"Multiplication" of accelerated electrons in a tokamak

Yu. A. Sokolov
I. V. Kurchatov Institute of Atomic Energy

(Submitted January 16, 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 4, 244–246 (20 February 1979)

The "short-range" collisions of the accelerated electron with the electron of the main plasma component in a tokamak can increase the rate at which the electrons go into the continuous acceleration mode.

PACS numbers: 52.20.Fs, 52.55.Gb

As is well known, because of the presence of longitudinal electric field ϵ in the tokamak, the electrons of energy W, which exceeds a certain critical value W_c [1]

$$W_c = Te\frac{\epsilon_{cp}}{2\epsilon} \approx 2\cdot 10^4 \frac{n_e}{10^{13}}\,\frac{10^{-3}}{\epsilon}\,\frac{\ln\lambda}{15}\quad [\text{eV, cm}^{-3},\ \ \text{L, cm}^{-1}] \tag{1}$$

go over into the mode of continuous acceleration. The number of accelerated electrons is determined by Coulomb collisions, which are responsible for the electron flux to the region $W > W_c$ in the energy space. Ordinarily in calculating the rate of departure to the acceleration region, only the collisions in the main component of the plasma usually are examined, taking into account the long-range Coulomb interaction.[2]

In the presence of the "tail" of the accelerated electrons, the acceleration rate can increase significantly due to the "short-range" collisions of the fast and slow electrons at which an energy $\Delta W > W_c$ is transferred to the slow electron. The number of accelerated electrons increases as a result of such collisions–they are "multiplied." The multiplication process occurs if the lifetime of the accelerated electron τ_L is greater than the elapsed time between the two short-range collisions.

The lifetime of the accelerated electrons τ_L in the tokamak plasma has not been determined exactly. In some experiments their lifetime is equal to or greater than that of the electrons of the main component of the plasma τ_p.[3] In other experiments $\tau_L \gg \tau_p$ is attributed to the loss of the accelerated electrons in the diaphragm due to the drift migration of their trajectories from the magnetic surfaces on which they were produced.[4]

Let us examine the most favorable case for the multiplication process, when the lifetime of the accelerated electron τ_L^{max} is equal to the time of free acceleration to the energy W_{max}-maximum electron energy, whose drift displacement of the trajectory is equal to the radius of the plasma column[1]

$$\tau_L^{max} = \frac{m_0 c}{e\epsilon}\sqrt{\gamma_{max}^2 - 1} \approx \frac{m_0 c}{e\epsilon}\gamma_{max}, \tag{2}$$

$$\gamma_{max} = \frac{W_{max}}{m_0 c^2} + 1 \approx 0.47 J\,(\text{кA})\,\frac{R/a}{4}. \tag{3}$$

The cross section of a single Coulomb interaction of two electrons with an energy transfer greater than ΔW is equal to[5]:

$$\sigma = 2\pi r_e^2 \frac{\gamma^2}{\gamma^2 - 1}\,\frac{m_0 c^2}{\Delta W}, \tag{4}$$

where $r_e = (e^2/m_0 c^2) = 2.8 \times 10^{-13}$ cm is the classical electron radius.

The collision frequency of the relativistic electron in the plasma with the concentration n_e is

$$\nu = \sigma n_e c. \tag{5}$$

The "multiplication" constant K of the accelerated electron during the time τ_L^{max} can be detrmined from Eqs. (1)–(5), taking into account that

$$\Delta W = W_c, \quad R/a = 4, \quad \gamma^2 >> 1:$$
$$K = \nu\tau_L^{max} \approx 3\times 10^{-2}\, J\,(\text{кA}). \tag{6}$$

The relation (6) was obtained for $\gamma^2 \gg 1$. This condition, however, does not limit greatly the applicability of this relation, since $\gamma_{max} \geqslant 14$ when the plasma current is

TABLE I.

