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TURBULENCE HEATING OF A PLASMA IN A TOROIDAL CURRENT-CARRYING SYSTEM

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Turbulent heating has been investigated experimentally in a toroidal current-carrying system in which an induced high-frequency emf parallel to the magnetic field is produced by discharging a capacitor into the copper wall that surrounds the ceramic vacuum chamber. In these experiments primary attention has been given to the plasma diamagnetism, the behavior of the rf current and voltage, and the plasma radiation in the wavelength range 4—16 mm. The maximum value of nT achieved in the heating process (n is the plasma density and T the temperature) is 3×10^{16} eV · cm^{-3} at a density of (2—4) $\times 10^{13}$ cm^{-3}; under these conditions the anomalous resistance is of the order of 6 Ω. The plasma radiation is modulated by the rf current and exhibits a peak at the plasma frequency ω_0. The nature of the radiation spectrum is in qualitative agreement with the excitation of plasma waves and ion-acoustic waves. It is proposed that the plasma-heating method described here can be used in toroidal devices.

EXPERIMENTS on turbulent heating of plasma in toroidal current-carrying devices are carried out in order to investigate the possibility of effective injection of energy into the devices of this kind and to study plasma heating (even if on a highly transient basis). Plasma heating in a toroidal device by means of nonlinear magneto-acoustic waves and by a longitudinal rf current in a discharge between two limiters has been described in[1,2]. In the present work we report on turbulent heating carried out by means of an induced rf current which is superimposed on the quasistationary current.

A diagram of the experimental arrangement is shown in Fig. 1. The plasma is produced by the induced electric field $E_0 = 0.2—0.6$ V/cm which is directed along the static magnetic field $H_0 = 4—6$ kG by means of a transformer winding 5. The rf voltage is induced in the transverse cross-section in a thick-walled copper wall 2 which provides equilibrium of an annular plasma loop with a current $I_0 = 3—5$ kA. The half period of the magnetic field is 2500 μsec and the half period of the quasistationary current is 250 μsec. The plasma diameter is bounded by the aperture of 4 cm diameter in a limiter mounted in the pumping tube 3 in an alundum chamber 1 whose major radius is 18 cm.

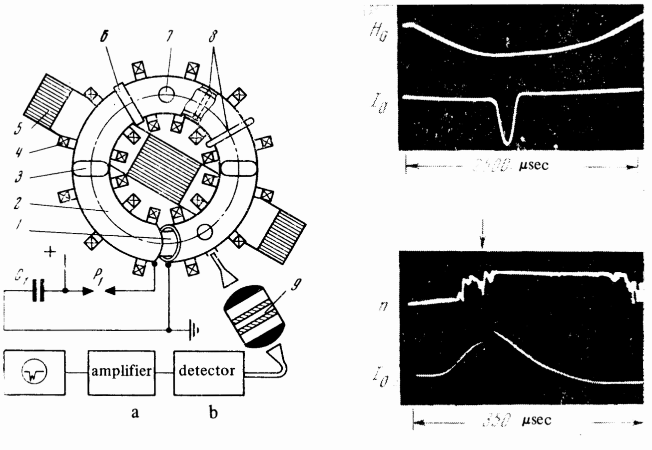

FIG. 1. Diagram of the apparatus (a) and oscillograms (b) of quasistationary processes (in the absence of (top)—and with rf current (bottom): 1) alundum chamber, 2) copper stabilizing liner, 3) pumping ports, 4) solenoid, 5) transformer core 6) diamagnetic pickup unit, 7) microwave ports, 8) Rogowski loop, 9) interference filter with horn—lens transmission system; H_0, magnetic field, I_0, oscillogram of the quasistationary current, n, oscillogram of the 4—mm microwave probe signal; the arrow indicates the time at which the rf current is switched on; the starting parameters are as follows: $p = 5 \times 10^{-4}$ Torr, $H_0 = 5$ kOe, $I_0 = 3.5$ kA.

The discharge is usually produced in hydrogen at pressures of $10^{-4}—1.5 \times 10^{-3}$ Torr and the limiting vacuum in the system is 10^{-6} Torr. The density and electron temperature in the current driven plasma vary between the limits $n_0 = 10^{13}—10^{14}$ cm^{-3} and $T_e = 5—10$ eV. The density is measured by means of a homodyne phase measuring system in which amplitude modulation is employed[3], and an 8-mm interferometer; a focused dielectric radiator system is also used to make cut-off measurements at 4 mm and 8 mm. The temperature is estimated from the plasma conductivity. The induced rf voltage at a frequency f ~ 1 MHz and an amplitude up to 30 kV is produced by discharging a capacitance $C_1 = 0.1$ μF through the low-inductance gap P_1 in the wall 2.

