Study of the phenomenon of runaway electron based on the effective interaction potentials

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Introduction. The electron runaway phenomenon has attracted great attention in many areas of plasma physics. High-energy electrons can appear in astrophysical objects, for example, as a result of the acceleration of electrons during a solar flare [1]. Under atmospheric conditions, runaway electrons are observed in electrical discharges associated with thunderstorms, where, as a result, they can cause an electrical breakdown [2]. It was also found that electrons with energy ≥ MeV can cause serious problems in power plants, for example, the presence of runaway electrons in the plasma of fusion reactors, namely in a Tokamak, under certain circumstances is one of the main obstacles to the implementation of the production of fusion energy [3]. It should be noted that these fast electrons underlie many studies in modern laser physics [4]. The phenomenon of electron runaway in plasma was predicted by Giovanelli and numerical calculations of this effect were first performed in [5].

In this work, the phenomenon of electron runaway in dense semiclassical plasma was investigated on the basis of the effective interaction potential, which takes into account collective (static) screening effect and the quantum mechanical effect of diffraction [6-12]. It should be noted that in order to study of the properties of dense plasma, it is also necessary to take into account the dependence of the screening on the velocities of the interacting particles. This kind of screening is called dynamic screening [6, 11].

For the convenience of describing the properties of nonideal plasma, following dimensionless parameters, which characterize the state of the system at certain densities and temperatures: $\Gamma = \left(Z_\alpha Z_\beta e^2\right) / a k_B T$ is the coupling parameter, $r_s = a / a_B$ is the density parameter; $a = \left(3/\left(4\pi n\right)\right)^{1/3}$ average distance between particles, $a_B = \hbar^2 / (m_e e^2)$ Bohr radius, $n = n_e + n_i$ concentration of electrons and ions, T plasma temperature, k_B Boltzmann constant.

There are several quantum mechanical methods for studying particle scattering. One of these methods is the method of phase functions [6, 11], which was used in this work to find phase shifts by solving the Calogero equation. Also one of the other methods, Born approximation method, was applied in work [12] to investigate the phenomenon of runaway electron.

The total collision frequency of an electron is defined as the sum of the frequencies of collisions of an electron with ions and other electrons:

$$\nu_e(\upsilon) = \nu_{ee}(\upsilon) + \nu_{ei}(\upsilon), \tag{1}$$

To calculate the individual frequencies of electron-electron and electron-ion collisions, it is necessary to know the transport cross sections for particle scattering, where phase shifts are used $\nu_{e\beta}(\upsilon) = n_\beta \sigma_{e\beta}^{tr}(\upsilon)\upsilon_e$.

The mean free path of electrons between collisions with ions or electrons is determined by using the average time between collisions, the reciprocal of which gives the electron collision frequencies:

$$\lambda_{e\beta} = \upsilon_e \tau_{e\beta} = \frac{1}{n_\beta \sigma_{e\beta}^{tr}(\upsilon)}, \tag{2}$$

where $\tau_{e\beta} = (\nu_{e\beta})^{-1}$ the average time between collisions of an electron with a particle of the sort β.

It is known that if electrons receive more energy from the field along their mean free path than they lose in elastic collisions, then they begin to escape in an external electric field.

For a full investigation of the electron runaway phenomenon, it is necessary to determine the friction force acting on the electrons from the side of the medium. The total frictional force is found as the sum of the frictional forces acting on an electron in electron-electron and electron-ion collisions. Each individual friction force can be determined directly from the collision frequencies and is written as follows:

$$\vec{F}_{e\beta}(\upsilon) = -\mu_{e\beta}\nu_{e\beta}(\upsilon)\vec{\upsilon}, \tag{3}$$

$$F_e(\upsilon) = F_{ee}(\upsilon) + F_{ei}(\upsilon) = (\mu_{ee}\nu_{ee}(\upsilon) + \mu_{ei}\nu_{ei}(\upsilon))\upsilon. \tag{4}$$

The dependence of the friction force on the electron velocity has a maximum at a velocity value approximately equal to the thermal velocity. After passing the maximum, the friction force begins to decrease with increasing speed, i.e. now, the higher the velocity, the lower the value of the electric field is necessary for acceleration; in this velocity range, continuous acceleration of electrons is possible. The primary acceleration, triggering the continuous electron acceleration mode, is achieved using an external electric field E. Its minimum value (critical field) sufficient for this purpose for an electron with a velocity corresponding to the maximum friction force is called the Dreiser's field E_D, and is found as follows:

$$E_D = F_e^{\max} / e, \tag{5}$$

since this Dreiser's field is able to balance the maximum value of the friction force.

