INFLUENCE ON THE SIGN OF AN ION CHARGE ON FRICTION FORCE AT ELECTRON COOLING

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Abstract. Some experimental results are given for the study of the friction force in the case of a strong magnetization of the electron motion. The cooling decrements of positively and negatively charged particles are found to be strongly different within the range of low relative velocities.

1. Introduction

The electron cooling method, proposed by G.I. Budker [1], is based on the heat exchange between a «hot» beam of heavy charged particles (ions) and an accompanying flux of «cold» electrons (see [2, 3, 5] and the references cited there).

If an electron gun is equipped with rather good optics, the transverse electron temperature $T_\perp$ remains the same during acceleration and will be approximately equal to the cathode temperature $T_\perp \simeq T_c$. At the same time the longitudinal electron temperature decreases inversely with the energy of the accelerated beam $T_\parallel \propto 1/W$. Usually, a decrease in the longitudinal temperature is limited by the intrabeam repulsion of the electrons [4]. For a Pierce gun [5] the electron temperature after acceleration will be

$$T_\parallel = \langle m v_{e\parallel}^2 \rangle \simeq \frac{T_c^2}{2W} + 2e^2 n^{1/3}. \qquad (1)$$

Here e, m and n are the electron charge, mass and density, respectively. For the most typical case of a thermo-cathode and for the electron density $n = 10^8 \div 10^9$ cm^{-3} we obtain $T_\perp \approx T_c \simeq$ $\simeq 0.1 \div 0.2$ eV, $T_\parallel \simeq 2e^2 n^{1/3} \simeq (1.4 \div 3)\cdot 10^{-4}$ eV. This shows that the longitudinal temperature is three orders of magnitude lower that the transverse one.

In the absence of a magnetic field such a flattening has not much influence on the dependence of the friction force on the velocity as compared to the isotropic distribution function. The friction force has its maximum at $v_p \simeq \bar{v}_{e\perp} \equiv \sqrt{T_\perp/m}$ and equals

$$F_{max} \simeq \frac{4\pi n e^4 L_C}{T_\perp} \qquad (2)$$

where L_C is the Coulomb logarithm. A strong magnetic field magnetizes the tranverse motion of electrons and eliminates it from the kinetics of collisions. In this case, the friction force grows for decreasing ion velocity until the later reaches a value comparable with the longitudinal spread in electron velocities [6]. The maximum friction force is then

$$F_{max} \sim \frac{4\pi n e^4}{T_\parallel} = 2\pi n e^{2/3}. \qquad (3)$$

Note that in this range of velocities, the Coulomb approximation is no longer valid. For rough estimation we put here $L_C = 1$. The magnetic field results in not only in an increase of the friction force in the range of low relative velocities and no parallelism between the friction force and the ion velocity also. In [5] the following expressions have been derived for the friction force components directed along and across the magnetic field in an approximation close to the logarithmic one

$$\begin{pmatrix} F_\parallel \\ F_\perp \end{pmatrix} \simeq -\frac{2\pi n e^4}{m v_p^2} \begin{bmatrix} \dfrac{3 v_{p\parallel} v_{p\perp}^2}{v_p^3} L_C + \dfrac{4 v_{p\parallel}^5}{v_p^5} H(z) \\ \dfrac{v_{p\perp}(v_{p\perp}^2 - 2v_{p\parallel}^2)}{v_p^3} L_C + \dfrac{4 v_{p\parallel}^4 v_{p\perp}}{v_p^5} H(z) \end{bmatrix}, \quad H(z) = \begin{cases} 0, & z = 1 \\ 1, & z = -1 \end{cases} \qquad (4)$$

Here $v_{p\parallel}$ and $v_{p\perp}$ are the components of the velocity of ions along and perpendicular to the magnetic field. It is seen that for $v_{p\parallel} > v_{p\perp}/2$ ($L_C \gg 1$) the friction force component, perpendicular to the magnetic field, becomes positive, thus leading to the heating of the transverse motion. The second summand in (4), different from zero for negatively charged ions ($z = -1$), is connected with a forward ejection (along the magnetic field) of the electrons with small impact parameters $\rho \lesssim e^2/m v_p^2$. At the low relative velocities $v_p \sim (e^2 n^{1/3}/m)^{1/2}$ its contribution becomes dominant and this results in a noticeably different friction force for positively and negatively charged particles.

