

Some Experiments on the Radiofrequency System of the Improved Kyoto University Cyclotron

Noboru FUJIWARA, Takao OHSAWA, Toshihiro MIYANAGA,
Dai Ca NGUYEN*
Kiyoji FUKUNAGA, and Shigeru KAKIGI**

Received October 15, 1973

Characteristics of the R. F. System of the improved cyclotron are described. The frequency of the R. F. system varies from 10 MHz to 19 MHz by changing the position of the shorting plate inside the resonant line. Frequency trimming is possible with a capacitor and a inductive loop. Two step excitation method is applied to get high dee voltage without suffering from the multipactoring phenomena.

I. INTRODUCTION

The cyclotron of Kyoto University built in 1955 was shut down in 1970 to be re-modeled.*** The design principle of the modification was twofold. First, the renewed cyclotron should be able to accelerate charged particles of $e/m=2/3$ and also of $e/m=1/2$. Second, the renewed cyclotron should be of energy variable from its maximum value down to 70% of this value. The feasible magnetic field strength of the cyclotron is from 18 kgauss down to 15 kgauss. Then the frequency range of the R. F. system should be from 15 MHz to 18 MHz for the acceleration of $e/m=2/3$ particles and from 11 MHz to 14 MHz for the acceleration of $e/m=1/2$ particles. Therefore, the frequency range was designed from 11 MHz to 18 MHz. In practice, a quarter-wave single-dee resonator tunes through this frequency band when the shorting plate at the end of the resonant line is moved to adjust the value of the dee-stem inductance. The fine tuning is accomplished automatically by a motor-driven capacitor coupled to the dee and also by a motor-driven loop coupled to the dee-stem. The peak voltage, dee to ground, was expected to be more than 100 kV at any frequency.

The resonator is coupled to the oscillator anode through a movable coupling electrode. The step-up ratio of the dee voltage to that of the anode can be kept constant by adjusting the capacitance between the coupling electrode and the resonator even if the radiofrequency was changed by a large amount. The resonator is driven by a self excited cyclotron oscillator. The R. F. output power of the oscillator is limited by the power tube and is 120 kW. The power supply, 200 kW at its maximum, is of a type

* 藤原昇, 大沢孝夫, 宮永俊博, 阮 大哥: Laboratory of Nuclear Reaction, Institute for Chemical Research, Kyoto University, Kyoto.

** 福永清二, 柿木茂: Nuclear Science Research Facility, Institute for Chemical Research, Kyoto University, Kyoto.

*** The details of the cyclotron modification is reported in the succeeding article.

of a six phase full wave rectifier. Its output D. C. voltage is regulated automatically by a inductive voltage regulator.

The design parameters and the results obtained about this R. F. system are described in the following sections. Further, the multipactoring process and the R. F. oscillation build-up process are discussed in detail in the last section.

II. THE RESONATOR AND THE FEEDER

Cross sectional view of the radiofrequency system is shown in Fig. 1. The capacitance between the dee and the liner surfaces is calculated to be 240 pF when the gap width between them is 42 mm. The resonant frequency of the R. F. system was measured as a function of the length of termination and the range was 10 MHz through 19 MHz. The results are shown in Fig. 2.

The R. F. voltage and current distribution in the resonator were calculated and are shown in Fig. 3. Based on the R. F. current distribution and the geometry of the resonator, the R. F. skin losses and the "Q-values" were calculated by neglecting the contact resistance of the shorting plate. These values are given in Table I together

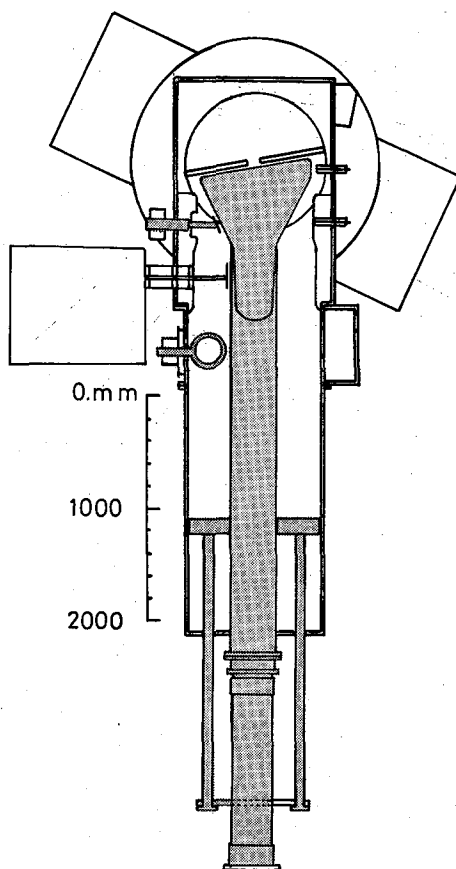


Fig. 1. Cross sectional view of the radiofrequency system.

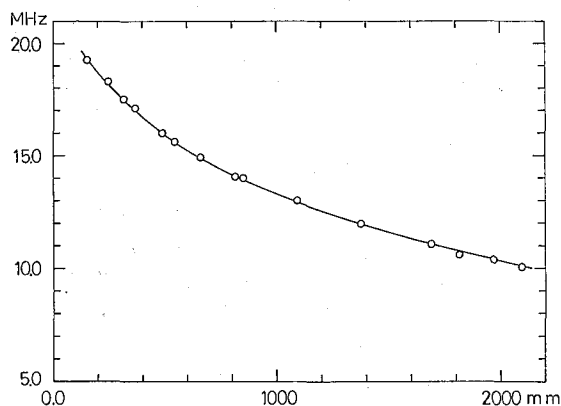


Fig. 2. Measured R. F. frequency as a function of the position of the movable shorting plate.

with the circuit constants of the equivalent lumped resonator circuit, which is shown in Fig. 4.

