CORRELATED EFFECTS DUE TO ELECTRON-ION COLLISIONS IN SUPERSTRONG LASER FIELDS IN PLASMAS

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The investigation of the strong electromagnetic (EM) field influence on the electron-ion collision in plasma has attracted considerable attention for a long time [1-5]. It was noted beginning with the pioneering papers of Dawson and Oberman [1] and Silin [2] that this influence can be rather essential. The best comprehension was gained in the model of small-angle collisions [5] when a straight-line trajectory can be chosen as an unperturbed trajectory of an electron. However, this approximation is well substantiated only in cases of distant collisions (large impact parameters).

Our statement is that in rather strong fields the account of small impact parameters is of basic importance. The major idea is as follows. Due to repeatedly returns of a rapidly oscillating electron to ion the resulting scattering angle may be and is proved to be much larger than that yielded in the hypothesis of independent collisions. Even a more surprising effect: together with the main bulk of electrons that have weak energy exchange with a field, there is a relatively small group of electrons, called by us "representative electrons", which are subject to strong inelastic scattering with a great change of the energy on the average over the field period. This scattering is essentially correlated with respect to the EM field. It manifests itself in the fact that, due to the focusing properties of the Coulomb potential, oscillating electrons are attracted to the ion without average change in energy and if the EM field phase at the instant of entering the region of essential energy exchange is suitable, the electrons are efficiently scattered with average change in energy.

We consider the problem of the scattering of an individual electron with the charge *e*, the drift velocity $\boldsymbol{v}$ in a uniform strong high frequency (hf) field polarised along the axis *z* in classical description

$$m\ddot{\boldsymbol{r}} = -\left(Ze^2/r^3\right)\boldsymbol{r} + e\boldsymbol{E}\cos(\omega t); \quad \boldsymbol{V}_\pm(t) = \boldsymbol{v}_\pm + \boldsymbol{v}_\sim \sin(\omega t), \quad \boldsymbol{v}_\sim = -eE/m\omega\, \boldsymbol{z}_0 \qquad (1)$$

We introduce the drift velocity $\boldsymbol{v}_\pm(t)$ of the electron (“-“ correspond to velocity before collision and “+” – after), assuming that its total velocity $\boldsymbol{V}(t)$ is given in the form:

In these terms, the effective differential cross-section of the scattering, characterising the scattering nonelasticity, and the transport scattering cross-section, being responsible for the drift velocity deflection of particles from the initial direction, have the form (more detail see [7]):

$$d\sigma_{eff}(\mathrm{v}_-, \mathrm{v}_\sim, \boldsymbol{\rho}) = 2\langle \upsilon_+^2 - \upsilon_-^2 \rangle / \upsilon_\sim^2 \, d\boldsymbol{\rho}, \quad d\sigma_{tr}(\mathrm{v}_-, \mathrm{v}_\sim) = \langle (\upsilon_+)_\perp^2 \rangle / \upsilon_-^2 \, d\boldsymbol{\rho} \tag{2}$$

Here $d\boldsymbol{\rho}$ is the area in the plane normal to the direction of the incident beam close to the vector of the impact parameter $\boldsymbol{\rho}$, $\boldsymbol{\upsilon}_{+\perp}$ is the output total velocity component normal to the initial direction.

To describe strong variation of the Keplerian trajectory influenced by the field, we make Eqs. (1) to be dimensionless. As a result we obtain an equation depending on a single parameter Ω (dimensionless frequency):

$$\Omega = \omega\left(m^2 Z / eE^3\right)^{1/4}. \tag{3}$$

It contains the field frequency and the intensity in the combination $\omega/E^{3/4}$. That is the static limit takes place not only at a low frequency but also at rather large amplitude of the hf field.

Basic calculations were carried out for longitudinal ($\boldsymbol{\upsilon}_- \parallel \boldsymbol{E}$) and transverse ($\boldsymbol{\upsilon}_- \perp \boldsymbol{E}$) collisions for several intermediate magnitudes of angles.

