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ABSTRACT

The design and performance of a single-dee self-excited radiofrequency system that tunes from 5.5 Mc to 16.5 Mc are discussed. Self-excited radiofrequency systems are compared with driven systems. The multipactoring phenomenon in variable-frequency systems is analyzed and discussed.

RADIOFREQUENCY SYSTEM OF THE BERKELEY 88-INCH CYCLOTRON[†]

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1. Introduction

The 88-inch cyclotron is primarily a variable-energy deuteron machine with an upper energy limit of 60 MeV. However, it seems desirable to be able to accelerate as many other particles as possible. The magnet has sufficient flutter to accelerate protons to 55 MeV. These have the highest orbit frequency of any of the particles, and therefore determine the maximum rf frequency required—16.5 Mc. The lowest frequency, one-third of 16.5 Mc (5.5 Mc), was chosen to permit transfer to third-harmonic acceleration without leaving a gap in the energy range of the machine. By using harmonic acceleration the energy range of the machine is limited only by the capabilities of the magnet, not by the rf system.

A quarter-wave single-dee resonator is used for acceleration. It tunes through the frequency band continuously, by varying the dee-stem inductance with a set of movable panels. The operating dee voltage is 70 kV (50 kV rms) and is independent of frequency.

The resonator is driven by a conventional self-excited cyclotron oscillator with a maximum rf power capability of 300 kW. The frequency is regulated by a servo-driven trimmer. Power-supply ripple is removed, and the oscillator anode voltage regulated, by a series modulator tube and electronic regulator. The modulator tube also serves as a high-speed anode

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[†] Work done under the auspices of the U.S. Atomic Energy Commission.

disconnect in the place of a crowbar (fault diverter). It also can be used to pulse the rf.

A system of D.C. clearing electrodes was installed to prevent multipactoring, but this proved to be adequate for only about half of the frequency range. To extend the system sufficiently to take care of the rest of the range would require an array of electrodes and insulators too complex to be practicable. The D.C. bias system was removed and a pre-exciter was developed. It has been tested on the cyclotron and is being installed as a permanent part of the machine at the present time. The details of the multipactoring process as they apply to variable-frequency cyclotron resonators, and the pre-exciter rf build-up process are discussed in following sections of this paper.

2. The Resonator

One of the first decisions that had to be made was whether to put the dees or magnet trim coils in the valleys of the magnet poles. The first choice would permit a smaller magnet gap, and particle acceleration to a larger radius and, consequently, higher energy. If the trim coils were placed in the valleys a much more extensive array of trim coils was possible, and the energy range of the machine would be much greater and continuous. These latter features seemed to meet the needs of the laboratory better than the former, so it was decided to use the valleys for trim coils rather than for dees.

The next question was whether to use one or two dees. For equal gain per turn, a two-dee system requires half the dee-to-ground voltage and has half the current on each dee stem as a single-dee system. However, for equal-size dee stem tanks the latter permits a dee stem of twice the perimeter of the former. Therefore, the current density and rf power required are the same in the two cases. In the single-dee system the three-to-one frequency range is more easily attained, the voltage taper along the dee edge is less, there is more space for beam probes and the deflector, and there is more voltage for extraction of ions from the source.

The resonator is tuned by varying the inductance of the dee stem. This could have been done by making the dee stem length variable, with a set of movable shorting fingers. However, the movable-panel system was selected (fig. 1). Previous experience indicates that movable panels produce somewhat less outage than movable shorting fingers.

The voltage and current distribution of the resonator are shown in fig. 2. 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.

The oscillator anode is coupled to the resonator with a drive loop and capacitive network designed to maintain an approximately constant step-up ratio between the anode and dee voltages (fig. 3). At the same time the first two higher modes move with frequency in such a way that they do not cross the second or third harmonic (fig. 4). In order to meet this condition the coupling-adjustment capacitance is driven by a cam that is attached to one of the movable panels. The details of the anode circuit analysis are given in ref. [1]).

The oscillator-grid transmission line is a foreshortened half-wave line operating at a very high standing-wave ratio, so that the phase shift is essentially 180 deg. The quarter-wave mode was adjusted to 3.0 Mc by suitable choice of the pick-up loop inductance, and by a loading capacitor near the grid end of the line. For the voltage at the load end of this line to be independent of frequency the driving voltage must be proportional to the frequency (fig. 5). To meet this requirement, the grid loop was mounted close to the dee stem so that most of the rf fringing field would

3. Multipactoring

If an oscillating potential is applied between two surfaces in a vacuum; and if the voltage, frequency, and spacing are such that the time of flight of an electron between the surfaces is an odd multiple of a half period of the oscillation, electron multiplication by secondary emission may occur. This phenomenon is called multipactoring. When this occurs in a cyclotron resonator, it produces such a heavy load on the oscillator that the dee voltage cannot build up. It ordinarily occurs at a dee voltage of a few hundred volts.