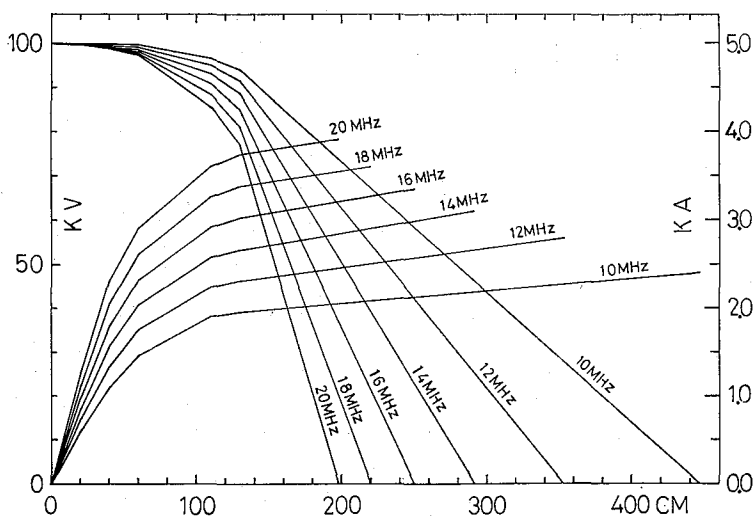


Fig. 3. R. F. voltage and current distribution in the resonator.

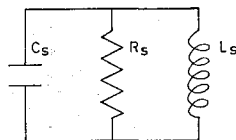


Fig. 4. Equivalent resonator circuit.

The resonator is coupled to the oscillator anode with a feeder which consists of a movable capacitive plate followed by a transmission line. The length of the transmission line was designed as short as possible to keep the resonance frequency of the feeder far apart from the frequency band of the resonator. The components of the

feeder are shown in Fig. 5. The characteristic frequency of this feeder was measured to be 30.4 MHz.

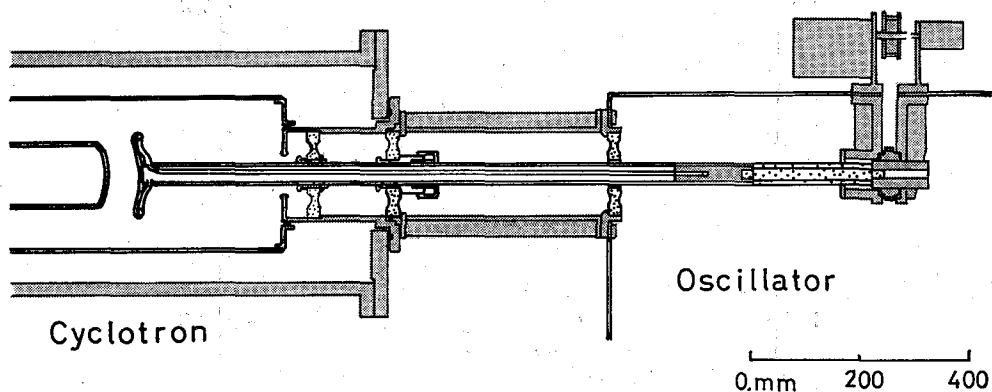


Fig. 5. Cross sectional view of the feeder.

Table I. Calculated Circuit Constants of the Equivalent Resonator Circuit.

F(MHz)	$L_S(\mu H)$	$C_S(PF)$	$R_S(M\Omega)$	W(KW)	Q	$C_T(PF)$
10.0	0.794	320	0.543	9.40	10900	444
12.0	0.578	306	0.442	11.3	10200	396
14.0	0.447	289	0.378	13.2	9620	366
16.0	0.357	280	0.325	15.4	9120	344
18.0	0.289	271	0.278	18.0	8520	329

The load resistance R_p of the resonator seen by the oscillator anode were measured with an impedance meter as a function of the distance D between the dee-stem and the coupling plate and also as a function of the resonator frequency when the grid resonant circuit was removed. In this case, the oscillator consists effectively of a capacitance C_p only. The results are shown in Figs. 6 and 7. The values of the load resistance depend strongly on the contact condition of the shorting fingers of the shorting plate. The shorting fingers are pressed against the dee-stem with the pressurized air. The values in Figs. 6 and 7 were measured at 2 atm. The load resistance at 1 atm is one fourth of the value at 2 atm and it is constant above 2 atm.

The ratios of the dee voltage V_{dee} to the oscillator anode R. F. voltage V_p were measured at 11.0 MHz and 13.0 MHz as a function of the distance D . The results are shown in Fig. 8.

The shunt resistance R_s of the equivalent resonator circuit were calculated by using

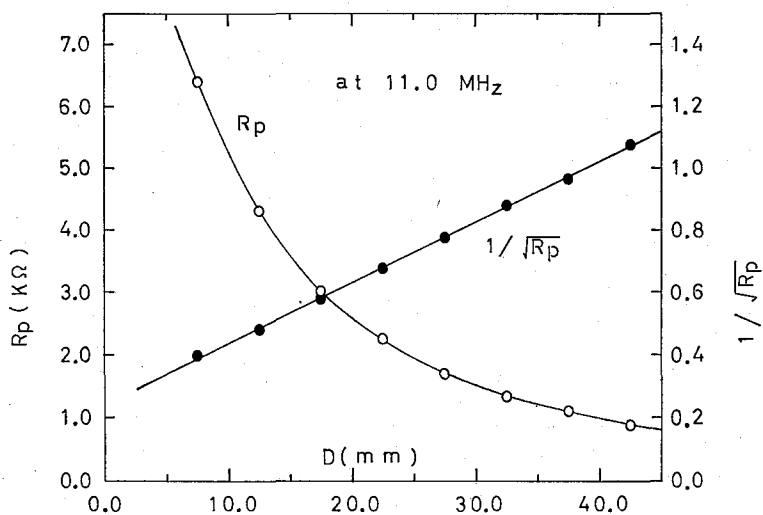


Fig. 6. Load resistance of the resonator seen from the feeder input point as a function of the distance between the dee-stem and the coupling condenser plate.

