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ELECTRON COOLING: PHYSICS AND PERSPECTIVE APPLICATION

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НОВОСИБИРСК

INTRODUCTION

The development of experimental investigation related to nuclear physics has resulted in raising sharply the requirements on the quality of particle beams. It is especially important to obtain beams of high density and small energy spread.

The easiest way to increase the particle density is to improve the focussing properties of the magneto-optical channel for particles confinement. Here, although transverse beam dimensions are reduced, transverse beam momenta grows in accord with the condition of six-dimensional phase density conservation. Cooling of the beam means a decrease in the spread of particle velocity not due to a change in the focussing, but due to the energy loss of the chaotic particle motion as a result of their interaction with the «cooler». This interaction provides for the increase in the phase density of the beam and for the storage of particles, filling them into the sections of the phase space vocated in the process of cooling.

The phase density of the beam cannot be increased by using any set of external electromagnetic fields, independent of the motion of specific particles of the beam. Then the statement, that the phase density of the beam particles is constant and is determined by initial conditions (Liouvilles theorem) holds true. In some unique cases, it is possible to increase the phase density of the beam particles by means of their specific production in the required points of the phase space. This process of particle production is bound up either with the decay of other particles, or, as if of charge-exchange injection, with the change in the charge state of particles. To increase the phase density of already existing beam of particles, it is necessary to introduce dissipative forces, which results in the loss by the particles of the energy of relative motion.

Furthest developed today is the radiation cooling [1—3], based on the principle that during motion of relativistic charged particles in a magnetic field, synchrotron radiation is induced and, correspondingly, the radiation reaction force counteracts the full particle velocity. If then the average energy loss is compensated by an external RF source, then, provided the magnetic structure is chosen correctly, deviations from the equilibrium motion are gradually damped radiation cooling finds its widest application in the storage of electrons and positrons and in experiments with electron-positron colliding beam and with superthin internal targets.

The extremely high rise in the magnitude of synchrotron radiation of electrons at energies of hundreds of GeV makes the change-over to linear colliders inevitable. To obtain the required luminosity one will have to compress intense bunches of electrons and positrons at their collision point down to fractions of a micron, which will require that the particles should be preliminary cooled at storage rings of a very special structure.

For hadron colliders SR is essential at energies over tens of TeV, which promises the possibility of additional increasing the luminosity at such installations.

A relatively new method is the so-called laser cooling [4, 5], based on the interaction of a beam of atom or ions, which is not completely deprived of its electron shell, and exclusively is such case, with the electromagnetic radiation from a laser. To obtain the cooling effect use is made of one of the absorption lines in the spectrum of an atom or an ion. The combination of few laser beams with appropriate directions and frequencies can give the three-dimensional cooling.

Ionization cooling [6, 7] is based on the energy loss of particles while moving in rather dense targets. The difficulties of this method are caused by strong absorbtion and scattering of beam particles by the target nuclei. Some modifications of this method have been used in system of beam extraction from the accelerator. The most natural application of the ionizing method is the cooling of muon beams.

The method of stochastic cooling, suggested by S. Van der Meer [8] in 1968, is based on the measurement of the particle position by pick-up electrodes and correction of its motion by this signal after

amplifying it by several orders of magnitude. The wide-scale development of UHF amplifies with a sufficiently high power provided for the use of this method at CERN and Fermilab for storing antiprotons. The notable discoveries of *W*- and *Z*-bosons evidenced the great importance of cooling method in establishing experiments with hadron colliding beams.

The idea of the electron cooling method [9—11] suggested already in 1966 by G.I. Budker is based on substituting for the target an electron beam moving with the same average velocity as the hadron beam under cooling. In this case, a noticeable drop in the electron density is compensated by the increase in the efficiently of the energy transfer to electrons due to low relative velocities of hadrons and electrons. The first experiments carried out in Novosibirsk in 1974 [12] showed the high efficiency of method and triggered on all the development of heavy particles cooling methods and made an important step for the realization of experiments with proton-antiproton colliding beams. In the course of the experiments carried out at the NAP-M facility it was discovered that the time required for the cooling, expected to be several seconds [13], in fact turned out to be 0.1s. Such an abrupt increase in the cooling efficiency was the result of a combined effect of two factors: first, the presence of the longitudinal magnetic field in the cooling section and, second, the electrostatic acceleration of the electron beam, which is accompanied by a considerable decrease in the longitudinal velocity spread of particles. The longitudinal magnetic field is necessary for transporting the electron beam from the cathode to the section of proton beam cooling and further to the electron collector. The magnetic field «magnetizes» the transverse electron motion, and as a result, the particles under cooling interact with a cool Larmor circle, but not with a hot (about the cathode temperature) free electron [14, 15]. This phenomenon resulted both in the facilitation of the process of cooling, and in the cooling of particles down to temperatures lower than that of the cathode (1200 K). A temperature of the particle's longitudinal motion of about 1 K was obtained for a proton beam with an energy of 65 MeV [16]. Such a low temperature caused some ordering in the partical position in the storage ring [17, 18]. The class of the phenomena discovered aroused so much interest, that the authors specifically called the process as «fast electron cooling».

For a detailed study of the kinetic of cooling under the conditions of strong magnetization an installation called MOSOL with a field of 0.4 T and a very good field homogeneity was built. The experiments performed at this facility in the regime of single transmission of an ion through an electron beam, were able to show an essential difference in the friction force for positively and negatively charged particles [23].

Successful experiments aimed at the development of the method of electron cooling later were carried out at CERN and Fermilab [19, 20]. Now installations with electron cooling operate in the USA and FRG for light ions and at CERN at the LEAR facility for cooling antiprotons. Other machines are under construction. All this show the beginning of an extensive utilization of the possibilities provided by electron cooling in real experiments [30—32, 34].

The goal of the present review is to supply the information on the present status of electron cooling primarily from the viewpoint of physics of cooling, methods of experimental investigations and potential applications.

ELECTRON BEAM FOR COOLING

To carry out electron cooling, an electron beam having the same average velocity, as that of the cooled particles, should be placed in the straight section of the particle orbit. It is evident that the larger fraction of the orbit is occupied by the electron beam and the more intense it is, the quicker the particles will be cooled. Let us briefly consider the restrictions arising in this way.

For the transition of an intense electron beam at large distances a longitudinal homogeneous magnetic field is most often used. Here, the larger the magnetic field H is, the less are the relative transverse electron velocities produced by the space charge of the electron beam [21]

$$\theta_{\perp e} = \frac{2\pi e n a}{\beta\gamma^2 H}, \tag{1}$$

where e is the electron charge; n is the density of electrons; a is the electron beam radius; $\beta = v/c$; $\gamma = 1/\sqrt{1-\beta^2}$.

The spread of electron longitudinal velocities is usually a great deal smaller at the electrostatic acceleration of the beam from the electron gun cathode. The effective temperature in the accompanying system is bound up with the spread of the electron energy on the

cathode $\Delta E \approx T_c$ and is:

$$T_{\parallel} = \frac{T_c^2}{\gamma^2\beta^2 mc^2} \approx T_c \frac{T_c}{2E_{kin}}\Big|_{\beta \ll 1} \tag{2}$$

(E_{kin} is the kinetic energy of beam electrons). While accelerating the particles up to energies of several kilovolts, the longitudinal temperature happens to drop so drastically ($T_c \approx 0.2$ eV) that the interaction of electrons in the beam becomes essential, raising the longitudinal temperature due to the mutual repulsion of initially chaotic electrons [22]:

$$T_{\parallel} = \frac{T_c^2}{2E_{kin}} + 2e^2 n^{1/3}. \tag{3}$$

The transverse motion of electrons is determined, as a rule, by the cathode temperature:

$$v_{\perp} = \sqrt{\frac{T_c}{m}}. \tag{4}$$

Under those conditions, when the longitudinal temperature of the electron beam is several orders of magnitude lower then the transverse one, of great importance is the problem of preserving this state for a sufficiently long path. Ipterbeam electron scattering, apparently, tends to equalize these temperatures, and, neglecting the influence of the magnetic field, the heating rate is determined from:

$$\frac{dT}{dz} = \frac{2\pi e^4 n L_C}{m v v_{\perp}} \tag{5}$$

where $z = vt$ is the longitudinal coordinate, L_C is the Coulomb logarithm of electron-electron collisions. The distance at which the temperature increment will make $\Delta T_{\parallel} \approx e^2 n^{1/3}$ can be estimated as follows:

$$\Delta z \approx \frac{v v_{\perp}/c^2}{2\pi L_C n^{3/2} r_e}, \tag{6}$$

where r_e is the classical radius of the electron. With these parameters, characteristic for electron cooling ($v = 0.3$ c, $v_{\perp} = 10^{-3}$ v, $L_C = 10$ cm, $n = 10^9$ cm^{-3}), the length of temperature growth will be at most $z = 5$ cm. It is evident, that to speak of the possibility to use magnetization for electron cooling, a strong suppression of the internal beam heating is required. The strong magnetic field alters considerably the kinetics of electron interactions. Provided its strength is large enough, such that an average Larmor radius of the transverse electron rotation is a great deal smaller than the distance between them:

$$\rho_L = \frac{mv_\perp c}{eH} \ll n^{-1/3}, \tag{7}$$

then the interaction of electrons will be of adiabatic character and the fast transverse rotation will not be transmitted to the slow longitudinal motion. To demonstrate this effect, the results of measurements of the electron beam energy spread are shown in Fig. 1 after it passes through a 3 m long section with different magnetic fields.

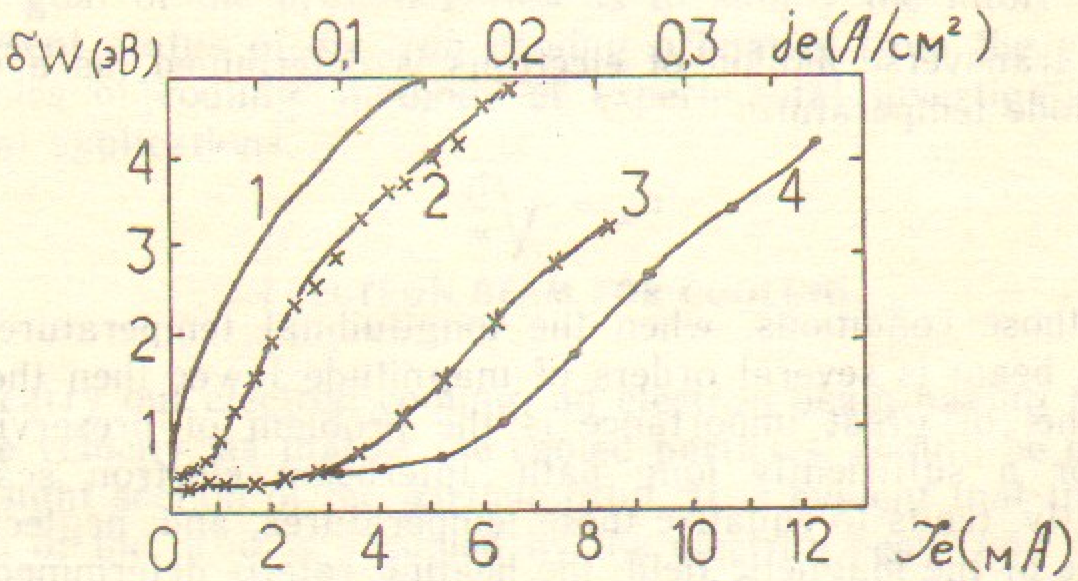

Fig. 1. Electron beam energy spread after passing through a 3 m long section of the magnetic field. The beam energy is 470 eV.

