ABSORPTION OF ENERGY PRODUCED BY THE TWO-STREAM INSTABILITY IN A TOROIDAL PLASMA

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We describe a toroidal plasma device with longitudinal magnetic and electric fields. Data obtained by measuring the current, loop voltage, optical radiation, and x-ray radiation in an rf discharge are presented. The observed anomalous resistance of the collisionless plasma is attributed to two-stream instability.

ONE of the important collective interactions in a plasma is the two-stream instability.[1-5] The two-stream instability associated with runaway electrons is evidently a serious obstacle [6,7] to the development of the plasma betatron proposed by Budker.[8] On the other hand, Zavoĭskiĭ and his colleagues have been successful in using the two-stream instability in so-called turbulence heating of a collisionless plasma in a "probkotron" [mirror device].[9]

In the present work we have investigated the possibility of using the two-stream instability to dissipate the energy of an external electric field in a collisionless plasma in a toroidal configuration.

The device (Fig. 1) consists of a toroidal glass vacuum chamber 1; magnet coils 2, which produce a quasistationary longitudinal field $H_\theta = 1$ kG along the axis of the torus; a titanium plasma injector 3; the rf circuit 4 which produces an electric field E_θ parallel to the quasistationary magnetic field H_θ in the plasma; a Rogowsky loop 5 which measures the current in the plasma; movable magnetic probes 6 and 7; external 8 and internal 9 x-ray detectors consisting of an absorber of variable thickness, a stilbene crystal and an FÉU-14 photomultiplier, a microwave density system 10 which operates at wavelengths of 8 mm and 3 cm, an electron-optical image converter 11 with "slit" sweep of the spectrally resolved emission of the plasma along the small diameter of the torus; and a UM-2 monochromator 12, with an FÉU-19 photomultiplier for detection of the spatially averaged but spectrally resolved emission of the plasma.

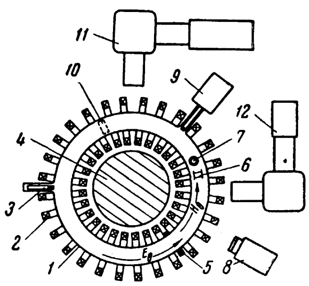

FIG. 1. Diagram of the apparatus.

The first step in the sequence of operation is the triggering of the titanium injector, which injects a hydrogen plasma into the vacuum chamber (evacuated to a pressure of 2×10^{-5} mm Hg). After a delay of at least 30 μsec, which is sufficient for equalizing the density of injected plasma along the perimeter of the torus, the ringing circuit is triggered (frequency 2.5 Mc/sec). The circuit produces a longitudinal electric field with an initial amplitude up to 150 V/cm around the loop. By adjusting the injector and the delay in the triggering of the rf circuit it is possible to obtain initial plasma densities over the range $n_{int} = 5 \times 10^{11}$—$2 \times 10^{13}$ cm^{-3}. Control measurements show that the neutral density is less than 3×10^{13} cm^{-3} in all experiments reported here.

It is evident from Figs. 2a and 2b that the plasma current decays before the longitudinal electric field does. This effect is observed over the whole range of values of n_{int} that has been investigated; when $n_{int} \approx 5 \times 10^{11}$ cm^{-3} the current flows for 0.15 μsec and at the upper limit of n_{int} it flows for 0.35 μsec.

The observed x-ray radiation is evidently a result of bombardment of the chamber walls by electrons; the x-ray transducer 8 only records the hard component ($E \sim 20$ keV) while 9 records the entire radiation spectrum. It is evident from Fig. 2c that the hard x-ray radiation starts some 0.05 μsec after the rf circuit is triggered and continues during the entire time in which current flows. The readings of transducer 9 indicate that the x-ray spectrum is dominated by photons with energies of 1.5 keV and that the x-radiation

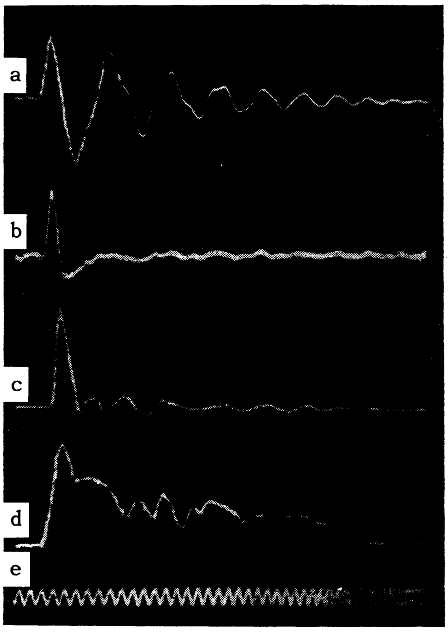

FIG. 2. Oscillograms: (a) electric field E_θ, (b) plasma current, (c) hard x-ray component, (d) emission of the H_α line recorded by the photomultiplier 12. The calibration oscillogram d shows a sine wave at a frequency of 12 Mc/sec. All oscillograms are taken at a plasma density $n_{int} \approx 1 \times 10^{12} cm^{-3}$ and have the same time scale.