In these experiments primary attention has been given to the investigation of plasma diamagnetism, the behavior of the rf voltage and current, the variation of density, and the plasma radiation in the wavelength region 4—16 mm. In Fig. 2A we show the typical time behavior of the rf voltage and current, the microwave signal at 4 mm in the cutoff regime and the diamagnetic signal as measured with a shielded coil extending out from the wall. In Fig. 2B we show the diamagnetic signal as a function of the voltage applied to the capacitor in the shock circuit; in Fig. 2C the time dependence of the quantity nT is shown.

It is evident that plasma heating (increase of nT) occurs in an extremely short time interval, something of the order of 0.3 μsec; under these conditions the initial density, usually (2—4) $\times 10^{13}$ cm^{-3}, remains essentially unchanged. In certain cases, especially at high densities $n \geq 7 \times 10^{13}$ cm^{-3}, the density shows a transient dip. During the time in which the quantity nT increases, the current and voltage are found to be in phase (cf. Fig. 3), that is to say, the real resistance of the plasma loop is

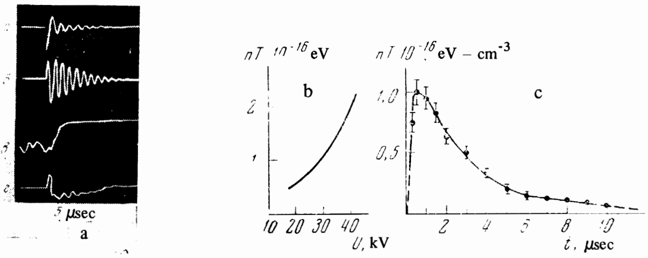

FIG. 2. A. Oscillograms showing the rf phenomena: a) voltage $\widetilde{U}_{\max}$ = 25 kV, b) current $I_{\max}$ = 5 kA; c) 4 mm microwave signal d) diamagnetic signal $(nT)_{\max} \approx 10^{16}$ eV · cm^{-3}. B. The diamagnetic signal as a function of the voltage applied to the capacity in the shock circuit. C. The quantity nT as a function of time.

greater than the inductive reactance; then, after two or three half-cycles the real resistance approaches the value of the inductive reactance and then becomes smaller than the latter.

The detailed dependence of the effective plasma resistance is computed from the instantaneous values of the current and voltage shown in Fig. 3. It is evident that during the plasma-heating phase (this coincides with the time at which intense noise is radiated) there is an anomalous resistance[4] which is greater than 6Ω; this value is two orders of magnitude greater than the ohmic resistance of the initial cold plasma. A noteworthy feature is the fact that the curve $R_{\mathrm{eff}}(t)$ is not monotonic in the vicinity of the current zero in the first half cycle. An estimate of $\int \widetilde{I}^2 R_{\mathrm{eff}}(t)dt$ can be obtained and this quantity can be compared with the thermal energy nT; it is found that for small time intervals the efficiency is close to 100%.

The plasma radiation, whose spectrum and time behavior are shown in Fig. 4, is also modulated by the rf current and exhibits a minimum in the vicinity of the zero of the rf current. The intensity of the radiation is detected by means of an assembly of interference filters[5] which cover the range λ = 4–16 mm, and microwave detectors, which are calibrated with InSb detectors at a temperature of 4° K; the radiation has a peak at ω_0. The initial density in these experiments is established by noting the time of cutoff of the 8 mm microwave signal. No peak is observed in the region of $2\omega_0$. The nature of the spectrum is such as to indicate qualitatively the excitation of plasma waves and ion-acoustic waves.

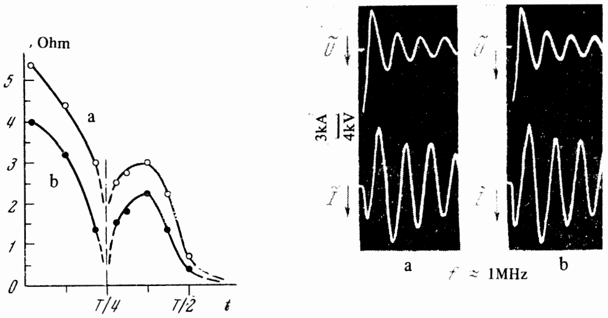

FIG. 3. The anomalous resistance associated with different values of the circuit voltage $E_{\max}$ and the oscillogram of the rf voltage and rf current. a) $I_{\max}$ = 4.5 kA, $\widetilde{U}_{\max} \approx$ 25 kV, $\widetilde{E}_{\max}$ = 250 V/cm; b) $\widetilde{I}_{\max}$ = 5.2 kA, $\widetilde{U}_{\max} \approx$ 20 kV, $\widetilde{E}_{\max}$ = 200 V/cm. Starting parameters H_0 = 5 kG, I_0 = 3.5 kA. n = 3 × 10^{13} cm^{-3}, p = 1.2 × 10^{-3} Torr.

