2.1. Introduction:

The cyclotron consists of two semi-circular shaped copper electrodes known as the dees, placed at a distance apart and are connected to two short circuited transmission lines known as the dee stems kept in vacuum, as shown in Fig. 2.1. The capacitances formed by the dees with the chamber linings, together with the inductances presented by the dee stems, form two capacitively coupled high Q antiresonant circuits. For accelerating ions which are introduced by placing an ion source in between the dees, a magnetic field is applied at right angles to the planes of the dees and a radio frequency electric field across the dees. The frequency of the electric field is equal to the cyclotron resonance frequency of the ions, \( \frac{eB}{m} \); \( e \) and \( m \) are the charge and mass of the ion and \( B \) is the magnetic field. Due to the combined action of the electric and magnetic field, positive ions ejected from the ion source move in circular orbits inside the dees and gain energy from the electric field during transit across the dee gaps. Thus, in order to obtain high energy particles, the oscillator supplying the radio frequency electric power is required to be of high power output and to oscillate at the cyclotron resonance frequency with good stability.

The electronic oscillator used earlier in cyclotron was essentially a separately excited system, consisting of a master oscillator coupled to a power amplifier which was again coupled to the dee system inductively by means of transmission lines. The separately excited system involved troubles
FIG. 2.1

Schematic Diagram of the Cyclotron Dee System
of neutralisation and difficulties of tuning due to several coupling systems. The oscillator used in cyclotrons now-a-days is almost universally of the type described by Backus and others. It is a grounded grid self excited oscillator where the tuned circuit represented by the dee system are used to be the resonant circuit of the oscillator.

In the cyclotron, the radius of the orbit of the ions increases with increases of ion energy. However, due to relativistic effects, as the mass of the ions increase with increase in energy for a fixed frequency of the oscillators, ions cannot be accelerated to orbits of diameter more than approximately 60°. This set an upper limit for the energy of the ions accelerated by the fixed frequency cyclotrons. In the synchrocyclotron, by so altering the oscillator frequency that the synchronism exists with the ion cyclotron resonance frequency for all energies of the ions, it is possible to accelerate ions to several hundreds of Mev energies by synchrocyclotrons. Conventional frequency modulation cannot be used at higher radio frequency power levels in the dee system of the synchrocyclotrons.

The resonant system of the synchrocyclotron consists of a single dee and a dee stem; the other end of the dee stem is connected to a variable capacitor instead of being shorted as in cyclotrons, shown in Fig. 2.2. Frequency modulation is achieved mechanically, by rotating the capacitor by a motor, in vacuum. The desired change of the resonant frequency with time can be attained by specially designing the capacitor. The mechanical frequency modulation system was first developed by Schmidt and was further discussed by Mackenzie, in designing this radio frequency system for the Berkeley synchrocyclotron.
**FIG. 2.2**

Schematic Diagram of the Synchrocyclotron Dee System
Parasitic oscillations are generally excited in the grounded grid oscillators for both cyclotrons and synchrocyclotrons. These oscillations are sometimes excited at the near harmonic mode of the fundamental. Oscillations are also excited at the transmission line frequencies which may be due to the connecting transmission lines and the tube capacitances.

In the present chapter the design details of the grounded grid cyclotron and synchrocyclotron oscillators are discussed. The problems associated with parasitic excitations will be discussed in the following chapters.

2.2. General Considerations Regarding the Design of the Cyclotron Oscillator:

An ion of charge \( e \) e.s.u. and mass \( m \) gm. moves in a cyclotron having a uniform magnetic field \( B \) gauss, with a velocity \( v \) normal to the field, will describe a circle of radius \( r \) cm. The angular frequency of revolution is given by

\[
\omega = \frac{v}{r} = \frac{eB}{mc} \quad \ldots \quad (2.1)
\]

where, \( c = \) velocity of light.