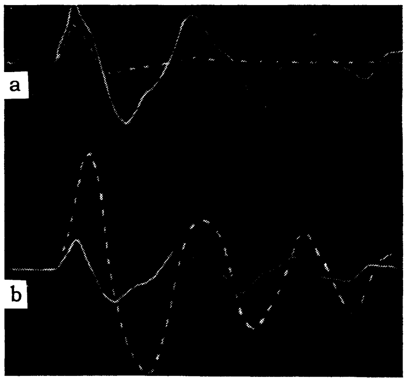

FIG. 3. Comparison of the oscillograms for the current (dotted) and electric field (solid): (a) for a toroidal chamber containing plasma, (b) for a copper torrus.

lasts somewhat longer than the current flow, sometimes 2-3 μsec. This same lifetime feature applies to the emission of the H_α line (Fig. 2d); the slit sweep of the plasma emission in the H_α line carried out by means of the electron-optical converter 11 shows no sudden disturbance or sharp loss of plasma to the walls during the entire indicated 2-3 μsec time period. The measurements with the movable magnetic probes also indicate that the plasma is not disturbed and does not escape to the walls when the current inhibition starts. The magnetic probes also show that the current is distributed almost uniformly over the cross-section of the chamber and that the center of the current distribution is displaced with respect to the geometric center of the emission in the direction of toroidal drift. A detailed comparison of the current and electric field oscillograms (Fig. 3a) shows that the plasma resistance is pure real in this stage of the discharge. The operation of the Rogowsky loop was checked by replacing the toroidal chamber containing plasma with a copper torus of the same dimensions (Fig 3b); this experiment shows that the measurement circuit used for obtaining oscillograms (Fig. 2a) does not introduce any phase shift between the electric field and the current.

The fact that the current in the plasma is pure real allows us to draw a number of conclusions concerning the interaction between the rf field and the plasma in this device.

Using the expression

$$J = Snev, \tag{1}$$

where n, e, v are the density, charge and velocity of the electrons and S is the chamber cross-section and assuming that $n_{int} \approx 10^{12}$ and that the maximum current J reaches 700 A, we find that the maximum velocity of the ordered motion of the electrons corresponds to an energy $\mathcal{E}_{el} \approx 150$-$200$ eV.

Because the resistance is real it is meaningful to introduce the concept of an effective electron-ion collision frequency

$$\nu_{\text{eff.}} = eE_0/mv, \tag{2}$$

where v is the velocity of the ordered motion as given by Eq. (1) while m is the electron mass. In the present case we find from Eq. (2) $\nu_{eff} \sim 10^9 \text{ sec}^{-1}$. Theory predicts that the electron-ion collision frequency for $\mathcal{E}_{el} = 150$ eV and $n = 1 \times 10^{12}$ should not be greater than 10^5 sec^{-1}; similarly, the electron-neutral collision frequency at a neutral density of 10^{13} cm^{-3} should not be greater than 10^6 sec^{-1}. The observed effective collision frequency cannot be attributed to collisions with the walls since the transit time of a runaway electron to the walls (by virtue of the centrifugal drift) is at least 5×10^{-7} sec.

The only mechanism known to us that can explain the observed anomalous real resistance of the plasma is the two-stream instability that arises when the velocity of the ordered electron motion becomes greater than the thermal velocity. The growth rate for the two-stream instability is given by (cf. [1])

$$\gamma = (m/M)^{1/3}\omega_{pe}, \tag{3}$$

where ω_{pe} is the electron plasma frequency while m and M are the masses of the electron and ion. For a dense plasma $\sim 10^{12}$ cm^{-3} we obtain from Eq. (3) $\gamma \sim 10^9$ sec^{-1}. Simple estimates show that if the initial electron temperature in the preheated plasma is 10 eV (in energy units) the transition to the unstable state can occur almost instantaneously (with $2\text{-}3 \times 10^{-9}$ sec after the E_θ field is switched on).

The fact that the resistance is real allows us to determine easily the energy of the rf circuit dissipated in the plasma; all that is required is simple multiplication of the current and loop voltage as determined from the oscillograms. The measurements show that at $n_{int} = 10^{12}$ cm^{-3} an energy of 3 keV per particle is injected into the plasma during the time that current flows (0.3 μsec). This value of transferred energy is found to be in agreement with the measurements of the "boost" in the voltage in the rf circuit.

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