2. Device

The device designed for electron cooling research is schematically shown in Fig. 1. The use of an H^- ions injector offers the possibility of performing the experiments with both negatively

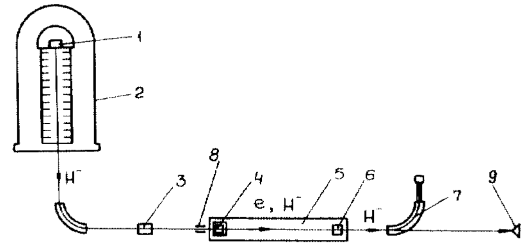

Fig. 1. Layout of the device:
1—source of H^- ions; *2*—electrostatic accelerator; *3*—magnesium vapor target; *4*—electron gun; *5*—solenoid; *6*—collector of electrons; *7*—spectrometer; *8*—plates of transverse ion spread; *9*—two-coordinate position-sensitive detector.

and positively charged particles. The ion charge state is changed with a magnesium vapor target at which a double ionization of H^- ions occurs. The beam of ions is then directed to a solenoid where it is overlapped with the electron beam. The electron beam is formed by an electron gun [7] immersed in a magnetic field of the solenoid [8]. The electrons are transported along the magnetic field to an electron collector. Having left the solenoid, through the collector the «cooled» ions arrive at an electrostatic spectrometer to measure the longitudinal friction force. In another arrangement they arrive at a two-coordinate position-sensitive detector which measures the transverse friction force. The main parameters of the experiment are:

Ion energy	850 keV
Energy stability of the ion injector	$5\cdot 10^{-5}$
Ion current	$\sim$1 nA
Angular divergence and ion beam radius on the cooling section	$\sim$0.7 mrad $\times$ 0.5 mm
Electron energy, W	460 eV
Electron beam current	$0 \div 15$ mA
Electron beam radius	1 mm
Magnetic field of solenoid, B_0	$1 \div 4$ kG
Non-parallelism of magnetic field, $B_\perp/B_0$	$\simeq 5\cdot 10^{-5}$
Length of solenoid	2.88 m
Length of cooling section	2.4 m
Vacuum	$(1 \div 100)\cdot 10^{-10}$ Torr

To reduce the space charge of the electron beam influencing on the cooled ions this space charge is compensated by the ions produced at ionization of the atoms of a residual gas by the electron beam. For the ions to be stored, at both ends of the electron beam the electrostatic mirrors have been created which impede the ions to leave along the beam. A 100% compensation degree was reached only at low electron current. For a current above 1.5 mA the excitation of an axi-asymmetrical electron-ion instability caused the compensation to cease. Under these conditions the compensation degree $k = \Sigma z_i n_i / n$ varies from 30 to 70% depending on the parameters.

The magnitude of the longitudinal friction force was determined with the aid of an electrostatic spectrometer by a variation in the energy of ions after its passage through the cooling section. To do this, at a fixed energy of the injector ions, measurements were made of the dependence of the energy of the ions leaving the solenoid on the electron energy. In coincidence of the velocities of the ion and electron beams the friction force is equal to zero and no variation in ion energy is observed. If the electron energy becomes higher (or lower) than the equilibrium one, the arising friction force contributes to an increase (or a decrease) of the ion energy. Fig. 2 illustrates the thus measured dependence of a variation in the ion energy vs the electron one for positively and negatively charged ions.

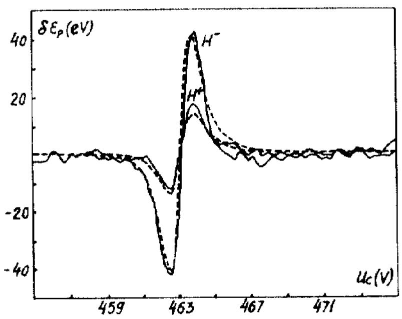

Fig. 2. Energy variations of the ions of different-sign charge vs the electron energy and fitting the expression (5) to this dependence: the electron beam current 3 mA, magnetic field 3 kG. Numerical processing yields the following parameters:

H^-: $F_{max}l=44.1$ eV, $\Delta E_0=1.21$ V, $U_0=463.1$ V;

H^+: $F_{max}l=15.4$ eV, $\Delta E_0=1.30$ V, $U_0=463.0$ V;