In order to derive the conditions for multipactoring, consider an electron between two surfaces excited by an rf generator (fig. 7). The electric field accelerating the electron is

$$E = \frac{V}{d} \sin(\omega t + \Phi_0) . \tag{1}$$

The equation of motion of the electron is

$$F = m\ddot{x} = + eE .$$

By integration, the velocity and displacement of the electron are

$$\dot{x} = - \frac{Ve}{\omega md} \cos(\omega t + \Phi_0) + c_1 , \tag{2}$$

$$x = - \frac{Ve}{\omega^2 md} \sin(\omega t + \Phi_0) + c_1 t + c_2 . \tag{3}$$

Consider an electron at $x = 0$ with zero velocity, and at $t = 0$. Then

$$c_1 = \frac{Ve}{\omega md} \cos\Phi_0 , \tag{4}$$

$$c_2 = \frac{Ve}{\omega^2 md} \sin\Phi_0 , \tag{5}$$

so

$$x = \frac{Ve}{\omega^2 md} \left[-\sin(\omega t + \Phi_0) + \omega t \cos\Phi_0 + \sin\Phi_0 \right] , \tag{6}$$

$$0 \leqslant x \leqslant d, \quad 0 \leqslant \Phi_0 \leqslant \frac{\pi}{2} .$$

The limitation on Φ_0 is determined by the boundary conditions. Its value must be greater than or equal to zero so that the acceleration is positive at t = 0. It must not be greater than 90 deg, so that the velocity will not be negative at x = d. At x = d the phase must have shifted by an odd multiple of 180 deg, so that the field is in a direction to accelerate the secondary electrons toward x = 0. If t_1 corresponds to x = d, then

$$\omega t_1 = (2n-1)\pi, \qquad n = 1, 2, 3, \cdots, \tag{7}$$

so

$$V_m = \frac{\omega^2 m d^2}{e[2 \sin\Phi_0 + (2n-1)\pi \cos\Phi_0']} \quad , \tag{8}$$

where V_m is the multipactoring voltage. The integer n, determines the order of the multipactor.

In addition to the transit-time requirement, the electron must arrive at x = d with sufficient energy to produce a secondary emission ratio in excess of unity. For most materials this is of the order of at least 100 eV. Under multipactoring conditions the velocity of the electron at x = d is

$$\dot{x}\Big|_{x=d} = \frac{2 V_m e}{\omega m d} \cos \Phi_0 \; . \tag{9}$$

The energy picked up by the electron is

$$U = \frac{1}{2} m[\dot{x}]^2_{x=d} = \frac{1}{2} m \left[\frac{2 V_m e \cos\Phi_0}{\omega m d}\right]^2 = V_0 e \; , \tag{10}$$

$$V_0 = \frac{\frac{m}{2e} (\omega d)^2}{\left[\tan\Phi_0 + (2n-1)\frac{\pi}{2}\right]^2} \; . \tag{11}$$

Here V_0 is the effective voltage accelerating the electron.

It is apparent that first-order multipactors produce more energetic electrons than higher-order multipactors. Also, the energy available to produce secondary emission falls off with increasing phase angle, becoming zero for Φ = 90 deg.

The threshold multipactoring voltage can be found by setting the derivative of the multipactoring voltage with respect to Φ_0 equal to zero, solving for Φ_0, and substituting this value in eq. (8). Thus

$$V_t = \frac{m/2e\,(\omega d)^2}{\left\{1+\left[(2n-1)\frac{\pi}{2}\right]^2\right\}^{1/2}};\quad \Phi_0 = \tan^{-1}\frac{2/\pi}{2n-1} . \tag{12}$$

Substitution of V_t into eq. (11) produces the voltage picked up by an electron, in terms of the threshold voltage:

$$V_0 = \frac{V_t\left\{1+\left[(2n-1)\frac{\pi}{2}\right]^2\right\}^{1/2}}{\left[\tan\Phi_0 + (2n-1)\frac{\pi}{2}\right]^2} . \tag{13}$$

At threshold the energy picked up by an electron is

$$\left[V_0\right]_{V_t} = \frac{V_t\left[(2n-1)\frac{\pi}{2}\right]^2}{\left\{1+\left[(2n-1)\frac{\pi}{2}\right]^2\right\}^{3/2}} \tag{14}$$

If the frequency is in megacycles and the spacing, d, in inches, eq. (12) becomes

$$V_t = \frac{0.0725\,(fd)^2}{\left\{1+\left[(2n-1)\frac{\pi}{2}\right]^2\right\}^{1/2}} . \tag{15}$$

The upper limit of multipactoring voltage V_{UM} is determined by the energy picked up by the electrons, and the secondary-emission characteristics of the surfaces. Equation (8) shows that the multipactoring voltage, when limited by transit time, is maximum for Φ_0 equal to 90 deg. Equation (11) shows that the energy picked up by the electron approaches zero as Φ_0 approaches 90 deg. Therefore, the less energy required to produce a unity secondary-emission ratio, the more nearly Φ_0 approaches 90 deg. Thus

$$V_{UM} < \frac{m}{2e}\,(\omega d)^2 = V_{t0}\sqrt{1+\left(\frac{\pi}{2}\right)^2} = 1.85\ V_{t0}, \tag{16}$$

$$V_{UM} < 1.85\ V_{t0} .$$

where V_{t0} is the first-order multipactoring threshold and V_{UM} is the upper multipactoring limit.

Once the first-order threshold voltage has been determined, the threshold of the higher-order multipactors can be read from table 1. This table also shows how little energy is picked up by electrons in the higher-order multipactors, when compared with those of first order. Probably most multipactoring in cyclotron resonators is of the first-order type. The preceding discussion can be summarized by the following equations:

$$V_t\Big|_{n=1} = 0.039\,(fd)^2 , \tag{17}$$

$$V_t = \frac{1.86\, V_t\big|_{n=1}}{\sqrt{1+[(2n-1)\frac{\pi}{2}]^2}} , \tag{18}$$

$$V_m = \frac{1.86\, V_t\big|_{n=1}}{\sin\Phi_0 + (2n-1)\frac{\pi}{2}\cos\Phi_0} , \tag{19}$$

$$V_t \leqslant V_m \leqslant 1.86\, V_t\Big|_{n=1} , \tag{20}$$

$$V_0 = \frac{1.86\, V_t\big|_{n=1}}{[\tan\Phi_0 + (2n-1)\frac{\pi}{2}]^2} . \tag{21}$$