1—analytical calculation at a zeroth magnetic field; *2*—*4*—correspond to the magnetic field values of 1, 3 and 4 kGs, respectively.

It is evident, that for larger values of the magnetic field an intense energy spread heating occurs at higher values of the current density. Assuming that $T_c = 0.2$ eV, we obtain the threshold value of the density (7) corresponding reasonably well to the estimate:

$$n_t \approx \left(\frac{0.35}{\rho_L}\right)^3. \tag{8}$$

Another important restriction on the electron current density they are the space charge effects, causing a transverse changing of the potential in the electron beam and strongly affecting the dynamics of the betatron motion of the cooled particles. The correct choice

of parameters of motion in the cooling section makes it possible to noticeably reduce the influence of these fields. Thus, for example, the nodes in the storage ring dispersion function $(P\,\Delta x/\Delta P)$ permit one to reduce essentially the role of potential space charge the redistribution of cooling decrements concerning respect to degrees of freedom.

One more way of controlling these effects dealing with the compensation of the space charge by trapped ions has been studied. At moderate current densities practically 100% compensation of the beam space charge is attainable, although if the current density increases there appear problems with providing coherent stability of ions and electrons concerning axially asymmetric oscillations.

Of great importance for the success of experiments is the electron energy recuperation of high efficiency ensuring low energy consumption at a rather powerful electron beam [21].

KINETICS OF ELECTRON COOLING

It is of common knowledge, that in the Coulomb interactions the momentum and energy exchange of colliding particles diverged logarithmically with integration over the large impact parameters. Therefore, it is necessary to classify the interaction by impact parameters and find such a value of beyond which the interaction should be essentially decreasing. Obviously for the interaction of heavy particles with electrons in a magnetic field an essential (and requiring special consideration) contribution to the integral of interaction can be provided for by the region of impact parameters satisfying the following condition:

$$\rho_L < \rho < \rho_{max}. \tag{9}$$

With this impact parameters, if the velocity of a heavy particle with respect to the Larmor circle, is equal to

$$\vec{v}_A = \vec{v} - \vec{v}_{e\parallel}. \tag{10}$$

($\vec{v}$ particle velocity, $\vec{v}_e$ is the electron velocity) is not very high compared with $v_{e\parallel}$, there can be found a region by ρ, where the interaction duration exceeds the Larmor period:

$$\tau = \frac{\rho}{|\vec{v}_A|} \gg \frac{\rho_L}{v_{e\perp}} = \frac{1}{\omega_L} ; \tag{11}$$

as a result, at small v_A the time of interaction is essentially increased, thereby increasing the efficiency of cooling at small relative velocities of cooled particles. It also results in a greater shift of the electron during the time of interaction, and, therefore, the first Born approximation becomes inapplicable at impact parameters over ρ_{min}:

$$\rho_{min} = \frac{e^2}{m|\vec{v}_A|^2} . \tag{12}$$

Let us assume, that ρ_{max} is determined only by the plasma frequency of electron oscillations ω_p:

$$\rho_{max} = \frac{|\vec{v}_A|}{\omega_p} . \tag{13}$$

In this case the equality $\rho_{max} = \rho_{min}$ is valid at

$$v_A = \sqrt{\frac{2e^2 n^{1/3}}{m}} = v_{e\parallel} ,$$

corresponding to the longitudinal temperature of the electron beam (2). This means that very close to equilibrium, when $v_A \ll v_{e\parallel}$, where should appear an essential difference in the interaction of positively and negatively charged particles with the electron beam.

The influence of the electron-proton interaction on the ion motion can be roughly divided into two parts. The first one, connected with the energy loss by the moving particle, produces the friction force, the other one, dealing with scattering, results in diffusion. Near equilibrium the influences of both these factors are mutually compensated, which provides for equilibrium values of the velocity spread. At substantial velocity deviations from the equilibrium value one can use the formula for ionizing losses and obtain the value of the friction force acting counter to the particle motion velocity v, $F = \frac{dE}{dt}/v$ where dE/dt is the energy loss rate.

Let us begin the description of the friction force with the simplest case, when the magnetic field is absent. In such a case, when the function of electron distribution in velocities has the form $f(\vec{v}_e)$, the friction force can be written down as follows:

$$\vec{F} = \frac{4\pi e^4 L_C n}{m} \int \frac{\vec{v} - \vec{v}_e}{|\vec{v} - \vec{v}_e|^3} f(\vec{v}_e)\, d^3\vec{v}_e , \tag{14}$$

where $L_S = \ln(\rho_{max}/\rho_{min})$ is the Coulomb logarithm of interactions, $\rho_{max} = \min(v/\omega_p, \tau v, a)$, $\rho_{min} = e^2/mv^2$, τ is the time of a particle's single path through the electron beam. The friction force increases as $1/v_e^2$ with the decrease of v down to the characteristic spread of electron velocities Δv_e, further decreasing linearly to zero $F \sim v$.

The presence of the magnetic field results generally in the appearance of 3 different regions of impact parameters:

a) small impact parameters, where the presence of the magnetic field is not essential:

$$\frac{v_A}{\omega_L} > \rho > \frac{e^2}{m v_e^2} ; \tag{15}$$

b) intermediate impact parameters, where multiply repeated passing of the electron by the particle are essential:

$$\frac{v_{\parallel e}}{\omega_L} = r_L > \rho > \frac{v_A}{\omega_L} ; \tag{16}$$

c) large impact parameters, where the particle interacts practically with the Larmor circle moving only along the magnetic field

$$\rho_{max} > \rho > r_L . \tag{17}$$

The relative contribution of the three regions to the total interaction integral depends on the particle velocity and the value of the magnetic field.

Let us estimate the contributions of these three regions to the friction force, assuming that the distribution of electrons in velocities is «flat» longitudinally: $v_{\perp e} \gg v_{\parallel e} = \sqrt{2e^2 n^{1/3}/m}$:

a) the contribution of fast collisions is

$$\vec{F} = -\frac{4\pi e^4 n}{m} \ln \frac{(v_A/\omega_L)}{e^2/(mv^2)} \begin{cases} * \dfrac{\vec{v}}{v^3} & v \gg v_{\perp e} \\ * \dfrac{\vec{v}_\perp + \vec{v}_{\parallel e} v_\perp / v}{v_{\perp e}^3} , & v \ll v_{\perp e} ; \end{cases} \tag{18}$$

b) in repeated collisions the momentum transfer to the electron is equal to

$$\Delta p_{\perp} = \frac{2e^2}{\rho v_{e\perp}}, \tag{19}$$

and the number of repetitions $\omega_L(2\rho/v)/2\pi$, hence the ion energy loss makes

$$\Delta E = \frac{1}{2m}\left(\frac{2e^2}{\rho v_{e\perp}}\right)^2 \frac{2\rho}{v}\,\frac{eH}{2\pi mc}. \tag{20}$$

Therefrom we can estimate the friction force

$$F = \int_{r_{\min}}^{r_L} \Delta E\, 2\pi\rho n v\, d\rho = \frac{4\pi e^4}{m v v_{\perp e}} \ln \frac{r_L}{(v/\omega_L)}; \tag{21}$$

c) in case of strong magnetization, the momentum transferred to the electron equals that of the particle passing it

$$\Delta p = 2e^2/\rho v. \tag{22}$$

But the energy loss here is bound up only with the component of this momentum along the magnetic field and the friction force is equal to:

$$F = -\frac{2\pi n e^4}{m v^2}\left(\frac{v_{\perp}}{v}\right)^2 \ln \frac{\rho_{\max}}{r_L}. \tag{23}$$

This part of the friction force continues to grow as $1/v^2$ with the decrease of v below $v_{\perp e}$ and attain its maximum near $v \approx v_{e\parallel} = \sqrt{2e^2 n^{1/3}/m}$, beyond which it drops linearly

$$F = -e^2 n^{2/3} v / v_{\parallel e}, \quad v < v_{\parallel e}. \tag{24}$$

Shown in Fig. 2 are the described variants of the friction force dependence at the motion transverse to the magnetic field. It should be underlined, that at especially low velocities $v \approx \sqrt{m/M}\, v_{\parallel e}$ the contribution of the diffusional part to the energy loss turns out to be important, and for this region a more accurate description of the friction force is required.

Note, that in the case of the ion motion along the magnetic field, the magnetized part of the friction force turn to zero. Near $v_{\parallel e}$, where the maximum friction force is attained, the most striking difference in the friction force for positively and negatively charged particles is occurred. While moving along the magnetic field a posi-

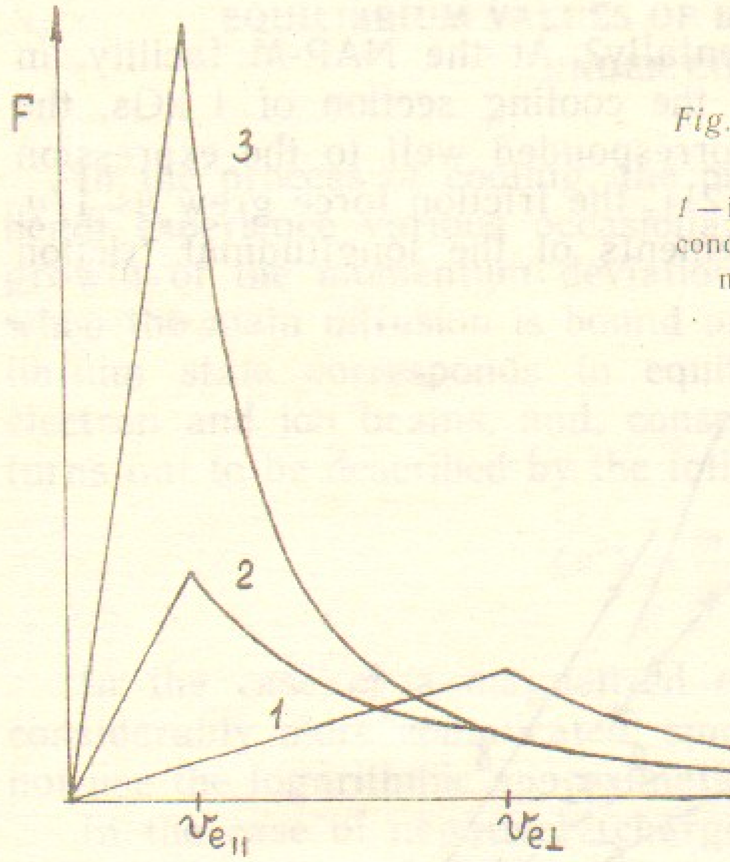

Fig. 2. Behaviour versus friction force at different values of magnetic field.

