ON SOME HIGH-FREQUENCY OSCILLATIONS IN A REFLEX DISCHARGE

S.K. GUHARAY
Saha Institute of Nuclear Physics,
Calcutta, India

I. INTRODUCTION

Oscillations in a reflex discharge have been investigated by numerous workers. Depending upon the conditions of the discharge, viz. gas pressure, magnetic field strength, discharge current, discharge voltage and, above all, nature of cathodes, various kinds of oscillations can develop. Particularly, situations with cold cathodes, operating in the neighbourhood of $10^{-3}$ Torr, show up interesting results as both low- and high-frequency oscillations can occur there due to the presence of a radial electric field as well as a strong potential drop across the cathode sheath. It is important to examine the oscillations under various conditions of discharge parameters in order to characterize them. Such a study is warranted particularly on the low-frequency oscillations in a reflex discharge. The aim of the present work is to delineate a controlled experiment with a cold-cathode reflex discharge to acknowledge the nature of the low-frequency oscillations. It is observed that oscillations of frequency in the neighbourhood of the ion dynamics are excited through the interaction of counterstreaming electron beams with a background plasma.

Experimental arrangement is described in Section II. Experimental results and discussions are given in Section III and Section IV contains conclusion.

II. EXPERIMENTAL ARRANGEMENT

The schematic diagram of the reflex or Penning discharge, as used here, is shown in Fig. 1. The device has been described in an earlier article. The spacing between the two aluminium cathodes is 4.7 cm and its diameter is 1.8 cm. A number of Langmuir probes were used to measure the plasma parameters and to detect oscillations as well. An external dipole antenna was also kept for high-frequency pick-up from the plasma. The spectrum of the h.f. oscillations was studied by a Type 491 Tektronix spectrum analyzer.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Observations were made through wide ranges of pressure $p(5 \times 10^{-2} - 6 \times 10^{-18}$ Torr), magnetic field strength $B (100 - 1100$ G), and discharge current $I_d (5-200$ mA). In this operating region, oscillations were observed in two distinct frequency ranges: (i) low frequency ($1-20$ kHz) and (ii) high frequency ($10-100$ MHz). A typical example is shown in Fig. 2. To recognize the driving agent of the oscillations, two symmetric grid structures were inserted across the plasma column as shown in Fig. 1 and they were operated as follows:

1. grids kept floating, and
2. grids biased at anode (ground) potential.

It was observed that the situation corresponding to floating grids favoured the excitation of both low- and high-frequency waves; while for grids at anode potential, only high-frequency waves could appear. This suggested that the l.f. oscillations were due to some radial gradients of plasma parameters and that the h.f. oscillations could be due to the interaction of the counterstreaming electron
beams from the cold cathodes with the background plasma. The h.f. oscillations in the reflex discharge were studied and reported earlier. The results on h.f. oscillations will be discussed here.

For the excitation of the h.f. oscillations, discharge voltage was observed to bear the most significant role. At a particular gas pressure $p$, with either the decrease of discharge current $I_d$ keeping $B$ fixed or increase of the magnetic field for certain $I_d$, the h.f. oscillations gradually disappeared. In both the situations it was necessary to lower the discharge voltage. This revealed that, unless the potential drop across the cathode sheath was strong enough to render electron beams emitted from the cathode surface much more energetic than the thermal energy of the plasma electrons, the interaction of the electron beams with the background plasma could not yield growing waves.

The spectra of some of the oscillations recorded under various discharge conditions are presented in Fig. 3. Two distinct peaks were observed in all the plots. However, analyses have been made on the lower frequency component in each case. The frequency $f$ is determined from the relation

$$ f = f_0 + N\delta, $$

where $f_0$ corresponds to the centre of the reference coordinate, $\delta$ is the dispersion, and $N$ is the number of divisions the component $f$ is displaced from $f_0$ (+ve sign for displacement towards left and -ve for displacement towards right). The results corresponding to Fig. 3 are tabulated below.