The maximum radius \( R \) cm. attained by the ions for acquiring energy of \( V \) electron volts is

\[
V = \frac{150B^2R^2c}{mc^2} \quad \ldots \quad (2.2)
\]

The cyclotron resonance frequency may be obtained from Eq. (2.1), and the diameter of the dees from Eq. (2.2) for a given energy \( V \). An
alternating electric field is necessary across the dees for ion acceleration to high energies. The frequency of this field is equal to the cyclotron resonance frequency of the ions and falls in the radio frequency region. The output power of this radio frequency oscillator when connected to a cyclotron develops equally between the two dee tank circuits, maintaining a voltage $E_d$ between the dee and the chamber linings. The oscillator power $P$ is related to the circuit $Q$, the impedance of the dee circuit at resonance $R$, and the peak dee to ground voltage $E_d$ by the following equation

$$P = \frac{E_d^2}{2R} = \frac{\pi f C E_d^2}{Q} \quad \cdots \quad (2.5)$$

where $C =$ Dee to ground capacitance.

An example is taken for a cyclotron accelerating deuterons to 20 MeV with a magnetic field of 15 kilogauss, the dee diameter in this case as obtained from Eq. (2.2) is found to be nearly 60". The oscillator frequency in this case is nearly 11.5 Mc/s for deuterons. The Q of an actual dee circuit including ion loading measures about 5000. The dee to ground capacitance is experimentally measured and is approximately 600 $\mu F$ for the cyclotron. The peak dee to ground voltage necessary is 100 KV for such machines. The oscillator power may now be obtained from Eq. (2.3) and is found to be 40 kW for 100 KV peak on each dee. Hence the total power of the oscillator for the two dees is 80 kW.

The equivalent electrical circuit of a cyclotron is shown in Fig. 2.3. The inductances represented by the dee stems are denoted by $L_1$, $L_2$ and $C_1$, $C_2$ are the respective dee to ground capacities. $C'$ is the
FIG. 2.3

Equivalent Circuit of the Cyclotron Dee System
dee to dee coupling capacitance. \( L_1, C_1 \) and \( L_2, C_2 \) determine the two resonant frequencies of the dee system. However, the two resonant frequencies are identical when \( L_1 = L_2 = L, C_1 = C_2 = C \) and \( R_1 = R_2 = R \). In this case the circuit can oscillate in phase with equal voltages to ground and the voltage across \( C' \) is zero. \( C' \) may be removed and the two dee circuits may now be electrically separated without affecting the oscillations. Thus, these oscillations may be one of the possible modes in a cyclotron and the frequency of oscillation at this mode, known as the parallel mode, is given by

\[
\frac{1}{2\pi \sqrt{LC}} \quad \ldots \quad (2.4)
\]

In the parallel mode of oscillation the dee to ground voltages are in phase and the r.f. voltage across the dees, i.e. across \( C' \) is zero. Oscillations at this mode however, do not accelerate ions hence are unwanted mode in cyclotron.

By considering Fig. 2.3 one may assume a ground conducting plane midway between the two plates of \( C' \) isolating them from each other. One may then argue that each dee circuit may start oscillating with equal voltages to ground but with 180° out of phase. The grounded plane may now be removed without affecting the oscillations, and this mode is known as the push-pull mode of oscillations for the circuit and the frequency of oscillation in this case is given by

\[
\frac{1}{2\pi \sqrt{L(C+2C')}} \quad \ldots \quad (2.5)
\]
Oscillations of the dee circuit at the push-pull mode accelerates ions. Hence, the radio frequency oscillator is to be so adjusted that oscillations at this mode may be established.

It has been discussed earlier that power requirements for cyclotron oscillators are usually high, and for high energy machines radio frequency oscillators are sometimes designed for 80 to 100 kW. The type of tube now-a-days used is Machlett ML-5681, which is a high power, water and forced air cooled transmitting triode with transconductance of 0.05 mho and amplification factor = 25. The oscillator is operated under class-C condition with the drive applied at the cathode and the grid is grounded radio frequencies by a ring of six 1000 μF vacuum capacitors. These capacitors are placed on the rim of a hollow copper dish, connected to the grid of the tube. This arrangement is made to reduce coupling between the anode and cathode of the tube. The coupling through the tube is however small owing to very small anode-cathode capacitance, which is 2 μF for ML-5681. The grounded grid oscillators with cathode drive have advantages over the conventional grid drive circuits. The drive applied at the cathode reduces the chances of excitation of parasitic oscillations, which are otherwise excited in the oscillator with grid drive, mainly through the grid plate capacitances of the tube. A typical operating condition of the tube for a given power output may be calculated easily from the tube characteristics. Table I showing the operations of the tube for two different power outputs, of which oscillator operation at 77 kW output will be used. The circuit components of the oscillator should be so designed that r.f. voltages and currents appear with proper magnitudes at
line of length \(d\)', the system will be resonant at an angular frequency, \(\omega_0\), given by the following expression:

