Hot electrons production in laser plasmas

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In the recent experiments with petawatt laser plasmas, interesting and unpredictable results were presented in review [1]. At first, a large number of fast electrons with energies up to several tens MeV was detected. The estimated energy of these electrons was up to ten's per cent of the pump laser energy. On the other hand, the plasma temperature was of the order of hundreds eV and slowly depended on laser intensity but revealed significant dependence on the pump pulse duration. It was shown also that the number of these hot electrons slowly depended on the laser intensity too, and the angle distribution function of these electrons was very wide. Finally, it seems difficult to present all these results as consequences of any plasmas wave turbulence, like wakes or something else, and that is why in the review paper [1] the electron distribution phenomena were called non-understandable.

Traditional models of electron-ion collisions in strong laser fields based on small-angle scattering approximation [2], i.e. under the assumption that quivering electrons pass near ions along straight lines, cannot explain the existing experimental results. In comparison with experimental data, these models predict less number of fast (sometimes called “hot”) particles and faster decrease of their number depending on particles energy. Recently, an alternative description of Coulomb collisions, taking into account substantial attraction of particles during the scattering process, was proposed by the authors [3]. Application of the proposed model to the description of hot electrons production provided by electron-ion collisions and comparison with experimental data from [1, 4] constitute the major emphasis of the present work.

In the beginning, let us determine the range of laser emission parameters, where the presented model is suitable. Plasma is assumed cold in comparison with the oscillatory energy:

\[ v \ll v_{osc} = eE / m\omega_0 \]  \hspace{1cm} (1)

This condition is satisfied easily and remains true practically for all plasmas interacting with short intensive laser pulses. The laser field intensity must be large enough for the characteristic spatial scale of scattering \( b_{osc} \) to be small compared to the radius of oscillations \( r_{osc} \):

\[ b_{osc} = e^2 Z / v_{osc} p_{osc} \ll r_{osc} = v_{osc} / \omega_0, \]  \hspace{1cm} (2)
where $p_{osc} = eE / \omega_0$ is the oscillatory electron momentum.

In order to describe particles scattering, let us make use of the fact that the collision process proceeds in two stages [3]. In the beginning, particles are attracting to the ion, i.e. variation of the test particles density occurs at practically constant kinetic energy of the drift motion. Then the “hard” collision, accompanied by substantial change of electron momentum and electron departure from the Coulomb center occurs, and at this stage, scattering on large angles and corresponding large energy exchange is possible.

To obtain the particles density $n(r,t)$ (or, better to say, probability) prior to the last hard collision, one can use both the results of numerical simulation and the results of analytical analysis [3]. In both cases, the dependence $n(r,t)$ is singular periodical function of $t$:

$$n(r,t) = n_\rho \frac{a}{\rho} \sum_{n=-\infty}^{\infty} \delta(t-(n+1/2)\pi/\omega_0), \quad a(v) \geq b = e^2 Z / \rho v.$$

Here $\rho = \sqrt{x^2 + y^2}$ is the transverse electron coordinate before the hard collision, $a(v)$ is some coefficient determining the efficiency of particles attraction to the ion and depending on the direction of the initial velocity $v$ relatively to $v_{osc}$. It is very important to emphasize that this dependence on drift velocity direction is weak [3]. Thus, for the major fraction of test particles we have quasi-isotropic scattering. Taking the latter into account, we use the expression (3) for further estimates. It is also very important to note that the obtained singularity of the probability function occurs independently from the wave polarization and intensity. In particular, it can be shown that the same estimate can be received for ultra-relativistic intensities as well.

The hard collision can be described by relations from the Rutherford problem solution [6]. With smallness of the drift velocity (1) taken into account, momentum variation here is determined by the oscillatory momentum value at the collision moment and by the parameter $\rho$:

$$\Delta p_{\Delta p = p_{osc}} = 2p_{osc} \cdot b_{osc} / \rho, \quad b_{osc} = e^2 Z / p_{osc} v_{osc}.$$ (4)

It is supposed in (3), collisions occur only when the oscillatory velocity reaches its maximum (it is the effect of bunching which provides the latter [3, 5]) and the collision is momentary. The latter condition implies the upper limitation on the impact parameter $\rho / v_{osc} \ll \pi / \omega_0$ or $\rho \ll r_{osc}$. Otherwise, velocity variation due to scattering is substantial and Rutherford's for-
mulas are not applicable. However, this limitation is not important, since energy variation of such far particles in strong fields (1, 2) is small compared to the oscillatory energy.

Eq. (4) allows finding the relation between the probability function on the impact parameters (3) and the distribution of particles production rate on momentum per unit volume and time:

\[
g(\rho) = v_n n_0 (\rho) \frac{d\rho}{dv} = 4 n_n p_{osc}^2 \frac{v_{ab osc}}{p_{osc} p^3}
\]

(5)

We will insert here the dimensional estimate for particles density of particles with energies exceeding some limit \( w \) in relativistic case for the period of field, supposing \( c p_{osc} \gg mc^2 \):

\[
\frac{dn(w)}{dt} \left[ \text{cm}^{-3}\text{e}^{-1} \right] \approx 10^{25} \times \frac{n^2 Z}{w \sqrt{T}}
\]

(6)

In this relation, particles energy \( w \) is in MeV, the electron temperature \( T \) is in eV and density \( n \) is in \( 10^{18} \text{ cm}^{-3} \). Note, this density don’t depend on laser intensity. However the total number of hot electrons depend on pump intensity due to dependence of interaction volume.

In particular, considering number of particles with energy higher than 1 MeV for plasma\(^1\) with density \( 10^{19} \text{ cm}^{-3} \) and volume \( 300\times20\times20 \mu\text{m} \) at the pulse duration of 10 ps, one gets that the hot electrons quantity must be of the order of \( 10^9 Z \) particles, where \( Z \geq 10 \) is the charge of ions in plasma, which coincides well with the number of particles \( 10^{10} \ldots 10^{11} \text{ cm}^{-3} \) measured experimentally. Another comparison with experimental data one can perform by taking into account that the number of hot electrons produced by collisions must be proportional to the squared of the plasma density. We compared this result with the data taken from Ref. [4] and found out good agreement between the theory and the experiment too.

In reality, in experiments [1, 4] it is the distribution of particles scattered off in the same direction that is measured, i.e., actually, the distribution function on momentums \( g(p) \) was found in (5). With the latter taken into account, superimposing the theoretical dependence (5) with the experimental curve one can see good coincidence between the two (see Figure). Note that in Figure, we combined four different series of experimental measurements [1, 4].

Figure represents another evidence of the collisional nature of hot electrons. In the collisional heating, there exists a natural upper limit of the momentum (and, correspondingly, the energy) variation, which particles may get. That is the doubled oscillatory momentum \( 2 p_{osc} \).

\(^1\) This data correspond to experiment [1].
which, in conditions of the experiment [4] (Fig. 1), corresponds to the energy of about 2 MeV. We see, indeed, the abrupt decrease of the hot particles number for energies higher than 2 MeV. Similar results were obtained also in [1].

Finally, our conception of hot electrons production in the experimental results was cited above. As said in Ref. [1], due to any prepulse it is generated the plasma region with density order $3 \times 10^{19} \text{cm}^{-3}$. In such plasmas, hot electrons are generated due to electron-ion collisions with energy (momentum) distribution given in the main part of the text. The number of hot electrons and the heating rate obtained in the framework of the proposed theoretical model demonstrate a good agreement with experimental data.

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