Equation (17) expresses the first-order multipactoring threshold voltage in terms of the frequency in Mc, and the spacing in inches. Equations (18) through (21) express the nth-order threshold, the multipactoring voltage for different starting phases, the range of multipactoring voltages, and the energy picked up by an electron crossing the gap (each in terms of the first-order threshold voltage). Equation (17) is plotted in fig. 8, which permits determination of the threshold voltage without further calculation. An expression for the highest-order multipactoring possible can be obtained by solving eq. (21) for n:

$$n = \sqrt{\frac{1.86\, V_t|_{n=1}}{\pi^2\, V_0}} - \frac{\tan}{\pi}\, \Phi_0 + 1/2 \quad , \tag{22}$$

$$0 \leqslant \Phi_0 \leqslant \frac{\pi}{2} \quad ,$$

therefore

$$n \leqslant \sqrt{\frac{1.86\, V_t|_{n=1}}{\pi^2\, V_0}} + 1/2. \tag{23}$$

V_0 is the energy picked up by the electron crossing the gap and must be at least as large as the minimum voltage necessary to produce a unity secondary-emission ratio. This value starts at about 100 V for most materials. Thus, for second-order multipactoring to occur, the first-order threshold would have to be at least 1190 V; for third-order, 3320 V, and for fourth order, 6480 V. (see table 2).

At 15 Mc. the 88-inch cyclotron multipactors only with dee voltage between 250 and 750 V. Thus this multipactoring can only be first order. By referring to the curves of multipactoring threshold versus spacing, the 250- to 750-V restriction shows that the path lengths of the electron trajectories must be between 5.5 and 6.8 in. The multipactoring must occur around the edges of, and across a very limited part of, the dee stem. It cannot multipactor between dee and liner because the spacing is only 1-3/8 in. By measuring the multipactoring limits as a function of frequency, one can determine the possible multipactoring regions.

4. The Pre-Exciter

The pre-exciter consists of a three-stage driven rf system designed for pulse operation. The pulse duration is 1 msec and the maximum repetition rate is 1 pps. The final amplifier is an eimac 4CX5000A capacitively coupled to the side of the dee. It is driven by a 4CX250B. The latter is driven by a 6197 (premium equivalent of 6CL6)oscillator. The oscillator uses the 4CX250B grid, tuned circuit, as the frequency-determining element, and this is ganged with the tuned circuit in the grid of the 4CX5000A. Thus, the pre-exciter is tuned as a unit. It is motor-driven with controls at the cyclotron console. The pre-exciter is keyed at the screen of the 4CX250B.

Tuning is done below the multipactoring level with the pre-exciter operating c-w from low-voltage power supplies. After it is tuned to the frequency of the cyclotron resonator, vacuum relays switch the pre-exciter to high-voltage pulse power supplies. The rf produced by the pre-exciter during the pulse overcomes the fixed bias of the main oscillator, thus starting its operation.

The 4CX5000A is capacitively coupled to the dee. The coupling circuit forms a voltage divider which divides the dee voltage to 10kV at the 4CX5000 anode. The anode circuit is shown in fig. 9, together with the simplified equivalent circuit.

The ratio of the voltage divider, α, is

$$\alpha = \frac{C_c}{C_c + C_e} = 1/7 \quad . \tag{24}$$

The purpose of a pre-exciter is to drive the dee voltage above the multipactoring level in a small enough number of rf cycles so that the electron loading does not become excessive. No one, to my knowledge, has done the basic work necessary to determine the electron load in a cyclotron during the first few cycles of build-up. Experience has shown that if the rf builds up at a rate of about a kilovolt per microsecond an rf system will drive through multipactoring. This factor was used as a design criterion in the 88-inch cyclotron.

Neglecting the electron load, the rate of rf build-up can be determined in the following way. In the quivalent circuit of fig. 9 the current source is the vacuum tube. Assume the angle of conduction of the first half cycle of anode current is 180 deg. Integrate the current over the first half cycle to determine the charge delivered to the anode circuit:

$$i = I_0 \sin\omega t, \quad 0 \leqslant t \leqslant \frac{\pi}{\omega}, \tag{25}$$

$$i = 0, \quad 0 \leqslant t \leqslant \frac{\pi}{\omega},$$

so

$$q = \int_0^{\frac{\pi}{\omega}} i\,dt = \frac{2 I_0}{\omega}. \tag{26}$$

Call the combined capacitance, C_e in parallel with C_c, and C_0 in series, C_2. During this first cycle, C_2 is charged to a voltage V_{a1}, where

$$V_{a1} \approx \frac{q}{C_2}. \tag{27}$$

This charges the dee to:

$$V_{D1} = V_{a1} \frac{C_c}{C_c + C_D} \approx \frac{2 I_0 a}{\omega C_D}. \tag{28}$$

During each rf cycle this same amount of charge is transported to the resonator until the voltage build-up affects the plate current. By this time the resonator is above the multipactoring upper limit, providing C_e is large enough. The number of rf cycles, n, required to reach the upper multipactoring voltage V_{UM} is

$$n V_{D1} = V_{UM}, \tag{29}$$

where

$$n \approx \frac{\omega C_D V_{UM}}{2 I_0 a}. \tag{30}$$

For the 88-inch cyclotron at 17 Mc the parameters are:

$C_D = 2000$ pF ,

$V_{UM} = 750$ V ,

$I_0 = 72.5$ A ,

$a = 1/7$.

Substituting these into eq. (30) produces a value for n of 7. The resonator is above the multipactoring upper limit in 7 rf cycles. This is a rate of rise of 1.1 kV/μsec.

It is not necessary to take the resonator Q into account in this kind of calculation because the energy loss due to resonator dissipation is totally negligible compared with the energy delivered by the tube and stored in the resonator in the time of interest.