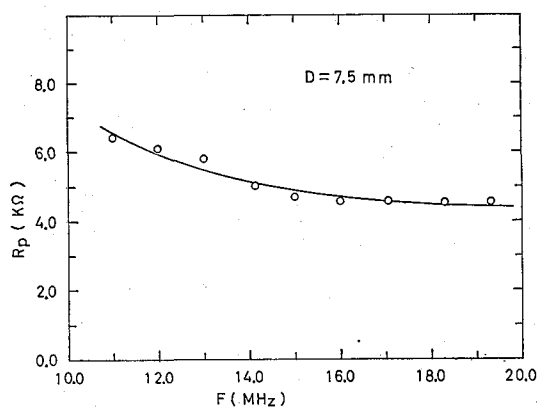


Fig. 7. Load resistance of the resonator seen from the feeder input point as a function of the resonant frequency.

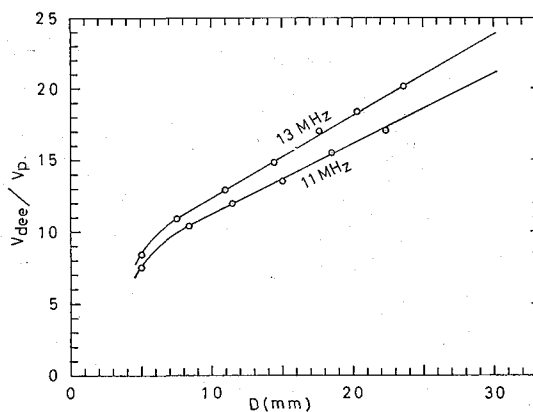


Fig. 8. Step-up ratios as a function of the distance between the dee-stem and the coupling condenser plate.

the formula

$$R_s = R_p \times (V_{dee}/V_p)^2,$$

and are given in Table II. The Q -values of the resonator were calculated by the formula

$$Q = R_s \times C_s \times \omega$$

and are given also in Table II. C_s is the capacitance of the equivalent resonator circuit. These values were determined at 11.0, 13.0, and 18.0 MHz by measuring the frequency shift Δf of the resonator when an extra capacitance ΔC was coupled between the dee and the liner. ΔC was selected to be 50 pF and 100 pF. The values of C_s are deduced by extrapolating the values obtained at $\Delta C = 100$ pF and $\Delta C = 50$ pF to the value at $\Delta C = 0$. The deduced C_s -values are close to the value obtained at $\Delta C = 50$ pF. The results are shown in Table II. The Q -values were determined separately by measuring

Table II. Measured Circuit Constants of the Equivalent Resonator Circuit.

F(MHz)	$L_s(\mu H)$	$C_s(PF)$	$R_s(M\Omega)$	W(KW)	Q_I	Q_{II}
11.051	0.713	291	0.460	10.9	9760	9290
13.032	0.489	305	0.336	14.5		8410
18.300	0.310	244	0.178	28.1		5000

the half decay time T of the dee voltage. To do this measurement, the self-excited oscillator using a single 7T40 triode was driven with a cut-off bias which was controlled with a mercury relay and was supplied to its grid. A typical decay form of the dee voltage is shown in Fig. 9. In this case, the Q -values were calculated by the formula

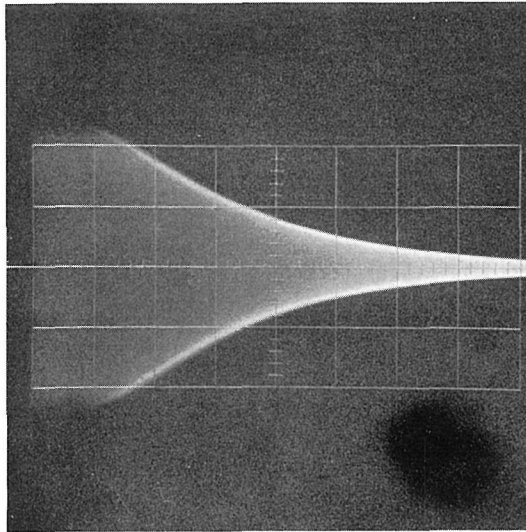


Fig. 9. Typical decay form of the dee voltage at 11.0 MHz. Horizontal scale: 100 μ sec/cm.

$$Q = (2\pi \times f \times T) / (2 \times 0.632)$$

where f is the resonant frequency of the cyclotron resonator. The results are also given in Table II. The Q -values obtained from two different methods coincide with each other.

The measured circuit constants of the equivalent resonator circuit are almost equal to the calculated ones given in Table I except for the values at 18 MHz. The maximum dee voltage hitherto obtained in our test acceleration of hydrogen molecular ions was 120 kV.

III. THE OSCILLATOR

Figure 10 shows a schematic drawing of the oscillator circuit. The cyclotron resonator is driven by a self excited main oscillator. A shortcoming of the self-excited oscillator is that it suffers from the well known low-voltage electron loading phenomenon called the "multipactoring". To overcome the multipactoring, a pre-exciter was prepared and was coupled to the grid of the main power tube. The main power tube works as a power amplifier until the dee voltage becomes larger than a critical value over which the oscillation is self-sustained.