1 — in the absense of magnetic field; *2* — under the condition of partial magnetization; *3* — complete magnetization of transverse electron motion.

tively charged particle attracts an electron, it (the electron) being accelerated while approaching the particle and decelerated when drawn off, so that almost no energy transfer takes place. In the case of a negatively charged particle, all the electrons within an impact distance under e^2/mv^2, will be reflected from the bombarding particle and acquire momentum of 2 mv. As a result, an additional friction force for negatively charged particles appears:

$$F = 2mv\pi\rho^2_{\min}\, vn = \frac{2\pi e^4 n}{mv^2} \approx \pi e^2 n^{2/3} \quad \text{at} \quad v \approx v_{\parallel e}. \tag{25}$$

Near the equilibrium, when $v \ll v_{\parallel e}$ for positively charged particles the cooling decrement is approximately:

$$\Lambda^{+} = \frac{1}{M}\frac{dF}{dv} = \frac{m}{M}\sqrt{\frac{e^2 n}{m}}, \tag{26}$$

and for negatively charged particles it is approximately 3 times higher:

$$\Lambda^{-} \approx 3\frac{m}{M}\sqrt{\frac{e^2 n}{m}}. \tag{27}$$

What was observed experimentally? At the NAP-M facility, in the case of a magnetic field in the cooling section of 1 kGs, the behaviuor of the friction force corresponded well to the expression for a partially magnetized case (21), the friction force grew as $1/v$. In Fig. 3 the results of measurements of the longitudinal friction

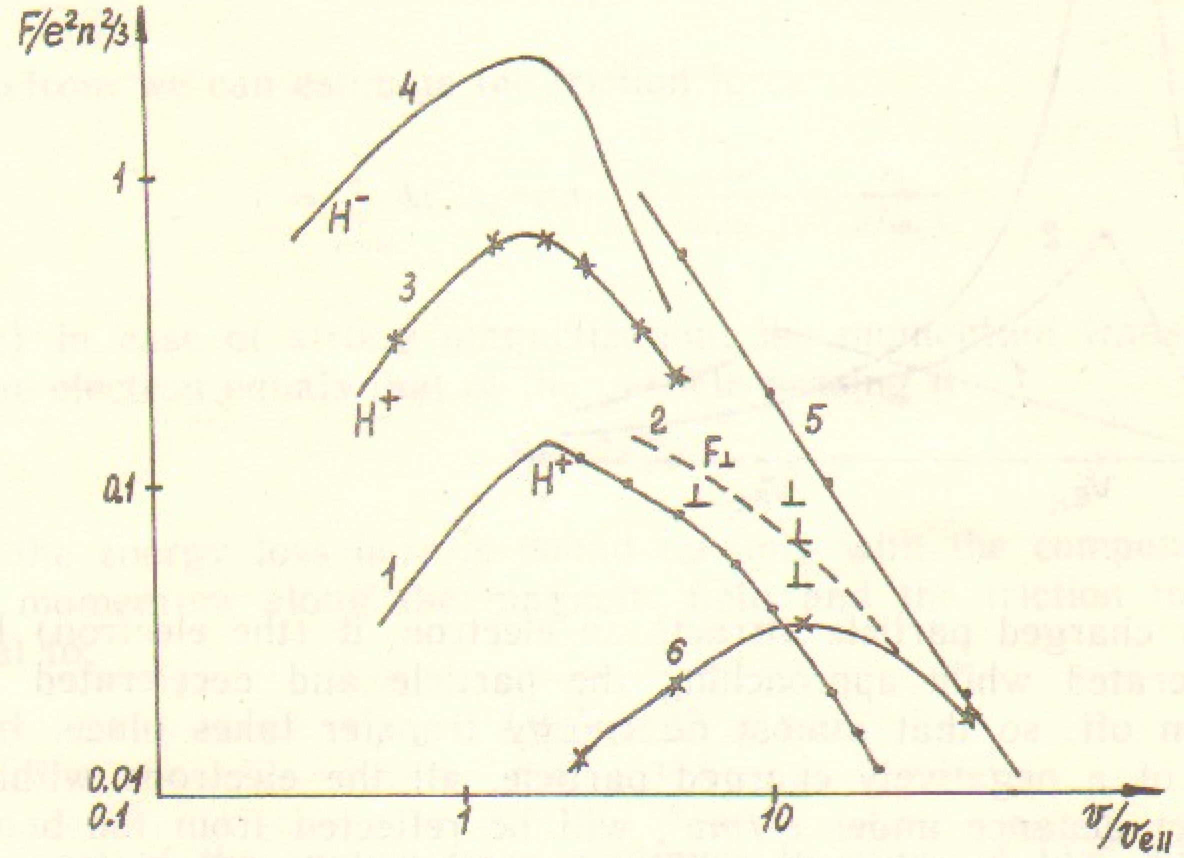

Fig. 3. Experimental measurement of friction force versus the relative velocity of particles and electrons. $F_{\parallel}$ (*1*) and $F_{\perp}$ (*2*) provided by measurements at NAP-M, $H-1$ kGs; protons, *3* for H^+ and *4* for H^- at $H=4$ kGs; both the curves—for $F_{\parallel}$; the MOSOL installation; *5*—theoretical limit for friction forces, expression (23); *6*—experiments at CERN, ICE, $F_{\parallel}$.

force at NAP-M and MOSOL are presented. It is evident that the friction force attains its maximum value at $v \approx 2v_{\parallel e}$ and with a further velocity growth it drops as $1/v$, approaching the logarithmically approximated value (23). The data presented in the same figure having been obtained at the ICE facility, show an essentially smaller value of the force at low motion velocities. This is accounted for by the fact, that a small magnetic field (0.7 kGs) is used, thus providing a small contribution of magnetized collisions, and the maximum force is attained at $v=15v_{\parallel e}=0.6\cdot+10^7$cm/s, which is close to the electron thermal transverse velocity.

EQUILIBRIUM VALUES OF BEAM VELOCITY SPREAD UNDER COOLING

In the process of cooling, the particles travelling in an electron beam experience various occasional pushes, leading to a diffusion growth of the momentum deviation squared. In the simplest case, when the main diffusion is bound up with electron motion, the equilibrium state corresponds to equilibrium in temperatures of the electron and ion beams, and, consequently, the spread in velocities turns out to be described by the following relation:

$$\langle v^2 \rangle = \frac{m}{M} \langle v_e^2 \rangle . \qquad (28)$$

In the case of a magnetized electron beam the calculation is considerably more complicated, since near the equilibrium one cannot use the logarithmic approximation any longer.

In the case of negatively charged particle, the diffusion is relatively easy to calculate. Electrons, having a specific velocity $v_{e\parallel}=\sqrt{2e^2n^{1/3}/m}$, while colliding with a slowly moving particle, transfer to them a momentum of $2mv_{\parallel e}$; the frequency of such collisions is $v_{\parallel e}n^{1/3}$, as a result, a diffusion rate will make:

$$\frac{d(\Delta P)^2}{dt} = 4v_{e\parallel}^2\, m^2\, v_{e\parallel}\, n^{1/3} = 4m^2 \left(\sqrt{\frac{2e^2n^{1/3}}{m}} \right)^3 n^{1/3} .$$

and give the equilibrium value equal to:

$$\frac{\langle \Delta P^2 \rangle}{2M} = \frac{d(\Delta P)^2/dt}{2M\Lambda^-} \approx 2e^2n^{1/3} . \qquad (29)$$

i. e. negatively charged particles are cooled down to the temperature of the longitudinal electron motion.

Positively charged ions have an additional mechanism of diffusion in the transverse direction, due to the production of longitudinally coupled macroscopic pairs (ion-electron ones) while entering the cooling section. In the rather strong magnetic field, an electron oscillates along the magnetic field lines and drifts slowly around the crossed electric and magnetic fields. At the cooling section output the electron is quickly separated from the ion. As a result, the time of electron-ion interaction increases, thus resulting in a strong increase in the transverse diffusion.

Shown in Fig. 4 are the results of numerical simulation of the

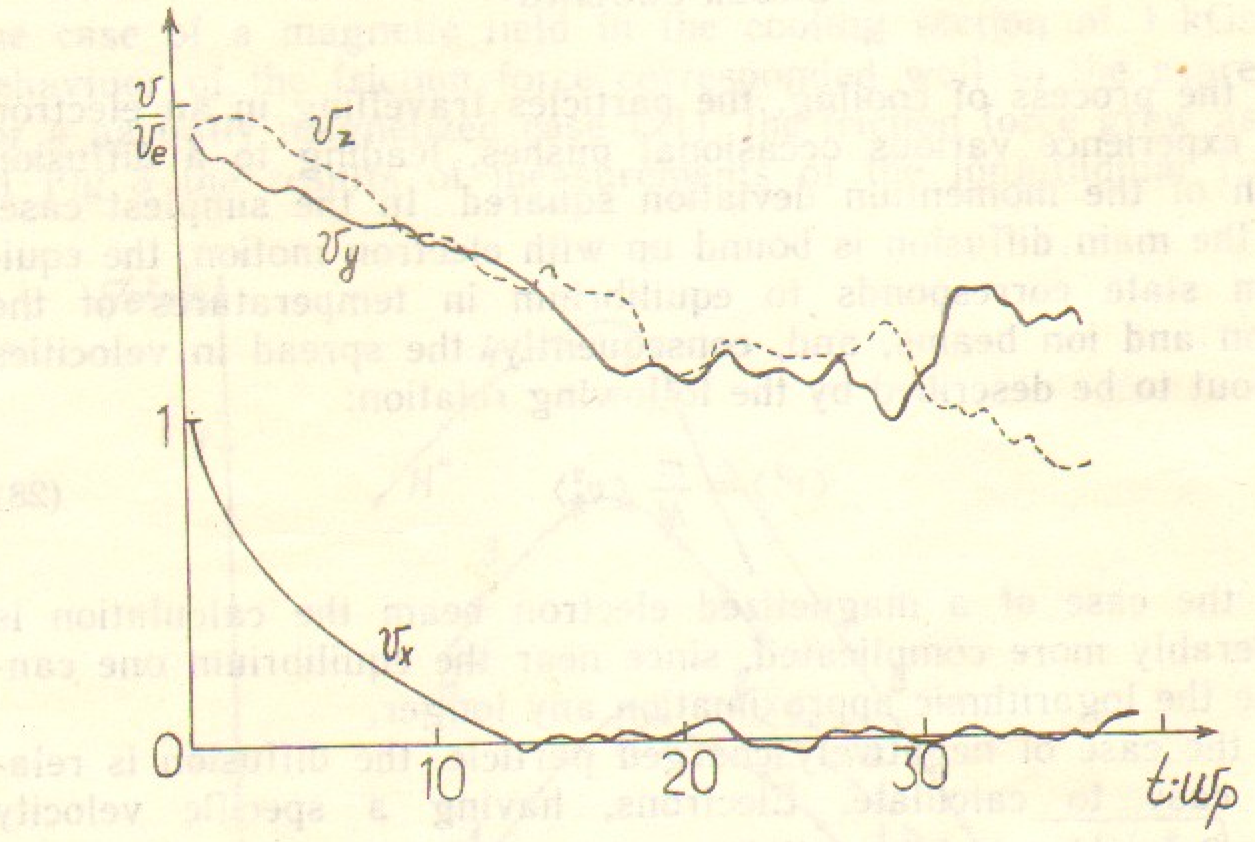

Fig. 4. Velocity components of the proton, cooled by an electron beam in a very strong magnetic field versus time (numerical simulation).

process of cooling of positively and negatively charged particles in the very strong magnetic field. As it seen, negatively charged particles are cooled down to $T \approx 2e^2 n^{1/3}$, while in the case of positively charged ones only the longitudinal degree of freedom is cooled, and transverse velocities are considerably higher.