Elastic processes

Elastic collisions (transverse scattering) are almost independent on the external field. The cross-section is close to the Rutherford one calculated for the drift velocity. At drift energies larger than a rather small magnitude $\upsilon \sim \upsilon_e$ elastic collisions are almost isotropic and their cross-section is well approximated by the expression $\sigma_{res} = 4\pi/\upsilon^4$. The correction at small energy is, obviously, due to inelastic processes (more detail see [7, 9]). We should stress once more that this estimate does not take into account the number of static Coulomb scattering at large distances, which, as known, logarithmically diverges at large impact parameters.

Inelastic processes

To estimate the scattering inelasticity degree, we have calculated the effective cross-section $d\sigma_{eff}(\theta, \upsilon, \Omega)$ (2) that is responsible for the energy exchange between the field and particles. The effective scattering cross-section for longitudinal ($\boldsymbol{\upsilon}_- \parallel \boldsymbol{E}$) collisions versus $\Omega\upsilon$ are presented elsewhere.

The most important features: (i) Change of sign at $\upsilon \sim \upsilon_\sim$ with $\Omega \leq 1$; (ii) Increase of the cross-section at $\upsilon \ll 1$ by as $d\sigma_{eff} \sim \Omega^2/\upsilon^2$. It is important to note that this approximation takes place for all scattering angles θ; (iii) Decrease in the absolute value of the scattering cross-section at $\upsilon \gg \upsilon_\sim$. In this region the curve is well approximated by the known dependence $d\sigma_{eff} \sim 1/\upsilon^4$ for all angles [1,2,5,6].

It should be noted that not all the electrons are responsible for the energy exchange as a whole, but only a small part of them – the representative electrons. Estimates show that these particles provide more than 70% of the total energy exchange. The share of these particles is not large, i.e., of the order of $\Omega^2 \ll 1$. And in spite of the initial uniformity of incoming phase distribution, all "representative" collisions occur in strongly correlated field phases depending on the initial drift velocity magnitude and weakly dependent on the impact parameter. In this case the mentioned collision correlation is arranged by "elastic" drift of particles in the Coulomb field of an ion.

As is seen from Fig. 1 the dependence of the change in energy averaged over incoming phases on the impact parameter is essentially non-monotonic.

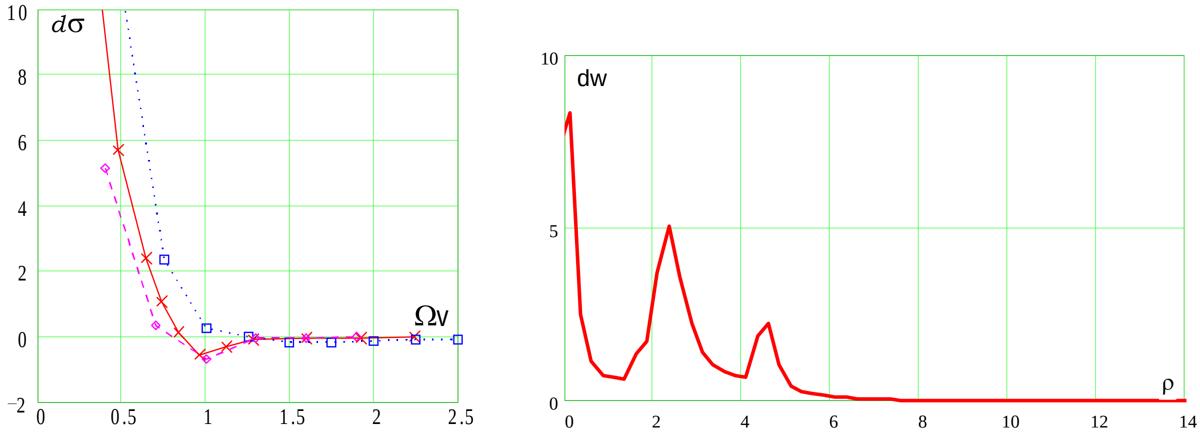

Fig. 1. Effective cross-sections of inelastic collisions $(\boldsymbol{v}_{-} /\!/ \boldsymbol{E})$ vs velocity for three frequency values (left); Energy variation value averaged over incoming phases vs impact parameter at $\Omega = 0.32$, $v = 1$, $\boldsymbol{v}_{-} /\!/ \boldsymbol{E}$ (right).