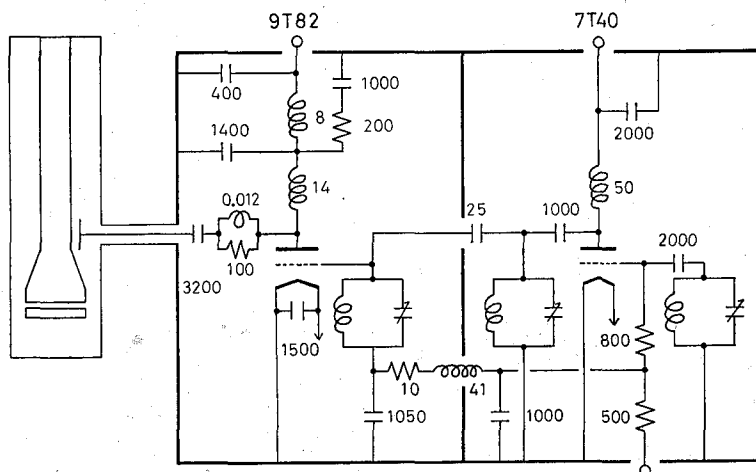


Fig. 10. Schematic drawing of the oscillator circuit. Capacitances, inductances and resistors are expressed in pF, μ H, and Ω , respectively.

(1) The Main Oscillator

The main oscillator is of a tuned-grid tuned-plate self-excited oscillator. It is equipped with a single water- and forced-air- cooled NEC 9T82 triode. The capacitance C_{pg} between a plate and a grid is 85 pF and the capacitance C_{gk} between a grid and a cathode is 100 pF. The grid current is controlled by adjusting a variable condenser of the grid tank circuit. The maximum input power is 300 kW and the plate loss is about 120 kW. The oscillator circuit is designed to be as simple as possible to avoid parasitic oscillations. The standing wave in the feeder is not built

up because that a corresponding resonant circuit is absent in the grid circuit. Moreover, the proper oscillation of the feeder is suppressed by inserting a resistor of 100Ω and an inductance of $0.012\mu\text{H}$ in parallel between the feeder and the oscillator anode. A parasitic oscillation caused by a plate filter circuit and a grid filter circuit remains and its frequency is about 1 MHz. This oscillation is suppressed by inserting a resistor of 100Ω and a capacitance of 1000 pF in series between a choke coil and the ground and by inserting also a resistor of 10Ω in series with a grid choke coil as shown in Fig. 10. To avoid an unwanted oscillation, the grid of the main tube is biased by minus 150 volts.

Typical working conditions are given in Table III. The input power of the main tube is about 30 kW to excite the dee voltage of 100 kV. The output power W_{out} of the main tube is calculated from the Q -value given in Table II. The efficiency of the main tube is calculated to be about 52%. Of course, this value varies according to the feed back ratio and to the gap width of the coupling condenser.

Table III. Typical Working Conditions of the R.F. System.

$V_{\text{dee}}(\text{KV})$	70.0	80.0	90.0	100.0
$V_{\text{p}}^{\text{dc}}(\text{KV})$	3.10	3.55	4.10	4.60
$I_{\text{p}}^{\text{dc}}(\text{A})$	4.35	4.95	5.60	6.30
$V_{\text{g}}^{\text{dc}}(\text{KV})$	0.81	0.93	1.06	1.19
$I_{\text{g}}^{\text{dc}}(\text{A})$	1.62	1.85	2.12	2.38
$V_{\text{p}}^{\text{rf}}(\text{KV})$	3.00	3.50	3.95	4.38
$V_{\text{g}}^{\text{rf}}(\text{KV})$	1.24	1.42	1.60	1.78
$W_{\text{in}}(\text{KW})$	13.5	17.6	23.0	29.0
$W_{\text{out}}(\text{KW})$	7.30	9.50	12.1	14.9
$\eta (\%)$	54.1	54.0	52.6	51.4

$$D=25\text{ mm} , F_0=13.055\text{ MHz} , f_g=17.5\text{ MHz}$$

(2) The Oscillator Power Supply

The oscillator plate voltage is regulated with an induction regulator. Three phase primary power is transformed into six phase power with a rectifier-transformer. A six phase full wave rectifier employing silicon diodes can supply up to 20 amperes at 8 kV. At present, the maximum power needed to excite the R. F. system is estimated

to be 60 kW, therefore, the power supply has a sufficient allowance. The maximum and minimum plate voltage with no load are 8.4 kV and 3.7 kV respectively. The ripple in the power supply with no load was measured and is 0.2% without a filter circuit.

(3) The Pre-exciter

The pre-exciter is of a tuned-plate, tuned-grid circuit employing a NEC 7T40 triode. It is coupled weakly to the grid of the main tube. The output power of the pre-exciter is about 2 kW. The pre-exciter oscillation is interrupted automatically by the self biased voltage of the main tube when the main oscillator become self-exciting. The frequency of the pre-exciter is shifted automatically by some 20% from the resonant frequency of the cyclotron. The main oscillation is built up just when the frequency of the pre-exciter coincides with the resonant frequency of the cyclotron. The circuit of the pre-exciter is shown in Fig. 10 together with the circuit of the main oscillator.

(4) The Control System of the Oscillator

The control system of the oscillator was designed to operate the equipments either locally or centrally and was designed also to operate the oscillator following a definite time sequence for the safety of the oscillator. The external interlock which works by signals from the other equipments such as the vacuum system or the cooling system of the resonator is provided for the safety of the oscillator and of the other equipments.

IV. THE FREQUENCY COMPENSATOR

The constant frequency of the resonator is accomplished by using the capacitance compensator and also the inductance compensator. The capacitance compensator is designed to compensate the change of the resonant frequency quickly. This compensator can shift the resonator frequency by 30 kHz and 50 kHz at 11.0 MHz and 18.0 MHz respectively. The construction of the capacitance compensator is shown in Fig. 11. Figure 12 shows the shift of the resonant frequency at 18.2 MHz as a function of the distance D between the dee and the capacitance plate. Figure 13 shows the maximum shift width ΔF_M of the resonant frequency as a function of the resonator frequency.

