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<u>Abstract</u> In recent years electron cooling in Novosibirsk has been developed in the following three directions:

1. experimental and theoretical studies of the possibilities of deep cooling of beams of heavy charged particles;
2. study of the possibilities of cooling large phase-space volumes of heavy particles and their accumulation;
3. development of the electron cooling technique: generation of cold electron beams, creation of devices of high voltage electron cooling and effective recuperation of electron energy.

DEEP COOLING OF ION BEAMS

Fast electron cooling, discovered in the Novosibirsk experiments [1] and also observed in the CERN and FERMILAB experiments [2-3], has demonstrated the possibility of deep cooling of heavy particles circulating in a storage ring. Further research of these possibilities has been performed at Novosibirsk using a special deviced called the "Solenoid model" [4] and paying special attention to the generation of a magnetic field with a high degree of homogeneity.

The results of these studies allow a more complete formulation of the behaviour of the frictional force of magnetized electron cooling at low ion velocities, with the electron flux.

<u>Interaction picture</u>

Electron cooling is based on energy exchange between a beam of heavy charged particles and an electron beam moving with the same average velocity [5-16]. The minimisation of the relative electron and ion velocities produces an increase in the interaction efficiency, and hence the cooling rate. At electrostatic acceleration of the electron beam, the longitudinal temperature of electrons is much lower than in the transverse plane [1]. The longitudinal magnetic field guiding the electron beam "magnetizes" the transverse motion of electrons. At low longitudinal electron temperature, this causes the growth of the contribution to cooling from collisions with large impact parameters [6-7-8].

Neglecting the thermal motion of electrons along the force lines of the magnetic field, the longitudinal and transverse components of the frictional force $F_\perp$, F_1 may be written as follows [7]

$$F_\parallel = \frac{2\pi n e^4}{m v^2} \cdot \left[\frac{2 v_\perp^2 v_\parallel}{v^3} L_c \right]$$

$$F_\perp = \frac{2\pi n e^4}{m v^2} \cdot \left[v_\perp \frac{(v_\perp^2 - v_\parallel^2)}{v^3} L_c \right] \qquad (1)$$

Here n is the electron density, e and m are the electron charge and mass, $v_\parallel$ and v_1 the longitudinal and transverse components of the ion velocity v, $L_c = \ln(\rho_{max}/\rho_{min})$ is the Coulomb logarithm, and ρ_{max} and ρ_{min} are the impact parameters of collisions. This can be simplified if the period during which the ions move in the electron beam is taken to be rather long: $\tau >> \omega_p^{-1}$ ($\omega_p = \sqrt{4\pi n e^2/m}$ is the plasma frequency of the electron beam). In this case, the estimates for the impact parameters are of the form:

$$\rho_{max} = v/\omega_p, \quad \rho_{min} = \max(v_{1e}/\omega_L,\ v/\omega_L,\ 2e^2/mv^2) \qquad (2)$$

where $\omega_L = eB_0/mL$ is the Larmor electron frequency.

If fairly high ion velocities are considered $v/\omega_L \gg 2e^2/mv^2$, there also exists a region of impact parameters in which one can neglect the action of the magnetic field on the electrons. The frictional force in this case will be of the form:

$$F_{\parallel} = -\frac{4\pi ne^4}{mv^2} \quad \frac{v_{\perp}^2\, v_{\parallel}}{v^3} L_B + \frac{v_{\parallel}}{v} L_0$$

$$F_{\perp} = -\frac{4\pi ne^4}{mv^2} \quad \frac{v_{\perp}(v_{\perp}^2 - v_{\parallel}^2)}{2v^3} L_B + \frac{v_{\perp}}{v} L_0 \tag{3}$$

where L_0 is the Coulomb logarithm for fast (non-magnetized) collisions :

$$L_0 = \ln (\varrho_1/\varrho_0), \; L_B = \ln (\varrho_{max}/\varrho_1) = \ln (\omega_L/\omega_p),$$

$$\varrho_1 = V/\omega_L, \; \varrho_0 = \max \quad \frac{v_{1e}}{\omega_L}, \; \frac{2e^2}{mv^2}$$