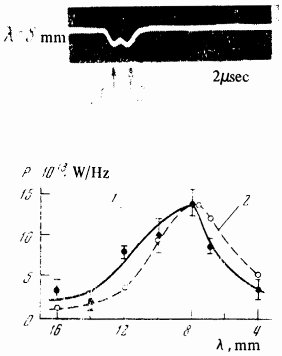

FIG. 4. The time behavior of the plasma radiation at λ = 8 mm and radiation spectra for two different times indicated by the arrows in oscillogram.

The absolute magnitude of the radiation is found to be several orders of magnitude greater than the equilibrium thermal radiation and amounts to 2 kW for the entire plasma volume.[6]

Making use of the results of[7-9] we can estimate the degree of turbulence in the plasma by means of the relation

$$P_{\omega_0} = 10\omega_0\left(\frac{\omega_0}{ck_0}\right)W_i\frac{W_e}{mnc^2}, \quad P_{2\omega_0} = 30\omega_0\left(\frac{\omega_0}{ck_0}\right)^3 W_i\frac{W_e}{mnc^2},$$

where P_{ω_0} and $P_{2\omega_0}$ are respectively the powers emitted at the plasma frequency (ω_0) and at twice the plasma frequency ($2\omega_0$); W_e is the energy density in the plasma waves, W_i is the energy density in the ion-acoustic waves, k_0 is the characteristic wave vector of the plasma waves, m and n are respectively the mass and density of the electrons and c is the velocity of light. Assuming equipartition of energy between the ion-acoustic waves and the plasma waves we find W/nT ≈ 0.01.

The total duration of the diamagnetic signal (the maximum value of which is 3 × 10^{16} eV · cm^{-3} at a density of (2–4) × 10^{13} cm^{-3}) is approximately 5 μsec. At higher densities the magnitude of the diamagnetic signal is reduced. The decay in the signal in time can be related to the equilibrium condition for a hot plasma in the torus which can be easily determined making use of the expression[10]

$$\Delta_r = \frac{b^2}{2R}\left[\ln\frac{b}{a} + \left(1 - \frac{a^2}{b^2}\right) \times \left(\frac{8\pi\bar{p}}{H_\varphi^2(a)} - \frac{1-l_i}{2}\right)\right] - \frac{H_\perp}{H_\varphi(b)}b,$$

where Δ_r is the displacement of the pinch with respect to the chamber axis, a = 2 cm is the plasma radius, b = 4.5 cm is the chamber radius, R = 18.5 cm is the major radius of the chamber, $\bar{p}$ is the plasma pressure as averaged over the cross-section of the pinch, H_φ is the magnetic field associated with the current and $H_\perp$ is the transverse component of the magnetic field.

Calculations carried out on the basis of the experimental data indicate that for a quasistationary current of the order of 3–5 kA the equilibrium value nT ≤ 3 × 10^{15} eV · cm^{-3}. Thus, the rather high level of the diamagnetism indicates "superheating" of the plasma; as a result the plasma looses energy to the limiter and to the walls of the chamber. This description is supported by a further increase in density, which occurs several microseconds after heating and which is correlated with the plasma cooling.

By the choice of the operating regime (the magnitude and phase of the quasistationary current and the rf current) it is possible to arrange a situation in which a noticeable increase in the quasistationary current (25% or more) appears after the shock circuit is operated (Fig. 1). The diamagnetic signal recorded in these cases asymptotically approaches the zero line while the increment ΔI_0 causes a dip in the direction of a paramagnetic signal. Hence it is reasonable to assume that some fraction of the total quantity nT after rearrangement of the discharge (no more than 3×10^{15} eV $\cdot$ cm^{-3}) can ''absorb'' the quasistationary current and maintain it at this level for some time period which is several times longer than the duration of the maximum diamagnetic signal. Knowing the maximum value of nT and the energy $\Delta\mathcal{E}$ absorbed by the plasma, which is related to the growth in nT, we can make a rough estimate of the total heating efficiency of a given device. The plasma absorbs 22 J (the initial stored energy is 80 J) and the thermal energy is 4 J, whence we find that the efficiency is approximately 18%.

It should be noted that the present method of heating the plasma can also be used for toroidal systems in which the parameters (primarily I_0 and H_0) allow complete equilibrium in the absence of an instability in accordance with the Kruskal-Shafranov criterion.[11]

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