Results. Figure 1 shows the dependences of the electron free path in electron-ion collision (Figure 1a) and in electron-electron collision (Figure 1b) on its energy for the value of the coupling parameter Γ=1 and for different values of the density parameter rs=2 and rs=4. In the figures, the red curves correspond to the data obtained on the basis of the effective potential taking into account the static screening and the blue curves correspond to the effective potential taking into account the dynamic screening. It can be seen from the figures that at high energies of electron, the electron free path increases, since at high velocities the electron does not have time to interact with plasma particles. It can also be noted that in denser plasma, the mean free path of an electron is less than in rarefied one, since a greater number of obstacles act on it.

Figure 2 shows the friction force (4) as a function of the velocity of electron on the basis of the static (red line) and dynamic (blue line) effective potentials for different values of the dense parameter and at a fixed value of Γ=1. As mentioned earlier, the Dreiser's critical field can be found by equating to the maximum value of the friction force acting on the electrons. The dependences show that for the case taking into account dynamic screening, a larger value of the minimum electric field is required for the beginning of the electron runaway process than for the case taking into account static screening.

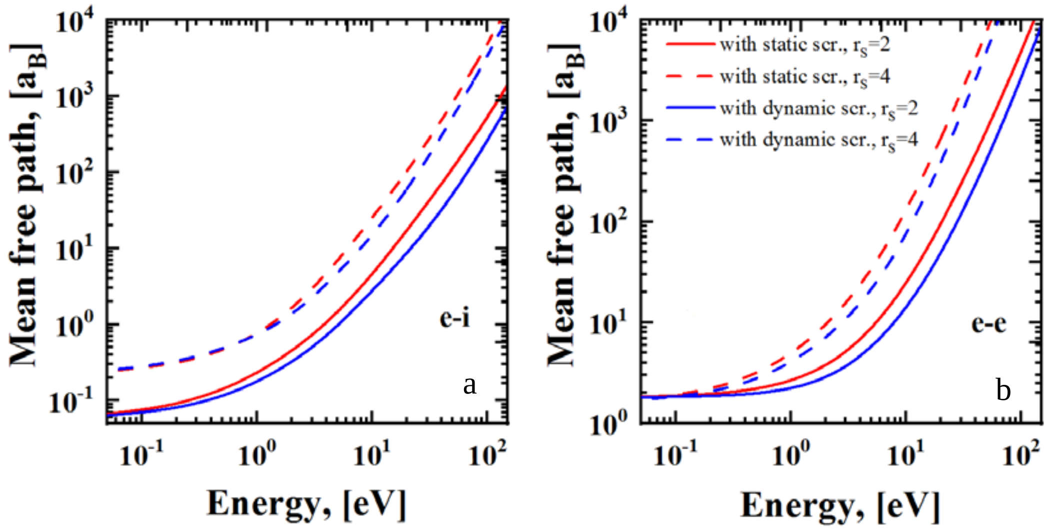

Figure 1. The mean free path of an electron as a function of its energies at different values of the coupling parameters and density, Γ = 1

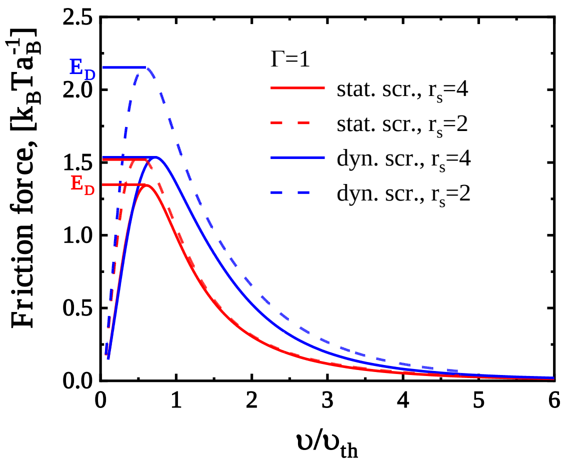

Figure 2. Friction force as a function of the velocity of electron on the basis of the static and dynamic effective potentials for different values of the dense parameter

Conclusion. On the basis of static and dynamic treatment of the charged particles interaction in the dense semiclassical plasma, the mean free path and the critical electric field, which brings the electrons into the runaway mode at the maximum value of the friction force, were investigated. Results of investigation showed an increase in the value of the mean free path for static screening in comparison with the results obtained with taking into account the dynamic screening. Also in the case of dynamic screening, the runaway of electrons requires higher values of the critical electric field than for the case of static screening, since in this case large friction force acts on the electron.

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