Electron acceleration in a sequence of localized plasma resonances

D. M. Karfidov and K. F. Sergeĭchev
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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Experiments show that when electrons are accelerated in a sequence of plasma resonances, and the number of resonances is progressively increased, the increase in the electron energy is accompanied by the formation of a "temperature" energy spectrum.

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The acceleration of electrons in the electric field of a plasma resonance[1] which results from the conversion of a transverse electromagnetic wave near the point with the critical density $n_c = m\omega^2/4\pi e^2$ on an inhomogeneous plasma profile is a key question in the larger problem of the interaction of intense electromagnetic radiation with plasmas. The reason for the interest is that this acceleration represents a highly efficient conversion of the energy of the electromagnetic radiation into the energy of the fast electrons, reaching several tenths. Fast electrons frequently are a nuisance in several applications, e.g., in laser controlled fusion[2] and in the plasma conversion of electromagnetic energy into a direct current,[3] where they waste radiation energy. The return plasma currents which compensate for the fluxes of fast electrons out of the volume where the plasma interacts with the electromagnetic field excite an intense ion-acoustic turbulence if the drift velocity associated with these return currents is higher than the ion-acoustic velocity ($v_{dr} > v_s$). Corresponding to this turbulence are an anomalous increase in the plasma resistance and the onset of macroscopic perturbations of the original density profile.[4] The multitude of fluctuational perturbations of the plasma density profile with respect to the critical-density level sets the stage for a sequence of plasma resonances. The acceleration of electrons in this sequence of resonances in a turbulent plasma is more probable than the acceleration in the field of an isolated resonance, which is the question usually studied theoretically.[1] An indirect argument for this assertion comes from the lack of coordination not only in the fast-electron energies which are observed but also in the very nature of the energy spectra, which range, in different experiments, from a spectrum corresponding to a distinct group of electrons[5] to a spectrum with an exponentially decaying tail on the energy distribution of the fast electrons, approximated by an "effective temperature [6] T_h.

The present experiments have convincingly demonstrated this resonant acceleration, and we have observed that the number of resonances affects the spectrum of fast electrons.

A rectilinear sequence of localized plasma resonances was arranged in a system of small plasmoids with a dimension $a \ll \delta l$, where a is the characteristic radius of the plasmoid at the $n = n_c$ level, and δl is the scale dimension of the fluctuations caused in the plasma density by the ion-acoustic (current-driven) turbulence.[4] This condition,

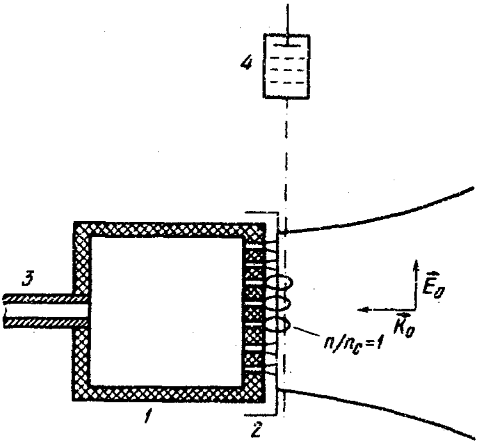

FIG. 1. Experimental arrangement. 1—Dielectric chamber; 2—diaphragm; 3—grounded metal tube; 4—multigrid probe.

which prevents the onset of a large-scale turbulence ($\delta l \sim 100 r_{De}$), reduces the instability of the spatial position of the resonant field.

The experiments were carried out with a pulsed microwave source (wavelength $\lambda = 5$ cm, electric field amplitude $E_0 \cong 3$ kV/cm at the center of the focus, typical spot radius $L_E \approx 2.5$ cm, and pulse length $\tau = 1.5\ \mu$s). The plasma (Fig. 1) was produced by the microwave radiation itself, through the ionization of argon jets entering a vacuum chamber from seven apertures $2r_0 = 0.1$ cm in diameter spaced at $h = 0.7$ cm in a row on the flat end of an rf-transport chamber 5 cm in diameter. The chamber was filled with argon through a grounded conducting tube at a pressure ~ 0.1 Torr. The vacuum chamber which the jets enter is pumped at a speed of 2×10^3 liter/s, and the pressure in it is 3×10^{-5} Torr. The electric field $\mathbf{E}_0$ is directed parallel to the apertures. Breakdown begins in the rf transparent chamber; then an ionization wave propagates out of this chamber opposite the microwave beam, goes through the apertures at the end of the chamber, and causes ionization in the argon jets. As a result of the expansion of the jets into vacuum, the scale dimension of the plasmoids, $a = 1 \pm 0.05$ cm, is only twice the aperture radius. Since $2a < h$, the $n = n_c$ boundaries of the plasmoids do not overlap. The microwave field penetrates essentially unattenuated into the plasmoids ($a < c/\omega$). The number of plasmoids, N, and the number of resonant localizations, $2N$, could be adjusted with a dielectric diaphragm which successively closed down the apertures, without disrupting the gas flow. The fast electrons from the "closed" plasmoids were intercepted by a crimped diaphragm.

