Proton cooling in ultracold low-density electron gas

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Abstract. A sole proton energy loss processes in an electron gas and the dependence of these processes on temperature and magnetic field are studied using molecular dynamics techniques in present work. It appears that for electron temperatures less than 100 K many body collisions affect the proton energy loss and these collisions must be taken into account. The influence of a strong magnetic field on the relaxation processes is also considered in this work. Calculations were performed for electron densities \(10^8\) cm\(^{-3}\), magnetic field 1–3 Tesla, electron temperatures 10–50 K, initial proton energies 100–10000 K.

1. Introduction

It is assumed in a plasma theory [1] that all kinetic properties of charged particles depend on the coupling parameter \(\gamma = \beta e^2 n_e^{1/3}\), where \(\beta = 1/T_e\) is inverse electron temperature, \(e\) is electron charge and \(n_e\) is electron density. When \(\gamma \ll 1\) charged particles’ collisions may be considered as pair processes, and energy loss during such a collision is determined by the Coulomb scattering cross section. Since the cross section does not depend on the charge sign, the energy loss is independent of colliding particles’ kind. To take into account both pair collisions and collective effects (by way of Coulomb screening) in weakly coupled plasma Coulomb logarithm is used.

A proton energy relaxation time in a pair collision approximation for the case when the proton energy \(E_p\) is higher than electrons temperature \(T_e\) and proton velocity is much lower than the characteristic velocity of electrons, is determined by the following

\[
\tau_{ep}^c = \frac{T_e^{3/2} m_p}{4 n_e e^4 L_e (2\pi m_e)^{1/2}},
\]

where \(m_p, m_e\) — proton and electron masses, \(L_e\) — Coulomb logarithm.

For nonneutral plasma \(N_i \neq N_e\),

\[
L_e = \ln \frac{l_p}{e^2 / T_e},
\]

where \(l_p\) — plasma length.

Energy transfer between particles with the same and opposite charges would be the same since it is determined only by Coulomb cross section.
Proton ($p^+$) and antiproton ($p^-$) energy loss in electron gas. Electrons density $n_e = 10^8$ cm$^{-3}$. Solid lines—initial temperatures $T_e = 50$ K, $T_p = 10000$ K; dash lines $T_e = 10$ K, $T_p = 100$ K; dot lines $f(t) = \exp (-t/\tau_{ep})$. Values of relaxation time $\tau_{ep}$ for high temperatures: $2 \times 10^{-4}$ s for antiproton, $10^{-4}$ s for proton, for low temperatures: $5 \times 10^{-5}$ s for antiproton, $1.8 \times 10^{-5}$ s for proton.

In the present paper, some insight into the influence of many-body collisions on the proton energy relaxation in electron gas has been gained using molecular dynamics method (with and without presence of a strong magnetic field). Axial and transverse proton-energy-loss rates were estimated in the presence of a strong uniform magnetic field. The rates were obtained for different magnitudes of a magnetic field. It was shown that even for $\gamma \ll 1$ in a weakly coupled plasma it is important to take into account many-body collisions of oppositely charged particles. This effect is reduced with increasing electron temperature.

## 2. Physical model

We consider charged particles system of protons with density $n_p$ and electrons with density $n_e$ interacting via Coulomb law. We use periodic boundary conditions and NVE ensemble. Number of protons was 50 times less than of electrons. We estimated that number of particles 100 in the molecular dynamics simulation cell is enough for calculations because electrons Debye screening length is much less than the cell size under these conditions. So the present results are obtained for two protons (or two antiprotons) and 100 electrons in the cell. Electrons density was $n_e = 10^8$ cm$^{-3}$. Initial electrons temperature was $T_e = 10$–50 K, initial proton temperature was $T_p = 100$ K. Magnetic field magnitude $B = 0$–3 Tesla. We calculated normalized dependencies of proton energy and electron energy on time averaged over all particles. We used method similar to [2] with two modifications: Boris algorithm [3] for magnetic force calculation and molecular dynamics with variable timestep to speed up calculations. We use maximum timestep $2 \times 10^{-13}$ s for particles distant from others. If a particle is near another particle timestep for it is decreased to achieve required full energy conservation precision. Maximum timestep is determined by Larmour period so it must be below this period. Full energy conservation in all calculation was about 0.1–1%. Calculated physical time was $10^{-5}$–$10^{-4}$ s.

To determine the influence of many-body collisions of opposite charges on proton energy relaxation we have carried out calculations for energy loss of particle with proton mass and charge $-e$ (i.e. antiproton in electron gas). In this case, there was no interaction between
Figure 2. Relaxation of proton and antiproton energies in electron gas in magnetic field $B = 1$ Tesla. Initial temperatures $T_e = 10$ K, $T_p = 100$ K. Solid line—antiproton energy, dash line—proton energy, dot lines $f(t) = \exp (-t/\tau_{ep})$. Values of relaxation time $\tau_{ep}$: $8 \times 10^{-5}$ s for antiproton, $2.1 \times 10^{-5}$ s for proton.

Figure 3. Relaxation of proton and antiproton energies in electron gas in magnetic field $B = 3$ Tesla. Initial temperatures $T_e = 10$ K, $T_p = 100$ K. Solid line—antiproton energy, dash line—proton energy, dot lines $f(t) = \exp (-t/\tau_{ep})$. Values of relaxation time $\tau_{ep}$: $1.1 \times 10^{-4}$ s for antiproton, $4 \times 10^{-5}$ s for proton.

particles with opposite charges.

In figure 1 energy loss of an antiproton without magnetic field ($B = 0$) is displayed. Averaging was made for 40 antiproton trajectories with different initial positions in electron gas but with the
same initial energies. Data is approximated well by exponent. Factor in exponent corresponds to the time of establishing of electron-antiproton equilibrium. This result accords well with formula (1).

Energy loss of a proton in electron gas is also shown in figure 1 for the same conditions as for the antiproton. One can see that relaxation time for a proton is much less than for an antiproton.

In figures 2 and 3, results for energy loss of proton and antiproton are shown in relation to magnetic field. Relaxation times increase with the increase of magnetic field, both for antiproton and proton. One can see that for an antiproton relaxation time is much more than for proton.

3. Conclusion

Our calculations show that analytical estimations based on Coulomb logarithm are not accurate enough to describe relaxation of heavy and light charges in plasma. It is necessary to note that calculations were made for low energies of particles. One can expect that the effect of many-body collisions decreases as energies of particles increase to about 1 eV.

Analytical estimations of heavy particle energy relaxation time in ultracold electron gas were made in [4]. These estimations were based on [5-8] for the case $\gamma \ll 1$ using Coulomb logarithm modified to take into account magnetic field. Our calculations show that these estimations are not accurate both in case of magnetic field and without magnetic field. The developed technique can be used to extend the results of works [9-12].

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