PLASMA INSTABILITY IN A TOROIDAL DISCHARGE EXCITED BY A TRAVELING ELECTROMAGNETIC WAVE

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The stability of a plasma excited in a toroidal chamber by a traveling TE wave has been investigated experimentally. It is shown that this system is subject to beam-type instabilities due to the interaction between the azimuthal current and the plasma.

ALTHOUGH a traveling-wave system is of interest for plasma confinement,[1] the stability of such a system has not been investigated experimentally at the present time and has not been examined in detail theoretically.

In the present work we report on the effect of discharge parameters on the frequency of the oscillations observed in a traveling-wave system.

1. DESCRIPTION OF THE APPARATUS

The basic measurements were made in a toroidal glass chamber in which the discharge was excited by a traveling electromagnetic field. The traveling wave was produced by a helical delay line terminated in its characteristic impedance ($R_{char} = 16.5\ \Omega$).[2] The delay line was driven by a pulsed radio-frequency generator with the following characteristics: frequency, $f_g = 900$ kc, pulse length $\tau = 4$ msec, power $W_g = 250$ kW. The peak value of the traveling magnetic field at the inner wall of the chamber was 150 Oe. The line could support a longitudinal wave with a phase velocity $V_{ph} = 5.6 \times 10^7$ cm/sec. The toroidal chamber (major diameter $D_{av} = 180$ mm and minor diameter $d = 40$ mm) had four ports for pumping, gas admission, and for measurement probes.

The investigations were carried out with an initial vacuum of 10^{-6} mm Hg. The working pressures ranged from 4×10^{-3} to 1×10^{-1} mm Hg. Spectroscopic observations of the discharge in hydrogen showed only the Balmer series.

In Fig. 1 we show the distribution of the magnetic field component H_z along the diameter of the chamber in relative units. Curve 1 shows the field distribution with no plasma and curve 2 shows the field distribution in a hydrogen plasma at $p = 10^{-2}$ mm Hg.[2] The measurements were made with magnetic probes. It is evident from the figure that in the present experiment the minimum in the distribution of the radio-frequency magnetic field is due to the plasma alone. When the discharge is excited there is a partial mismatch between the delay line and the load resistance; this mismatch produces an inhomogeneity in the electromagnetic fields in the toroidal chamber.

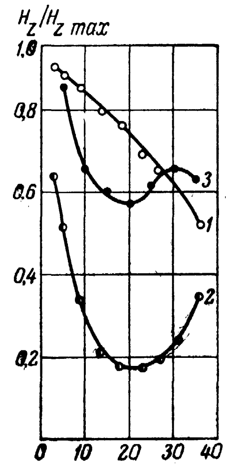

FIG. 1. Distribution of the H_z component of the radio-frequency magnetic field over the diameter of the chamber. Curves 1 and 2 apply for a device with a delay line terminated in its characteristic impedance while curve 3 applies for a device with a uniform (along the toroidal chamber) radio-frequency traveling wave. Curves 1 and 3 apply for the case in which there is no discharge.

For this reason some of the experiments were carried out with a traveling radio-frequency field that was uniform over the toroidal chamber; this field was produced by a helical delay line that closed on itself. Two generators, 90° out of phase, were connected to two points of the line at which the voltage was 90° out of phase. The line could support 8 wavelengths. At a pulsed power of 1 MW per generator and a frequency $f_g = 1.5$ Mc the peak value of the magnetic field at the inner wall

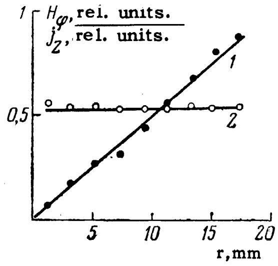

FIG. 2. The distribution of field H_φ (curve 1) and current density j_z (curve 2) over the radius of the chamber.