The plasma density distribution, the plasma potential V_p, and the temperature of the bulk of the electrons, T_e, were measured with a Langmuir probe. The electrons accelerated along the E_0 direction were detected by a multigrid probe 20 cm from the axis and analyzed by the retarding-potential method. The fast-electron measurements were carried out after the corresponding current reached a steady-state level at the end of the microwave pulse.

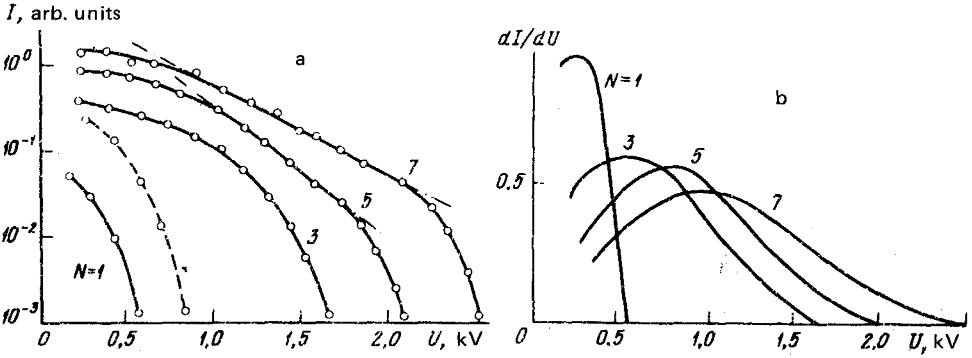

FIG. 2. Retardation curves (a) and energy spectra (b) of the accelerated electrons for various numbers of plasmoids, N. The dashed curves show the retardation curves obtained when the plasmoids were moved closer together.

Figure 2 shows retardation curves of the fast-electron current (a) and the corresponding differential spectra $dI/dU(U) \sim dn/dv(U)$ (b) which demonstrates the effect of the number of plasmoids on the electron acceleration. Here $T_e \cong 20$ eV. The curves in Fig. 2 show several aspects of the electron spectra. First, all the spectra are bounded at some maximum energy $\epsilon_m = eU_m \sim N^{2/3}$, near which the current is cut off. The nature of the energy dependence near this cutoff is similar in the interval $(2\text{–}3)T_e$, but here the amplitude of the total current increases in proportion to N^2. Second, the increase in the maximum energy overtakes the increase in the average energy, as can be seen clearly in Fig. 2b, from the outgrowth of the tails on the high-energy side of the spectra at large values of N. Third, these tails, which correspond to an exponential dependence of the current on the retarding potential (a straight line in the semilogarithmic scale of Fig. 2,a), can be characterized by an effective temperature T_h if we ignore the current cutoff. The temperature T_h also increases with increasing N. The increase in the energy of the fast electrons in proportion to $N^{2/3}$ involves an increase in the plasma potential from 60 V ($N = 1$) to 300 V ($N = 7$). Since the current of the fast electrons is sustained by emission from the wall of the grounded tube, breaking the grounding circuit results in an increase in the plasma potential to several kilovolts.

Control experiments showed that the total length of the plasmoids along the $\mathbf{E}_0$ direction does not by itself affect the result of the acceleration, and on this basis we can rule out a volume acceleration of the electrons. For example, if the seven apertures are moved closer together, to the point at which the inner boundaries of the plasmoids (with respect to the $n = n_c$ level) merge, there is a sharp decrease in the energy of the accelerated electrons from $\epsilon_m = 2.5$ to 0.8 keV (the dashed curve in Fig. 2a). On this basis we may conclude that the presence of plasmoid boundaries with critical layers $(n \approx n_c)$ is a necessary condition for acceleration. Further evidence for this resonant acceleration mechanism comes from the dependence of the energy of the accelerated electrons on the scale dimension of the inhomogeneity of the plasmoid, $L \sim a$. The proportionality found here, $\epsilon_m \sim a^{0.7 \pm 0.3}$, is consistent with the theoretical predictions,[1] as is the proportionality of this energy to the microwave field E_0:$\epsilon_m \sim E_0^{0.8 \pm 0.3}$.

In summary, the electrons are accelerated by virtue of a plasma resonance which arises at an inhomogeneous plasma boundary. The acceleration of the electrons in the sequence of localized resonances results in an increase in their energy in proportion to $N^{2/3}$, rather than $N^{1/2}$, as would be the case in the absence of a phase synchronization of the acceleration. With increasing N, the "group" spectra of fast electrons transform smoothly into "temperature" spectra, so that the differences among the spectra observed in earlier studies can be attributed to the possible spontaneous onset of a sequence of plasma resonances associated with a current-driven turbulence.[4] The acceleration of electrons in a sequence of plasma resonances might be exploited to increase the efficiency at which the energy of electromagnetic radiation is converted into a direct current.

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