5. Conclusion

A curve of the maximum spacing in the resonator where multipactoring could occur as a function of frequency was made, and this data was plotted on a copy of fig. 7. Between 5.3 and 8 Mc the maximum first-order threshold exceeds 1190 V; second-order multipactoring can occur in this range. The first-order threshold does not exceed 3320 V anywhere, so third-order multipactoring can not occur.

In addition to the transit-time requirement, an electron must pick up at least 100 V of energy for the secondary-emission ratio to exceed one. Equation (14) shows that the first-order threshold must be 262 V for an electron to pick up this much energy. This agrees fairly well with observations at 15 Mc.

During its development the pre-exciter was operated as a self-excited, rather than a driven, system. To do this the anode of the 6197 was coupled to the grid of the 4CX250B by a primary winding in order to make the phase correct for oscillation, and its grid was excited from a voltage divider in the 4CX5000A anode circuit. The self-excited system seemed to be slightly marginal—as though it needed more gain. In addition, the driven system seemed a little easier to maintain because it always has a signal available; the other case loses its signal everywhere when anything is wrong. The motivation for the self-excited study was simply to see if it would be less sensitive to tuning. It was, but tuning the driven system below the multipactoring level proved to be trivial.

For the main oscillator, a number of factors appear when comparing self-excited and driven systems. Parasitic oscillations are a little less of a problem in driven rf systems, since the grid circuitry is isolated from the anode circuit. Also, the frequency can be determined by a crystal oscillator of much higher frequency stability than the cyclotron resonator. Except for the final amplifier anode circuit, the circuitry can be worked out independently of the cyclotron construction. This makes construction more efficient.

The self-excited cyclotron oscillator is a little more reliable than a driven system. For the latter, failure of a component in the driver makes the cyclotron inoperative. The corresponding trouble in the self-excited system would be a failure in the pre-exciter. Although inconvenient, this does not put the cyclotron out of operation—all the operator has to do to turn on rf is to move to a frequency where the pre-exciter is not necessary, bring the rf on, and move back to the desired frequency. It is not necessary to remove rf when changing frequency—one need only press the panel-drive button, and wait for the digital frequency meter to indicate the desired frequency.

Both types of rf systems require about the same amount of equipment. The final amplifier is comparable to the cyclotron oscillator; the driver is comparable to the pre-exciter—although the pre-exciter, being a pulsed device, is a little smaller. Similarly, its power supplies are a little smaller. Both systems require trimmer servos. The driven system requires a little more electronic competence in the maintenance personnel.

Removal of the power-supply ripple and regulation of the oscillator anode voltage seems to make a big improvement in orbit stability. Beam current versus radius can be plotted by chart recorders, and the individual turns identified out to full radius. All of the orbit centers can be determined.

The power-supply ripple can be removed by grid modulation. This was the first method that was used on the 90-inch cyclotron at Livermore. It required too much adjustment for day-to-day operation.

For grid modulation to be satisfactory in cyclotron operation, an electronic circuit needs to be included which will adjust the grid drive as the final amplifier anode voltage is changed, so that the grid does not become saturated. This problem does not occur for anode modulation.

Table 1

Tabulation of multipactor formulae

Order of multipactor (n)	Threshold voltage (V_t)	V_t as a percent of first-order threshold voltage	Electron energy, in percent of V_t	Electron energy, in percent of first-order threshold volts.
1	$0.039\ (fd)^2$	100	64	64
2	$0.015\ (fd)^2$	38.5	59	22.7
3	$0.00916\ (fd)^2$	23.2	12.6	2.9
4	$0.00656\ (fd)^2$	16.8	9	1.5
5	$0.0051\ (fd)^2$	13.1	7	0.92

f = frequency in Mc.

d = spacing in inches.

Table 2

Relation of permissible order of multipactoring to the first-order threshold voltage *

n	$\min\left(\dfrac{V_t\big\|_{n=1}}{V_0}\right)$ This ratio must be greater than the value shown below for n to occur
1	1.33
2	11.9
3	33.2
4	64.8
5	109

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*Here n is the order of multipactoring, $V_t\big|_{n=1}$ is the first-order threshold voltage, and V_0 is the voltage necessary for unity secondary-emission ratio.

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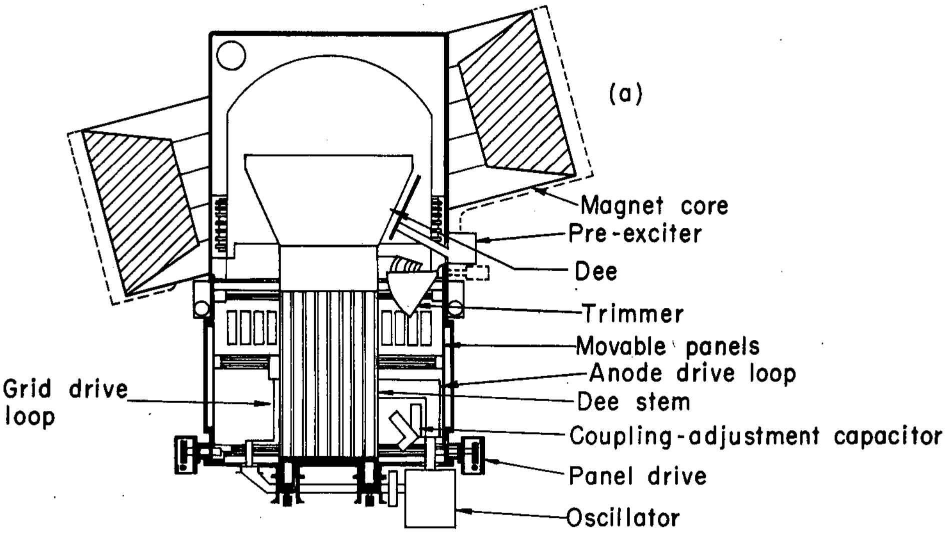
1) B. H. Smith, 88-Inch Cyclotron–Anode Loop, R.F. Analysis, Lawrence Radiation Laboratory Eng. Note UCID-1132, March 30, 1960 (unpublished).[†]