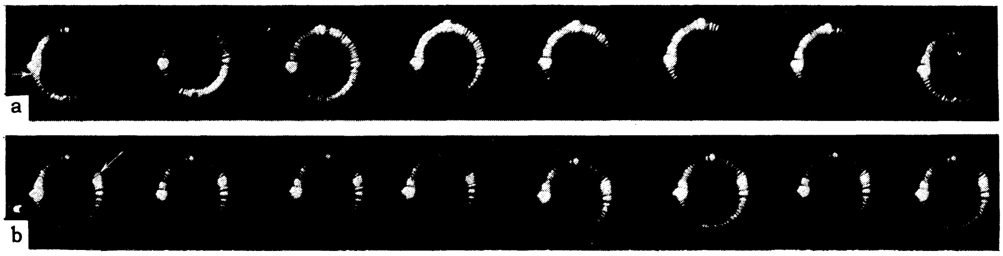

FIG. 3. Photographs of a discharge with $p = 2\times10^{-2}$ mm Hg. The traveling wave moves in the counterclockwise direction: (a) discharge without magnetic mirror (the arrow indicates the beginning of the delay line) b) discharge with a magnetic mirror field $H_{mir} = 125$ Oe (the arrow indicates the position of the magnetic mirror).

of the chamber was 1100 Oe with no plasma present. The field strength was reduced by approximately a factor of two with plasma in the chamber.

The magnetic field distribution along the tube diameter with no plasma for this configuration is shown in Fig. 3. The asymmetry in the magnetic field distribution with respect to the center of the tube is caused by the toroidal inhomogeneity and effects of the measurement ports.

A toroidal traveling-wave system produces a constant azimuthal electron current, i.e., a current J_z that flows along the major axis of the toroidal chamber. The current J_z is due to a force that acts on the electrons in the crossed electric (E_φ) and magnetic (H_r) fields;[3] this force is in the direction of motion of the traveling wave. In turn, the current J_z produces a constant magnetic field H_φ in the discharge chamber. The distribution of the H_φ field along the chamber radius in a hydrogen discharge was measured with magnetic probes (curve 1, Fig. 2). The distribution of the current density j_z was obtained by graphical differentiation of the H_φ distribution (curve 2, Fig. 2).

The current density j_z and the density of charged particles n_e were then used to determine the ordered electron velocity v_{drift} in the z direction. At a generator power of 250 kW and a pressure of 2×10^{-2} mm Hg we find $v_{drift} = 10^7$ cm/sec.

The charged particle density was determined by double electric probes[4] and monitored by microwave transmission at 8.15 and 4.07 mm. The azimuthal currents were measured with a Rogowski loop and the optical emission was observed with a photoelectric unit. High-speed photographs of the discharge were taken with an SFR-1 camera.

2. RESULTS OF THE MEASUREMENTS

The investigations indicate that plasma instabilities arise over a wide range of gas pressures and magnetic fields; these instabilities manifest themselves by oscillations in the particle density, the optical emission, the azimuthal current, and the amplitude of the radio-frequency magnetic field. The oscillations are nonsinusoidal but the frequency and amplitude do not vary by more than 15% in a typical measurement time interval (500 μsec). Hence, to some approximation the envelope of the probe signal can be expanded in a Fourier series. In all tables and curves given below the frequencies refer to the fundamental only.

The oscillation frequencies depend on the strength of the radio-frequency magnetic field H_z. The following data apply for $p = 2\times10^{-2}$ mm Hg:

H_z, Oe	80	90	105	140	150
J_z, A	190	300	380	430	530
f, kc	5	7.5	10.4	14	25

The oscillation frequency increases with increasing field, as does the pressure range over which oscillations can be supported. At a peak azimuthal current $J_z = 530$ A oscillations are observed over the whole range of working pressures, 10^{-1} to 4×10^{-3} mm Hg.

At low gas pressures $4\times10^{-3} - 4\times10^{-2}$ mm Hg and high azimuthal currents the oscillations occur throughout the pulse; at the higher pressures the oscillations appear only at the end of the pulse. The presence of impurities in the discharge reduces the range of pressures over which oscillations can be observed and can damp them completely in some cases.

In Table I we show the frequency of oscillation of the azimuthal current, the current to the double probe, the optical emission, and the amplitude of the radio-frequency magnetic field as functions of pressures at times $t = 0.5$ msec and $t = 3$ msec (the time reference is the beginning of the radio-frequency pulse). For a given time and pressure the frequencies of the oscillations detected by the double probes, the magnetic probes, the Rogowski loop, and the photoelectric unit all coincide to within the experimental errors.

