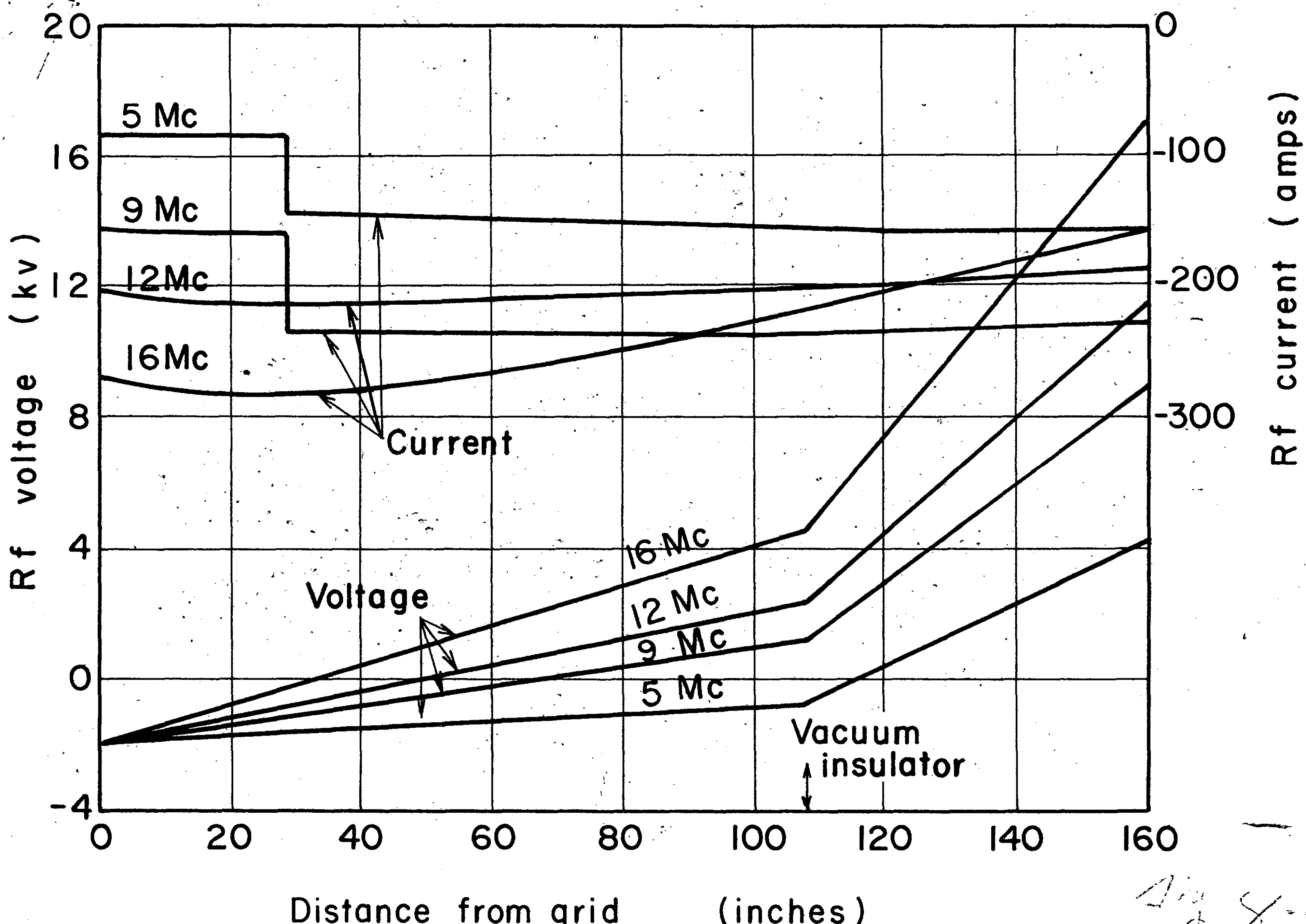
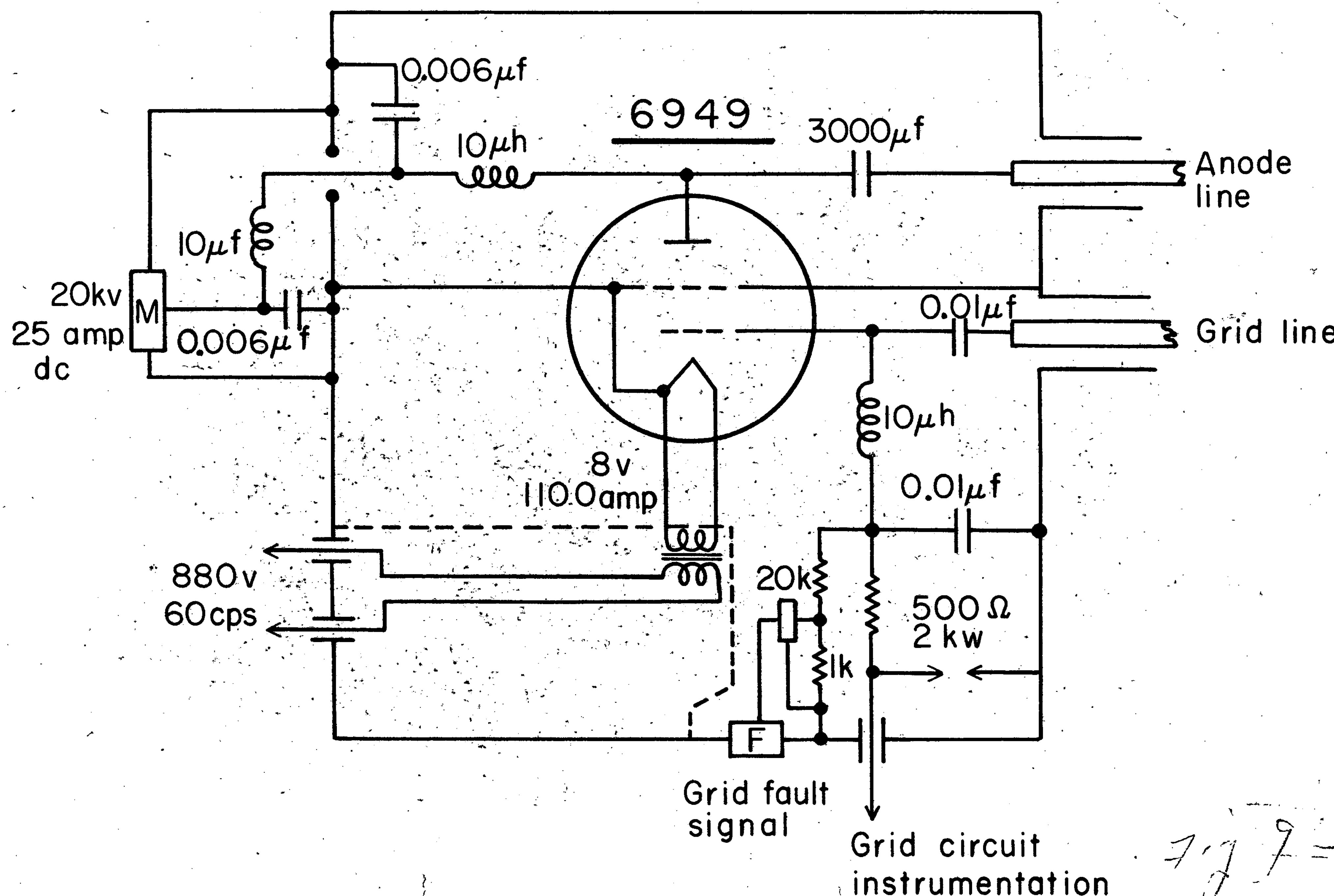


