Current-driven turbulence caused by the emission of fast electrons in an inhomogeneous plasma in an intense electromagnetic field

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It has been shown experimentally that the emission of currents of fast electrons from a critical sheath in a plasma under the influence of an intense electromagnetic field occurs against the background of a current-driven turbulence of the plasma. This turbulence may be responsible, along with a modulational instability, for the transfer of energy from the electromagnetic field to fast electrons.

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One situation in which a plasma is subjected to intense electromagnetic radiation with a field pressure $E^2/8\pi$ comparable to the gas pressure of the plasma, nT (n is the particle density, and $T = T_e + T_i$ is the plasma temperature), is in laser-fusion devices,[1] in which substantial currents of fast electrons are emitted.[2] We have shown previously[3] that the anisotropic "temperature" T_h corresponding to this emission is one or two orders of magnitude higher than the vibrational energy of an electron in the applied field, $W_e = e^2E^2/2m\omega^2$ (e and m are the charge and mass of the electron, and ω is the angular frequency of the electromagnetic radiation). Furthermore, we have found that this emission is directed preferentially along the electric field, rather than at the optimum angle for the conversion of the radiation into longitudinal waves, $\theta_{\text{opt}} \approx \arcsin [0.7(kL)^{-1/3}]$ (Ref. 4), as has customarily been assumed (in Ref. 5, for example). Here $k = \omega/c$ is the wave number and L is the characteristic dimension of the plasma.

In this letter we are reporting experiments on the fast-electron currents and the density fluctuations in the plasma itself. The results reveal a current-driven turbulence and an associated anomalous plasma resistance,[6] which opposes an increase in the electron emission. In the stage of the intense emission of fast electrons, the current-driven turbulence seems to become the primary mechanism for the dissipation of the electromagnetic energy in the plasma because of the high effective rates of electron collisions. Study of these effects is of interest for both the laser-fusion problem and the problem of converting the energy of an electromagnetic field into a direct current.[7]

The present experiments were carried out with pulsed microwave radiation (wavelength $\lambda = 5$ cm, power level $P = 0.1$ MW, and pulse length $\tau = 10$ μs). The plasma was produced by the microwave pulse itself, through breakdown of a stream of argon injected into the chamber at a pressure of 8×10^{-4} Torr from a narrow nozzle (0.2 cm in diameter) at the end of a ceramic tube 0.8 cm in diameter in which a pressure $\sim 10^{-1}$ Torr was maintained. The region of elevated pressure in the stream did not extend radially more than 4 cm from the nozzle. Breakdown began in the tube and then propagated into the free gas stream. Figure 1 shows the plasma density distribution in the polarization plane of the wave (**E**, **k**) at the end of the microwave

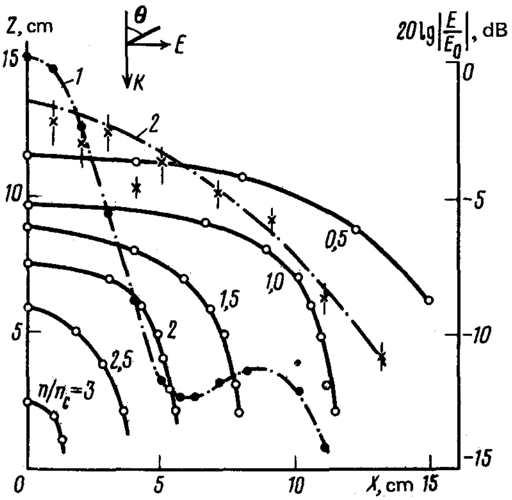

FIG. 1.

pulse, at $t = \tau$, along with the corresponding distributions of the peak microwave electric field along the X axis at $Z = 10$ cm in a vacuum (curve 1) and in the plasma (curve 2). The maximum field at the center of the microwave beam is $E_0 = 2$ kV/cm. The plasma density is normalized by dividing by the critical density $n_c = m\omega^2/4\pi e^2 = 4.5 \cdot 10^{11}$ cm^{-3}. The temperature of the bulk electrons is $T_{e0} \approx 8$-10 eV, and that of the ions is $T_i = 1$-2 eV. The electron collision rate is $\nu \approx 10^7$ s^{-1}.