<table>
<thead>
<tr>
<th>Case</th>
<th>Pressure $p$ (Torr)</th>
<th>Magnetic field B (Gauss)</th>
<th>Discharge voltage $V_d$ (volt)</th>
<th>Discharge current $I_d$ (mA)</th>
<th>Observed frequency $f$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>$3 \times 10^{-2}$</td>
<td>325</td>
<td>1500</td>
<td>200</td>
<td>14</td>
</tr>
<tr>
<td>(b)</td>
<td>$6.5 \times 10^{-3}$</td>
<td>325</td>
<td>1000</td>
<td>200</td>
<td>19</td>
</tr>
<tr>
<td>(c)</td>
<td>$6.5 \times 10^{-3}$</td>
<td>650</td>
<td>750</td>
<td>200</td>
<td>14</td>
</tr>
<tr>
<td>(d)</td>
<td>$6.5 \times 10^{-4}$</td>
<td>1100</td>
<td>600</td>
<td>200</td>
<td>13.5</td>
</tr>
<tr>
<td>(e)</td>
<td>$6.5 \times 10^{-4}$</td>
<td>1100</td>
<td>600</td>
<td>175</td>
<td>13.5</td>
</tr>
<tr>
<td>(f)</td>
<td>$6.5 \times 10^{-5}$</td>
<td>1100</td>
<td>600</td>
<td>150</td>
<td>13.5</td>
</tr>
</tbody>
</table>

It is noted that, apart from the result in the case of higher gas pressure ($3 \times 10^{-2}$ Torr), frequency of oscillation increases, in general, with the increase of discharge voltage. In other words, the variation of frequency occurs similarly as that of the energy of electron beams. However, as the collision free path of electrons is less at higher gas pressure $p$, the electron beams, while passing through the background plasma, cannot maintain their energy acquired from the potential drop across the sheath. At $p = 3 \times 10^{-2}$ Torr, the mean free path of electrons in nitrogen gas is about 1.5 cm corresponding to the case as referred; while for $p = 6.5 \times 10^{-4}$ Torr, the free path is about 68 cm. As the length of the plasma column is 47 cm, it is likely that the effective energy for interaction of the electron beams with plasma is reduced at higher pressure.
It is apparent that the observed frequencies can not be related to any characteristic motion of electrons; rather they are in the neighbourhood of frequencies involving ion dynamics. Such waves may grow due to the following three possibilities:

1. interaction of slow space charge wave on the beam with the forward plasma wave;
2. interaction of slow cyclotron wave with the forward plasma wave;
3. reactive medium amplification between ion-cyclotron and lower hybrid frequencies.

For the sake of simplicity, the analysis is made here using the dispersion relation for a filled waveguide following Vermeer. The potential disturbance in a cylindrical waveguide is taken of the form

\[ V = A J_\nu(p r) \exp(j \omega t - k z), \] (1)

where \( A \) is a constant, \( J_\nu(p r) \) is the \( \nu \)-th order Bessel function of the first kind, \( p \) and \( k \) are the transverse and axial wave numbers respectively. Assuming the signals to be weak to permit linearization of the relevant equations and also the quasi-static approximation \( v_{ph}^2/c^2 \ll 1 \) (\( v_{ph} \) being the phase velocity of the wave and \( c \) the velocity of light) to be valid, the dispersion relation for a filled wave guide is obtained as

\[ \omega^2 = -k^2 \frac{M}{N}, \] (2)

where

\[ M = 1 - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{pb}^2}{(\omega - \omega_{pb})^2}, \]

\[ N = 1 - \frac{\omega_{pi}^2}{\omega^2 - \omega_{ci}^2} - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2} - \frac{\omega_{pb}^2}{(\omega - \omega_{pb})^2 - \omega_{ce}^2}. \]

\( \omega_{pi}, \omega_{pe}, \omega_{ci}, \omega_{ce} \) correspond to ion-plasma, electron-plasma, ion-cyclotron and electron-cyclotron frequencies, respectively. \( \omega_{pb} \) is the plasma frequency of electron beam and \( v_b \) is its velocity. It can be shown that for the interaction of the cyclotron wave

\[ \omega = k v_b \pm \omega_{ce}, \] (3)

and for the space-charge wave

\[ \omega = k v_b \mp R \omega_{pb}, \] (4)

where \( \pm \) correspond to slow and fast waves, respectively, and \( R \) is given by

\[ R = \left(1 + \frac{v_b^2}{c^2}\right)^{-\frac{1}{2}}. \] (5)

In order to evaluate \( \omega \) from Eqs. (3) and (4), it is necessary to determine \( v_b \), density of beam electrons, \( k \), and \( p \).