\[
\frac{1}{\omega_0 C_d} = Z_0 \tan \frac{2\pi d}{\lambda} \quad \ldots \quad (2.6)
\]

where \(Z_0\) = characteristic impedance of the line. However, the characteristic impedance, \(Z_0\), of a co-axial transmission line may be related to its inner and outer diameters \(d\) and \(D\) inches, respectively, by the following equation

\[
Z_0 = 138 \log \frac{D}{d} \quad \ldots \quad (2.7)
\]

The characteristic impedance of the dee stem is usually 72 \(\Omega\) and is made of co-axial copper tubes: the inner conductor is made of a hollow copper tube of diameter about 6" and the outer one with 20". \(C_d\) is usually 600 \(\mu F\). From Eq. (2.6) one may now determine the approximate length of the dee stem line. This is roughly, within 5 to 6 feet in length from the dee capacitance to the short circuit.

It should be remembered that the dee to ground voltages should be 180° out of phase with each other for ion acceleration. Let us denote these quantities by \(E_{d1}\) and \(E_{d2}\) respectively. When an r.f. voltage is established at the dees the voltage and current standing wave patterns along the dee stem lines will be as shown in Fig. 2.4. A voltage maxima is accompanied by a current minima and vice versa. The solid and dotted lines represent respectively the voltage and current waves along the dee stem transmission lines. The oscillator is coupled inductively to the dee system by means of two loops, one of which is connected to the plate, the
Voltage and current standing wave patterns along the Cyclotron dee stems.
other to the cathode of the oscillator tube via two transmission lines. The position of the coupling loops are almost equidistant along the dee stem. The coupling loops are usually made from 1" dia. copper tube bent in the shape of U and is projected to the dee stem tank to via two insulators in vacuum. A voltage $E_1$ induced in series with the loop by the dee stem current $I$ and $E_1$ is related to the dee stem current $I$ by $E_1 = j\omega MI$, where $M$ is the mutual coupling coefficient. Thus, the loop induced voltage leads the dee stem current by 90°. The loop voltage $E_l$ is related to the dee to ground voltage $E_{d1}$ by the following expression:

$$E_l = \frac{L \log_2 \left( \frac{b-c}{b-a} \right)}{L \log_2 \left( \frac{b-a}{a} \right)} \cdot E_{d1} \quad \ldots \quad (2.8)$$

the symbols are explained in Fig. 2.5. Eq. (2.8) shows that the loop voltage is in phase with the dee voltage $E_{d1}$ and increases with the depth of the loop inside the dee stem tank. The peak dee to ground voltage $E_{d1}$ is to be 100 KV, $a$ and $b$ the radii of the inner and outer conductor of the dee stem are known quantities; hence the variation in the magnitude of the induced voltage with permissible values of depth in the dee stem tank is known. The length of the dee stem line $L$ is already determined and this is 5.5 feet.

The voltages induced in series with the loops at the ends of the dee stem lines are 180° out of phase with each other because the dee stem currents are 180° out of phase with each other. This is however possible when the signs of the mutual inductances between the respective loop and the dee stem is positive. For opposite signs of the mutual inductances, the
respective induced voltages in the loops are in phase maintaining 180° phase shift between the respective dee to ground voltages. One end of each loop is connected, respectively to the plate and cathode of the oscillator tube by two transmission lines and the other ends are connected to ground in series with a capacitance.