The microwave measurements can not detect clearly sharp changes in the density of charged

Table I

	t = 0.5 μsec					t = 3 μsec				
		f, kc					f, kc			
100 p, mm Hg	10^{-13} n_i, cm^{-3}	Rogowski loop	double probes	optical emission	magnetic probes	10^{-13} n_i, cm^{-3}	Rogowski loop	double probes	optical emission	magnetic probes
0.8	–	2.5	2.4	2.2	–	–	–	–	–	–
1	–	16.3	17.2	12.9	13.1	–	4.6	7.5	2.9	4.0
2	11.9	23.8	25.0	18.3	23.3	5.5	9.5	10.8	11.3	–
4	12.7	19.0	20.8	19.1	18.0	5.9	13.8	13.6	12.9	14.0
6	15.3	17.8	18.3	16.7	21.0	6.4	12.5	11.3	11.2	12.0
8	15.4	16.0	18.7	16.7	20.0	6.5	10.0	8.0	10.1	10.2
10	15.5	15.1	16.0	13.5	18.4	6.95	12.5	13.5	9.5	10.4

particles in the discharge. However, at pressures for which the oscillations could be seen on the microwave signal the frequencies were the same as those shown in Table I.

In Fig. 3 we show photographs of the discharge in a toroidal chamber photographed from above by a high-speed camera (SFR) operated in the framing mode. The time interval for 8 frames is 80 μsec. It is evident from Fig. 3a that a longitudinal optical-emission wave is produced in the chamber and that this wave travels at a velocity of 7×10^5 cm/sec in the same direction as the traveling rf wave. These patterns appear in the pressure range and at the time at which oscillations appear in the current to the double probes, the azimuthal current, and the radio-frequency magnetic fields. The double-probe measurements show that the period of rotation of the emission wave T_{SFR} (data obtained with the SFR) is equal to the period of oscillation of the current to the probe T_{probe} (Table II). Thus the observed plasma oscillations are to be associated with longitudinal density waves in the chamber.

Observations of the current pulse shape in the delay line show that the plasma oscillations are not a result of the reaction of the radio-frequency generator to the load change caused by firing the discharge. This finding is reasonable because the generator uses a GI-4A tube and provides five times as much power as is needed.

Table II

Number of run	H = 90 Oe		H = 150 Oe	
	T_{probe} μsec	T_{SFR} μsec	T_{probe} μsec	T_{SFR} μsec
1	120	120	70	70
2	112	110	84	80
3	124	160	91	85
4	124	170	91	89

Note: p = 1.10^{-2} mm Hg

To clarify the origin of the observed instabilities measurements were made with a standing wave in the toroidal chamber and with a traveling wave in a cylindrical chamber. In both cases the discharge parameters (particle density n_e, electron temperature T_e, radio-frequency fields) were the same as for the traveling-wave toroidal case; no oscillations were observed over the entire range of pressure and radio-frequency fields. From this result we conclude that the oscillations in the toroidal device with the traveling electromagnetic field were due to the azimuthal current. This conclusion follows from the fact that there is no azimuthal current in the standing-wave toroidal chamber or in the traveling-wave cylindrical chamber.

Two series of measurements were carried out to investigate the effect of the azimuthal current on the oscillation frequency.

1. A circular plate of metal or mica, which partially obstructed the cross section of the toroidal chamber, was introduced through a port. A gap was left between the plate and the chamber wall. In this way it was possible to reduce the azimuthal current considerably without cutting it off completely. In Fig. 4 we show oscillograms of the azimuthal current with the mica or metal plates in the chamber. With the mica plate in the chamber the azimuthal current is reduced by 50% and the current oscillation frequency is reduced by approximately a factor of two. With the metal plate, the current is reduced by a factor of 2.85. The oscillations disappear completely in this case but the particle density and electron temperature in the discharge remain unchanged.