In Fig. 5 the equilibrium transverse velocities are shown versus the value of the magnetic field. With the increase of the magnetic field, apparently, the established transverse velocities first drop with the growth of the transverse electron motion magnetization, and then begin to grow due to the diffusion growth due to the production of quasi-coupled pairs. The estimates, given in [24], show that in this case the transverse temperature is

$$T_\perp \approx 5e^2 n^{1/3}\left(\frac{e^2\tau^2 H^4}{nm^3c^4}\right)^{1/6}, \qquad (30)$$

where τ is the duration ion interaction with the electron beam.

In the process of cooling the beam density is increased by many orders of magnitude and, as a result, for the equilibrium values of

velocity spreads the effects of interbeam interaction turn out to be very essential. Coherent interaction of particles in the transverse direction results in reduction of focusing and shifts of betatron oscillation frequencies to resonances, which in principle, may limit further cooling of the beam. To estimate the limiting emittance of the cooled beam in this case one can make use of the following expression:

$$\varepsilon = \frac{NR_0 r_0}{\pi l \beta^2 \gamma^3 \Delta\nu_{max}}, \qquad (31)$$

where N is the number of particles in the bunch with a length l, R_0 is the average radius of the storage ring, $r_0 = e^2/Mc^2$ is the classical radius of the particle; $\Delta\nu_{max}$ is the maximum admissible shift of betatron oscillation frequencies.

From this expression it is evident that this effect is most essential at a small energy of the beam. In Fig. 6 the change in the proton beam diameter versus its current at an energy of 1.5 MeV is shown. The current of the electron cooling beam is 1 mA, its diameter is 1 cm.

Another effect, which appears in an intense proton beam, especially in an ultimately cooling one, is the mutual scattering of the beam particles. In the particle revolution frequency in a storage ring grows with the energy (H=const), the interbeam scattering leads only to hermalizing of temperatures over all the degrees of freedom in the accompanying system. Quite a different situation occurs, when the revolution frequency drops with the increase in the particle energy (25). Then two particles radially oscillating and having strictly equilibrium energies, can abruptly change their energies after scattering, radial betatron oscillations with an amplitude exceeding the initial one being simultaneously excited. Therefore, it is not thermalizing of particle temperatures in degrees of freedom that takes place, but «self-heating» of beam particles, which can be limited only by friction, for example, by electron cooling. In the general case, when transverse degrees of freedom have a noticeably higher temperature, to evaluate the transverse degree heating rate one can make use of expression (27):

$$\frac{d}{dt}\frac{\Delta P_\parallel^2}{P} = \frac{4r_0^2 NC L_C}{\gamma^3 l \varepsilon_\perp^{3/2}\sqrt{\langle\beta\rangle}}. \qquad (32)$$

The particle interaction in a strongly cooled beam becomes especi-

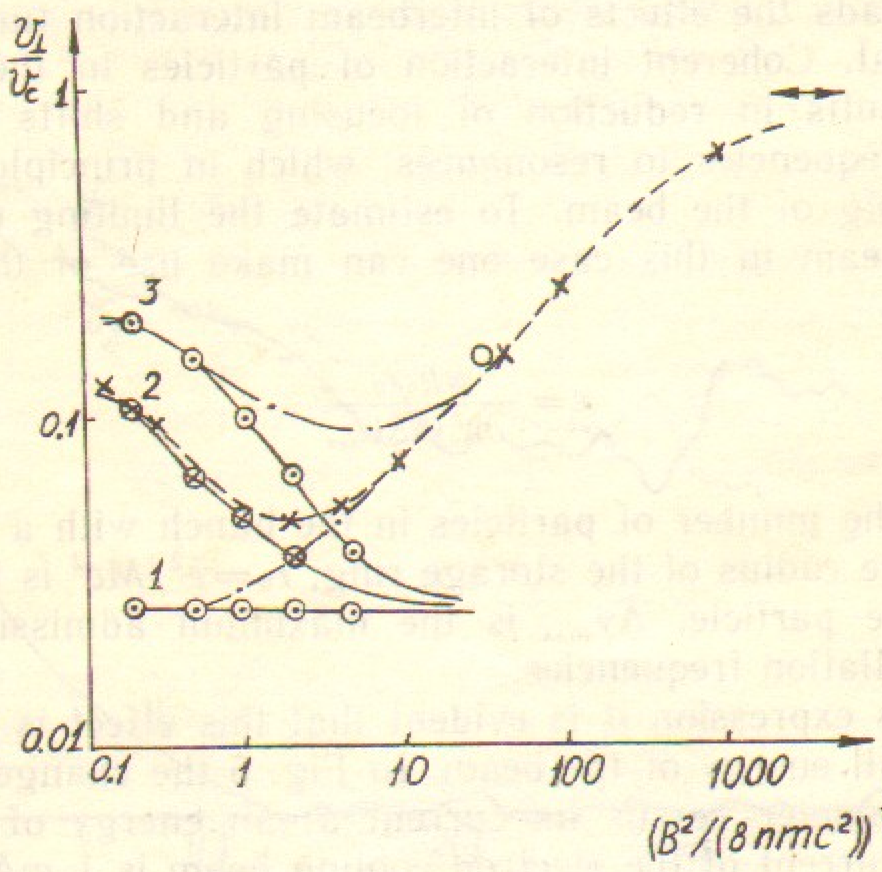

Fig. 5. The determined transverse velocity spread versus the value of the magnetic field in the cooling sector.

Curves *1, 2, 3* correspond to different transverse temperatures of the electron beam $v_{e\perp}/v_{e\parallel}$, 8, and 16, respectively. $v_{e\parallel}=\sqrt{2e^2n^{1/3}/m}$. Solid curves - for negatively charged particles, dashed curves — for positively charged ones. ⊕ — results of experiments at NAP-M for protons, ↔ — calculation results for positively charged particles at $H\to\infty$.

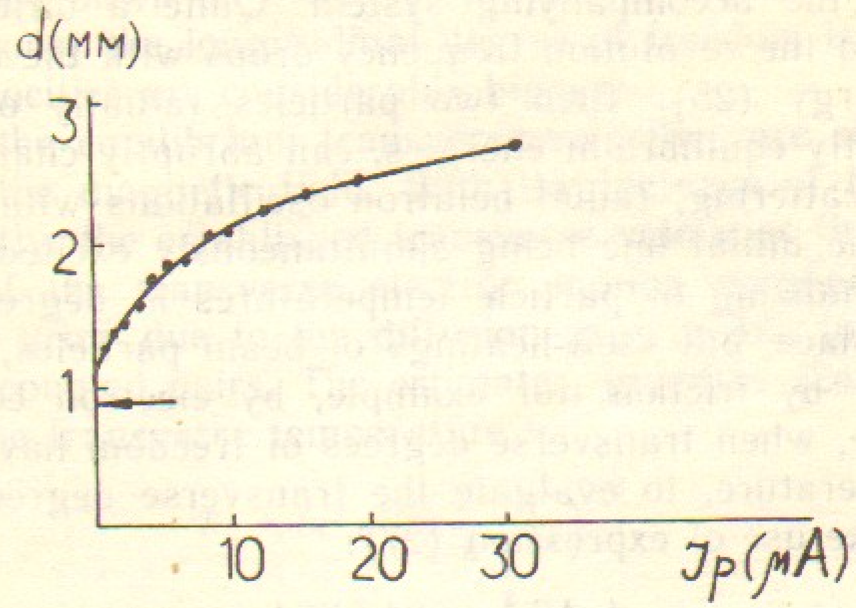

Fig. 6. Proton beam diameter versus current at an energy of cooling of 1.5 MeV.

Current of electron beam — 1 mA, diameter 1 cm; the NAP-M storage ring. The value corresponding to expression (30) is indicated by an arrow. $H=500$ G, $T=266e^2n^{1/2}$.

ally and noticeable in the longitudinal motion. The influence of particle interaction is most easily observed in the change of the noises induced by a beam on pick-up electrodes which characterize the value of the electric field fluctuations along the beam [28, 29].

Thus, the voltage induced in a circular pick-up electrode, is proportional to the local density of the beam:

$$\rho(\theta, t) = \sum_{a=1}^{N} \delta(\theta - \theta_a(t)) = \sum_{n=-\infty}^{\infty} \frac{\exp(in\theta)}{2\pi} A_n(t), \tag{33}$$

$$A_n(t) = \sum_{a=1}^{N} \exp(-in\theta_a(t)),$$

where $\theta_a(t)$ is the azimuthal position of a particular particle a; θ is the azimuth of observation; N is the number of beam particles, $\delta(\theta)$ is a periodical δ-function. If the particle motion is not correlated, it is easy to show, that the amplitude of the harmonic density

$$\langle A_n \rangle_{n\neq 0} = 0, \quad \langle A_n \rangle_{n=0} = N, \quad \langle |A_n^2| \rangle = N, \tag{34}$$

i. e. the power of the noise at the n-th harmonic of the revolution frequency is proportional to the number of beam particles — this is the ordinary Schottky noise. The potential energy of the electromagnetic field, produced on the n-th harmonic is equal to

$$E_n = \int \frac{E^2 + H^2}{8\pi} dV \approx (1+\beta^2) \frac{e^2 A_n^2 \ln(b/a)}{2\pi R_0}.$$

The particle interaction at the longitudinal motion turns out to be essential when the field energy becomes equal to the kinetic energy of the beam particle synchrotron motion:

$$\frac{M_s (\Delta v_\parallel)^2}{2} = \frac{1}{2} \frac{(\Delta\omega)^2 R_0}{(d\omega/dP)} \gamma^2.$$

As a result, from $E=kT/2$, we obtain, as is shown in [28], the expression of the critical particles number, at which the interaction is capable of affecting the mutual particle motion, and taking into account this interaction, the harmonic amplitude is:

$$\langle |A|^2 \rangle = \frac{N N_{th}}{N+N_{th}} = \begin{cases} N, & N \ll N_{th} \\ N_{th} & N \gg N_{th} = \dfrac{\pi R_0 (\Delta\omega)^2}{e^2 \dfrac{d\omega}{dP} \omega Z_0} = \dfrac{\pi R_0 (\Delta P/P)^2 \eta\gamma}{r_0 Z_0 c}, \end{cases} \tag{35}$$

where $\Delta\omega = \frac{d\omega}{dP} \Delta P = \eta\omega \frac{dP}{P}$ is spread in frequencies of the particle revolution in a beam, $Z_0 = \ln \frac{b}{a} / v\gamma^2$ is the chamber impedance with respect to the beam. From this expression one can see, that with a decrease in the beam temperature $\Delta\omega^2 \sim T_{\parallel}$, T_{th} is also decreased, and at $N_{th} \ll N$ the Schottky noise is considerably decreased and turns into a so-called thermal one, at which the power is proportional to the temperature. Under this conditions, the noise spectrum turns out also considerably distorted, since density fluctuations begin to propagate along the beam as waves at the velocity dependent on the number of particles. Therefore, the noise spectrum will comprise 2 peaks near the revolution frequency harmonic $n\omega_s$, the distance between the peaks being $\Delta\omega = \pm n\Delta\omega\sqrt{N/N_{th}}$.

The change in the spectrum in the course of beam cooling is shown in Fig. 7. For curve *1* the temperature is high and the spectrum corresponds to the Schottky noise; in case of curve *3* the threshold number of particles appears *2* times smaller than the number of particles and a considerable change in the spectrum is observed.