In grounded grid oscillators the plate and cathode to ground r.f. voltages should be in phase with each other for oscillations to occur at the fundamental frequency. Hence, the phase shift between the loop induced voltage and the anode to ground voltage, along the plate transmission line and the phase shift between the loop voltage and the cathode to ground voltage, along the cathode line should be adjusted to be equal. This statement is true for opposite signs of the mutual couplings. The above argument is important regarding the design of the lengths of the transmission lines.

2.4. Design of the Transmission Lines:

The plate and cathode of the oscillator tube is coupled to the dee system by means of two transmission lines and loops. The schematic diagram of an actual radio frequency oscillator for use in cyclotron is shown in Fig. 2.6. The tube end of the plate transmission line is terminated by the anode to grid capacitance, in parallel with a small variable capacitance. The maximum current pulse under the class-C condition occurs when the anode swing is minimum and therefore represents a current which is in antiphase with the anode to ground voltage.
FIG. 2.6
Schematic diagram of the Cyclotron oscillator.
This can be represented by a negative resistance, which is of course a source of power. Thus looking at the anode side of the oscillator tube, one may find a negative resistance in parallel with a capacitance to ground. The current through the resistance is in phase with the anode to ground voltage while the current through the capacitance is leading the anode to ground voltage by 90°. Hence, the total current is the vector sum of these two as shown in Fig. 2.7. The tube end of the anode transmission line is connected to a parallel combination of a negative resistance and a capacitance whereas the other end is terminated by a loop in the dee tank, the other end of the loop being connected to an open circuit stub line. In order to calculate the length of the anode transmission line the impedances on both sides of the line as well as the voltages and currents at these ends must be known. The impedances are essentially complex and voltage and current standing waves are formed on the line. Theoretically, the ratio of the loop induced voltage to the voltage at the plate side of the anode line along with the impedances at both ends of the line, may be calculated according to Fig. 2.8. The formulae involving the loop induced voltage $E_l$ and the plate to ground voltage $E_{pg}$ for an electrical length $x^o$ of a transmission line is given by

$$\frac{E_l}{E_{pg}} = \left[\left(1 + \frac{X_l}{X_L}\right) \cos x + \left(\frac{Z_r - X_L}{X_L}\right) \sin x\right] + j \left[\frac{X_l \cos x + Z_o \sin x}{-R_L}\right]$$ ... (2.9)

the above symbols are explained in Fig. 2.8. $Z_o$ is the characteristic impedance of the line. On examining Eq. (2.9) one observes that it consists of a real part and an imaginary part. The magnitude of $E_l/E_{pg}$ may be obtained from the absolute magnitude of Eq. (2.9) and the ratio
FIG. 2.7
Vector diagram of currents at the plate end of the oscillator tube.

FIG. 2.8
The transmission line connecting oscillator and cyclotron.
of the imaginary part to the real part will give the phase shift between the two voltages. The line length should be so chosen such that the phase shift is small. Also $E_1$, the loop induced voltage, should not be too large or too small, compared to the values obtained from Eq. (2.8) for possible depths in the dee stem tank when the peak dee to ground voltage is 100 KV. The order of magnitudes of $X_1$ and $X_L$ may be obtained by ascertaining correctly the inductance of the loop and the values of the terminating resistance and capacitance. The characteristic impedance of the anode transmission line is $80\Omega$. This is however realised by constructing inner conductor of the co-axial anode line with a copper tube of diameter $4\text{"}$ and the hollow outer conductor of diameter $16\text{"}$ from Eq. (2.7). The peak anode to ground voltage at the tube end of the line is also known from Table I in Sec. 2.2. By taking Eq. (2.9), now one may compute the magnitude of $E_1$ for various values of the line lengths from $20^\circ$ to $120^\circ$ and also the corresponding phase shift between $E_1$ and $E_{pg}$. The considerations discussed above keep the line length between $70^\circ$ to $90^\circ$. Line length of $75^\circ$ may be used in an actual case, by applying Eq. (2.8) the magnitude and the phase shift between $E_1/E_{pg}$ is calculated. The magnitude of $E_{pg}$ is known hence the magnitude of $E_1$ is known. The value of the loop induced voltage $E_1$, may be matched correctly by adjusting the position of the loop in the dee stem tank. Small values of $E_1$ should not be chosen as the phase shift between $E_1$ and $E_{pg}$ will be larger.

