Energy relaxation rate in antiproton–positron nonneutral plasma

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Abstract. Energy relaxation of antiprotons injected in strongly magnetized positron gas is studied by molecular dynamics method. Relaxation rates are calculated for different initial energies and densities of the particles. Influence of strong magnetic field is discussed.

1. Introduction
In experiments in CERN [1] atoms of antihydrogen are formed after injection of antiprotons into the cloud of cold (\(\sim 10\) K) positrons. After the injection antiprotons and positrons form nonneutral plasma—number of positrons is about \(10^4\) times higher than number of antiprotons. Injection energy of antiprotons varies in great range in these experiments from about 100 K to about 30 eV. After plasma formation antiprotons collide with positrons and processes of energy relaxation and recombination take place. The main purpose of the experiments on antihydrogen is to trap formed atoms in atomic trap to study antimatter properties. Formed atom of antihydrogen has kinetic energy equal to energy of antiproton just before the recombination occurs (since high antiproton to positron mass ratio)—that is why it is important to know energy relaxation rate for antiprotons in experimental conditions. Theoretical estimation of relaxation rate is complicated by the presence of strong confining magnetic field and our present work is concerned with numerical study of antiproton energy relaxation by means of molecular dynamics method. We simulated the relaxation process in a wide range of energies and densities of the particles as well as magnetic field values.

2. Physical model
As described in the previous section the plasma of antiprotons and positrons in [1] was substantially nonneutral. To prevent plasma from expansion due to high charge electric and magnetic fields were used. Strong uniform magnetic field directed along the axis of the experiment setup provided confinement in transverse direction and electric field applied at the edges of the plasma cloud prevented axial expansion. As a result in the bulk of the cloud charged particles formed nearly homogeneous nonneutral plasma on the uniform magnetic field background.

Work on molecular dynamics modeling of the kinetics of cold neutral plasma has been conducted for a long time and this area has been well studied, see e. g. [2]. Our current research is focused on applying well developed molecular dynamics method to study the influence of...
Figure 1. Antiproton energy relaxation time as a function of magnetic field magnitude at $E_p(0) = 150\,000$ K and $T_e = 15$ K: solid squares—axial energy relaxation, $n_e = 10^8$ cm$^{-3}$; solid circles—transverse energy relaxation, $n_e = 10^8$ cm$^{-3}$; open squares—axial energy relaxation, $n_e = 10^9$ cm$^{-3}$; open circles—transverse energy relaxation, $n_e = 10^9$ cm$^{-3}$.

strong magnetic field on energy exchange in nonneutral plasma. To simulate energy relaxation process we solve classical equations of motion for antiprotons and positrons placed in 100–200 cubic cells of equal size. In every cell we set same total initial energies for particles but different spatial homogeneous distributions. In this work we considered positron densities $n_e = 10^8–10^9$ cm$^{-3}$, positron temperatures $T_e = 10–15$ K, initial antiproton energies $E_p(0) = 1–150\,000$ K and magnetic field values $B = 0–3$ T. Antiproton to positron number ratio was 1 to 50–100 in the simulations.

The $B = 0$ case is obviously a pure hypothetical one since nonneutral plasma can not exist without external confinement field. Nevertheless it is useful to compare zero and nonzero field results to understand better how the presence of a field affects the energy relaxation processes. Technically we can simulate spatially homogeneous nonneutral plasma even when $B = 0$ since we use periodic boundary conditions in our simulations.

During simulation process antiprotons energy decreases (or increases if $E_p(0) < T_e$) while positron temperature remains practically the same due to high number ratio. After simulation continues for sufficient time we plot average dependence of antiproton energy on time $(E_p(t))$ and approximate it by exponent function. From exponent power index we derive relaxation rate that is $\tau_{ep}^{-1}$, where $\tau_{ep}$ is the relaxation time. For more detailed description of simulation method used see [3].

3. Results
We considered the energy relaxation process in three regions of antiproton energy. In the first region initial velocity of antiprotons is higher than thermal velocity of positrons. In this region energy relaxation rate depends only on antiproton energy. Magnetic field has little influence on relaxation since antiprotons are not magnetized due to their relatively high mass. Antiprotons
Figure 2. Antiproton energy relaxation time as a function of magnetic field magnitude at $E_p(0) = 100$ K and $T_e = 10$ K: solid squares—axial energy relaxation, $n_e = 10^8$ cm$^{-3}$; solid circles—transverse energy relaxation, $n_e = 10^8$ cm$^{-3}$; open squares—axial energy relaxation, $n_e = 10^9$ cm$^{-3}$; open circles—transverse energy relaxation, $n_e = 10^9$ cm$^{-3}$.

move through positrons and lose energy due to dynamic friction force exerted by positrons. In figure 1 results of our simulations are presented for antiproton energy 150 000 K, positron temperature 15 K and two density values $10^8$ and $10^9$ cm$^{-3}$.