Shown in Fig. 8 is the proton beam noise power versus the current (at energy of 65 MeV) before and after the electron cooling. Before the cooling the momentum spread is $3 \cdot 10^{-4}$, which corresponds to the temperature $T \approx 6 \cdot 10^4$ K and the threshold particle number is $N_{th} = 6 \cdot 10^9$, therefore, no interaction effects at a number of particles under $1 \cdot 10^8$ is observed and the signal power from the pick-up electrode is proportional to the number of particles. After the cooling the temperature drops down to 1 K, and the threshold number of particles is drawn to reduce down to $1 \cdot 10^5$, which results to abrupt signal drop. This decrease in the noise power is bound up with the fact, that the potential energy of density fluctuations turns out to be considerably in excess of the kinetic energy of the relative particle motion and an ordering in the particle distribution along the orbit begins to develop. At a storage ring, energy

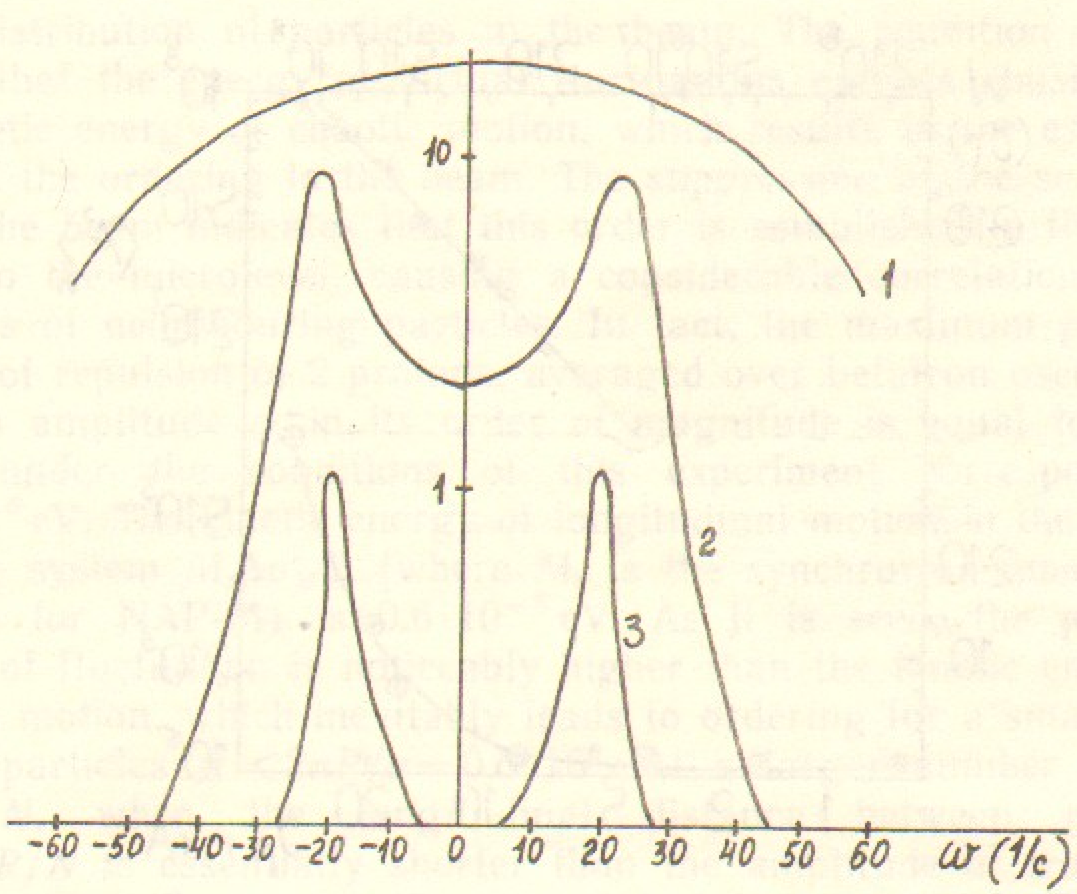

Fig. 7. Beam signal spectrum at different «temperatures» of the proton beam. Revolution frequency spread 40, 10 and 2.5 rad/s for curves 1, 2, 3, respectively. Relation of number of particles to the threshold one is 0.125, 0.5, 2, respectively.

exceeding the critical value, when start to be negative, $d\omega/dp < 0$ the cooled beam is self-bunched: $N_{th} < 0$ (negative mass effect). But even at $N_{th} > 0$ in order to attain the beam stability (in case of $N \gg N_{th}$) special measures are required to provide against the interaction with the surrounding passive resonators, since in this case $Z_0(\omega)$ can be considerably changed.

What happens to the spread while $N_{th} > 0$ and the conditions of stability are satisfied? In Fig. 9 the results of measurements from NAP-M are shown at different numbers of protons in a beam (PC=355 MeV, $I_e = 0.3$ A, $\tau_{\perp}^{-1} = 10\,s^{-1}$, $\tau_{\parallel}^{-1} = 130\,s^{-1}$). With a proton current of up to 10 μA, the spread is seen to be constant and equals $\Delta P/P \approx 10^{-6}$, but with a further increase in the numbers of particles it begins to grow. The value $\Delta P_{\parallel}/P \approx 10^{-6}$ well corresponds to the effective temperature in the accompanying system $T_{ef} = 2e^2 n^{1/3} \approx 1$ K. Nevertheless, at the given values of the beam current the proton scattering inside the beam should have been observed more prominently, thus resulting in the heating [17]. The wake influence at a beam current $I_p < 10$ μA can be provided for by the suppression of this scattering due to the ordering in the longitu-

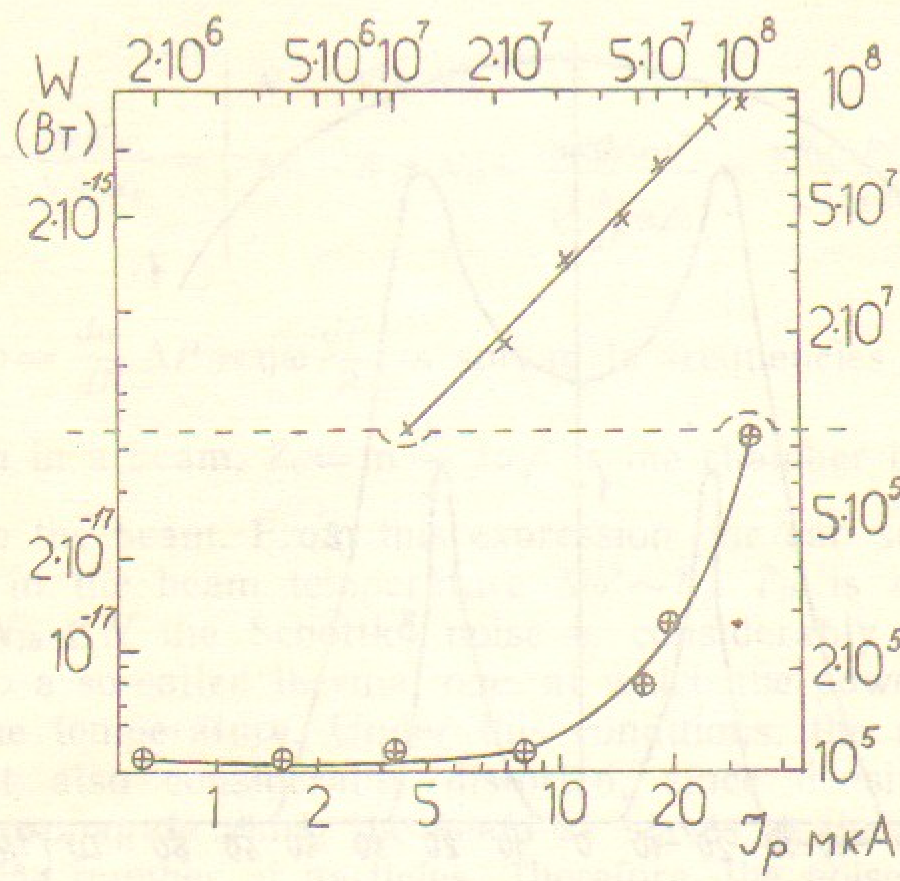

Fig. 8. Noise power versus the value of proton current.

Proton beam energy — 65 MeV, *1* — uncooled beam, *2* — cooled beam; electron beam current 0.3 A.

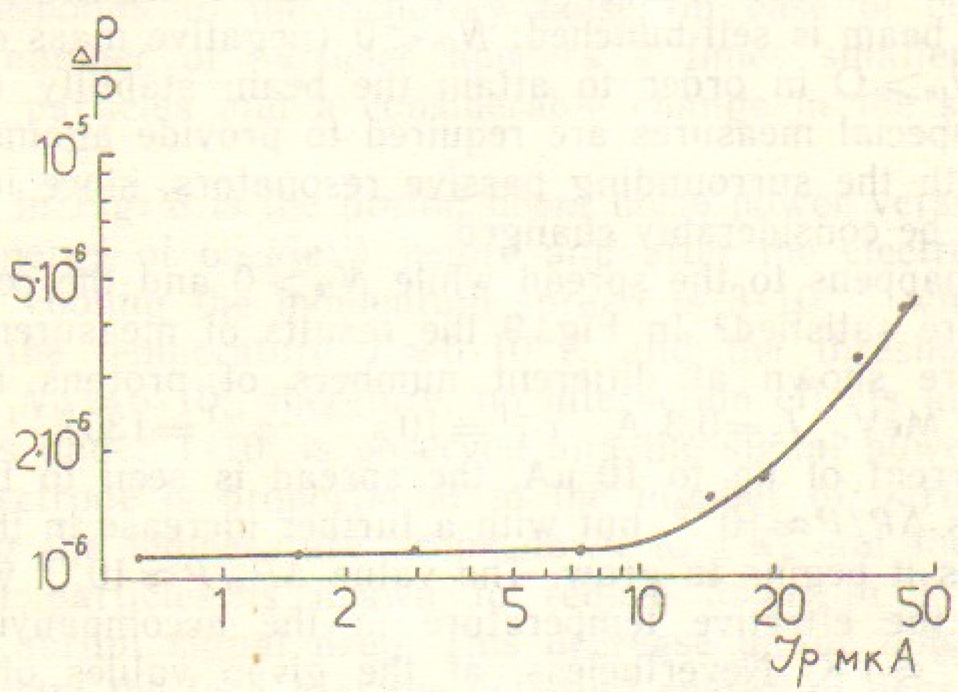

Fig. 9. Longitudinal momentum spread of a cooled proton beam versus the value of proton beam.

Proton beam energy — 65 MeV, electron current 0.3 A.

dinal distribution of particles in the beam. The condition $N \gg N_{th}$ means that the energy of virtual fluctuations exceeds considerably the kinetic energy of chaotic motion, which results in the establishment of the ordering in the beam. The suppression of the scattering inside the beam indicates that this order is established in the beam down to the microlevel, causing a considerable correlation in the positions of neighbouring particles. In fact, the maximum potential energy of repulsion of 2 protons, averaged over betatron oscillations with an amplitude a, in its order of magnitude is equal to $2e^2/a$, which under the conditions of this experiment corresponds to $2.9\cdot10^{-6}$ eV. The kinetic energy of longitudinal motion in the accompanying system $M_s\Delta v_{\parallel}^2/2$ (where M_s is the synchrotron mass equal to M/η for NAP-M) is $0.6\cdot10^{-5}$ eV. As it is seen, the potential energy of fluctuation is noticeably higher than the kinetic energy of thermal motion, which inevitably leads to ordering for a small number of particles $N<2\pi R/a=0.5\cdot10^6$. At a larger number of particles N, when the longitudinal distance between particles $\Delta_{\parallel}=2\pi R/N$ is essentially shorter than the amplitude of transverse oscillations a, the process of proton interaction becomes more complicated [18]. Experimentally there was observed a suppression of the internal scattering down to the value of the proton current of 10 mkA ($N=2.8\cdot10^7$), which corresponds to the case, when the longitudinal distance is $\Delta_{\parallel}=1.7\cdot10^{-4}$ cm at $a=10^{-2}$ cm.