For the cathode line design the same argument as used for designing the length of the anode line is employed. The cathode end of the line is terminated by a parallel combination of a positive resistance and the cathode
to grid capacitance. The positive resistance in this case indicates the loss of power at the cathode. The dee stem end of the cathode transmission line is terminated in a loop and a variable capacitance in series. The combined reactance of the cathode loop side may however, be obtained by knowing the loop inductance and the range of the variable capacitance. These values fix $X_1$, shown in Fig. 2.8. The value of the positive resistance, $R_k$ may be determined from the driving power and the peak cathode to ground voltage. The reactance of the cathode to grid capacitance, $X_k$ at the working mode of the oscillator, i.e. at 11 Mc/s, may be found out. Eq. (2.9) may now be written in terms of $R_k$, $X_k$, $E_{kg}$ and $E_L$ by the following equation

$$\frac{E_L}{E_{kg}} = \left[ (1 + \frac{X_1}{X_k}) \cos x + \left( \frac{Z_o}{X_k} \right) \sin x \right] + j \left[ \frac{X_1 \cos x + Z_o \sin x}{R_k} \right] \quad \text{(2.10)}$$

The characteristic impedance of the cathode line is usually kept at 78 Ω by using co-axial hollow copper tubes of diameters 2" and 7" respectively. Eq. (2.10) may be used for various line lengths $x$, such that the phase shift between $E_L$ and $E_{kg}$ for the cathode line, is made identical with that of $E_L$ and $E_{pg}$ for the plate line calculated earlier. The induced loop voltage corresponding to this value will be about four times higher than that at the cathode side of the oscillator tube. Computation shows that an electrical line length of about 100° will suit the purpose. This will keep the phase shift between $E_L$ and $E_{kg}$ small and equal to that between $E_L$ and $E_{pg}$. From the magnitude of $E_L/E_{kg}$ calculated for 100° length, $E_L$, the induced loop voltage at the cathode line end may be determined, since the value of the peak driving voltage at the cathode,
is known from Table I in Sec. 2.2. The length of the cathode line should
be such that $E_L$ is not too small or too large as can be obtained from
Eq. (2.8). The cathode loop voltage may then be adjusted by changing the
position of the loop inside the dee stem. The finer adjustments of the
phase shift can be performed by adjusting the variable capacitance in
series with the loop. This adjustment will alter $X_1$, the total reactance
in the cathode loop side, which changes the imaginary term in Eq. (2.10)
and hence alters the phase shift between $E_{kg}$ and $E_L$. The diameters of the
inner and outer tubes of the co-axial transmission lines used in these r.f.
systems are usually of big size for handling large radio frequency voltages
and currents.

2.5. Radio Frequency System of the Synchrocyclotron:

The energy of the accelerated particles could be increased
indefinitely by increasing the radius $R$ of the dees in a cyclotron as
is evident from Eq. (2.2). Increase of $B$ could have the same effect.
There are however material limitations to these problems. Firstly, the
magnetic field diminishes towards the periphery. Secondly, as the radius
increases, the higher velocity of the particles increases their mass due to
relativistic effects. This causes the electric angular frequency of the
particles for resonance $\omega = eB/\mu q$ to diminish. However, the resonance
condition of the particles may be established and acceleration to higher
energies would be possible if the frequency of the radio frequency oscillator
is varied in step with the relativistic increase of mass and also with the
drop of the magnetic field. The conventional FM circuits using reactance
tubes cannot be used as the tuned system has a very high $Q$ and has to handle
large radio frequency power. However, the frequency modulation may be achieved by mechanically rotating a condenser by a motor in series with the dee stem. This makes the design simpler and lowers the cost.

