STATUS OF ELECTRON COOLING ON NAP-M

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I. Introduction

The main purpose of electron cooling /1/ studies carried out at the Novosibirsk Institute of Nuclear Physics during last years has been to clear up the possibilities of further increasing the efficiency of this method. The use of the previously discovered effect of fast electron cooling /2,3/ makes it possible to substantially improve the parameters of the beams of heavy particles in storage rings and offers new possibilities in setting up the experiments in nuclear and elementary particle physics. It is the specific properties of magnetized electron beam accelerated in an electrostatic device (gun) that are responsible for the existence of this effect. Upon such an acceleration the spread of longitudinal velocities of electrons in an accompanying system becomes much less than the spread of transverse velocities and the longitudinal magnetic field of a device with electron beam results in the fact that heavy particles interact with "Larmor circles" having no transverse velocities. In principle, the cooling in this case can proceed untill a temperature determined by the spread of longitudinal velocities of electrons and by the wavities of magnetic field. For instance, in the experiments at NAP-M /2/ the proton beam was cooled down a few Kelwin degrees. The cooling time for the protons with low transverse velocities achieved 50 ms (proton energy 65 MeV).

The experimental and theoretical studies on the fast electron cooling /2,3/ have shown that the smallness of the longitudinal velocities spread of electrons plays an important role in the kinetics of cooling. Its increase can be caused mostly by the action of two factors: intrabeam scattering of cooling electrons and the influence of the field of electron beam space charge. The first leads to energy transfer from the transverse degrees of freedom to the longitudinal one and as a result the isotropic Maxwellian distribution over velocities is established in the electron beam at a large enough length, i.e. the beam is thermalized. The second causes the dependence of longitudinal electron velocities on the transverse coordinates. Both these effects are dependent on the electron beam intensity and, hence, they can reduce the efficiency of the method by increasing the time of cooling and raising the temperature of the cooled beam.

Conditions which are specific for electron cooling are making non-trivial the question on conservation of a low enough longitudinal temperature of electrons. Magnetization of the transverse motion of electrons decreases the energy transfer from the transverse degrees of freedom to the longitudinal one /3/. Complexity of an accurate theoretical analysis of this phenomenon has required its experimental examination /4/. The space charge field of electron beam, also increases the effective longitudinal temperature of electrons, can be decreased substantially, with compensation of the charge of electron beam by ions. The high vacuum conditions in the device and the use of an effective collector for electron energy recovering permit one to achieve the necessary compensation with conservation of collective beam stability.

The present report is a review of the studies on relevant problems.

2. A study of thermalization processes in electron beam

Theoretical conceptions on the thermalization processes in a magnetized electron beam are the following. The electron beam in a strong enough magnetic field is a gas of Larmor circles propagating along the force lines of the field; the sizes of circles r_L can attain or be much less than the characteristic distances between electrons $\sim n^{-1/3}$ (where n is beam density in the rest frame system). In this case, long range collisions of particles proceed adiabatically slow with respect to Larmor oscillations of transverse velocities and cannot lead to transferring the thermal energy from the transverse motion to the longitudinal one. The close-range collisions with violation of the interaction adiabaticity turn out to be impossible for the overwhelming majority of electrons because of the longitudinal repulsion of circles. A detailed analysis shows that the rate of transversely-longitudinal exchange is strongly suppressed over parameter:

$$S \equiv \left[\frac{e^2}{\tilde{n}\, r_L} \ln\left(\frac{r_L T_\perp}{e^2}\right) \Big/ T_\parallel \right]^{2/3}, \quad \frac{e^2}{\tilde{n}\, r_L} \ll T_\perp$$

The quantity $(e^2/\tilde{n}\, r_L) \ln(r_L T_\perp / e^2)$ is a typical potential barrier of the Coulomb interaction between Larmor rings. With $S \ll 1$ the rate of transversely-longitudinal relaxation becomes independent on longitudinal temperature and magnetic field, and is described by the usual classical formula of plasma theory.

The process of thermalization of a magnetized beam, after its acceleration, comprises two stages. In the first stage, a fast maxwellization of the longitudinal spread of velocities of Larmor circles with temperature $T_\parallel^0$ occurs on account of the longitudinal shifts (during for a time of the order of the Langmuir period). The temperature $T_\parallel^0$ is determined by two competing factors: residual thermal spread $\Delta v \sim T_\perp/\sqrt{mW}$ (W is a kinetic energy in the laboratory system) and the spread occuring because of the spatial fluctuations of the energy of Coulomb interactions Larmor circles ($m\Delta v^2 \sim e^2 n^{1/3}$ at $r_L \ll n^{-1/3}$). In realistic situations the contribution of this fluctuational part, as a rule, to be dominant due to the smallness of the parameter $T_\perp/W$ *).