Measurements of the angular distributions of the signal received by a microwave dipole antenna in the (X, Z) plane in the plasma show that the broadening of distribution 2 in comparison with distribution 1 is a consequence of the refraction of the microwave radiation in the plasma, accompanied by a rotation of the electric vector through an angle $\lesssim 15°$ ($\theta_{\min} \approx 75°$). At the same angle we observe the most intense emission of fast electrons, with a maximum "temperature" $T_h \approx 200$ eV. An increase in the argon pressure in the chamber and the consequent increase in the characteristic dimensions of the plasma lead to a simultaneous rotation of the electric vector and of the direction of maximum electron emission to a larger angle, furnishing further evidence of refraction, rather than of an optimum wave conversion angle, in contradiction of Ref. 5.

Intense low-frequency fluctuations of the plasma density (reaching 20%) and a modulation of the field amplitude are observed in the region in which the microwave radiation penetrates into the dense plasma, with $n/n_c \gtrsim 1$ [see the plasma density profiles $n/n_c(Z)$ and the field profiles1) $|E|(Z)$ in Fig. 2, which were measured on the principal optical axis, OZ, at $T = \tau$]. The dot-dashed line shows the calculated distribution of the damped field of a plane wave incident normally on a plasma with the given profile whose properties are homogeneous in two dimensions. In the per-

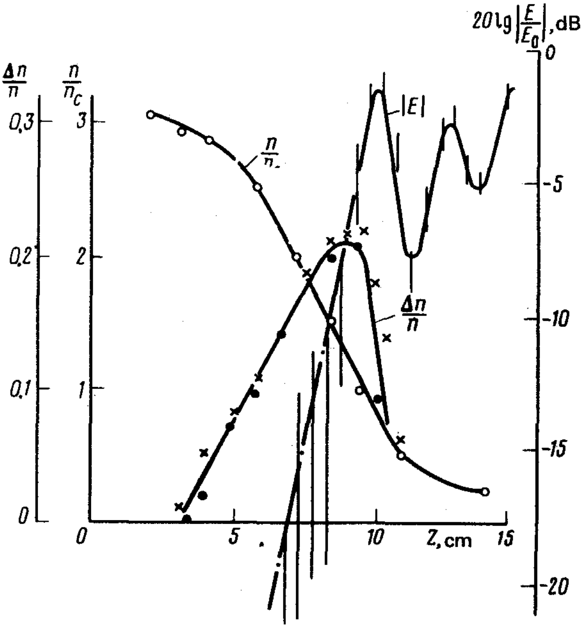

FIG. 2

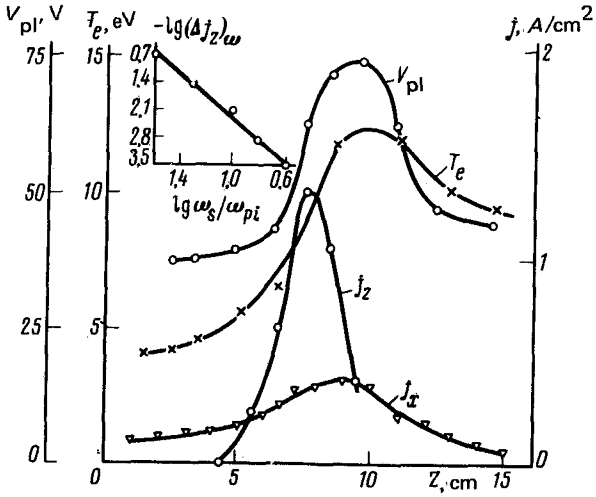

FIG. 3.