Fig 7



5 Mc
9 Mc
12Mc
16Mc
Current
16 Mc
12 Mc
9 Mc
5 Mc
Voltage
Vacuum insulator
Rf voltage (kv)
Rf current (amps)
Distance from grid (inches)
20
16
12
8
4
0
-4
0
-100
-200
-300
0
20
40
60
80
100
120
140
160

57 58512-1



6949
0.006µf
10µh
3000µf
Anode line
10µf
20kv
25 amp
dc
M
0.006µf
0.01µf
Grid line
10µh
8v
1100amp
0.01µf
880v
60cps
20k
500 Ω
2 kw
1k
F
Grid fault signal
Grid circuit instrumentation

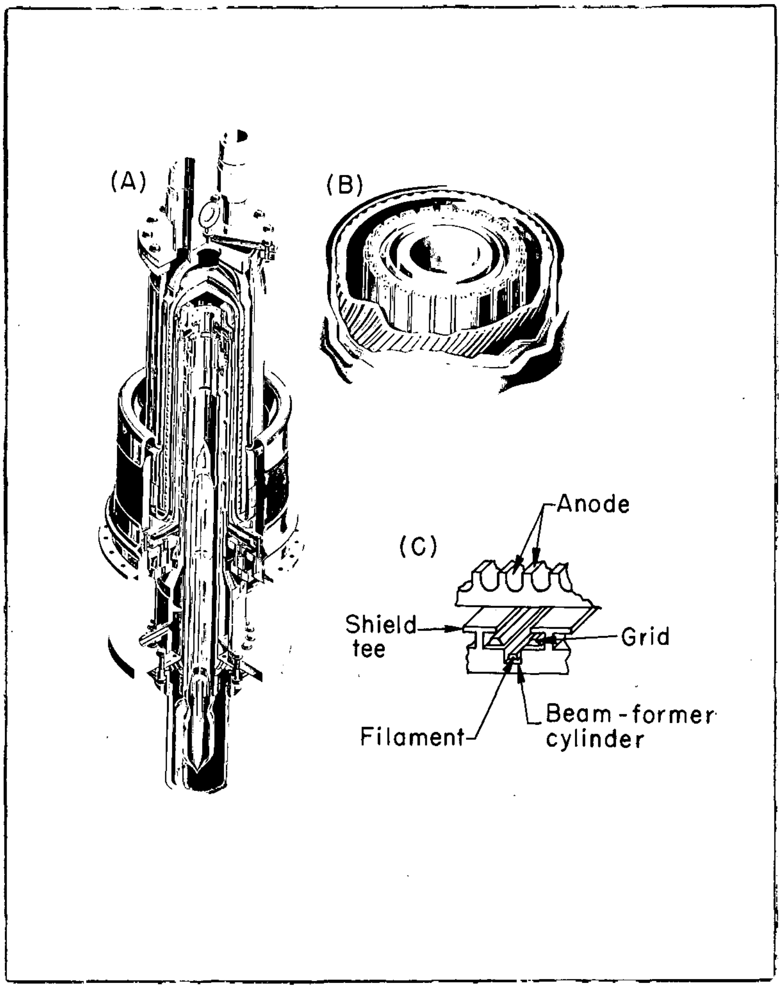


Fig 10