To measure the damping decrement for transverse oscillations, the transverse ion velocity was excited at the entrance of the solenoid by applying an alternating voltage ($f\approx 400$ Hz) to the spread plates. The ions leaving the solenoid were directed to a two-coordinate position-sensitive detector fixing a time dependence of the position of the beam. The detector is about 5 m distant from the solenoid. Synchronous detection of the detector signals made it possible to find the amplitude of oscillations of the ion beam (as a whole) in the vertical and horizontal planes. Fig. 3 demonstrates

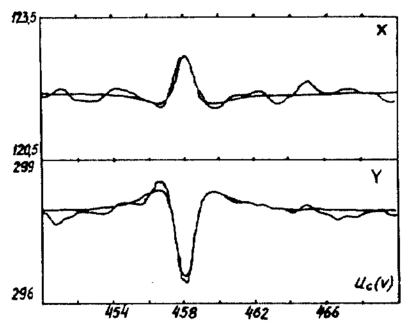

Fig. 3. The amplitudes of transverse oscillations (along the *X*- and *Y*-axis) of the H^- ion beam vs the electron energy. The oscillations are excited in the vertical plane (*Y*), $B_0=3$ kG, $I_e=1.54$ mA. After numerical processing the parameters are (see (6)): $l_c=333$ m, $\Delta E_1=1.33$ eV, $\Delta E_2=0.83$ eV, $n_i/n=0.65$.

the dependence of these amplitudes on the energy of the electron beam. In coincidence of the velocities of the ion and electron beams, there appears a specific feature in the signals due to the damping of transverse oscillations. Relative value of detector signals is determined by the damping decrement of transverse oscillations, the magnetic field and by the non-compensated space charge of the electron beam. A numerical processing of signals allows both the damping decrement and the compensation degree to be defined.

3. Results of the Experiments

The dependence of a variation in the ion energy after their passage through the cooling section on a deviation of the ion energy $\delta\varepsilon_e$ (on the difference in the longitudinal beam velocities) is in good agreement with the following empirical formula:

$$\delta\varepsilon_p=F_{\parallel max}\, l\,\frac{25\sqrt{5}\,\Delta E_0^4\,\delta\varepsilon_e}{16(\Delta E_0^2+\delta\varepsilon_e^2)^{5/2}} \qquad (5)$$

in the asymptotics $\delta\varepsilon_e\gg\Delta E_0$ corresponding to the expression (4). Here $F_{\parallel max}$ is the maximum longitudinal friction force and ΔE_0 is the characteristic energy width of the dependence. In what follows, these parameters, defined by the least-squares technique from experimental results, will be used to characterize the friction force. Fig. 2 shows one of the experimentally measured dependence and the appropriate fit to the expression (5).

Figs 4 and 6 demonstrate $\delta\varepsilon_{p\,max}=F_{\parallel max}l$ and ΔE_0 vs the electron beam current. It is seen that the maximum friction force for

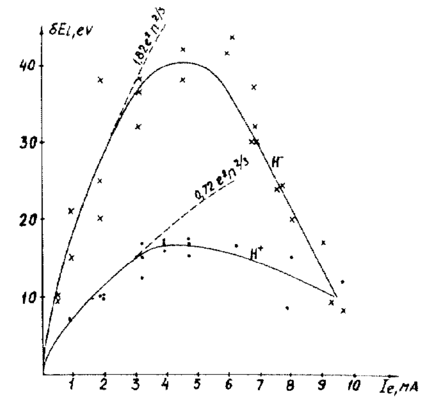

Fig. 4. The maximum energy variation for ions $\delta\varepsilon_i=lF_{\parallel max}$ vs the electron current: $B_0=3$ kG, × — H^-, ● — H^+, cooling section length $l=2.4$ m. The dotted curves correspond to following expressions: $F^-_{max}=1.82e^2n^{2/3}$, $F^+_{max}=0.72e^2n^{2/3}$.

H^- ions is noticeably higher than for protons. At a fixed value of the magnetic field, the characteristic energy width ΔE_0 is independent of the charge sign of the cooled ion. As the current increases, the quantity $\delta\varepsilon_{p\,max}$ reaches saturation and begins decreasing at a current higher than 6 mA. This is due to several factors and it seems difficult to estimate the relative contribution of each of them. First of all, this is an increase of the longitudinal electron temperature along the beam which is due to the intrabeam collisions in electron flux [4]. The second, the absence of the complete space-charge compensation, which leads to increasing the transverse ion velocities and the radial gradient of the longitudinal electron velocity.