It should be noted that at any high ion velocities the magnetization effects give a significant contribution because for obtaining low transverse electron velocities, the condition $\omega_L \gg \omega_p$ must be satisfied. As the velocity v decreases, the minimum impact parameter $\varrho_0 = 2e^2/mv^2$ grows, and the region of fast collisions disappears: $L_0 \to 0$ at $v = v_1\ (2e^2\omega_L/m)^{1/3}$. With further reduction of the ion velocity, the Couloumb lagorithm for the magnetized collisions decreases and vanishes at the velocity $v \approx v_2 = (2e^2\omega_p/m)^{1/3}$. In this region the energy exchange calculations based on the perturbation method are insufficient because the kinetic energy of the relative motion is comparable to potential interaction energy:

$$v_2 = (2e^2\omega_p/m)^{1/3} = (2e^2 n^{1/3}/m)^{1/2}. \tag{4}$$

This value corresponds to the characteristic velocity of the electron beam when the initially chaotically arranged electrons push each other apart. Approximately the same values of the longitudinal-velocity spread are obtained in the electron beam after fast acceleration in a strong magnetic field [6-7]. Meanwhile the established values of the velocity spread of heavy particles during the cooling process are $\sqrt{M/m}$ times less, and therefore near equilibrium the expressions (1) are not applicable for the frictional force. Under these conditions appears a difference in the frictional force for positively and negatively charged particles moving in the electron flux. In the system of the cooled particle, if its charge is negative, it repels the electrons incident ot it with the impact parameters $\rho < \rho_{min} = 2e^2/mv^2$. Here the electron-particle momentum transfer is 2mv. In the case of a positively charged particle, such electron will pass by it without a change in momentum. This effect leads to the appearance of an additional contribution to the friction force for the negatively charged particles:

$$\Delta F_{\parallel} = -\pi \rho_{min}^2 \, nv.2mv = 8\pi e^4/mv^2 . \qquad (5)$$

Under the conditions $L_c \sim 1$ this noticeably increases the frictional force for negatively charged particles.

In the presence of strong transverse magnetization, the longitudinal temperature of the electron beam in the particle system is of prime importance in cooling kinetics. After acceleration the temperature is determined by the cathode temperature and by a mutual repulsion of electrons [4]:

$$T_{\parallel} \approx \frac{T_c^2}{2W} + e^2 n^{1/3} \qquad (6)$$

where W is the electron energy after acceleration, and $T_{\parallel} \approx 10^{-4}$ eV = 1 K under typical conditions for electron cooling. The transverse temperature does not change during acceleration and is $T_\perp \sim T_c \gg T_\parallel$. In the cooling section the transverse-motion energy is transferred to the longitudinal plane due to mutual electron scattering and the longitudinal temperature of the electrons grows. However, the high magnetic field suppresses to a considerable extent this process, simultaneously making the Larmor radius less than the space between electrons[9]:

$$\rho_L = \sqrt{2T_c\, mc^2}/e\, B_0 \ll n^{-1/3}. \qquad (7)$$

It is seen from expression (1) that the frictional force $F_\parallel$ grows when increasing $v_\parallel$ up to a certain maximum (dependent on $v_\perp$ and on the velocity spread of the electron beam) and then decreases rapidly. If the characteristic spread of longitudinal electron velocities is $v_e \lesssim (e^2 n^{1/3}/m)^{1/2}$, the maximum longitudinal frictional force is equal to

$$F_{max} = C\, e^2\, n^{2/3}, \qquad (8)$$

where $C \sim 1$ is the constant of the order of unity. The dependence of the frictional force on the ion velocity is determined in the region $v \lesssim v_e$ by the expression

$$F = F_{max} \cdot \frac{v}{v_e} \qquad (9)$$

Experimental study of the frictional force

The device intended to measure the frictional force is schematically shown in Fig. 1. The use of a negative hydrogen-ion injector makes it possible to perform experiments with both the negatively and positively charged ions. The change in the ion charge is obtained by switching on, at the entrance of the solenoid, a special magnesium cloud target, in which double ionization of negative hydrogen ion occurs. Then the ion beam is directed to the solenoid where it interacts with the electron beam.

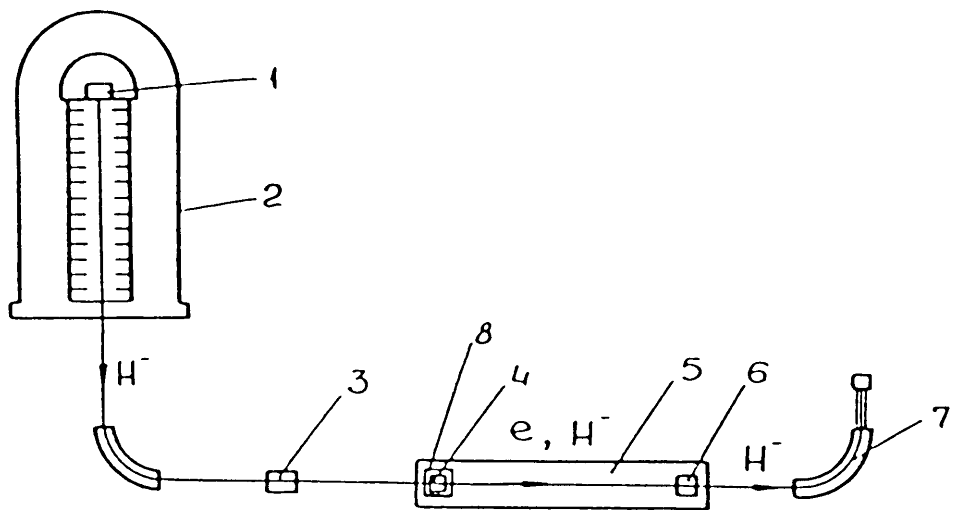

Fig. 1 : Scheme of the experimental device; 1: source of H^- ions, 2: van-de-Graaf accelerator, 3: magnesium target, 4: electron gun, 5: solenoid, 6: electron collector, 7: spectrometer.