In the second region energy of antiprotons is significantly higher than positrons temperature but antiproton velocity $v$ is small compared to thermal velocity of positrons. Antiproton energy loss rate now depends on positron temperature. Since positrons are strongly magnetized antiproton energy loss rates are different for axial and transverse directions (in relation to magnetic field). Transverse rate is approximately the same as relaxation rate without magnetic field but energy loss in axial direction is strongly suppressed. Our simulation results in this region are presented in figure 2 for two positron densities $n_e = 10^8$–$10^9$ cm$^{-3}$ and magnetic field values $B = 0, 1$ and 3 T.

In the work of Derbenev and Skrinskii [4] on electron cooling estimations for average friction force that acts on a proton propagating through electron gas were made. Obviously we can apply this approach for the case of antiproton–positron interaction. The friction force was derived for infinite magnetic field and for $E_p > T_e$ and $v < \sqrt{T_e/m_e}$ transverse and axial force components are:

$$F_\perp = -2\sqrt{2\pi} \frac{n_e e^4 L \sqrt{m_e}}{T_e^{3/2}} v_{\perp} \ln \frac{\sqrt{T_e}}{m_e v_{\perp}}, \quad (1)$$

$$F_\parallel = -2\sqrt{2\pi} \frac{n_e e^4 L \sqrt{m_e}}{T_e^{3/2}} v_{\parallel}, \quad (2)$$

where $m_e$—electron mass, $L$—Coulomb logarithm, $v_\perp$ and $v_\parallel$—proton velocity components in transverse and axial directions. Since the force (1)–(2) was derived for infinite magnetic field it does not depend on magnetic field, but nevertheless it agrees well with our results. First,
Figure 3. Antiproton energy relaxation time as a function of magnetic field magnitude at $E_p(0) = 1$ K and $T_e = 10$ K: solid squares—axial energy relaxation, $n_e = 10^8$ cm$^{-3}$; solid circles—transverse energy relaxation, $n_e = 10^8$ cm$^{-3}$; open squares—axial energy relaxation, $n_e = 10^9$ cm$^{-3}$; open circles—transverse energy relaxation, $n_e = 10^9$ cm$^{-3}$.

qualitatively, transverse component contains log factor and is significantly larger than axial term. Second, if we substitute Coulomb logarithm in the usual form

$$L = \ln \frac{\sqrt{T_e/4\pi e^2 n_e e^4}}{e^2/T_e}$$

and derive relaxation time from the force, we will get $\tau_\perp \approx 1.5 \times 10^{-5}$ s, $\tau_\parallel \approx 8 \times 10^{-5}$ s for $n_e = 10^8$ cm$^{-3}$ and $\tau_\perp \approx 3 \times 10^{-6}$ s, $\tau_\parallel \approx 1.5 \times 10^{-5}$ s for $n_e = 10^9$ cm$^{-3}$, which agrees well with our results for maximum magnetic field.

Further we considered the case when antiproton energy is lower than positron temperature. During collisions with positrons mean square of antiproton velocity grows in diffusion like process. As in the previous case energy growth rate depends on positron temperature and positrons magnetization leads to different rates for axial and transverse directions. Antiproton energy in transverse direction increases significantly faster as seen from figure 3.

In [4] diffusion coefficients for average square of velocity change were also derived for infinite magnetic field for the case when $E_p < T_e$:

$$\frac{d}{dt}<\Delta p_\perp^2> = \left(8\sqrt{2\pi n_e e^4 \sqrt{m_e/T_e}}\right) \ln \frac{\sqrt{T_e}}{m_e v_\perp} L,$$

$$\frac{d}{dt}<\Delta p_\parallel^2> = \left(8\sqrt{2\pi n_e e^4 \sqrt{m_e/T_e}}\right) L.$$

Again the result [4] is in good agreement with our calculations results if we substitute $\sqrt{T_e/m_p}$ for $v_\perp$ in the log factor. As can be seen from the formulas energy exchange in transverse direction is more intensive. If we again derive relaxation time from diffusion coefficients (4)–(5) we get
for \( n_e = 10^8 \text{ cm}^{-3} \); \( \tau_\perp \approx 5.5 \times 10^{-6} \text{ s} \), \( \tau_\parallel \approx 2 \times 10^{-5} \text{ s} \) and for \( n_e = 10^9 \text{ cm}^{-3} \); \( \tau_\perp \approx 1 \times 10^{-6} \text{ s} \), \( \tau_\parallel \approx 3.8 \times 10^{-6} \text{ s} \).

4. Conclusion

Antiproton energy relaxation process was simulated in a wide range of energies, densities and magnetic field values. Results show that strong magnetization of positrons leads to suppression of energy transfer rate in axial direction while decrease of relaxation rate in transverse direction is not significant. Comparison with existing Derbenev and Skrinskii theoretical approach was made and calculation results are in good agreement with analytical formulas.

Acknowledgments

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