2) B. H. Smith and R. Cox, 88-Inch Cyclotron–Final R.F. Tests, Lawrence Radiation Laboratory Eng. Note UCID-1507, Sept. 5, 1960 (unpublished).[†]

[†] In addition, the following unpublished engineering notes contain design considerations which may be of interest. They are available from the University of California Lawrence Radiation Laboratory, Information Division, Berkeley, California.

1. B. H. Smith, 88-Inch Cyclotron–R.F. Forces, UCID-1098, June 29, 1959.
2. B. H. Smith, 88-Inch Cyclotron Oscillator, UCID-1104, December 4, 1959.
3. H. Baumann, 88-Inch Cyclotron R.F. System, Modification for 16 Mc, UCID-1109, January 26, 1960.
4. B. H. Smith, 88-Inch Cyclotron Grid Line, UCID-1317, October, 27, 1960.

Top view



Side view

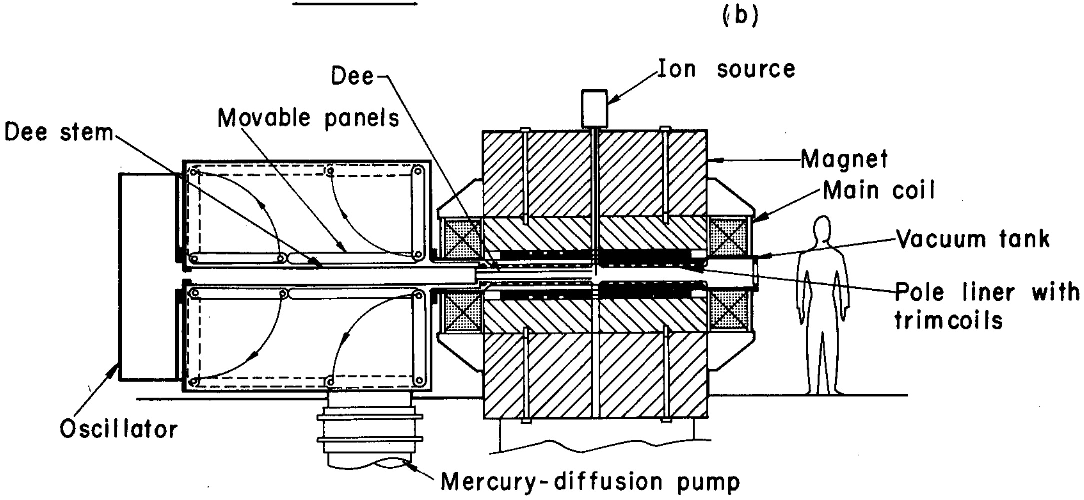


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Fig. 1. Cross-sectional views of rf system. The rf system tunes from 5.3 to 16 Mc by adjustment of the dee-stem inductance with a set of movable panels. The panels are shown in the 16-Mc position by the solid lines and in the 5.3-Mc position by the broken lines. The resonator is self-excited by a 300-kW oscillator. The coupling adjustment capacitor is driven by a cam attached to the upper panel and maintains a constant step-up ratio between dee voltage and oscillator anode voltage over the three-to-one frequency range.

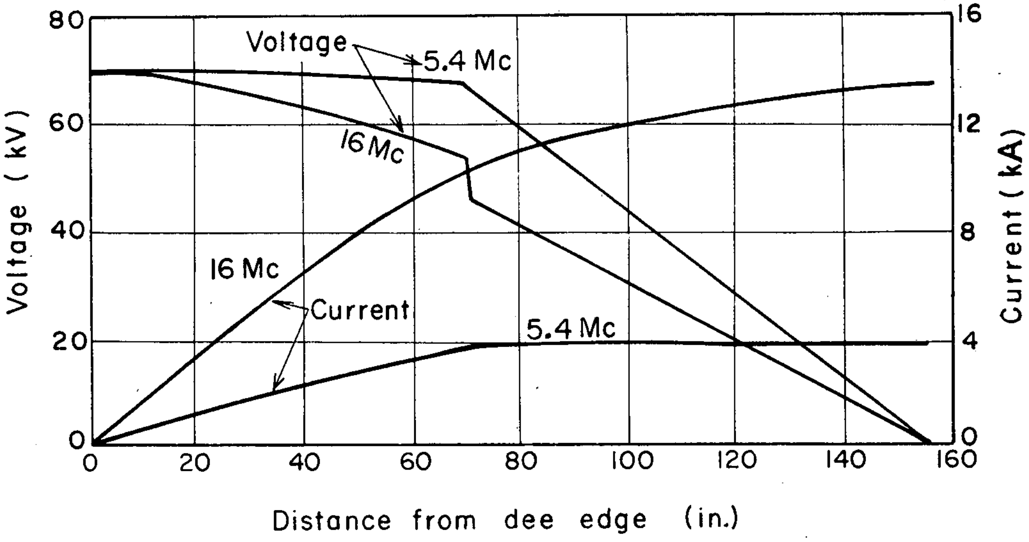

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Fig. 2. Resonator current and voltage distribution. Compared with conventional cyclotrons, spiral-ridge machines optimize at lower dee voltage and higher dee-stem currents. This leads to larger dee-stem cross section, and consequently a larger dee-stem tank.