The inductance compensator is designed to compensate a slow change of the resonant frequency such as the change with temperature. A rate of the frequency shift is 2 kHz/sec and 10 kHz/sec at 11.0 and 18.0 MHz respectively. This compensator can shift the resonant frequency by 20 kHz and 100 kHz at 11.0 MHz and 18.0 MHz respectively. The structure of the inductance compensator is shown in Fig. 14. Figure 15 shows the shift of the resonant frequency at 18.2 MHz as a function of the rotation angle of the loop. Figure 13 shows the maximum shift width ΔF_M of the resonant frequency as a function of the resonator frequency. The shift width depends directly on a current density of the resonator. Therefore, it depends on the position of the shorting plate. As shown in Fig. 13, the frequency dependence of the shift width is very sensitive.

The frequency shift due to the mechanical deformation of the resonator caused by the temperature rise is very small and it does not exceed 5 kHz even when the

beam is loaded. The frequency compensator is automatically regulated by a digital signal from a frequency comparator.

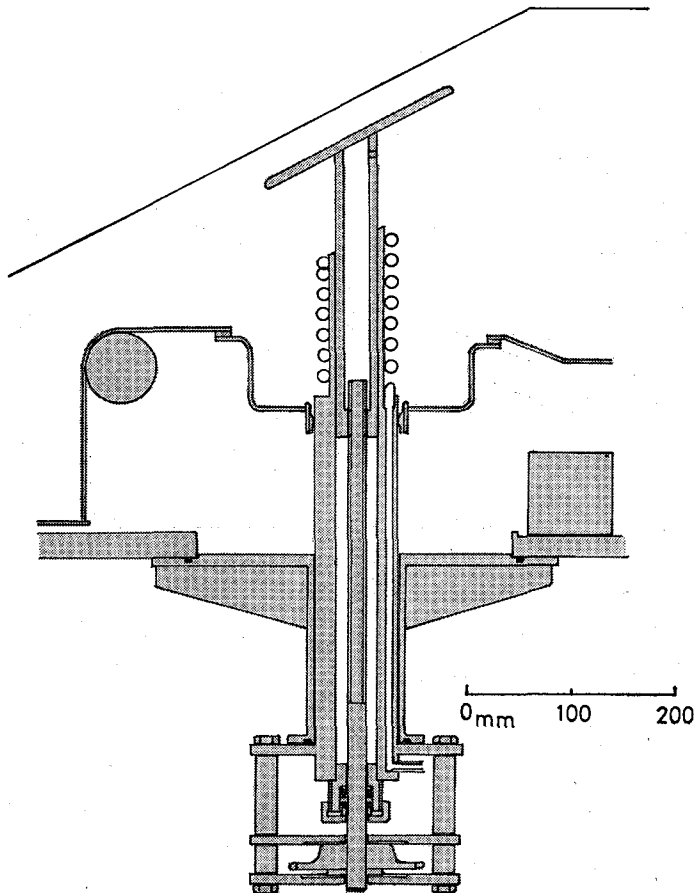


Fig. 11. Cross sectional view of the capacitance compensator.

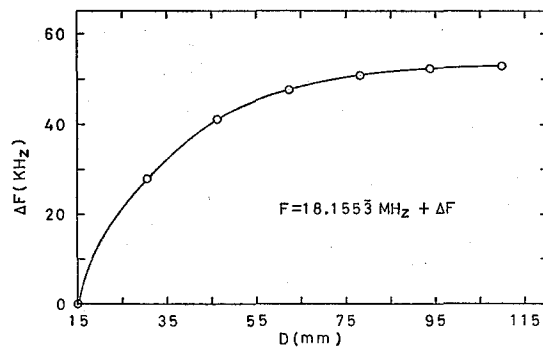


Fig. 12. Shifts of the resonant frequency as a function of the distance between the dee and the capacitance plate.

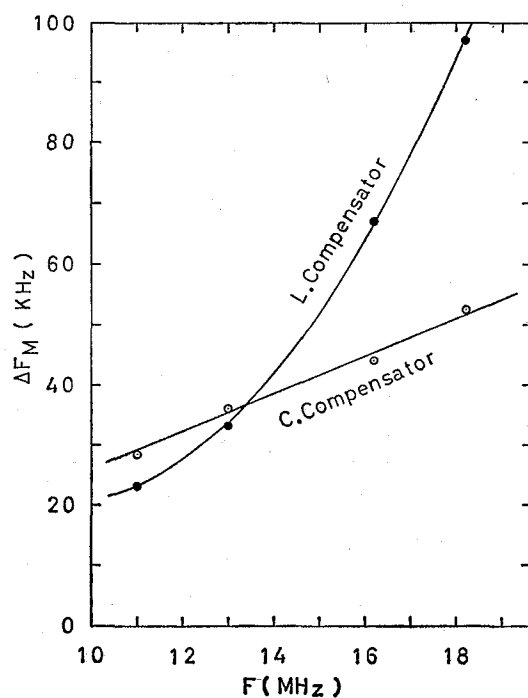


Fig. 13. Maximum shift width of the resonant frequency as a function of the resonator frequency.