	Δt sec	J kA	ϵ V/cm	τ_L^{max} sec	K	ν sec^{-1}	γ_{max}
TM-3	0.015	30	8×10^{-3}	0.03	1	30	14
TM-10	1	400	5×10^{-3}	0.65	12	18	190

>30 kA and the acceleration time $\tau_L(\gamma=2)$ before reaching the energy $W_0=m_0c^2$ is much smaller than that of the accelerated electron τ_L^{max}:

$$\frac{\tau_L^{max}}{\tau_L(\gamma=2)} = \sqrt{\gamma_{max}^2 - 1} \approx \gamma_{max}\,. \tag{7}$$

It can be seen from Eq. (7) that for a large part of its lifetime the accelerated electron has a higher energy than its rest energy.

When the multiplication process is dominant ($\nu \gg 1/\tau_L$), the number of accelerated electrons $n_L(t)$ is to:

$$n_L(t) \approx n_L(0)\exp\left\{\gamma - \frac{1}{\tau_L}\right\}t \approx n_L(0)e^{\nu t}. \tag{8}$$

Thus, in a tokamak with a plasma current >30 kA and a duration of the discharge pulse $\Delta t>\tau_L$, the accelerated electrons can "multiply" as a result of collision with the electrons of the main plasma component.

We present the calculated results for two tokamaks: In the T-10 tokamak the multiplication of accelerated electrons is sufficiently efficient. Even if the lifetime of the accelerated electrons is $>\tau_L^{max}$, the multiplication is possible up to $\tau_L \approx 55$ msec. This lifetime of the accelerated electron is comparable to the energy lifetime of the plasma.

The multiplication of accelerated electrons can possibly account for the long duration of the acceleration discharge in the T-10 tokamak.[6] In such a discharge the accelerated electrons are produced primarily at the moment of "stripping" when the electric field increases sharply. Subsequently, the electric field decreases and the plasma concentration increases slightly. This creates poorer conditions for acceleration than those that existed before "stripping." In spite of this and the continuous loss of accelerated electrons, which is recorded by x-ray radiation from the diaphragm, the duration of the acceleration discharge is at least $\Delta t=0.5$ sec. The compensation for the loss of accelerated electrons in this case in possible because of "multiplication."

In fact, the electrons with energies up to 30 MeV were recorded in the acceleration discharge. The time of the free acceleration up to this energy is larger than that between the two "short-range" collisions ν^{-1}. Since each of these electrons is responsible for acceleration of four more electrons τ_L ($\gamma = 60$) $\nu = 4$, we can see that if 25% of the accelerated electrons reach an energy of 30 MeV, then the multiplication process will support the stationary acceleration discharge.

Thus, the collisions between the accelerated electron and the electron of the main plasma component in the tokamak with the transfer of energy $\Delta W > W_c$ to the latter increases the rate at which the electrons go into the acceleration mode. This process does not play an important role in small tokamaks and in plasma with $W_c \approx m_0 c^2$. Its role increases in tokamaks with longer duration of the discharge pulse and better confinement of electrons.

[1]H. Knoepfel and D.A. Spong, CNEN SULLA Fusione 77.24/p, 1977.

[2]R.M. Kulsrud, Y.C. Sun, N.K. Winsor, and H.A. Fallon, Phys. Rev. Lett. **31**, 690 (1973).

[3]V.V. Alikaev, G.A. Bobrovskiĭ, V.I. Poznyak, K.A. Razumova, V.V. Sanikov, Yu. A. Sokolov, and A.A. Schmarin, Fizika plazmy **2**, 390 (1976) [Sov. J. Plasma Physics **2**, 701 (1976)].

[4]H. Knoepfel, D.A. Spong, and S.J. Zweben, the Physics of Fluids **20**, 511 (1977).

[5]L.D. Landau and E.M. Lifshitz, Teoreticheskaya fizika (Theoretical Physics), Nauka, M., Vol. 4, 1968.

[6]A.B. Berlizov *et al.*, Atomnaya energiya **43**, 90 (1977) [Sov. J. Atomic Energy **43**, 703 (1977)].