A further transversely-longitudinal thermalization starting at the entrance of the drift section of a beam with longitudinal temperature $T_\parallel^0$ lasts during a large number of Langmuir periods. And when the initial value of parameter δ turns out to be large thermalization is suppressed by freezing influence of magnetic field. As a result, a low temperature $T_\parallel$ can be kept throughout the length of the cooling section.

In principle, there is a possibility to obtain longitudinal temperatures below $e^2 n^{1/3}$ by acceleration of the beam adiabatically slowly with respect to plasma oscillations. High value of the beam current can be obtained by preacceleration in the electron gun operating in the space charge limit ($^3/2$ low) and additional adiabatic acceleration.

With the existence of substantial transversal gradients of longitudinal velocities of electrons in the beam (e.g., as a consequence of the space charge) one has to take into account the possibility of non-adiabatic collisions of the Larmor circles, travelling along the "neighbouring" force lines, which are accompanied by a transfer of the transverse energy to the longitudinal one. In this case, the role of effective longitudinal temperature in the expression for parameter δ is played by the quantity

$$(T_\parallel)_{eff} \sim m \left(\frac{dv_\parallel}{dr} r_L\right)^2 .$$

The impact of collisional processes in beam thermalization is dominative if the collective stability of its stationary state is provided. Apparently, this condition can be violated with a decrease of the magnetic field down to a magnitude such that the Larmor frequency Ω becomes lower than the Langmuir electron frequency ω_e. This can take place, first of all, in the near-cathode region of the gun in the (3/2) regime of space charge current limitation as a result of a high density of the beam. Actually, the condition $\Omega > \omega_e$ is satisfied at comparatively readily attainable values of magnetic fields, even near cathode.

Thermalization studies experiments have been performed at an electron cooling device /4/ in which the electron beam produced with a three-electrode gun was transported in a longitudinal magnetic field (with H up to 1.4 kG). Having passed the three-meter drift section, the beam arrived at an analyser. The intensity of longitudinal magnetic field in the gun region ranged within 0.5 ÷ 4.5 kG with an additional short solenoid. The variation of longitudinal magnetic field from gun region to the drift section was adiabatically slowly. At the analyser entrance the beam hit a collimating diaphragm with a central hole of 0.1 mm in diameter. The collimated beam was decelerated by an analysing diaphragm of potential U and arrived at a collector, where the current was measured. The differential energy spectrum dI_{coll}/dU and its width ΔU were calculated according to the measured integral spectrum. The experiments have been carried out at a low electron energy to prevent heating the analyser by an electron beam.

Fig. 1 demonstrates the differential spectra for electron current I_e = 2.4 mA, electron energy W = 400 eV at various values of the magnetic field in the gun. A strong influence of the latter on the thermalization process is clearly observed. In Fig. 2 the energy spread of electrons as a function of current at various magnetic fields and beam energies is plotted. Curve (1) shows the calculated enlargement of energy spread without magnetic field. The Figure clearly demonstrates the suppression of relaxation with increasing of the magnetic fields on the drift section and especially in the gun. One should note, that the relaxation is suppressed with increasing of the electron energy (curve 5 in Fig. 2).

Thus, a magnetic field leads to suppression of the transverse-longitudinal heat exchange, that is in qualitative agreement with theoretical conceptions.

3. Space charge compensation

Equilibrium concentration of ions in the cooling section is determined by the balance of their production and loss. In our case, the ion losses along the electron beam were prevented by creation of electrostatic mirrors at the ends of the compensation section. These mirrors "draw off" simultaneously the ionization electrons by a special transverse electric field, as described in Ref. /2/. As a result of the storing of ions in the beam, overcompensation occurs and the ions begin go out of trap towards the transverse direction. However, the longitudinal magnetic field hinders the transverse motion of ions and they execute only the drift motion with spiralling along the drift trajectory with radius ρ_L,

$$\rho_L = \frac{E}{eH^2} \cdot Mc^2 \qquad (1)$$

(M is the ion mass).