The number of lateral maxima depends on the ratio of the drift velocity to the oscillatory one (Ωv) and decrease with this parameter. The width of the central peak can be estimated as the size of the Rutherford region, determined of the total velocity of the electron. Only the central peak is present at large drift velocities and the result, as expected, agrees with the weak field approximation (small-angle scattering). Thus, the cross-section becomes of the order of $1/v^4$. In this case the incoming phase dependence is not essential and, hence, the small energy exchange approximation is valid.

Calculations have shown that two types of the representative electrons can be singled out (Fig. 2): (i) electrons with the energy exchange time much smaller that the field period; (ii) electrons with the energy exchange time comparable with the field period.

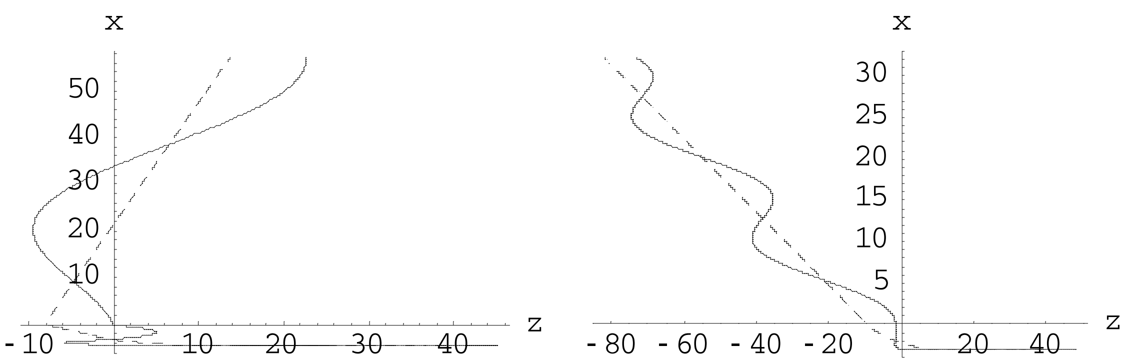

Fig. 2. Particle (solid) and drift center (dash) trajectory for $\Omega = 0.32$ (left $v = 1$, right $v = 3$).

Note that slow collisions, primarily, occur at velocities of the order of the oscillatory one. Their efficiency rapidly decreases both at small and large velocities. They more often result in diminishing of the drift energy of the electron. Their probability falls with growth of the angle between the initial drift velocity direction and the field direction.

A significant difference of transverse collisions from longitudinal ones is that the energy exchange region in this case represents a narrow band stretched along the field over $2r_{\sim}$ and having the width of the order of the Rutherford radius determined by the total velocity. In this case the calculation data are well approximated by the dependence $dw \sim 1/v^4$ for large velocity magnitudes and by $1/v^2$ for the small ones (compared with the quiver velocity).

Inelastic collisions at drift velocities lower than the oscillatory one are mainly determined by the small part of electrons – the representative electrons. A general results for the inelastic scattering cross-section at large drift velocities are in good agreement with the DOS model [1,5].

In conclusion we note that marked variations in the traditional concept occur only in rather strong fields, namely, $r_{\sim} >> r_e = \sqrt{eZ/E} \rightarrow \omega_E >> \omega$ (more detail see [8]) or in dimensional variables

$$\omega << \omega_E \approx 2 \cdot 10^{10} \cdot Z^{1/4} \cdot \left(P\left[Wt/cm^2\right]\right)^{3/8}. \qquad (4)$$

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