2. The azimuthal current was reduced by means of a magnetic mirror. The mirror field was produced by passing direct current through four turns

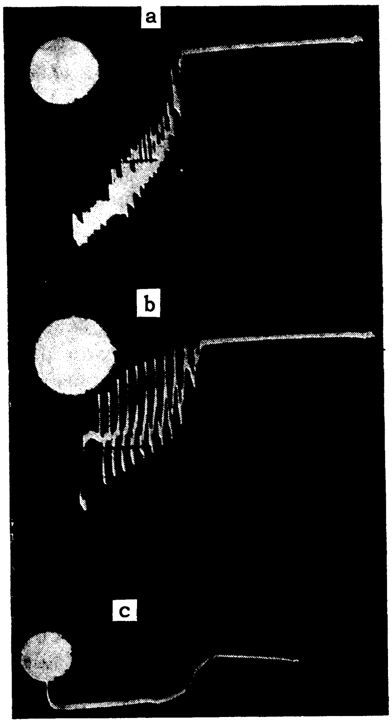

FIG. 4. Oscillograms of the signals in the Rogowski loop (with $p = 2 \times 10^{-2}$ mm Hg): a) without a plate in the chamber, b) with a mica plate, c) with a metal plate.

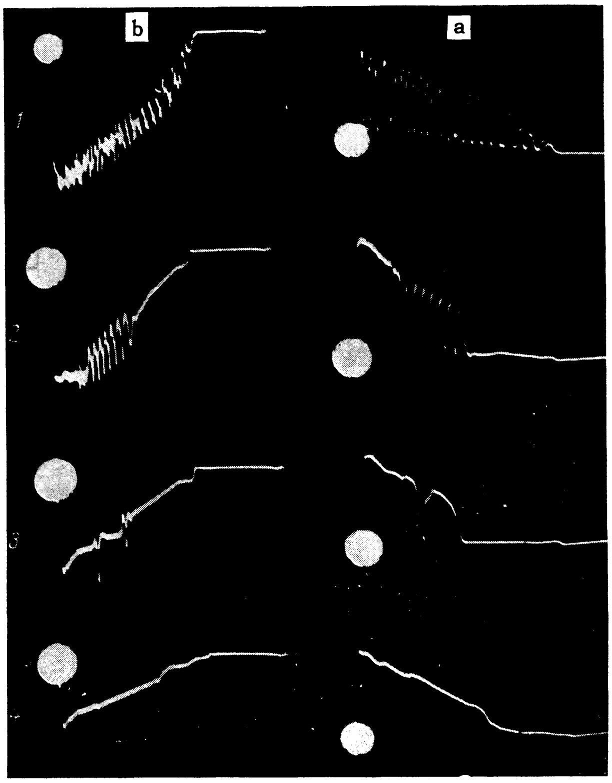

FIG. 5. Oscillograms of the current to the double probes (series a) and in the Rogowski loop (series b) with $p = 2 \times 10^{-2}$ mm Hg: (1) $H_{mir} = 0$, (2) $H_{mir} = 10$ Oe, (3) $H_{mir} = 25$ Oe, (4) $H_{mir} = 125$ Oe.

of the delay line (4 cm along the length of the torus). In Fig. 5 we show oscillograms of the currents to the double probes (series a) and oscillograms of the azimuthal currents (series b) for various values of the mirror fields H_{mir}. It is evident from the oscillogram that the oscillations are cut off at a mirror field of 125 Oe. Under these conditions the azimuthal current is 2.25 times smaller than the current with no mirror. The mirror field does not change the mean density of charged particles in the chamber. In Fig. 3b we show a photograph of the discharge with the magnetic mirror. No optical-emission wave is observed along the torus in this case.

All the measurements described above were carried out in the device in which the traveling electromagnetic wave was produced by a helical delay line terminated in its characteristic impedance. The optical emission of azimuthal current could not be measured in the device with the uniform magnetic field (helical delay line closed on itself) because of the high-density, double-layer winding. Measurements with double probes and magnetic probes showed, however, that there are plasma oscillations of the same nature as in the device with the unshorted line. The oscillation frequency is reduced considerably when the mirror is used. Thus, it may be assumed that inhomogeneity of the radio-frequency field in the chamber is not responsible for the plasma oscillations.