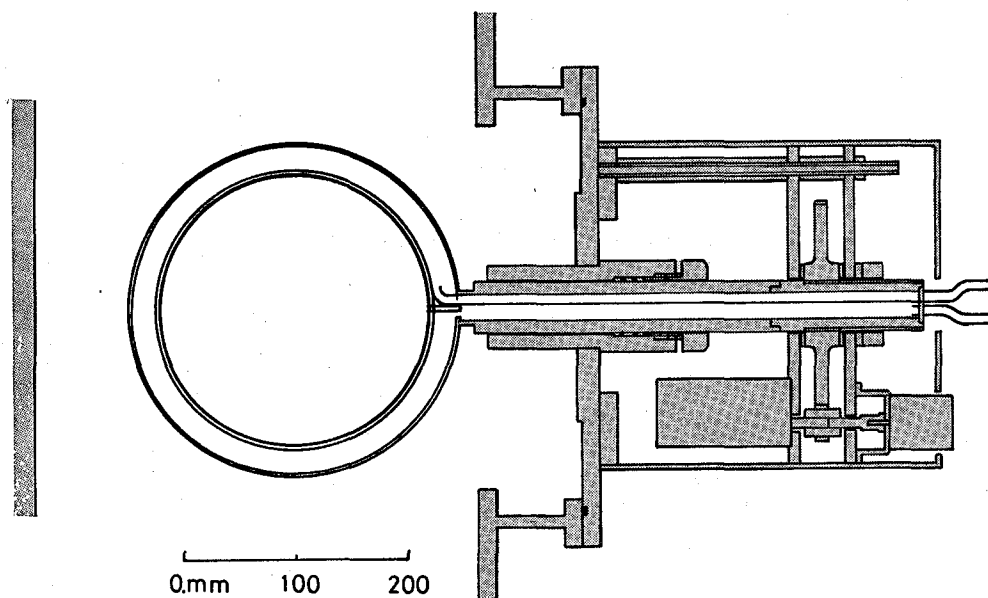


Fig. 14. Cross sectional view of the inductance compensator.

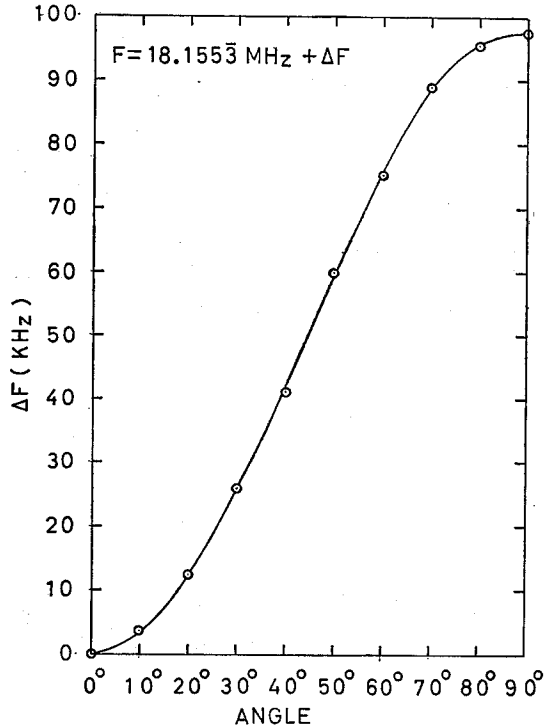


Fig. 15. Shifts of the resonant frequency as a function of the rotation angle.

V. THE DEE VOLTAGE PICK UP CONDENSER

The R.F. voltage of the dee is picked up simultaneously by two pick up condensers. The one was designed to pick up the dee voltage free from the resonator frequency using a capacitive divider. The other was terminated in a 75Ω real impedance which is the same value as the characteristic impedance of the cable and is used for frequency measurement. It is also used as an automatic control device of the frequency. The structure of these condensers are shown in Fig. 16. The circuit of the dee voltage meter is shown in Fig. 17. The calibration curve of the meter was obtained using by the JENNINGS ITT R. F. VOLTAGE METER. The result is also shown in Fig. 17.

VI. THE RELATION BETWEEN THE BUILD-UP TIME OF THE OSCILLATION AND THE MULTIPACTORING PHENOMENON

In this section, the experimental results on the multipactoring phenomenon are discussed. Both resonators of old and renewed cyclotron were used to clarify this phenomenon.

It is well known that if an oscillating potential is applied between two opposing 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 phenomenon occurs in a cyclotron

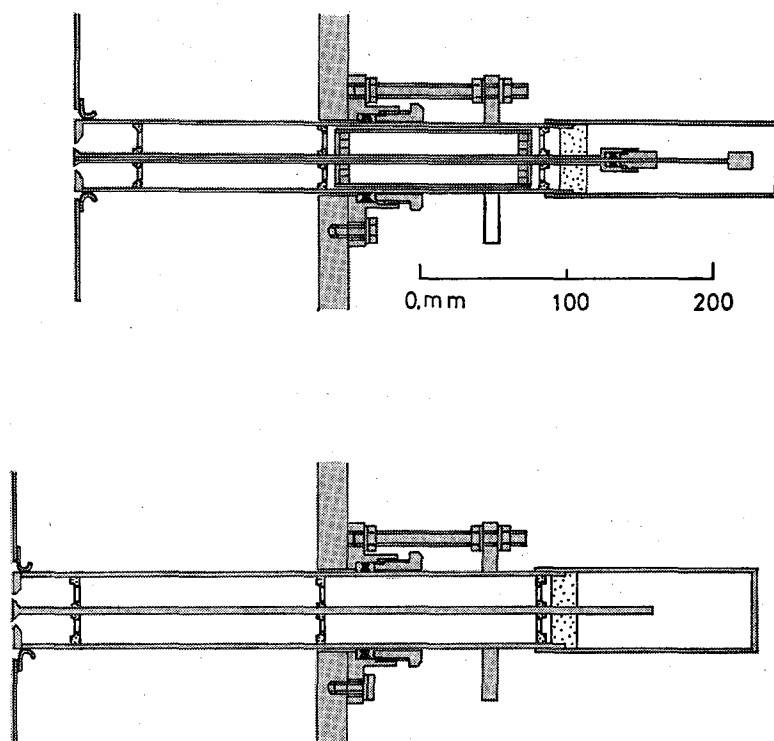


Fig. 16. Cross sectional views of the dee voltage pick-up condenser.