The magnitude of the longitudinal frictional force was determined using an electrostatic spectrometer to measure the change in the ion energy after the passage through the cooling section.

This was done for a range of electron energies. When the average velocities of the ion and electron beams are equal, the frictional force is equal to zero and the ion energy does not change. When the electron energy deviates from the equilibrium energy, the frictional force which arises leads to a change in the ion energy. The magnitude of the energy variation δE_1 will be proportional to that of frictional force $F_\parallel$ over the length of the cooling section ($\delta E_1 = F_\parallel . l$). The relative change in the ion energy is small ($\delta E_1 / E_\parallel < 5.10^{-5}$) and is comparable to the stability of the accelerating voltage of the ion injector. To identify the useful signal in the accelerating-voltage noises, multiple measurements were made and their results were summarized.

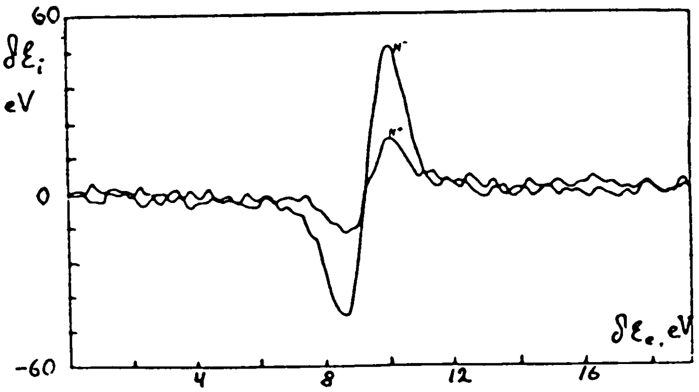

Fig. 2 : The dependence of energy deviation for H^- and H^+ ions on electron energy, B_0 = 4 kG, I_e = 3 mA.

Fig. 2 illustrates the dependence of a change in the ion energy (H^- and H^+) on the electron beam energy at a magnetic field of 4 kG and a current of 3 mA. It can be seen that the frictional force for negative ions is about 2.5 times higher than that for positive ions. The maximum longitudinal friction force versus the electron current is demonstrated in Fig. 3 for a 3 kG magnetic field. At low currents, the frictional force grows according to the law $Ce^2n^{2/3}$ for both the positive and negative ions. As the current increases, the frictional force reaches saturation and begins to decrease at a current higher than 6 mA. A decrease of the frictional force as the electron beam current grows is a result of the action of several factors whose relative contribution is difficult to estimate. The first of them - an elevation of the longitudinal electron temperature along the beam length, is due to the intrabeam scattering in the electron flux. The second is the absence of the complete compensation of the space charge of the electron beam. This leads to the defocusing (focusing for H^+) of the ion beam by a radial electric field and to an increase of the transverse angles in the cooling section, as well as the increase in transverse ion velocities at the entrance of the cooling section due to the ion beam being subjected to the action of the field of the non-compensated electron beam in the electron gun. Finally, the third factor is the non-chromaticity of the electron beam over the cross section, which is associated with the action of the beam space charge.

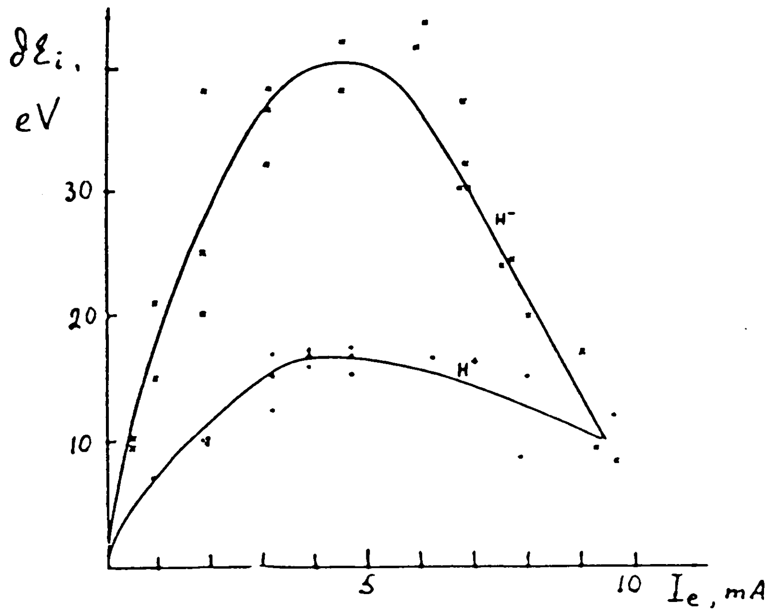

Fig. 3: The dependence of the frictional force on electron current. B_0 = 3 kG, xxx : H^-, ... : H^+.