LIFETIME OF BEAMS UNDER COOLING CONDITIONS

The electron cooling suppresses the process of multiple scattering of beam particles by residual gas atoms. As a result, the lifetime of the beam is considerably increased. In this case, a single scattering of particles at an angle exceeding the maximally acceptable by aperture one θ_{max} remains the determining process:

$$\tau=\frac{\theta_{max}^2\ \gamma^2M^2v^3}{4\pi n_a\, Z_a^2\, Z_i^2\, e^4}=\frac{\varepsilon_M\gamma^2M^2v^2}{\beta n_a\, Z_a^2\, Z_i^2\, e^4}, \qquad (36)$$

Here Z_a is the charge of nuclei of the residual gas, Z_i is the beam particle charge, n_a is the density of the residual gas. From this expression it is obvious that in the case of experiments with a target, provided the value of β-function is small in the vicinity of target, with one and the same acceptance of the storage ring, the lifetime can be considerably increased ($\beta\theta_{max}^2=\varepsilon_M=$ const).

With the increase in the energy of the stored beam, the process of particle loss may become more and more important due to their nuclear interaction. Estimates show, that this process turns out to be essential at a momentum of cooled particles of about and over 1 GeV/c/nuc. The lifetime of particles in the course of their interaction with the residual gas can be increased by improving the vacuum conditions, but for positively charged particles there appears a process of particle loss, caused by the capture of an electron from the cooling beam.

The lifetime of particles with respect to the radiation recombination, at low relative velocities compared to atomic ones, is proportional to the thermal electron velocity and drops considerably with the ion charge growth:

$$\tau_p = \frac{\gamma^2 v_e}{20\, a r_e^2 c^2 Z_i^2 \eta n_e \ln(Z a c / v_e)} . \quad (37)$$

The relation of τ_p to the cooling time τ is

$$\tau_p/\tau = 0.07\theta_T/(A\gamma^3\beta^2\theta_{ef}^3) , \quad (38)$$

where $\theta_T = v_e/v$ is the thermal (angular) spread of electron velocities, and θ_{ef} is the effective relative velocity spread of the cooled particles and electrons which depends on the magnetization of electron motion: A is the atomic weight of the cooled ion. It is clear that at $\gamma \approx 1$, β, nevertheless, with an increase of the angles in the beam under cooling and the atomic weight A the recombination may turn out essential. This difficulty is completely eliminated by using a special method of «proton cooling», i. e. cooling by a cool proton beam [11].

Note one feature peculiar to electron cooling in the diffusion process on the residual gas. Since the time for cooling is quickly reduced with the decrease in the angular spread of particles $\tau \sim \theta^3$, the particles scattered at small angles (under the aperture angle) are quickly cooled down to the temperature of the main beam. As a result of scattering, the beam becomes encircled by a halo of scattered particles, its density increasing with the beam oscillation angle (probability of scattering at an angle $> \theta$ drops only as θ^{-2}). Similar effects are also observed in the distribution over the energy due to ionization loss fluctuations. This peculiarity of the established distribution is necessary to take into account while carrying out experiments with cooled beams.

Table 1

Parameters of the Electron Cooling Rings

Name	NAP-M	ICE	Fermilab	IUCF	TSR	GSI	TRAN-2	LEAR
Country	USSR Novosibirsk	SWISS CERN	USA Chicago	USA Blum.	FRG Heidelberg	FRG Darm.	Japan Tokio	Swiss CERN
Years of Operation	1974	1979	1980	1988	1989	1989	1989	1989
Sort of Particles	protons	protons	protons	light ions	heavy ions	heavy ions	light ions	anti-protons
Electron Energy, keV	60	35	111	300	7	310	120	40
Electron Current, A	1	22	3	4	1	10	10	2
Circumference, m	47	74	135	87	55	103	78	78
Energy of ions, MeV/n	85	46	200	500	120	570	220	73
Cooling section magnetic field, kGs	1	0.5	0.7	1			1.2	

For the first realization and experimental investigation in Novosibirsk there was created the proton storage ring NAP-M and the cooling system with the necessary parameters [12]. In following years the similar cooling rings were created at CERN and USA (Fermilab) for assimilate the experience of electron cooling [19, 20].

The next generation of this type installation take aim at application of the electron cooling, as a rule, of heavy ion complexes for solution of the experimental problems. The first installation for the physical experiments was began to operate in 1988 y. in USA (ICUF) [30]. In the next table we are tried to show the mean parameters of few storage rings [12, 19, 20, 30, 31, 32].

After finishing the experiments on the cooling ring NAP-M in Novosibirsk adopted decision to continue investigation cooling by the strong magnetization electron beam. For this purpose was construction equipment «Model of Solenoid» (MOSOL) where it was studied the friction force for single pathing ions through solenoid [23]. The reason of this are connected with difficulties include the strong solenoid in the magnet system of the ring but for simple measuring enough a single path of the ions.

The parameters of this installation are presented in the

Table 2

Proton energy, keV	850
Electron energy, eV	470
Magnetic field, kGs	1—4
Length of solenoid, m	2.88
Length of cooling section, m	2.4
Electron current, mA	15
Proton beam current, μA	0.1

Such an installation makes it possible to study the cooling process in very high densities of the electron beam, when the electron heating inside the beam is already a limiting factor.

Let us describe experiments with electron cooling, considering the installations most familiar to the authors (NAP-M and MOSOL) as typical ones and mentioning also some new techniques introduces while designing new installations.

The NAP-M storage ring was designed in 1970 as a prototype of an antiproton storage ring, hence is its name: Antiproton Storage Ring—a Model. This fact also accounts for the choice of parameters

for the storage ring as well as its construction with very long sections.

In one of the straight sections of the storage ring an installation with an electron beam is placed, its lay-out is given in Fig. 10. The installation has 3 straight sections, two of them housing a gun and

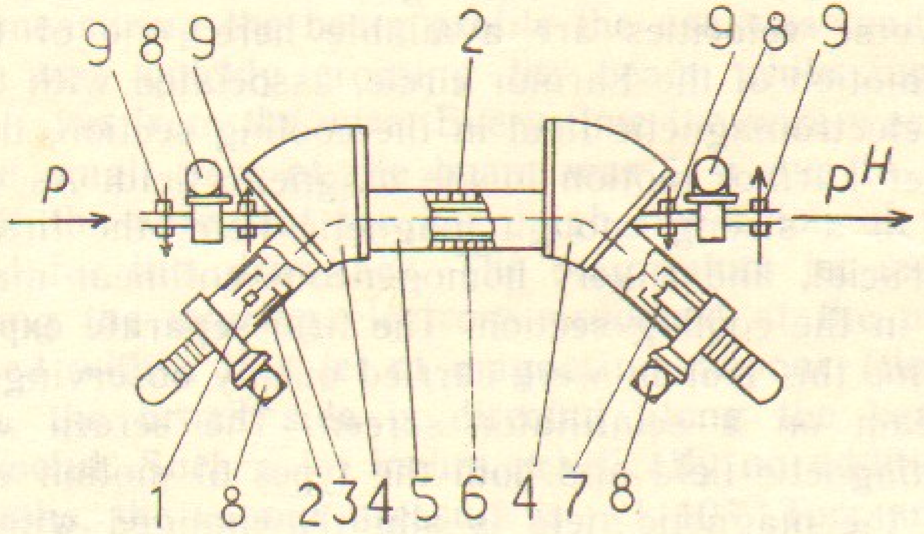

Fig. 10. Schematic diagram of the electron beam device:
1—electron gun; *2*—electromagnet winding; *3*—electron gun electrodes; *4*—electron beam bending section with a toroidal magnetic field, *5*—cooling section; *6*—vacuum chamber; *7*—collector; *8*—vacuum pumps; *9*—correcting magnets.

a collector and the third one—the cooling section, where protons move together with the electron beam. To form and transport the electron beam an electron gun with an accompanying magnetic field is used. The straight sections are connected with one another by 2 sections with toroidal magnetic fields, which are used for introducting the beam into and extracting it from the cooling section. The centrifugal drift at the curved parts of trajectory is eliminated by introducing a transverse magnetic field, which directs the electrons along the trajectory, so the curvature coincides with that of the longitudinal field line [21]. The ma n difference of next installations (for example, ICE) from this first consists in the change of the collector bend orientation with respect to the gun one. In this case the correction of the vertical motion is simplified, since the transverse field of the solenoid is acting in the same direction from both sections, and therefore, the trajectory of the proton beam experiences a parallel transition with respect to the ideal orbit without the solenoid. But in this case a problem appears concerning the storage of reflected electrons, oscillating from the gun to the collector. In the case of NAP-M a permanent drift of such electrons in the transverse direction takes place, while with the lay-out of ICE, the drift from different sections of the storage ring is mutually compensated and these electrons can be trapped. In the author's opinion the effects dealing with the electron storage make the operation of these storage rings more complicated.

Of great importance for electron cooling is the absence of transverse electron motion in the cooling section. Two essentially different transverse velocities are available here: one of them is the transverse motion of the Larmor circle, associated with the parasitic transverse electromagnetic field in the cooling section, the other one is the proper Larmor motion in the magnetic field. As was already mentioned, in a strong enough magnetic field, the first one turns out most crucial, and a very homogeneous collinear magnetic field is required in the cooling section. The first separate experiments on the search for this motion were carried out by observing a very thin electron beam on a scintillator screen. The screen was moving along the magnetic field and both the types of motion were easy to observe. If the magnetic field is slightly changed with the screen position remaining unchanged, a strong alteration of the Larmor revolution phase takes place and the motion becomes observable.

Accurate measurements with an optical tube performed behind the electron spot made it possible to attain an accuracy in the angle measurement of up to $4 \cdot 10^{-4}$. For measurements at the MOSOL installation this accuracy was inadequate and another technique, based on observing the magnetic compass orientation, handed in a gimbal was used. The compass was supplied with a secondary mirror of a digital autocollimator providing the measurement of angular deviations of up to $5 \cdot 10^{-6}$, which made it possible in this installation to obtain a field collinearity even slightly better then this value [33].

For measuring the Larmor revolution the method of observing the SR of electrons in an accompanying magnetic field is widely used, both suggested and realized at CERN on the ICE storage ring. This method provides a control over the Larmor revolution directly during the full-scale run of the storage ring at a full electron current.