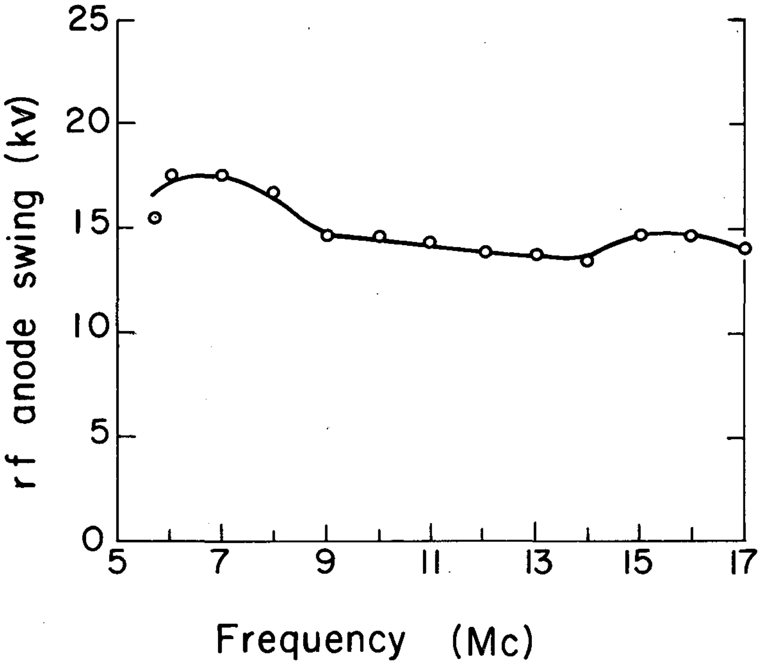

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Fig. 3. Oscillator anode rf voltage vs frequency for 70-kVdee voltage.

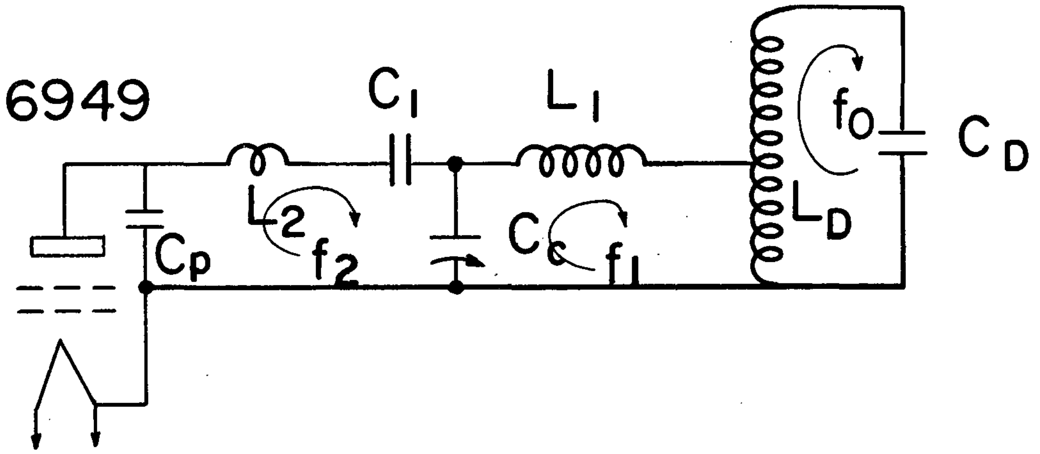

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Fig. 4a. Equivalent oscillator anode circuit. The components primarily responsible for the higher modes are shown. The coupling adjustment capacitor is driven mechanically from the panels so that it varies in such a way that the modes are not excited by the second or third harmonics. The higher harmonics, though they excite the f_2 mode, are too small to be significant.

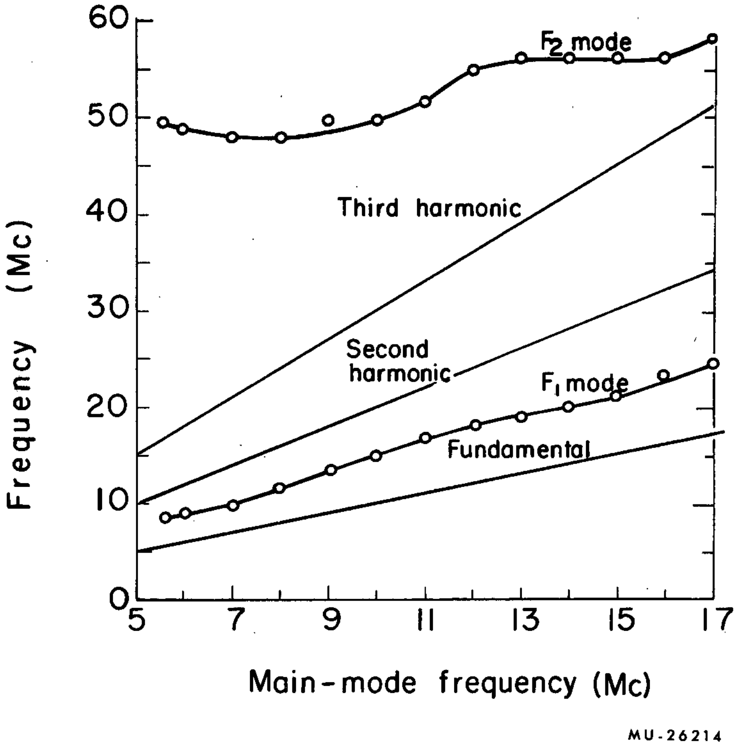

Fig. 4b. Anode modes of the cyclotron.