The synchrocyclotron dee system consists of a single dee, the dee stem and a rotating capacitance at the end of the dee stem. The other dee is grounded. The dee, dee stem and the rotating capacitance are kept in a chamber in vacuum. The schematic diagram of the synchrocyclotron oscillator is shown in Fig. 2.9. As has already been mentioned, the angular frequency of the ions moving in orbits in a synchrocyclotron gradually decrease up to the outer periphery due to relativistic increase of mass. The angular frequency of the particles is maximum near the centre of the dee and decreases slowly to the outer edges. When synchronism is maintained, the dee diameter can be increased for accelerating particles to higher energies. For accelerating deuterons to 190 MeV, the dee diameter is made usually 184". The upper frequency limit of the oscillator for deuterons is nearly 12.0 Mc/s at the centre and 9.8 Mc/s at the edge for the 184" machine at Berkeley, taking into account the magnetic field. For protons the frequency variation is from 25 Mc/s to 16 Mc/s from the centre to the periphery for the same machine. The necessary RF power required for the oscillator can be calculated from the following equation:

\[ P = \frac{\omega C_d V^2}{2Q} \]  \hspace{1cm} \cdots (2.11)

where \( C_d \) = Dee capacitance, \( Q \) = Quality factor of the dee system, \( V \) = Peak dee to ground voltage, \( \omega \) = Angular frequency of the oscillator. The experimentally measured value for the dee capacitance is 500 \( \mu \)F for the 184"
Schematic diagram of the Synchrocyclotron oscillator.

DEE VACUUM

DEE STEM

DEE VARIABLE CAPACITANCE

VACUUM

ROTOR INSULATOR

INDUCTION MOTOR

EARTHING CAPACITANCE

FILA TRANSFORMER

RECT
FIG. 2.10(a)

Standing wave pattern from the ice view of a synchrotron.

FIG. 2.10(b)

Standing wave pattern from the side view of a synchrotron.
at this frequency. The length of the line corresponding to the voltage node may, however, be found out from Eq. (2.12). The total length $L$ of the dee stem is then double the value so obtained from Eq. (2.12). The dee capacitance for the 184" cyclotron is $500 \mu F$ and the length of the dee stem is 7 meters. As the value of the rotating capacitance is increased the voltage node shifts towards the variable capacitance and the frequency of resonance of the dee is hence decreased. Let us consider Fig. 2.10b denoting the length of the dee stem by $L$, the dee capacitance by $C_D$. If $\omega_L$ is the lowest angular frequency corresponding to the final angular resonance frequency of deuterons near the edge of the dee, then the value of the variable capacitance $C_v$ necessary for resonance is given by

$$\frac{1}{\omega_L C_v} = Z_0 \tan \frac{2\pi}{\lambda_L} (L - x_L)$$  \hspace{1cm} \ldots \hspace{0.5cm} (2.13)$$

$$\frac{1}{\omega_L C_D} = Z_0 \tan \frac{2\pi}{\lambda_L} x_L$$  \hspace{1cm} \ldots \hspace{0.5cm} (2.14)$$

where $x_L$ is the length of the voltage node from the dee capacitance. $C_v$ may be found out by solving Eqs. (2.13) and (2.14) at a lowest frequency of 9.0 Mc/s for deuterons. The capacitance corresponding to this frequency is 1850 $\mu F$. Thus, the rotating capacitance should have a value from 500 $\mu F$ to 1850 $\mu F$ for deuteron acceleration.

The rotating capacitance is split into two capacitances and two sets of blades are placed on the rotor shaft as shown in Fig. 2.11. In the first part of the split capacitance, there are a set of fixed stator blades connected to the dee stem and one set of the rotor blades moves in between. In the second part of the capacitance, known as earth capacitance,
Diagram of the modulating capacitor.
the remaining set of blades on the rotor moves in between the fixed stator blades connected to ground. The rotating capacitance is therefore divided into two capacitances such that the high radio frequency voltages may be divided between these capacitances. The splitting is done in such a way that the maximum and minimum value of the combined capacitance equals the value stated above. Eight stator rings, each two feet in diameter with 24 teeth, are connected to the dee stem, the rotor having a matching set of seven discs. The rotor to ground coupling capacitor consists of seven rotor discs of identical shape in between a similar set of fixed grounded discs. The blades are made from copper plated steel plates. The rotor shafts are mounted on insulators in order to prevent by passing of r.f. currents. The entire system is kept at a pressure of $10^{-5}$ mm of Hg. The rotor is driven by an induction motor at a speed reaching the highest modulating frequency. The speed of the motor is usually 3000 rpm.