In the experiments on electron cooling various methods of observation were used. Pick-up electrodes for measuring the time, structure and position of the bunched beam, as well as the thermal noises of the cooled continuous proton beam were used. The pick-up electrodes proved also very useful in operating the electron beam, since applying a small RF voltage to the anode caused an electron

current modulation, thus making it possible to control the beam position with fine precision. Contactless ferromagnetometers were used for measuring the proton and electron currents. Much information on the beam distribution, especially at large amplitudes, were provided by flag-probes, the protons scattered off at its edges, being registered by a special scintillator probe positioned close to the beam. For measuring the beam profile the use was made of a micron quartz wire quickly crossing the beam while registered the electron emission from the wire. Every time the wire was crossed by the beam, a small part of the beam was lost due to the protons scattered off the wire, but the very high revolution of this method compensated for this drawback. The magnesium jet method based on registering the ionizing electrons produced at the proton beam being crossed with a thin jet of magnesium vapour (the jet size is 0.5×20 mm, the broad side is directed along the beam) proved especially useful. Such a jet incurs practically no additional scattering of protons, the vapour pressure is $\sim 1 \cdot 10^{-6}$ Torr and the additional pressure (with respect to the average one) totals $4 \cdot 10^{-10}$ Torr. The jet can be moved across the beam, the signal from the ionizing electrons proportional to the proton beam density being applied to the y-input of the oscillograph, while the signal from the jet position is applied to the x-input, which made it possible to observe the proton distribution. The jet could be stopped at any desired point; in this case, one could observe the change in the proton beam density in time, for example, the density increase in the process of cooling.

The observations of the flux of fast hydrogen atoms, outgoing from the cooling section, performed with a 2-coordinate proportional chamber with a good resolution of about 30 mcm provided the measurements of equilibrium dispersions in the proton beam.

Of great importance for a successful work with an electron beam is the control of its charge state, since secondary electrons and ions can be accumulated in the beam. To control these processes special electrodes capable of accumulating ions in the beam in order to compensate the space charge and «brushing» the beam from electrons [13] have been worked out. In the experiments at MOSOL the charge compensation provides for noticeable increase in the electron current density. Unlike in the experiments on storage rings, here the change in the ion energy was measured at the single path through the cooling section [23].

The results of measurements of the maximum friction force, obtained on this storage ring for positively and negatively charged H^+ and H^- particles at different values of the magnetic field are shown in Fig. 11 [23]. As is seen, with the growth of magnetic

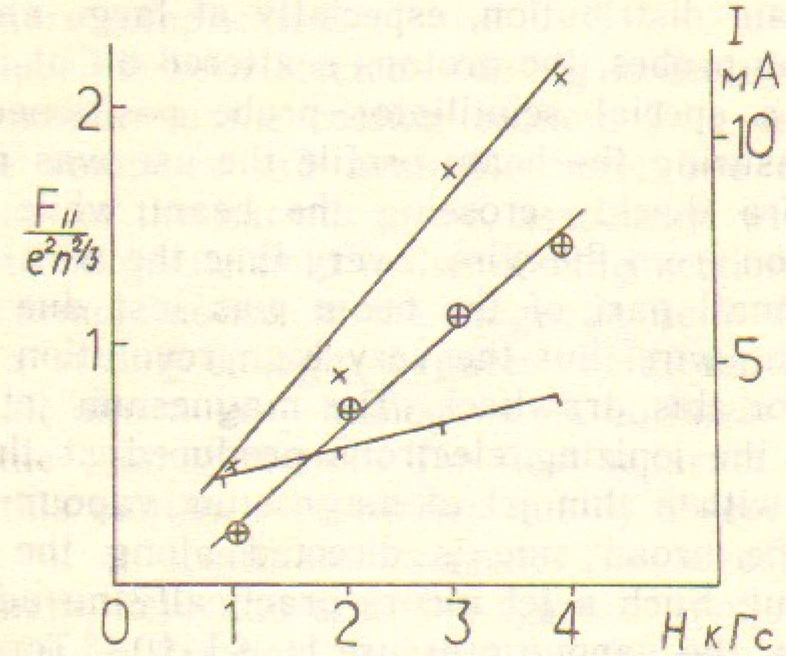

Fig. 11. Relation of maximum friction force to $e^2n^{2/3}$ and optimal current versus magnetic field. $E=470$ eV, electron beam diameter—2 mm.

field, the electron current at which the maximum friction force is attained, is increased; furthermore, for H^- the relation $F/e^2n^{2/3}$ is also considerably increased. This means an increase in the attainable friction force growing as H^2.

These results proved that for obtaining maximally cooled ion beams of great importance is the optimal choice of the longitudinal magnetic field value. It should be kept in mind that for positively charged particles a too strong field causes an increase in the transverse angular beam spread.

APPLICATIONS OF ELECTRON COOLING METHOD

The program for using electron cooling in physics of elementary particles and nuclear physics given in the review in UFN in 1978 [11] in its main features remains applicable today. In the present review we shall try to reconsider these prospects, drawing attention to some features which are not yet conventional for many specialists. We shall also briefly touch on very different ranges of the

method application where electron cooling has advantages compared to stochastic cooling and where it is worthwhile to combine them both.

1. The Storage of Beams and the Improvement of their Quality

A. Interesting possibilities are opened up by using electron cooling for obtaining the intense and high quality ion beams both for their sequential injection and acceleration and also for experiments in the regime of internal targets. Particularly important is the use of the method for obtaining heavy ions having no electron shell. In this case, it is reasonable to accelerate ions up to sufficiently high energy, extract them from the accelerator and focus them onto the appropriate target; ions having lost their electron shell being collected should be injected into the storage ring and compressed into a small phase space volume with cooling. At a sufficiently high energy an efficiency of the «complete strip» can be close to unity. The storage cycles can be multiply repeated.

It is very important that electron cooling enables one to obtain isotopically pure beams by storing them up to high intensity, if necessary, even the ions of rare isotops.

An important branch of such applications is the use of electron cooling to store highly intense beams of polarized protons and other ions, and particularly in combination with a charge-exchange injection.

B. This cooling is feasible with a total separation of unstabled nuclei generated in nuclear reactions of accelerated ions if their lifetimes are longer than the cooling time practically, starting from the lifetime of 10 ms.

It is interesting that during the production of nuclei in nuclear reactions, the separation can be performed even for the long living isomers starting approximately from excitation energy of 1 MeV. Such a difference in total energies and concequently in mass of the cooled particles is already sufficient, under the equalizing of the linear velocities of all the particles of a beam, to separate spatially the isomers on the structurally optimized part of a storage ring.

The precise measurement of the electron accelerating potential enables one, with the same accuracy, to determine in fact linear velocity of the cooled particles. By knowing their exact mass, it provides the precise value of energy (momentum). At the same time, with the totally fixed fields of a storage ring, the comparison of the potentials providing the exact equality of the revolution frequencies for protons (deuterons) and cooled particles enables one to measure their mass with an accuracy approximating the accuracy on the proton mass knowledge ($3\cdot10^{-7}$). The precision in determining masses with such a method is possible not only for any very rare stable isotopes but also for unstable nuclei with the lifetime long enough

$$\tau > T_{rev}\left(\frac{\Delta m}{M}\right)^{-1}. \tag{39}$$

C. Interesting possibilities are opened up for the physics of multielectron systems (that are shells of not completely stripped atoms) on the base of deeply cooled stored ions. A very high monochromaticity of the beam and its good collimation provide sufficiently good resolution for work with the laser, synchrotron is other appropriately exciting radiation. In this case, the smooth and fine alignment of the effective wavelength of the incident radiation, due to the Doppler effect is gained by varying either the incident direction of beam energy in the storage ring.

A serious problem for work with ions not having completely stripped off their electron shells, is the provision of very high average vacuum in the storage ring, because the loss cross section for such ions (even one electron loss always precedes the ion loss) is very high—of the order of the atomic scale $10^{-17}\,cm^2$ and does not drop with the growth of ion energy. The attainment of vacuum required for quite a long lifetime for such beams is quite well developed and in use. The most difficult problem is the provision of the superhigh vacuum in the vicinity of the electron cooling system (elimination of the strong gas emission of the collector, accepting the whole electron beam and the details of the vacuum channel on which the electrons lost by the beam fall, and especially to avoid the storage of ions in the trap of space charge of electron beam).

It is not inconceivable, in particular, that studies with long living cooled ions with electron shells enable one not only to study the media for the generation of laser radiation in the ultraviolet and X-ray spectra, but also to obtain the coherent radiation in this range with a smooth Doppler regulation of the generated wavelength. From this viewpoint, the discussed above the phenomenon of longitudinal ordering in deeply cooled ion beams might be interesting; under these conditions, the perturbation of neighbouring ion spectra is strongly suppressed.

Such studies are also interesting from the viewpoint of laser cooling of nonstripped ions; it is not inconceivable that with time it will provide even deeper additional cooling of ion beams. As a by-product the data obtained in this experiments will be important for studies of ions in space.

D. After the first observation and study of longitudinal ordering in proton beams had been performed in Novosibirsk, many publications and projects appeared discussing the problem of obtaining transverse ordering also [17, 18, 34]. Some specific ion crystals became a subject of discussions. Apparently, however, the transverse ordering is not feasible because of the contradictory character of the requirement to keep the beam in the compressed state, which is only possible with the external focusing, and the requirement of a constant, at any rate relative, position of the ions in the transverse direction (or exact compensation for external focusing and the Coulomb repulsion). In addition, the expression itself «crystallization» is apparently not appropriate (the estimates show that quantum properties, for example, of longitudinal motion may be exhibited only at a temperature many orders of magnitude lower then that already attained).

Nevertheless, the systematic continuation of studies of ordering phenomena in ion beams is quite interesting.

E. With a long confinement of ion beams in the regime of electron cooling as already mentioned, a steady loss of ions occurs due to the «capture» by ions of electrons from the cooling beam. In this case, the main process is radiative recombination (37). The probability of production of a bound state with the transfer of excess energy to a second electron of the cooling beam is small at electron beam densities attained presently.

The role of radiative recombination increases especially for quite multicharged ions (in this process the ion beam lifetime is inversely proportional to the ion charge squared). One can manage to cool these beams of heavy ions, but one cannot cool them indefinitely; the ratio of lifetime and cooling time is inversely proportional to the ion mass. The problem of continuous cooling of such beams can be solved with the help of a two-chain cooler [11]: an electron beam cools a coasting proton beam of the same linear velocity and the proton beam cools the necessary ion beam. The efficiency of proton cooling can be made sufficiently high. Thus (at a given effective temperature of the cooling beam) the maximum cooling rate even grows proportional to $\sqrt{M/m}$ with all the rest of the parameters being the same.

F. A complex and not well studied problem is the storage of sufficiently low-emittance beams with high intensity. This problem is of great importance for the substantial increase (compared to the already attained) storage rate of antiprotons in proton-antiproton facilities, which is primary both for the enhancement of the colliders luminosity and for a wide range of other experiments. The optimum, to our mind, is the combination of the stochastic precooling of each new portion of antiproton and electron cooling on the stage of storage and the final preparation of high density bunches [35].