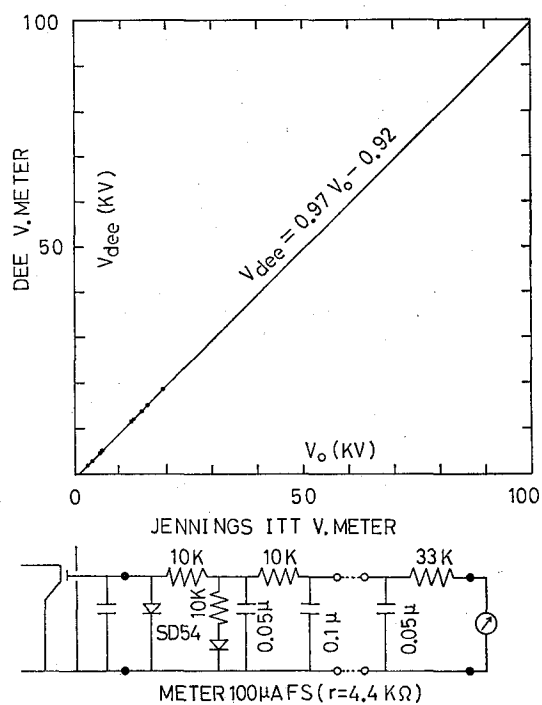


Fig. 17. Calibration curve of the dee voltage meter and its circuit.

resonator, it produces such a heavy load on the oscillator that the dee voltage cannot build up. The threshold multipactoring voltage V_{th} is given by Eq. (1) as a function of the distance d between two surfaces.

$$V_{th} = \frac{m/2e \cdot (\omega \cdot d)^2}{\left\{1 + \left[(2n-1) \cdot \frac{1}{2}\pi\right]^2\right\}^{\frac{1}{2}}} \quad (1)$$

The integer n determines the order of the multipactoring. At threshold, the energy gained by an electron is

$$E_{th} = \frac{V_{th} \left[(2n-1) \cdot \frac{1}{2}\pi\right]^2}{\left\{1 + \left[(2n-1) \cdot \frac{1}{2}\pi\right]^2\right\}^{\frac{3}{2}}} \quad (2)$$

The upper limit of multipactoring voltage V_{up} is given by Eq. (3).

$$V_{up} = \frac{m}{2e} (\omega d)^2 \quad (3)$$

At the upper limit voltage, the energy gained by an electron equals to zero.

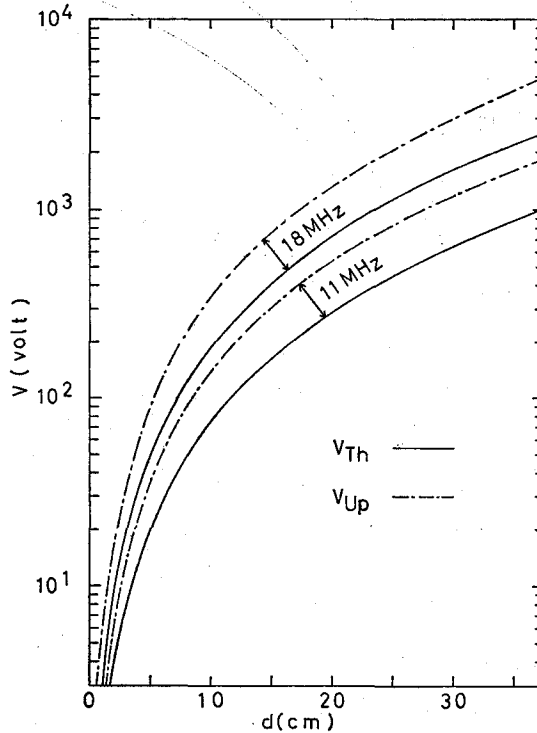


Fig. 18. First order multipactoring threshold voltage and upper limit voltage as a function of the distance between two opposing surfaces.

Figure 18 shows first order multipactoring threshold voltage V_{th} and the upper limit voltage V_{up} as a function of distance d at 11 MHz and 18 MHz. The range of the voltage in which the multipactoring phenomenon occurs is about 1 kV at $d=20$ to 30 cm. The energy gained by an electron at the threshold voltage 18 MHz is shown in Fig. 19. As shown in Fig. 19, the energy gained by an electron in the higher-order multipactoring is very small compared to that of the first order. The electron energy range in which the secondary-electron multiplication factor is larger than unity is from 200 eV to 2 keV, if the resonant line is made up from copper.

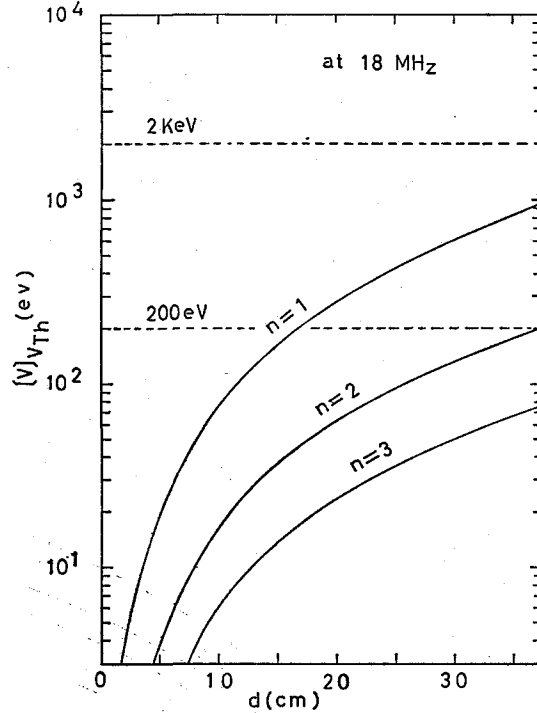


Fig. 19. Energy picked up by the electrons at the threshold voltages.