turbed part of the plasma there is a local increase in the plasma potential V_{pl} and in the electron temperature T_e, according to data from a Langmuir probe (Fig. 3). The increase in the potential is caused by the emission of the fast electrons accelerated by the microwave field and also by the deficiency of slow electrons entering from the surrounding plasma. The constant electric field formed in the plasma, with a maximum strength (at Z $\approx$ 8 cm) of $\langle E\rangle_Z \approx 15$ V/cm, tends to cause a current with a density $j_Z = \sigma\langle E\rangle_Z = (ne^2/m\nu)\langle E\rangle_Z \approx 200$ A/cm^2. This current is directed into the electron-acceleration region; according to measurements with a collimated multigrid probe, this current actually flows. It is directed primarily along the Z axis, but its maximum density j_Z does not reach 2 A/cm^2 (Fig. 3) because of the anomalous resistance.[6] It is simple to show that in this case the conditions clearly correspond to the driving of a current-driven instability, which is responsible for the anomalous resistance: either the Buneman instability, for which $v_{dr} = e\langle E\rangle_Z/m\nu \gg v_{Te} = (T_e/m)^{1/2}$, if v_{dr} is evaluated from the electron collision rate ν and the measured value of $\langle E\rangle_Z$, or the acoustic instability, for which $v_{dr} = (j_Z/en) \gg v_s = (T_e/M)^{1/2}$, if v_{dr} is evaluated from the measured current density. Here v_{Te} and v_s are the electron thermal velocity and the acoustic velocity, respectively. Under conditions corresponding to saturation of the instability, the effective electron collision rate can reach an extremely high value: $\nu_{eff} \approx 10^{-2}\omega_{pe}(v_{dr}/v_{Te})(T_e/T_i)$. Working from the actual value of the conductivity, we find $\nu_{eff} \approx 2 \times 10^9$ s^{-1}. The existence of a high value of ν_{eff} is confirmed indirectly by the existence of electron temperature gradients (Fig. 3), with scale dimensions much shorter than the mean free path v_{Te}/ν. The direct heating of the electrons by the current-driven turbulence leads to a temperature $T'_e \approx \Delta \approx \Delta V_{pl} \approx$ 30–40 eV for some of the electrons. As a result, the electron energy distribution becomes a two-temperature distribution with $T_e \approx 10$ eV and $T'_e \approx$ 30–40 eV (~10%), and in addition there are the fast electrons with a directed velocity and with $T_h \approx 200$ eV (~1%). According to Ref. 6, the ion-acoustic turbulence spectrum should "creep" toward smaller wave numbers and frequencies, $\mathcal{F}_\omega + (1/\omega_s^r)$, because of the induced scattering by ions. This assertion is confirmed by measurements of the spectrum of current-density fluctuations (Fig. 3). Since the "epicenter" of the plasma turbulence, $\Delta n/n(Z)$, essentially coincides with the "epicenter" of the fast-electron emission, $j_X(Z)$ (cf. Figs. 2 and 3; the fast-electron current was measured at a distance $X = 14$ cm from the Z axis, with the same multigrid probe), it can be suggested that the formation of fast-electron tails on the electron distribution function in the steady state is a consequence of the dissipation of microwave energy by the strong, current-driven turbulence, which is sustained in a self-consistent manner by the electron emission currents. An estimate of the "temperature" of the fast electrons, which are "heated" through the dissipation of microwave energy in the turbulence, at a rate $\nu_{\text{eff}} \approx 2 \times 10^9$ s^{-1} over the transit time across the interaction region, with $L \approx 10$ cm, with an initial thermal velocity $v_{Te} \approx 2 \times 10^8$ cm/s, and with an average vibrational energy $W_{e\text{-vib}} \approx 2$ eV, yields $T_h \approx W_{e\text{-vib}} L \nu_{\text{eff}} v_{Te}^{-1} \approx 200$ eV, in approximate agreement with the measured value. These arguments do not, however, rule out the possibility that there are other mechanisms for the nonlinear dissipation of microwave energy in the plasma, involving a modulational instability or a resonant absorption,[8] without which the electron emission could not begin.

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[1)] More precisely, this is the signal from the antenna uncorrected for the dielectric constant of the plasma.

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