In the electron cooling device, typical is a situation when

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*) At this stage comprising the acceleration section in the gun, the contribution of transversaly-longitudinal exchange is negligibly small as compared to that of the spatial fluctuations, according to the hierarchy of plasma times.

$$\rho_L \ll a, \qquad (2)$$

a is the electron beam radius. Under these conditions the ion current to the vacuum chamber walls can be caused only by non-adiabatic collisions of ions with azimutally-nonsymmetric fields in the region of mirrors, these mirrors changing the position of the centres of Larmor circles of ion. The non-adiabaticity of such collisions is associated with the fact that a thickness of the layer dividing the compensated sections of the electron beam in the mirror region, is of the order of the Debye radius of ions, $\sqrt{M v_i^2 / 4\pi n e^2} \ll v_i / \Omega$ (where v_i is the thermal velocity, n is the density, Ω is the Larmor frequency of ions, the ions are regarded as the single-charged ones). The systematic flux of ions is connected with losses of the drift velocity of a particle upon collision with the mirror: after such a collision the ion begins, as if again, its motion in the field E, shifting along the radius, in average, by a magnitude of the order ρ_L from (2).

The equilibrium concentration of ions can be calculated by equalizing the rate of production and the losses corresponding to the mechanism described above. For an electron beam of radius a and density n_0, constant in its cross section, the stationary distribution of ions is of the form

$$n_i = \begin{cases} \dfrac{n_0}{2} + \sqrt{\left(\dfrac{n_0}{2}\right)^2 + A n_0} \equiv n_{i0}, & r \le a \\[2ex] \dfrac{n_{i0}}{\sqrt{1 + \dfrac{2 n_{i0}}{A}\left(\dfrac{r^2}{a^2} - 1\right)}}, & r > a, \end{cases} \qquad (3)$$

where

$$A = \frac{n_{aT}\, \sigma\, v_e L H^2}{4\pi M c^2 v_i}, \qquad (4)$$

n_{aT} is the density of residual gas atoms, σ is the ionization cross section, v_e is the electron velocity, L is the length of the compensation section.

As is seen from (3), the ion density inside the beam is close to the electron density if $A \ll n_0$, that was true in our case. Therefore, the field inside the beam is much lower than that outside the beam, which is created by the outgoing ions. The potential difference between the chamber walls and the beam (under conditions $A \ll n_0$ and $a \ll R$, R is the chamber radius) can be written down as follows:

$$\Delta U = 2\pi e \sqrt{2 n_0 A}\; a \cdot R = R \sqrt{\frac{2 e I_i}{v_i} \cdot \frac{H^2}{M c^2}} \qquad (5)$$

where $I_i = e \pi a^2 L n_0 \sigma v_e n_{aT}$ is the current of ions produced at the compensation section. Correspondence of this model to the experiment is demonstrated in Fig. 3 which lists the data at various electron energies (W = 35 keV, W = 550 eV) and compensation section lengths. The direct line is plotted according to formula (5) for the following parameters: ion temperature 300 K°, M = 14 amu, H = 1000 Gs, R = 3.5 cm. A change of the magnetic field was accompanied by a change in the beam potential in accordance with expression (5).

Knowing the electric fields at the beam radius, one can using distribution (3) rewrite the condition (2) in the form which makes it possible to evaluate the conditions for applicability of these calculations:

$$\tau_K = (n_{aT}\, \sigma\, v_e)^{-1} \gg \frac{L}{v_i}$$

As it is seen, the above condition has a simple physical meaning: during compensation period the ion must undergo many collisions with the electrostatic mirrors. With improving the vacuum, this condition is satisfied better and better. However, as the time of presence of the ions in the beam increases, their heating by the electrons in the beam and their diffusion become both the much and much significant, that worsens the degree of compensation at a pressure lower than 10^{-11} Torr, as a result.

The potential difference at the edge and the centre of the beam characterizing the quality of the compensation can be written, for the ion distribution (3), as follows:

$$\Delta U = \frac{a^2 L n_{aT}}{4} \cdot \frac{v_e}{v_i}\, \sigma \cdot \frac{e^2 H^2}{M c^2}. \qquad (6)$$

Estimation of ΔU for a device of length L = 3 m, H = 10^3 Gs, T_i = 300 K°, W = 35 keV, M = 14 amu, P = 10^{-9} Torr, a = 1 cm, gives ΔU = 0.003 eV, that is much less than the energy spread determined by the cathode temperature.