The frictional force was measured for a magnetic field ranging from 1 to 4 kG. Fig. 4 shows the maximum friction force for positive and negative ions, in terms of $e^2 n^2 {}^3$. Al'so shown is the electron-beam current at which the frictional force reaches a maximum. It is seen that at a field of 1 kG the values of the frictional force for positive and negative particles are equal. As the magnetic field grows, the frictional force for H^- increases drastically, while for H^+ it remains nearly constant.

A weak dependence of the frictional force on the magnetic field for positive ions means that the strong magnetization of collisions only gives a certain gain in the quality of the electron and ion beams. It can be distinctly seen that the contribution from electron collisions with their reflection from the moving negative ion increases strongly with an increasing field and, as a result, the difference in the frictional force for H^+ and H^- arises at high magnetic fields.

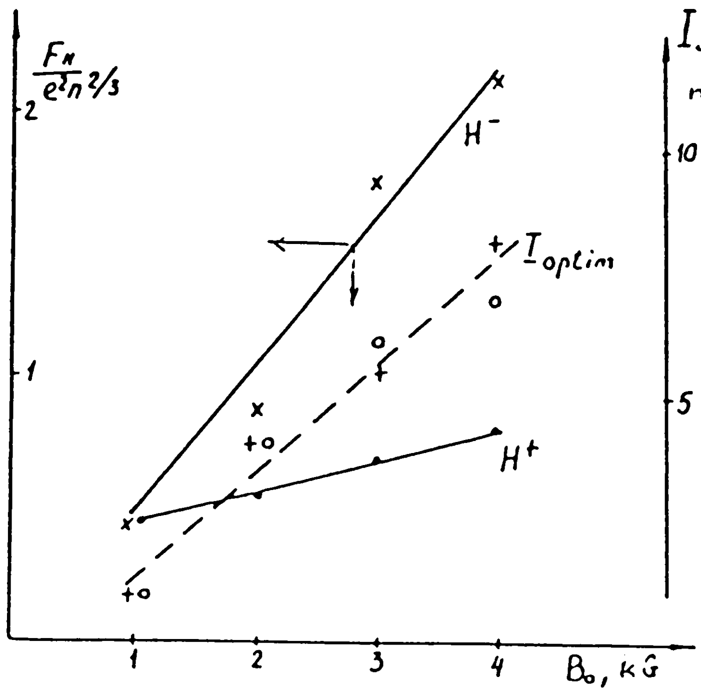

Fig. 4: The dependence of the maximum frictional force ($e^2 n^{2/3}$ units) on magnetic field (xxx H^-, ... H^+) and the optimal electron current (+++ H^-, ... H^+).

The possibilities of obtaining cold ion beams

The application of electron cooling for experiments with the heavy-particle beams is mainly attractive owing to the possibility of obtaining extremely low emittances and energy spread in the beam. In principle, the cooling process proceeds to the equalizing of the temperatures of the particle and electron beams. However, at such low effective temperatures of the electron beam $T_{eff} \sim e^2 n^{1/3} \sim 1$ K, a significant difference appears in cooling positively and negatively charged particles (see formula (5)). The negatively charged particles indeed damp down to T_e, while the positively charged particles are subjected to an additional diffusion in the transverse direction because of the formation and breaking of electron-ion (particle) pairs when they enter or leave the cooling region (quasi-recombination).

Under the condition that the velocities of the cooled particles are rather high, the cooling decrement is of the form[5-16]

$$\lambda_\perp = \frac{4\pi r_e r_p c L_c n\eta}{\beta^3 \gamma^5 (\Delta p_\perp / p)^3} \tag{10}$$

where r_e and r_p are the classical radii of an electron and a heavy particle, respectively; L_c is the Coulomb algorithm and η is the orbital section occupied by the electron beam. The parameter $\lambda_\perp$ is the instantaneous value of the decrement because during the cooling process when $\Delta p_\perp \to 0$, the cooling rate grows drastically. Cooling of the negatively charged particles proceeds to the effective electron temperature T_{eff} (when $n \sim 2.10^8$ cm^{-3}, $T_{eff} \sim 1$ K) and, hence, the transverse emittances can reach the values

$$\varepsilon_\perp = \pi\beta_o \left(\frac{\Delta p_\perp}{p} \right)^2 = \pi\beta_o \frac{2\,T_{eff}}{\beta^2 \gamma^2 Mc^2} \tag{11}$$

where β_o is the beta-function on the cooling section. So, at $\beta\gamma = 1$ the minimum achievable beam emittance is $\varepsilon_\perp = 2.10^{-5}$ π mm.mrad (if β_o = 10 m) and this opens great possibilities of applications on such beams.