Boksen12 showed that ions strike the cathodes with an energy approximately equal to the discharge voltage. So \( \omega_b \) may be taken that the secondary electrons (beam electrons) emitted from the cathode surface due to the bombardment of ions acquire velocity \( v_b \).
ponding to

\[ V_b \approx \sqrt{\frac{2eV_d}{m_e}} \]  

where \( V_d \) is the discharge voltage. The density \( n_b \) of the beam electrons is determined from

\[ n_b = \frac{I_b}{V_b \epsilon} \]  

where \( I_b \) is the beam current and \( \epsilon \) is the cross-section of the cathode surface. Backus measured the effective number of secondary electrons in a reflex discharge. Using these results, it is estimated that for the region of operation of the present discharge

\[ I_b = \frac{I_d}{3} \]  

So, from the Eqs. (6), (7), and (8) it is obtained that

\[ n_b = \frac{I_d}{3\pi e} \left( \frac{m_e}{2eV_d} \right)^{\frac{1}{2}} \]  

where \( r_b \) is the radius of cross-section of the beam (cathode). The density of beam-generated plasma electrons will be

\[ n_p = \frac{n \epsilon V_b \ell}{2 V_d} n_b \]  

where \( n \) is the density of neutral gas, \( \epsilon \) is the ionisation cross-section of electrons on neutrals, \( \ell \) is the length of the plasma column and \( V_d \) corresponds to the drain velocity of plasma, given by

\[ V_d = \left( \frac{eV_d}{m_e} \right)^{\frac{1}{2}} \]  

where \( K \) is the Boltzmann constant. For a typical case: \( p = 6.5 \times 10^{-6} \) Torr, \( B = 1100 \), \( V_d = 600 \) volt, and \( I_d = 200 \) mA, when \( K T_e = 20 \) eV, it is obtained that:

\[ V_b \approx 1.4 \times 10^9 \text{ cm/sec}, \]

\[ n_b \approx 3.5 \times 10^6 \text{ cm}^{-3}, \]

\[ n_p \approx 1.2 \times 10^8 \text{ cm}^{-3}. \]

Taking \( K = \frac{e}{m_e} \) and \( p \eta = 2.405 \) (\( \eta \) being the transverse scale length of variation of the r.f. potential disturbance), it is determined from Eqs. (4), (6), and (9) that growing wave would occur by interaction of the slow space charge wave with the forward plasma wave at frequency \( f_{int} \) (MHz)

\[ f_{int} = 0.633 V_d^{\frac{1}{2}} = 26.3 \frac{I_d^{\frac{1}{2}}}{V_d^{\frac{1}{2}}}, \]  

where \( V_d \) and \( I_d \) are in rationalized aks unit. Taking \( I_d = 200 \) mA, a curve for \( f_{int} \) versus \( V_d \) is plotted in Fig. 1. It is noted that the observed frequencies agree well with the calculated values. Eqn. (12) reveals that discharge voltage plays the most significant role in determining \( f_{int} \). The second term in Eqn. (12) involving \( I_d \) acts as a correction term. As in the results in Table I, variation of \( I_d \) was between 150-200 mA, its influence on \( f_{int} \) could not be detected. The spectral power density was observed to depend strongly on the discharge voltage and gas pressure. The amplitude is larger corresponding to higher values of interaction energy of beam electrons.
It was checked experimentally that, for the other types of interaction as mentioned earlier, the dependence of frequency on plasma parameters was different from the observed results. The characteristics of the higher frequency component in each spectrum could not be identified in the present experiment.

IV. CONCLUSION

Previous investigators observed various types of interactions in the present operating region of the discharge and oscillations from a few MHz to the range of GHz were reported. The significance of the present work lies in the observation of some r.f. oscillations (within a few tens of MHz) due to the interaction of counterstreaming electron beams with a background plasma in a cold-cathode reflex discharge. It has been established from the present study that, apart from the low-frequency gradient driven instabilities (frequency << ion-cyclotron or ion-plasma frequencies), growing waves in the neighbourhood of the characteristic ion-plasma oscillations could occur in a cold-cathode reflex discharge due to the interaction of the slow space charge electron beam wave with the forward plasma wave.

ACKNOWLEDGMENT

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REFERENCES

Fig. 1 Schematic diagram of the discharge system. K: Cathode, A: Anode, G: Grid

Fig. 2 For $p=7\times10^{-3}$ Torr, $B=320$ G, $I_d=45$ mA: (i) l.f. floating potential oscillation, sweep speed: $50 \mu s/cm$; (ii) h.f. spectral plot.
Fig. 3 Power spectra for discharge conditions (a)–(f) as in Table I. Ordinate: relative scale, $5 \text{ MHz/cm.}$

Fig. 4 $f_{in} \text{ Vs. } V_d$ plot; solid line: theoretical, ○: experimental.