An ultimate current of the compensated beam can be determined by oneself the development in the beam of collective instabilities. This question has been previously discussed both in a variety of theoretical and experimental works /6,7/. Foremore, as has been established, in these papers the excitation of axial-nonsymmetric oscillations for which the threshold current density j_{th} decreases inversely proportional to the beam length L is most dangerous for long beams:

$$j_{th} = \frac{v_e^2 H}{8 L c}. \qquad (7)$$

In the electron cooling devices the compensation conditions posses a number of specific features which impel to perform an experimental study of the stability of collective oscillations.

The dispersion properties of compensated beam has been studied by measuring the propagation of waves excited by external electrodes. Using the pick-up electrodes located along the beam, one can measure the wave amplitude and phase at different distances from the excitation point with a synchronous detector separating the cosine and sine parts of beam oscillations.

Fig. 4 shows the signals of longitudinal oscillations measured at a distance of 1,2,3 m from the excitation point. A strong damping of waves (by a factor of 20 at a three-meter distance) turned out to be unexpected. A similar damping was revealed in transverse oscillations as well. The specific feature of this damping was its dependence on amplitude: the waves with a larger amplitude were damped much less.

Under the conditions which are typical for electron cooling the self-excitation of axial-nonsymmetric oscillations was not observed up to maximally attainable, for a given device, current densities both at a high and low energy of the beam: 3 A/cm^2 at W = 35 keV (j_{th} = 0.46 A/cm^2) and 1.3 A/cm^2 at W = 550 eV (j_{th} = 8.3 mA/cm^2). A substantial exceeding of the current densities as compared to the calculated thresholds made us to study the influence of the compensation conditions on the stability of oscillations. One could initiate the instability by:

1. a strong excitation of oscillations in the ion column (decreasing the discovered wave damping). When approaching the speed of coherent ion motion to the thermal motion of ions the spontaneous bursts of the oscillations of the ion column appear;

2. by a deterioration in vacuum of the device. Fig. 5 shows that at a vacuum worse than 2 10^{-8} Torr the transverse oscillations are excited in the beam;

3. by an decrease of the capture efficiency of electrons into the losses of the current collector from the collector. As shown in Fig. 6, with a decrease of the potential barrier in the collector and with an increase of the current of reflected electrons in the beam, the oscillations arouse in the beam. In these experiments the collector was used which was based on a joint operation of the electrostatic and magnetic traps. This collector captured both the slow electrons of secondary emission and the reflected electrons. The replacement of this collector by a plate with a locking grid led to the fact that the oscillations occured at threshold currents close to the calculated ones (7).

The nature of the discovered wave damping is not clear enough. However, the revealed stability of ions enables one to produce fairly long compensated beams with density necessary for highly effective electron cooling.

4. Conclusion

The main result of the performed studies is the conclusion on the possibility of conservation a small spread of longitudinal velocities in the electron beam at large enough intensities and considerable elongation of the cooling section. The magnetic field which accompanies the electron beam hinders energy transfer from the transverse degrees of freedom to the longitudinal one which has a very low temperature because of electrostatic acceleration. The gradient of longitudinal velocities over the electron beam cross section, which is due to its electric field, is removed by compensation of the space charge of the electron beam by ions. Under the conditions inherent in the electron cooling the compensated by remains stable at high intensities.

The smallness of longitudinal temperature of electrons can be used for rapid cooling of the beams of heavy particles down to very low temperatures at sufficient straightness of magnetic field and exact coincidence of mean velocities of particles.

References

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Figure captions

Fig. 1. The dependence of dI_{coll}/dU on the voltage U on the analysing diaphragm with different values of magnetic field: 1 - magnetic field is H_o = 1.4 kGs in the drift region and H_g = 0.6 kGs in the gun region, the spectrum width is ΔU = 4.3 eV; 2 - $H_o = H_g$ = 1 kGs, ΔU = 3.1 eV; 3 - H_o = 1 kGs, H_g = 3.4 kGs, ΔU = 1.3 eV. The beam current I_e = 2.4 mA, the energy of electrons W = 400 eV.

Fig. 2. The dependence of the spectrum width - ΔU on beam and device parameters: 1 - calculation neglecting the influence of the magnetic field, W = 400 eV; 2 - H_o = 1 kGs, H_g = 1 kGs; 3 - H_o = 1.4 kGs, H_g = 1.4 kGs; 4 - H_o = 1.2 kGs, H_g = 3.25 kGs; 5 - H_o = 1 kGs, H_g = 3.2 kGs, W = 1200 eV.