The friction force was measured for a magnetic field ranging from 1 to 4 kG. For a low current of the electron beam when there are no saturation effects, the dependence of the maximum friction force on the current is in agreement with the expression $F_{max}=ce^2n^{2/3}$, $c\sim 1$. Fig. 5 illustrates $c=F_{max}/e^2n^{2/3}$ vs the magnetic field. One can see also the electron beam current at which the

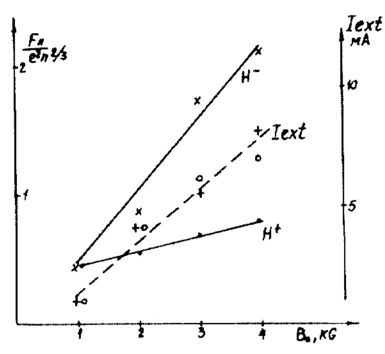

Fig. 5. The ratio $F_{max}/e^2n^{2/3}$ for low currents of the electron beam (× — H^-, ● — H^+) and the electron beam current I_{ext} at which the longitudinal friction force F_{max} is maximum (+ — H^-, ○ — H^+) vs the magnetic field.

friction force reaches a maximum. For a field of 1 kG the friction force for positive and negative particles are equal; for H^- particles the friction force grows fast with increasing the magnetic field, while for H^+ ones it remains nearly constant. A weak dependence of the friction force on the magnetic field for positively charged ions implies the already strong enough magnetization of the collisions and it is due to better quality of the ion beam. The H^- ion collisions in which the electrons are reflected from a moving ion give the contribution to the friction force increasing with the field, thus leading to a difference in the friction forces for H^+ and H^- ions at high magnetic fields. As the estimates show, for H^- ions the increase of the friction force will occur up to the fields of about 5—6 kG at $n=5\cdot 10^8$ cm^{-3} and $T_\perp \simeq 0.1$ eV.

The dependence of ΔE_0 on the magnetic field (see Fig. 6) is rather weak and mainly connected with an increase in the longitudinal electron temperature at the end of the cooling section because of the transverse-longitudinal relaxation. In the range of the low currents and high magnetic fields when such a relaxation is suppressed [4], the dependence of ΔE_0 on the electron density is well consistent with the expression $\Delta E_0 \approx \sqrt{32\, We^2 n^{1/3}} \approx 1.2$ eV and noticeably higher than the energy spread in the electron beam $\Delta W = \sqrt{2WT_\parallel} \approx \sqrt{4\, We^2 n^{1/3}} \approx 0.4$ eV. With growing the electron current the variation in the behaviour of $F_{\parallel \max}$ and ΔE_0 is observed when the energy spread at the end of the cooling section ΔW achieves ΔE_0.

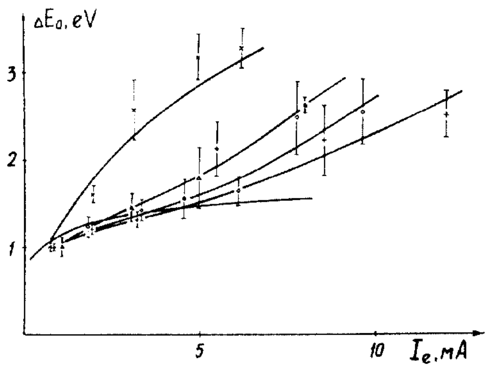

Fig. 6. The energy width ΔE_0 vs the electron current for different magnetic fields: 4(+), 3(o), 2(△) and 1 kGs (×), for positive and negative ions the values of ΔE_0 coincide accurate within the measurements. The dotted curve corresponds to expression $\Delta E_0 = \sqrt{32\, We^2 n^{1/3}}$.