The particle interaction in the transverse direction leads to the attenuation of the focusing effect and can shift the betatron-oscillation frequencies to dangerous "machine" resonances and limits, in principle the beam compression. Compensation of such a shift of betatron frequencies by a retuning of the focusing structure of the storage ring is inefficient because of a strong dependence of the shift on the oscillation amplitudes inside the beam. The shift in frequency for a heavy particle beam of length L in the longitudinal direction must be smaller than the distance to the nearest resonance ($\Delta\nu_{max}$). This limits the minimum emittance $\varepsilon_\perp$ of the beam to

$$\Delta \nu_p = \frac{r_p R_o}{2(\varepsilon_\perp/\pi)\beta^2 \gamma^3} \frac{N}{L} < \Delta \nu_{max} \qquad (12)$$

Here, R_o is the average radius of storage ring, N-particle number per bunch.

Another effect in the intense cooled beam is intrabeam scattering [10-11-12], in which the mutual scattering of the particle in the beam produces a "self-heating" of the particles. In the case of electron cooling, this effect becomes significant if the beam density is $n_p > \eta n M/m$, which means that in fact the conditions for this effect is absent in real storage rings. The limitations associated with the beam defocusing [12] appear much earlier. Fig. 5 shows the results of the measurements dealing with the emittance of the cooled proton beam at a low energy of 1.5 MeV ($\beta^2 \approx 3.2\ 10^{-3}$) where these effects can be seen most clearly.

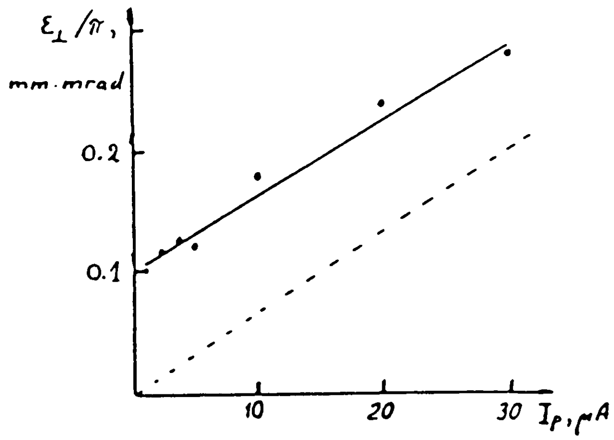

Fig. 5: The dependence of the emittance of the cooled proton beam (the ANP-M storage ring, proton energy is equal to 1.5 MeV)

The dashed line is for the emittance calculated according to formula (12) at $\Delta\nu_{max} \simeq 0.15$. The large value of the emittance at $I \to 0$ ($\varepsilon_\perp$ 0.1 π mm.mrad) compared to the calculated emittance 10^{-3} π mm.mrad, derived from formula (11) demonstrates the role of transverse diffusion of positively charged particles. Under these conditions, proton cooling goes to the temperature $T_\perp \sim 100$°K, while their longitudinal temperature is $T_\parallel \sim 1$ K.

COOLING OF THE BEAMS WITH LARGE PHASE-SPACE VOLUMES AND THEIR ACCUMULATION

Accumulation of intense antiproton beams was and remains one of the most interesting applications of electron cooling. The modern methods of antiproton beam generation enable one to achieve a 10^8-10^9 $\bar{p}$/s accumula tion rate [14]. However, the the phase volumes and the energy spreads of the beam coming from the target prove to be large, within the reasonable energy ranges. Since the time of electron cooling is proportional to (see Eq. (10)

$$\tau \quad \gamma^5 \, \phi^3_{\bar{p}} \, a^2_{\bar{p}}/I_e \, , \tag{13}$$

($\phi_{\bar{p}}$ is the angular spread, $a_{\bar{p}}$ the radius of an antiproton beam and I_e the electron current), in the application of the electron beam to cool the particles coming from the target, one is faced with considerable technical problems. For this purpose, it is reasonable to use stochastic cooling. However, the use of stochastic cooling for accumulation also presents difficulties. As shown in ref. 15, one of them is the limitation on the coherent beam stability which restricts directly the accumulation rate (within the 10^8 $\bar{p}$/s range). Electron cooling eliminates the difficulties caused by a mutual influence of the stored particles. Bearing this in mind, it seems to be preferable to use a combined accumulation scheme in which particle pre-cooling is performed stochastically, while storing is carried out using the electron cooling method. In this case, it is reasonable to employ two storage rings: one for stochastic pre-cooling and the other for accumulation by means of the electron beam. The energy at which accumulation is performed is determined by the achieavable depth of stochastic pre-cooling. If it is high, the particles are accumulated at the production energy. Estimates show that an energy of 8 GeV, accumulation with a 2 s periodicity requires the formation of an electron beam of 2 cm diameter, at a current of 12 A.