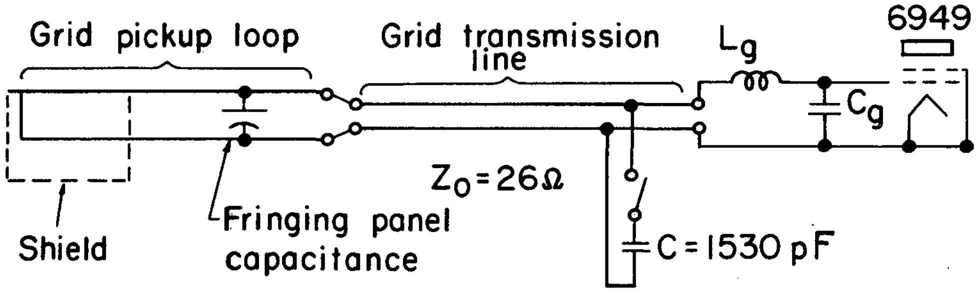

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Fig. 5a. The oscillator grid circuit in schematic form. The voltage picked up by the grid drive loop must be roughly proportional to frequency, as shown in fig. 5. This requirement was met by taking advantage of the way in which the rf fringing field along the dee stem varies with panel position.

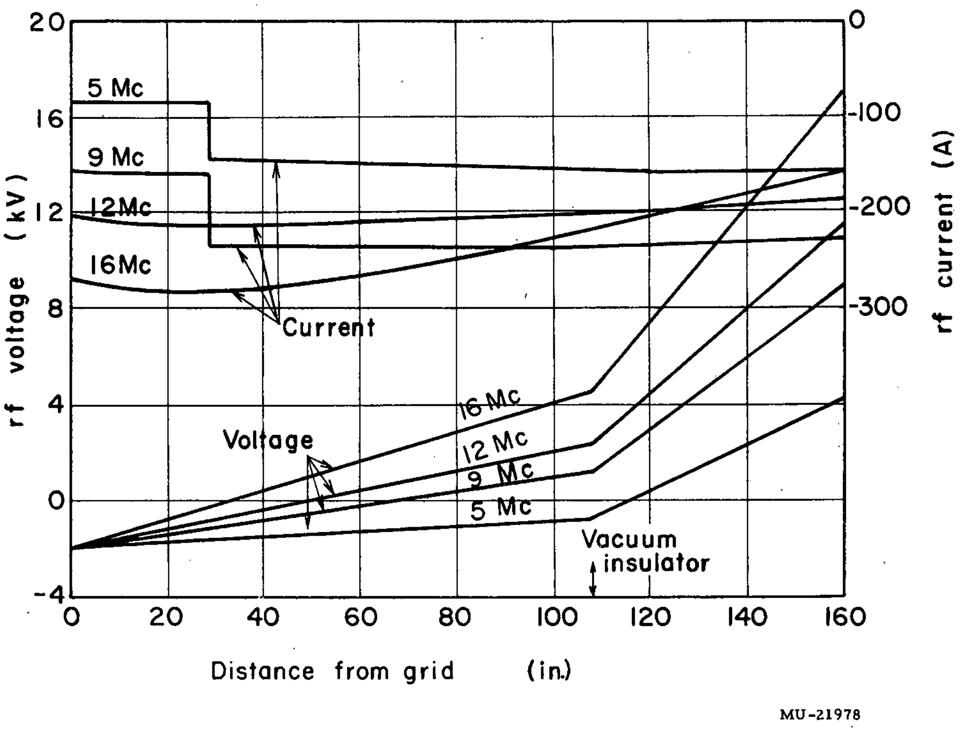

Fig. 5b. Voltage and current distribution of the grid transmission line.

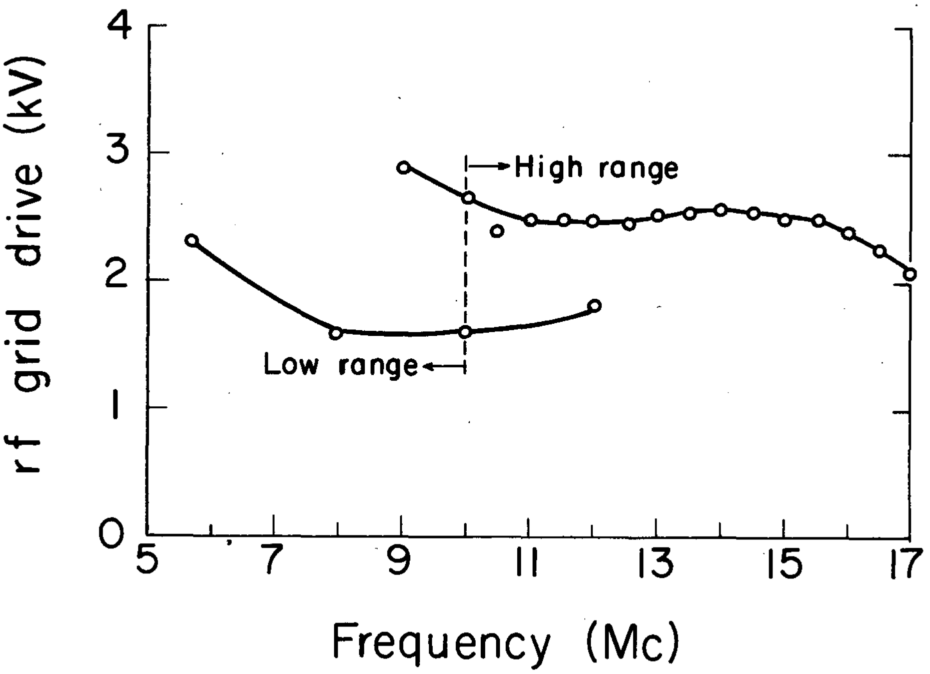

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Fig. 6. Oscillator rf grid voltage vs frequency for 70 kV dee voltage. Below 10 Mc the grid-line capacitor switch shown in fig 5a is closed. It moves the line''s quarter-wave mode down to 3.5 Mc and prevents excessive grid drive at the low end of the range.