Therefore, the multipactoring phenomenon cannot occur between the dee and the liner surfaces. It must occur at around a very limited place of the dee-stem, especially at the linking part between the dee and dee-stem, the neck. It is most probable that the multipactoring phenomenon in the old cyclotron should occur when the dee voltage is of a few kV which corresponds to the critical voltage at the neck. In the case of the former cyclotron, the relation between the voltage and the tube input power at 13 MHz is as shown in Fig. 20. This datum was obtained by using a small power oscillator equipped with a 7T40 triode and a capacitive coupling to the dee. As seen in Fig. 20, the dee voltage range in which the multipactoring occurs is from 0.5 kV to 4 kV and is consistent with the above analysis.

Assuming that the multipactoring in the first-order occurs at $t=0$, number N of electrons at $t=t$ is given by the following equation

$$N = N_0 \times \delta^{2ft} \quad (4)$$

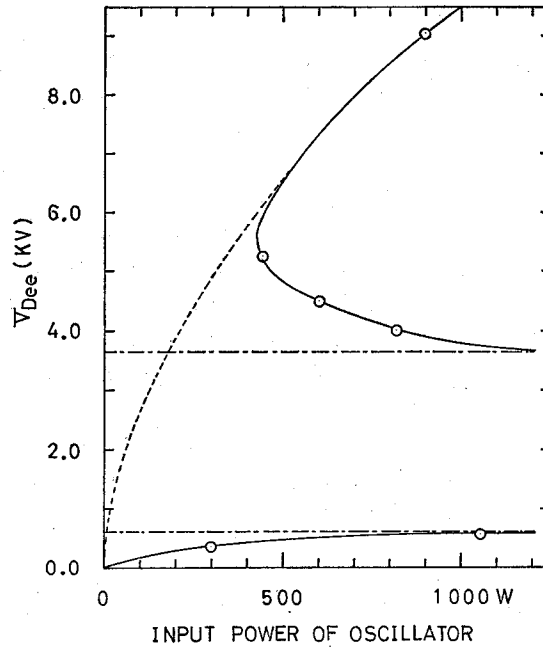


Fig. 20. Relation between the dee voltage and the tube input power at 13 MHz.

where N_0 is a primary electron number and δ is a secondary-electron multiplication factor. The consumed power W_M by electrons is given by Eq. (5).

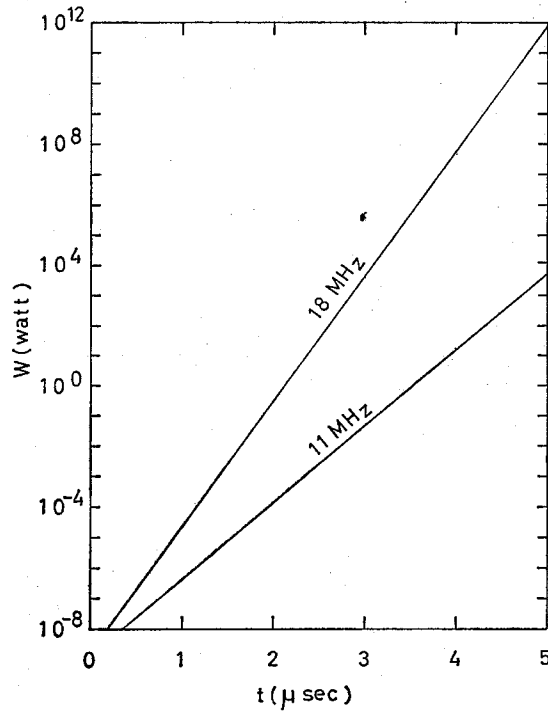


Fig. 21. Build up time of the multipactoring at 11 MHz and 18 MHz.

$$W_M = 3.20 \times 10^{-19} \times [2f \cdot \bar{E} \cdot N_0 \cdot \delta^2 s'] \text{ watt} \quad (5)$$

where $\bar{E}$ is an average electron energy in eV. Figure 21 shows the loading due to the multipactoring at 11 MHz and 18 MHz as a function of time assuming $N_0=1$, $\bar{E}=400$ eV and $\delta=1.3$.

As shown in Fig. 21, the multipactoring grows up and results in a heavy load to the oscillator in a few μ sec. As mentioned above, the voltage range in which the multipactoring occurs is about 1 kV. Therefore, to avoid the loading due to the multipactoring, the build up rate of the dee voltage should be larger than 1 kV/ μ sec.

To assure this prediction, the build up time of the dee voltage of the former cyclotron was observed. A cut-off bias was applied to the grid of 7T40 triode in a pulse form with the aid of a reed relay. The maximum dee voltage was 10 kV. The build up rate of the dee voltage was estimated at the dee voltage of 3 kV and was about 0.5 kV/ μ sec. Under this condition, the oscillation grows up easily without suffering from the multipactoring phenomenon. Therefore, to overcome the multipactoring phenomenon in our present R. F. system, two step change of the distance of the coupling capacitor of the R. F. system is needed. That is, the distance is held narrow at the time of switching on the oscillator and then the gap is widened to make the dee voltage high. In our remodeled cyclotron, the coupling capacitance can be moved quickly even when the main oscillator is excited.

Test operation of our R. F. system shows that, if the distance of the coupling capacitor is adjusted to give maximum dee voltage of 30 kV at the beginning of the free running oscillation, the dee voltage grow up without suffering from the multipactoring phenomenon even if no pre-exciter is used. In the present stage of the cyclotron, electric discharge occurs frequently and results in the break down of the oscillation, so that this two step method is somewhat annoying and unpractical. However, in near future, the R. F. system will be replaced by the two-step method when the warming up of the cyclotron operation becomes sufficient and discharge occurs seldomly, because of the simplicity of the R. F. system and of no parasitic oscillations.

ACKNOWLEDGMENTS

We would like to acknowledge the late Professor Y. Uemura and Professor T. Yanabu for their kind advices and encouragements throughout this work. Also we would like to thank Mr. T. Shimayama and Mr. H. Yoneta of Fuji Electronic Industrial Co. for their patient co-operation.