If the pre-cooling depth is limited, it is reasonable to accumulate at a lower energy. If the antiproton beam is decelerated, its emittance and momentum spread inevitably increases. But the reduction in electron energy allows the power of the electron beam device to become an acceptable parameter. For faster cooling of large-amplitude particles, special methods may be applied as well. One of them has been described in ref. 16 and uses the so-called mono-chromatic instability. Estimates show that the use of a storage ring with electron cooling enables an accumulation rate of the order of 5.10^{11} p/h and higher to be reached. An additional advantage of such schemes is the possibility of achieving, in the stored beam, high phase-space densities permissible by electron cooling.

DEVELOPMENT OF THE ELECTRON COOLING TECHNIQUE

Cold electron beam formation

The effective method of transverse velocity minimization for electrons outgoing from the gun is the so-called "resonant optics"[17]. This produces a quasirectangular distribution of the radial component electric-field E_r and provides the resonant dependence of the electron transverse velocity on the longitudinal magnetic field strength B_0.

Many attempts in the simple realization of resonant optics have helped to understand that "smooth" E_r distribution in the gun is the best approach for transverse velocity minimization. The criterium for minimum $v_\perp$ is

$$v_\perp < v_D = c\, E_{beam} / \gamma^2 B_0 \tag{14}$$

where E_{beam} is the electric field of the not neutralized electron beam, v_D the electron drift velocity.

The value of $v_\perp$ depends obviously on the magnitude of E_r and its distribution smoothness. For the distributions similar to that shown in Fig. 6, the Larmor velocity is

$$v_\perp \lesssim c\, E_r^{max} / B_0 \qquad (15)$$

where E_r^{max} is the maximum value of the $E_r(Z)$ function.

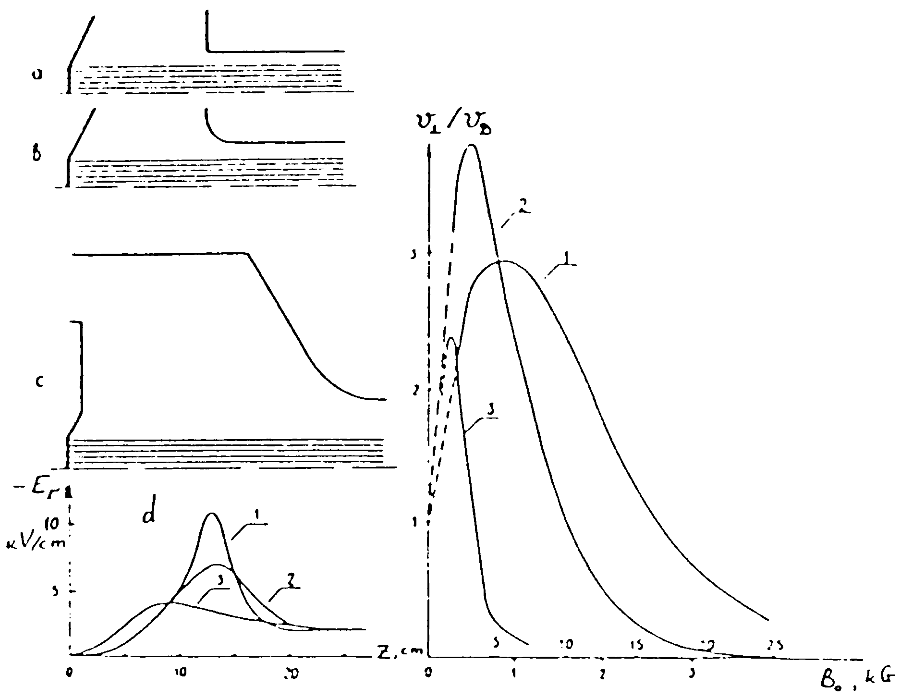

Fig. 6: Diode gun schemes with equal perveance (a,b,c) and their characteristics; d: radial electric field distribution, e: the dependence of electron transverse velocity (v_s units) on the magnetic field strength. Curves 1, 2, 3 correspond to schemes a, b, c.

To decrease E_r^{max}, it is necessary to "smooth" the E_r distribution. This can be illustrated by Fig. 6 where the dependence of $v_\perp/v_D$ on B_0 for guns with an equal perveance, but with different electrode designs are shown. For the smooth function $E_r(Z)$, the given value $v_\perp < v_D$ can be achieved in a a considerably lower magnetic field. The optimal geometry is depicted in Fig. 6.