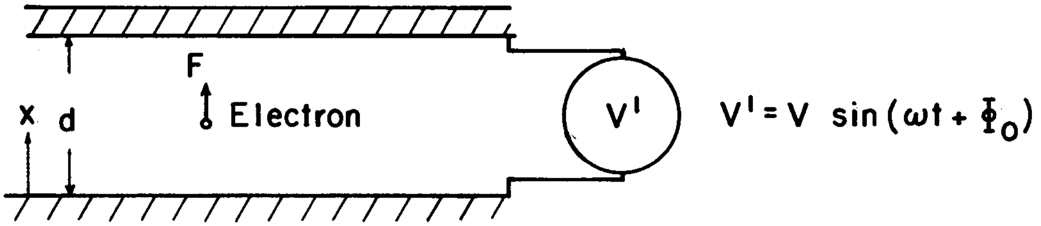

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Fig. 7. Multipactoring geometry.

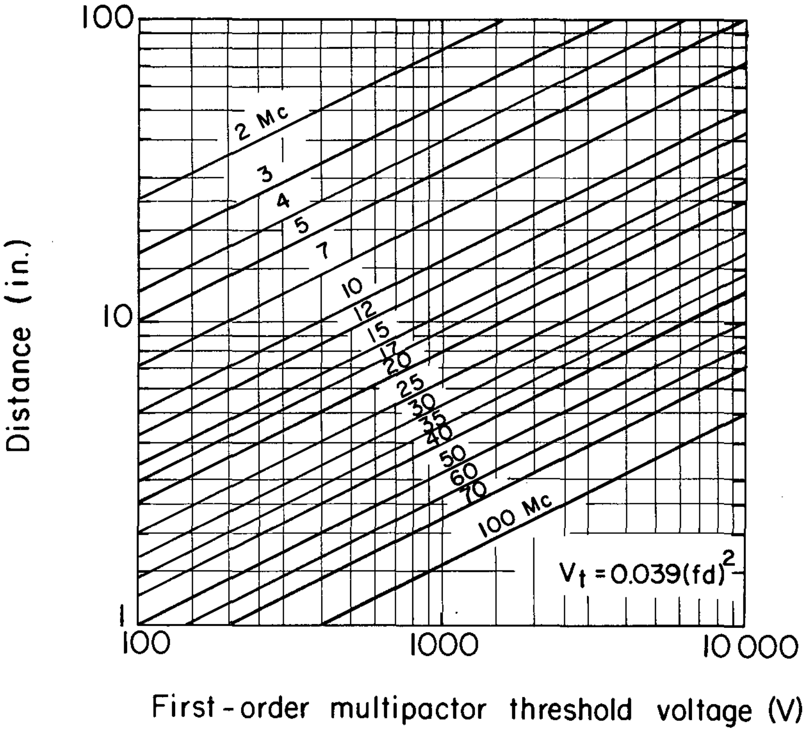

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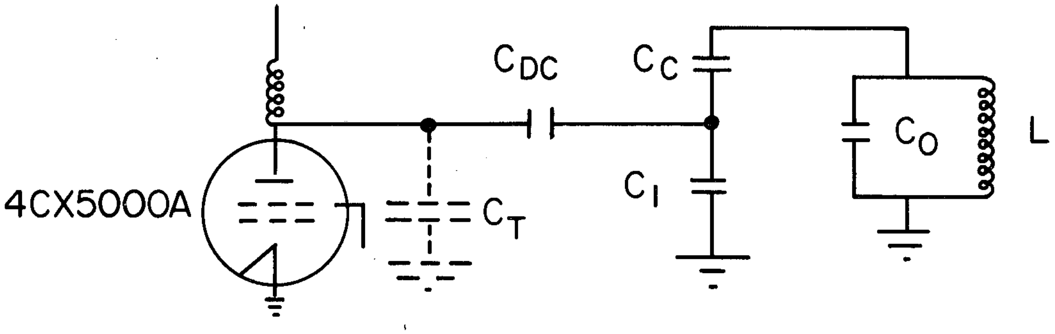
Fig. 8. First-order multipactoring threshold voltage vs spacing.

ANODE CIRCUIT OF THE PRE-EXCITER



$L =$ dee stem inductance

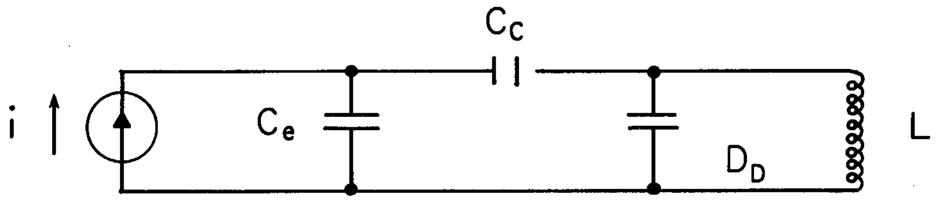
$C_D =$ dee capacitance $= 2000$ pF

$C_C =$ pre-exciter coupling capacitance $= 25$ pF

$C_I = 100$ pF

$C_T = 50$ pF

EQUIVALENT CIRCUIT



$C_e = 150$ pF

$C_c = 25$ pF

$C_d = 2000$ pF

MUB-1003

Fig.9. Anode circuit of the pre-exciter, and its simplified equivalent.