The dependence of the transverse cooling decrement on the deviation in the electron energy (on the difference in the longitudinal beam velocities) is in agreement with the formula

$$\lambda = \lambda_{\perp \max} \frac{1-(\delta\varepsilon_e/\Delta E_2)^2}{(1+(\delta\varepsilon_e/\Delta E_1)^2)^{5/2}}, \qquad (6)$$

that is corresponding to (4) in the asymptotics. The transverse cooling length $l_0 = (\lambda_{\perp \max}/v)^{-1}$ and the quantities ΔE_1 and ΔE_2 vs the electron current are shown in Fig. 7. The quantities ΔE_1 and ΔE_2 are independent, accurate up to the measurements, on the charge sign of the cooled particles: $\Delta E_1 \simeq \sqrt{2}\,\Delta E_2 \simeq \Delta E_0 \simeq \sqrt{32\, We^2 n^{1/3}}$. The cooling decrements increase as $\lambda_{\perp \max} \simeq (m/M)(e^2 n/m)^{1/2}$. The cooling decrement for H^- ions exceeds that for H^+ ions.

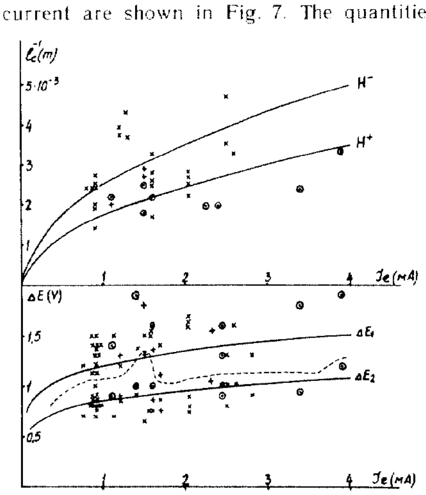

Fig. 7. The inverse length of cooling of transverse oscillations $l_c^{-1} = \lambda/v_0$ and the parameters ΔE_1, ΔE_2 vs the electron beam current: × —H^-, 3 kG; o —H^+, 3 kG, + —H^-, 4 kG; the points for ΔE_2 are under dotted line.

Fig. 8 gives the cooling decrements for the longitudinal and transverse velocities against the electron density for low ion velocities $v_p \leqslant \sqrt{2e^2 n^{1/3}/m}$ when the friction forces increase as $\sim v_p$.

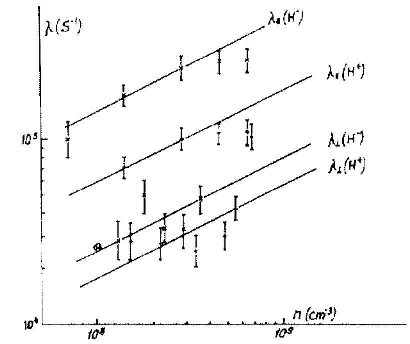

Fig. 8. The longitudinal and transverse damping decrements in the range of low velocities vs the electron density. $B_0 = 3$ kG.

The experimental data obtained are in good agreement with the following empirical expressions for the friction forces:

$$F_\parallel = -\frac{2\pi n e^4}{m}\,\frac{3v_{p\parallel}(4v_e^2+v_{p\perp}^2)}{(8v_e^2+v_{p\perp}^2+v_{p\parallel}^2)^{5/2}}(L_k+2+L_1+L_2),$$

$$F_\perp = -\frac{2\pi n e^4}{m}\,\frac{v_{p\perp}(8v_e^2+v_{p\perp}^2-2v_{p\parallel}^2)}{(8v_e^2+v_{p\perp}^2+v_{p\parallel}^2)^{5/2}}(L_k+2+L_1),$$

$$L_k = \ln\left(1+\frac{v_p^3}{10v_e^3}\right), \quad v_e = \sqrt{\frac{2e^2 n^{1/3}}{m}},$$

$$L_1 = \begin{cases} 0, & \text{for } H^+ \\ 1, & \text{for } H^- \end{cases}, \quad L_2 = \exp\left(-\frac{17.5\, T_\perp\, mc^2 n^{2/3}}{e^2 B_0^2}\right)\cdot\begin{cases} 3, & \text{for } H^+ \\ 12, & \text{for } H^- \end{cases}$$

Within the parameters achievable for the device,

$10^8 < n < 10^9$ cm^{-3}, 1 kGs $< B_0 <$ 4 kGs, $T_e \simeq T_\perp \simeq 0.1$ eV,
$0 < v_{p\perp} < 1.5\cdot 10^6$ cm/s, $0 < v_{p\parallel} < 7\cdot 10^6$ cm/s.

The longitudinal electron temperature is assumed to be low enough $T_\parallel \leqslant 16\, e^2 n^{1/3}$. The asymptotics of these expressions coincide with the calculations in a logarithmic approximation.

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