The method described here has been used, in particular in the development of a "smooth" gun for the "solenoid model" device [18].

<u>High voltage electron cooling</u>

The development of the methods of cooling of heavy particle beams and their applications have shown the effectiveness of the use of electron cooling for antiproton and ion energies of a few GeV per nucleon. For this reason, the design and construction of the device which is the prototype of a high voltage electron cooling system with an electron energy of 1 MeV and a beam current of 1-10 Amps [19] has been started at the Novosibirsk Institute of Nuclear Physics in 1983. The system also provides the possibility of studying electron accelerating tubes with the beam of the required parameters, thereby offering the possibility to design the future high-voltage accelerators with a beam power higher than 1 MW. Such accelerators are the object of interest for many industrial and technical applications.

The scheme for electron beam energy recupreation, which is reasonable for electron coolers [8] is used in this device. The device scheme is shown in Fig. 7. The vacuum chamber is U-shaped and the accelerating tubes are placed in its vertical parts. Such a location permits one to avoid the undesirable mechanical tension in the tubes and to design most conveniently the high voltage supply system whose cathode and collector have close potentials. The electrons leaving the cathode (1) acquire the total energy eU_0 in the accelerating tube (2). Then the beam turns by an angle of 90° in the equipotential region, drifts along the horizontal section and turns again by an angle of 90°.

In the bending regions, the transverse magnetic field is applied to compensate the centrifugal drift. The electrons are decelerated in the tube (3) and reach the collector (4) whose potential is positive with respect to the cathode. The secondary electrons not trapped by the collector are accelerated to the total energy and come to the bending region. Their centrifugal drift direction coincides with the direction of the displacement caused by the bending field. Hence, the horizontal drift causes these electrons to be put on the vacuum chamber walls or in the special collector (5).

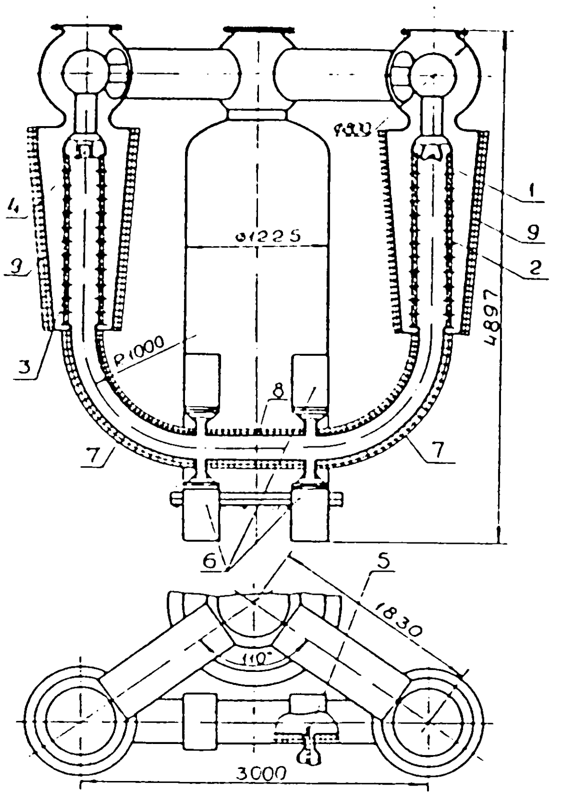

Fig. 7: Scheme for the high voltage electron cooling device; 1: cathode, 2-3 : accelerating tubes, 4: collector, 5: collector of secondary electrons, 6 : vacuum pumps, 7-8-9 : solenoid coils (7: toroidal, 8: cylindrical, 9: conical).

The electrical scheme is based on the components of the industrial electron accelerator ELV-6, designed at the Institute. The maximum voltage of the sectionized high-voltage rectifier is 1 MV and its power is 20 kW. The total energy instability constitutes about 3% and the voltage ripple under the full load is about 0.5%. The recovering energy source (2) is connected to the cathode (3) and the collector (4), and its maximum voltage is equal to 5 kV, the power is 20 kW and the voltage ripple is about 5%. The potential distribution along the accelerating and decelerating tubes is performed by active dividers [5-6].

In the device, there are no complicated electron circuits located near the high voltage potential. For this reason, and owing to a high efficiency of the special safety system, the device can operate successfully, even with repeated high-voltage breakdowns. This safety system is inevitably necessary for the recovering scheme similar to that described here. Otherwise, the effects of high voltage redoubling are possible during the breakdowns.