3. DISCUSSION OF THE RESULTS

There are a number of mechanisms which might lead to the excitation of the observed plasma oscillations in toroidal traveling-wave systems. Among these we might include the interaction of the electron current with the traveling-wave field (traveling-wave-tube mechanism); the entrainment of the entire gas mass, with subsequent motion in the direction of the traveling electromagnetic wave; the interaction of the azimuthal current with the plasma ("beam"-type instability).

The investigations that have been carried out show that the first two mechanisms can not be responsible for the oscillations. The velocity of the density wave along the torus is at least an order of magnitude lower than the phase velocity of the traveling electromagnetic wave. Hence, the traveling-wave-tube mechanism can not explain the observed plasma instability. In the field of the traveling wave, in addition to being subject to a containment force, the plasma is subject to a force that entrains it in the direction of propagation of the wave. This kind of plasma motion can lead to an instability. However, no Doppler shift was observed in the excited gas lines measured with an ISP-51 interferometer spectrograph. If there is an entrainment effect in the discharge the resulting velocity is less than 10^4 cm/sec and can not be responsible for the observed oscillations.

The mechanism responsible for the oscillations is evidently the interaction of the azimuthal current with the plasma; traveling-wave toroidal devices are apparently subject to "beam"-type instabilities. The possibility that ion sound waves can be excited by Maxwellian velocity distributions in electrons and ions moving with respect to each other has been indicated by Velikhov et al[5] and by Gordeev[6]. The excitation of ion "sound" waves in the positive column of a gas discharge has been experimentally investigated by Nedospasov.[7]

It is important to note that the frequencies of the investigated oscillations, which are of the same order of magnitude as the frequency of ion sound waves, depend on the magnitude of the azimuthal current. This gives us a basis for assuming that the plasma oscillations in toroidal traveling-wave devices are associated with "magnetic sound" waves propagating across the H_φ field produced by the azimuthal current J_z.

The calculated frequencies of the "magnetic" sound" waves are of the same order of magnitude as the experimentally observed oscillation frequencies. Moreover, the dependence of oscillation frequency on gas pressure and strength of the radio-frequency field is the same as that of the current (Fig. 6, Table I).

In order to clarify the nature of the instability we have measured the dependence of oscillation frequency on M the atomic weight of the gas in which the discharge is excited. Spectrally pure hydrogen, helium, neon, argon, krypton and xenon were used in the chamber. By changing the power of the radio-frequency generator it was possible to keep the azimuthal current constant; the density of charged particles n_e and the electron temperature T_e were also measured. In Fig. 7 we show the oscillation frequency as a function of the atomic weight of the gas as obtained experimentally and as computed using the measured values of n_e and T_e. The discrepancy between the curves can be attributed to the fact that in describing the observed oscillations in terms of "magnetic sound" waves we have not taken account of all the factors that can affect the wave velocity in the discharge. In particular, we have not considered the effect of the radio-frequency traveling-wave on the oscillation frequency.

It is well-known that the growth rate is very sensitive to the geometry of the system; in the present case the important parameters are the skin depth and the radius of the plasma column. It is of interest, therefore, to investigate instabilities when the skin depth is very small compared with the plasma radius.

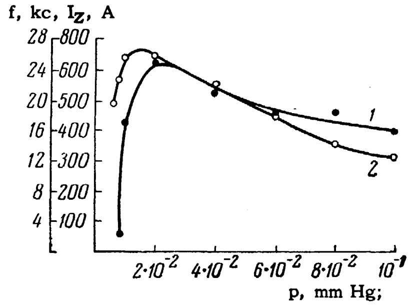

FIG. 6. The oscillation frequency for the current to the double probe (curve 1) and the azimuthal currents J_z (curve 2) as a function of pressure (H_z = 150 Oe).

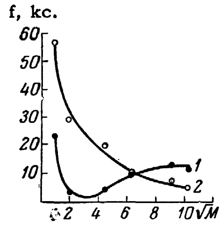

FIG. 7. The frequency of the oscillations as obtained experimentally (curve 1) and the "magnetic-sound" frequency (curve 2), as functions of M, the atomic weight of the gas in which the discharge is excited.

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