The oscillator used in synchrocyclotrons is usually a grounded grid self-excited oscillator used under class-C condition. It is coupled to the dee stem by means of two short transmission lines, terminated in two loops as shown in Fig. 2.9. The loops are placed near the voltage node and are oriented in such a way that the coupling between them may be neglected. The anode to ground and the filament to ground instantaneous voltages of the oscillator tube should be in phase for oscillations to occur at the dee frequency. The oscillator is coupled to the dee stem by transmission lines of such lengths that the dee voltage remains stationary irrespective of the frequency variation along the dee stem as shown in Fig. 2.12a. The calculation of the transmission line length is almost
similar as was discussed for cyclotrons in Sec. 2.4 by using Eqs. (2.9) and (2.10). The plate and the cathode lines are terminated at the tube ends by the respective plate to grid capacity in parallel to a negative resistance and the filament to grid capacity in parallel to a positive resistance. The other ends are coupled to the dee stem by loops. The voltage distribution along the plate transmission line for a fixed value of the plate to ground r.f. voltage, at different frequencies, is shown in Fig. 2.12b. The length of the plate line with the impedances at both ends is such that the variation of the radio frequency voltage at the loop end for different frequencies should be made to match the dee stem voltage variation at the corresponding frequencies near the loop, as indicated in Fig. 2.12a. The length of the plate line is less than at the highest operating frequency. The characteristic impedance of the line is about 80Ω.

The length of the filament line is obtained in the same fashion. The r.f. voltage variation with frequency near the cathode loop of the dee stem is matched to the voltage at the loop end of the cathode line. The voltage at the tube filament side remains the same due to the frequency variation. The fixed anode to ground and the filament to ground driving voltage should have the values specified from the operating characteristics of the tube for a given power output. However, this matching is accomplished by adding extra vacuum capacitors 50-100μF at the filament side. Sometime extra capacitors are placed near the voltage node of the filament line. The change in voltage with frequency at the coupling loop end of the line may be increased or decreased depending on which side of the node the capacitors are placed. The adjustments are done empirically for voltage matching at the
FIG. 2.12 (a)

FIG. 2.12 (b)

RF voltage variation at the coupling loop end of the dee stem and anode line with frequencies.
different frequencies as well as for correcting small phase shifts between the plate to ground and the filament to ground r.f. voltages. This line length is also nearly $\lambda/2$ and may be a few feet long.

As regards the excitation of the modes of oscillation in a synchrocyclotron, oscillation at the dee frequencies over the frequency modulation range are the wanted modes. Parasitic oscillations are also excited along with the dee frequencies including numerous overtones of a complex system. These overtones are sometimes greater than 100 Mc/s. They are eliminated by putting thyrite resistors at the voltage nodes of the plate and the filament lines. These resistors, however, absorb some power at the fundamental frequency and this lowers the amplitude of the dee voltage. Other high frequency parasitic oscillations due to the overtones of the stray tuned circuits are more difficult to eliminate.

2.7. Conclusions:

A brief review regarding the design of the radio frequency system of the cyclotron and synchrocyclotron is described. This review includes the working equations regarding the design of the dee stem, the lengths of the coupling transmission lines both for the cyclotron and for the synchrocyclotron. The excitation of the different r.f. voltages along different parts of these circuits, specified from the tube operating conditions, are maintained by adjusting different circuit components for optimum operation of the respective oscillators at the desired dee frequency.

Besides the desired dee frequency oscillations, various other high frequency oscillations are excited in these systems. The elimination of
some of these high frequency oscillations is achieved by placing rejection circuits. Others are more difficult to eliminate by circuit adjustments.

The excitation of all of the possible modes in both these systems has not yet been well studied. An extensive study may however establish criteria for the excitation of the right mode and elimination of the undesired ones. It is expected that these criteria will depend on circuit adjustments.