All the high voltage components are placed in the common system of gas tanks, which can operate at a pressure of 12 Atm of SF_6. The longitudinal magnetic field is generated by a solenoid (Fig. 10) which includes two identical conic coils (9), two toroidal coils (7) and the cylindrical coil (8). All the solenoid parts are winded with a copper conductor which has a cross-section of 26 x 26 mm and an internal channel for the cooling water. The solenoid can provide a magnetic field strength of up to 2 kG.

The transverse magnetic field coils are put along the solenoid to bend the beam inside the toroidal sections and to correct the beam trajectory in the straight section and near the collector. With these transverse fields, it is possible to correct the beam trajectory in the straight section without changing its position at the entrance of the collector. Such corrections permit to minimize the electron transverse velocities caused by the solenoid magnetic field perturbations.

The electron gun is of the diode type, with a 1 $\mu A/V^{3/2}$ perveance. The LaB_6 cathode has a diameter of 10 mm. The collector of the "Faraday-cylinder" type is made from magnetic steel. It is cooled with boiling freon-12, which is carried by polyethylene pipes winded around the accelerating tube. The maximum cooling power is about 8 kW.

Measurements have shown that work with a low current loss is possible only at definite values of the magnetic field, or at a high enough strength of this field. The corresponding values of the cyclotron lengths coincide with the experimental data. Up to now a stable beam with a current of 1 A to 1 MeV energy was obtained at a magnetic field of about 800 G. The collector potential was 3 kV and the relative current losses were about 1.10^{-3}

Electron energy recuperation

The work on the creation of effective recuperators have been in progress. As before, much attention has been paid to the devices with the transformation of the electron-beam geometry. In ref. 19, a recuperator has been described in which the cyclindrical elecron beam is transformed into a "pipe beam" (Fig. 8). In such a device, one has succeeded in achieving a 500 $\mu A/v^{3\ 2}$ collector perveance : at a total beam current of 4 A, the collector potential was 400 V (the total electron energy - 25 keV)

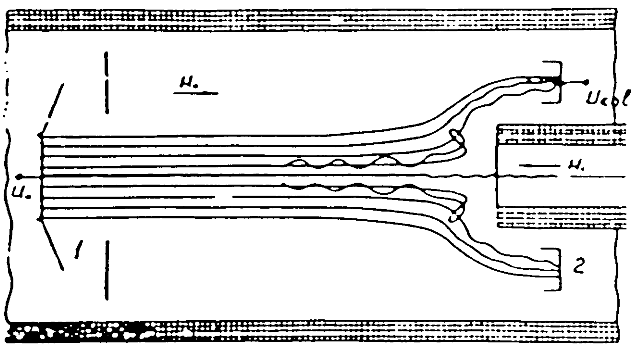

Fig. 8: The scheme for the transformation of a cylindrical beam into a disk-shaped beam (a) and the distributions of the potential (U) and magne- tic field (H) on the axis (6).

Studies have been performed of a recuperator with the transformation of the cylindrical beam into a "disc beam" (Fig. 9). This scheme has significant advantages over the first one and enables the area of the collector surface to be considerably enlarged. This helps the dissipation of heat and, hence, enables the use of higher currents. In preliminary experiments, the 3 A electron beam was successfully received by the collector at 400 V potential; this corresponds to a 350 $A/V^{3\ 2}$ perveance. The experimental results allow the conclusion to be drawn on the possibility of effective electron energy recuperation in the beam with a current up to 50 A.

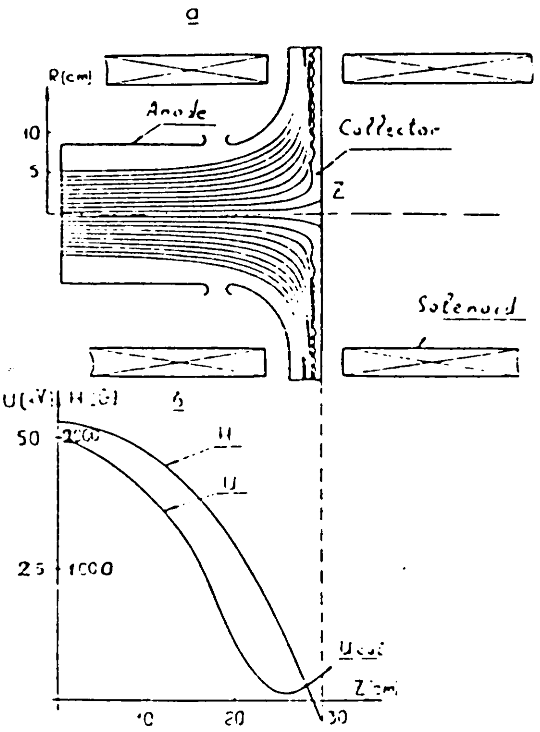

Fig. 9: The scheme of the transformation of a cylindrical beam into a disk-shaped beam (a) and the distributions of the potential (U) and magnetic field (H) on the axis (б).

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