Fig. 3. The dependence of the potential for compensated beam ions current (•) = 550 eV L = 300 cm; Δ - 35 keV, L = 100 cm.

Fig. 4. Spectra of longitudinal oscillations of ions at different distances from the excitation point: 1 - the distance from excitation 1 m; 2 - 2 m, 3 - 3 m. H_o = 1 kGs, W = 550 eV, I_e = 25 mA, a = 0.1 cm.

Fig. 5. The influence of vacuum conditions on the spectra of spontaneous transversal oscillations for the compensated electron beam: 1 – P = $= 10^{-7}$ Torr; 2 – $4.8 \cdot 10^{-8}$ Torr; 3 – $2.6 \cdot 10^{-8}$ Torr; 4 – $6 \cdot 10^{-9}$ Torr, H_0 = 1 kGs, W = 550 eV, I_e = 22 mA.

Fig. 6. The influence of the collection efficiency on spectra of spontaneous transversal oscillations for the compensated beam: 1 – the current of reflected electrons I_{refl} = = 33 μA, U_{coll} = 600 V, 2 – 280 μA, 300 V. H_0 = 1 kGs, W = 400 eV, I_e = 20 mA, a = 0.1 cm, L = 3 m.

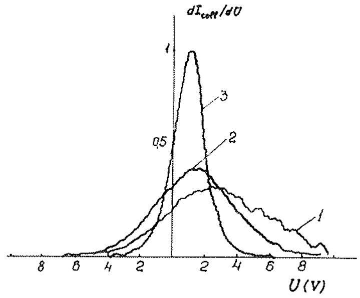


Fig. 1

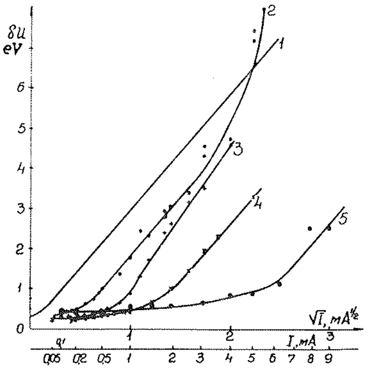
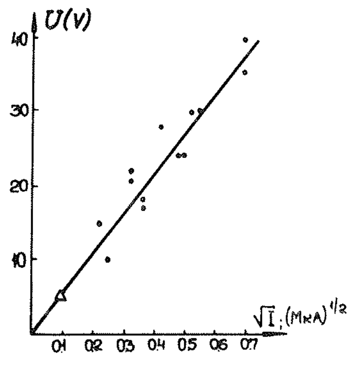


Fig. 2.



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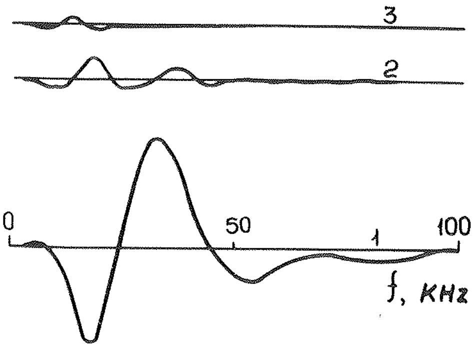

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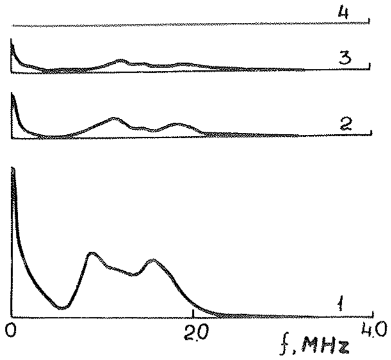

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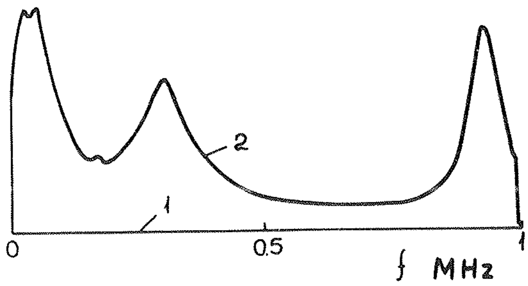

Fig. 6.