2. Operation with Superthin Internal Gas Targets

Quite an efficient set-up of experiments became possible with the use of the so-called method of superthin internal targets, which is successfully demonstrated by the development of electronnuclear studies in electron storage rings, mainly at Novosibirsk [36]. In this method the processes of diffusional scattering of the beam both in the transverse and longitudinal directions are suppressed by sufficiently powerful damping (in the case of the electron beam—by radiative friction). Thus, the method provides the small emittance of a coasting beam and its high monochromaticity, with the realization of a total luminosity $\mathscr{L}_t$ for the experiment limited only by the productivity of injection $\dot{N}$ and the cross section for the loss σ_0 of its particles due to the process of a single interaction with the target nuclei and electrons:

$$\mathscr{L}_t = \frac{\dot{N}}{\sigma_0}. \tag{40}$$

If there appear physical or technical obstacles for attaining an appropriate thickness of a target $n_t\Delta$, the attainable luminosity may turn to be limited by the admissible (by large current effects) number of particles in the storage ring N_M. In this case, the maximum luminosity will be

$$\mathscr{L}_t = \frac{N_M n_t \cdot \Delta}{T_0}, \tag{41}$$

where T_0 is the revolution time in the storage ring. One of the limitations $n_t\Delta$ can be the lack of power of electron cooling, which

should have enough time to damp the diffusional degradation of beam parameters due to interaction with a target.

A. Let us evaluate the cross-section of particles kicked out of the beam because of various interactions with the target atoms. Their relative role depends on many parameters and certain features of the storage ring.

One of the main processes leading to the ion loss is an angular deflection in the Coulomb field of nuclei and electrons of the target. In this case, the cross section of loss is

$$\sigma_0 = \frac{4\pi e^4 Z_i^2 Z_t^2}{\gamma^2 M_i^2 v^4} \frac{\beta^*}{\varepsilon_A}, \tag{42}$$

where ε_A is the transverse acceptance of the storage ring, β^* is the value of β-function in the point of target placement. It is seen, that the role of this process goes down with an increase energy in and might be diminished by the arrangement of the section with a strong focusing in the target region.

At low admissible deviations ε_{add} from the equilibrium energy the beam ion loss becomes important due to energy transfer to the target electrons, if

$$\varepsilon_{add} < \varepsilon_{max} = \frac{2mv^2\gamma^2}{1 + 2\gamma\frac{m}{M} + \left(\frac{m}{M}\right)^2}. \tag{43}$$

In this case, the ion loss cross section per target atom is equal to

$$\sigma_{los} = \frac{4\pi e^4 Z_t Z_i^2}{\gamma m v^4 M_i} \left(\frac{\varepsilon_{add}}{E_{i\,kin}}\right)^{-1}. \tag{44}$$

At low energies ($\beta_i \ll Z_i\alpha$) for heavy nuclei of the beam and target the determining factor can become the ion loss due to the capture of electrons when passing the target (cross sections are of atomic scale and drop not too sharply with the growth of energy).

Let us remind that for not completely stripped ions, the cross section of electron loss is still larger and the use of such ions with internal targets is extremely unreasonable.

At high energies the determining loss becomes the loss of ions due to strong interactions with the target nuclei with the cross section:

$$\sigma_{los} \approx 10^{-25}\ \text{sm}^2\ A_i A_T\ .$$

B. The quality of beam under cooling, from the viewpoint of experimental conditions, is determined by the competition of small perturbations (within the limits of the transverse and longitudinal acceptances of storage ring) due to interactions with the target nuclei — and cooling.

For the accuracy of «spectrometric» experiments of especial importance is the actual energy distribution of the ion beam. The energy loss occurs by portions by the energy transfer to the target electrons. The probability of energy loss per unit of time is

$$dW = \frac{4\pi e^4 Z_i^2 Z_t^2 \langle n_t \rangle}{mv} \frac{d\varepsilon}{\varepsilon^2}, \tag{45}$$

where $\langle n_t \rangle$ is a mean (over the storage ring orbit) density of the target atoms. The mean rate of energy loss, being equil to

$$\frac{dE}{dt} = \int_{\varepsilon_{min}}^{\varepsilon_{max}} \varepsilon\, dW = \frac{4\pi e^4 Z_i^2 Z_t^2 \langle n_t \rangle}{mv} \ln \frac{\varepsilon_{max}}{\varepsilon_{min}}, \tag{46}$$

where ε_{min} can be taken equal to the mean potential of ionization; it is easily compensated for by the mean longitudinal force from the cooling electron flux; in this case, the mean velocity of ions will consequently be somewhat lower than the velocity of electrons. Note that it is reasonable to place the target in the region with the zeroth dispersion function of the storage ring in order to avoid the additional excitation of ion transversal oscillations by the energy jumps.

Depending on the target thickness and power of electron cooling qualitatively different equilibrium energy distributions are possible. The decrement of longitudinal damping in quite a large range of parameters at $v \ll c$ is described by the formula

$$\Lambda = \frac{4\pi e^4 \langle n_e \rangle Z_i^2 L_c}{m} \frac{M^2 v^3}{m(\Delta E_0^2 + \varepsilon^2)^{3/2}}, \tag{47}$$

where $\Delta E_0 = M_i v 2\sqrt{2e^2 n^{1/3}/m}$ is the characteristic deviation of ion energy at which its velocity in r.m.s. is comparable to longitudinal velocities of cooling electrons and the drop of cooling decrement commences.

An especially simple and elegant criteria for the efficient suppression of energy deviations is obtained at $\varepsilon_{max} = 2mv^2 \gg \Delta E_0$ (i. e. under the condition $v/c \gg M/m \sqrt{2 r_e n_e^{1/3}} \sim 5 \cdot 10^{-2}$) if one requires

that even maximal jumps have enough time to damp prior to the next jump:

$$\frac{4\pi e^4 Z_i^2 Z_t \langle n_t \rangle}{mv} \frac{1}{\varepsilon_{max}} < \frac{4\pi e^4 Z_i^2 L_c M^2 v^3}{m \varepsilon_{max}^3}, \tag{48}$$

hence

$$Z_t \langle n_t \rangle < \langle n_e \rangle \frac{L_c}{4} \left(\frac{M}{m}\right)^2. \tag{49}$$

Under these conditions the narrow nearly unperturbed distribution of ions over energies is accompanied by the «tail» of ions deviated by an energy of up to ε_{max}, with a fraction of particles there of the order of

$$\xi = \frac{Z_t \langle n_t \rangle}{3 n_e L_c \left(\frac{m}{M}\right)^2} \ll 1. \tag{50}$$

The maximum luminosity here will be equal to:

$$\mathscr{L}_{max} = N_M v \langle n_e \rangle \xi \frac{3 L_c}{Z_t} \left(\frac{M}{m}\right)^2. \tag{51}$$

C. One more process of diffusional character which electron cooling has to overcome is multiple scattering on the target nuclei (and electrons). In the regime of the superthin target, as well as for energy distribution it may happen that due to strong cooling the single processes are the only essential ones. The maximum deflection angle, when scattering on the target nuclei, as a rule, exceeds the admissible angle by the storage ring aperture. This process determines the lifetime of ions at low energy. The probability to be scattered at an angle θ is

$$dW = \frac{8\pi \langle n_{os} \rangle Z_t^2 Z_i^2 e^4}{M^2 v^3} \frac{d\theta}{\theta^3}, \tag{52}$$

and the damping time from the angle θ down to the equilibrium value is

$$\tau = \frac{1}{3} \frac{m M v^3 \theta^3 \left(\frac{\beta_м}{\beta_c}\right)^{3/2}}{4\pi e^4 \langle n_e \rangle Z_i^2 L_c}, \tag{53}$$

where the factor $(\beta_t/\beta_c)^{3/2}$ corresponds to different values of β-function in the region of the target β_t and cooling β_c. As a result, the fraction of scattered particles will be

$$\int_0^{\theta_{max}} dW\tau = \frac{1}{6} \frac{mZ_i^2 \langle n_t \rangle \left(\frac{\beta_t}{\beta_c}\right)^{3/2}}{ML_c \langle n_e \rangle} \theta_{max} = \frac{\xi Z_i \frac{M_i}{m} \theta_{max} \left(\frac{\beta_t}{\beta_c}\right)^{3/2}}{2}. \quad (54)$$

From this expression it is seen that under the condition $z_i M/2m\theta_{max}(\beta_t/\beta_c)^{3/2} \ll 1$ the transverse scattering does not add particles to the fraction of scattered particles ξ.

The use of a superthin internal target regime with electron opens up wide possibilities for both increasing the quality of conventional experiments and for carrying out fundamentally new experiments. These could include: 1) the precision measurements of antiproton-nuclei, antiproton-neutron and nuclei-nuclei interactions starting from the lowest energies (including experiments with precision measurement of the absolute energy of stored particles by the measuring potential providing cooling electrons); 2) the generation of a well-marked and sufficiently intense fluxes of antineutrons and antihyperons for studying their interactions with nuclei; and even 3) the development of antiproton-proton «factory» of K^0, $\bar{K}^0$-pairs for the experiments to study the CP-violation [37].

A brief analysis of various physics possibilities for such experiments is given in the review mentioned above [11].

3. Experiments with Interacting Beams

In many cases the preferable possibility (and sometimes the only one) is an experiment where the reactions under study occur between particles, both of which belong to cooled beam. The problems solved in this way might be quite different, and, consequently, the nature and relative motion of interacting beams could be different.

A. Even in the energy region accessible for experiments with stationary (including internal superthin) target the optimal experiments might be those carried out with continuously cooled colliding beams in the cases when the ultimate monochromaticity and ultimate energetic purity are required.

At any rate, the formally ultimate luminosity limited by the beam-beam effects might occur in this case higher. One only needs to estimate accurately the difference in the effective energy in different points of the beams interaction region which depends on the actual experimental set-up. In addition, for attaining maximum luminosity with the limited number of particles in the beam it is reasonable to shift to the shortest possible bunches. The use of such bunches will require the exploration of the deep cooling of short intense bunches, the problem which has not still been seriously studied.

Such an experimental set-up might be optimal, for instance, for the study of families of $C\bar{C}$- and $B\bar{B}$-meson in proton-antiproton interactions. In this case, it is easy to attain an effective energy spread lower than the state width itself, and the states can be generated with weaker limitations by the quantum numbers than that in the case of electron-positron collisions.

Such an experimental set-up can also be promising for the study of the fine energy structure of nuclei-nuclei interactions. Some additional advantage could be the shift to interactions of completely stripped nuclei when studying the electromagnetic effect (for example, the production of photons and electron-positron pairs accompanying the collision).

A. Special area for the application of electron-cooled coasting beams and, in particular, of protons and antiprotons might occur in the region of high (ultrarelativistic) energies if, of course, it becomes necessary to carry out experiments with high resolution at these energies. The maintenance of the low effective temperature of the electron can be provided in this case by radiative friction and suppression of the influence of transverse electron velocities due to the strong external focusing [38].

B. An interesting area for the study of the electromagnetic structure of the nucleus (quark-gluon effects in nuclear matter at sufficiently high energies in c.r.m.) might occur in the use of electron-nuclei colliding beams cooled with radiative and electron cooling respectively. Most importantly, such a set-up could be a reasonable one for the study of the structure of the difficult to obtain, rare or unstable nuclei.

C. The study of interaction of protons (deuterons) and antiprotons at ultimately low energies becomes very attractive with the use of beams moving in parallel with the file-aligned slightly differing velocities of cool beams of antiprotons and neutral hydrogen atoms. In this case, with a high efficiency, the electromagnetically bound states are produced with high and selectively enriched orbital momenta [11]. The competing set-up, the use of gas targets (with deceleration of antiprotons) or the use of negatively charged ions of hydrogen moving in parallel, apparently do not provide a comparable degree of experimental accuracy.

D. Very intriguing is the possibility of obtaining cooled antiproton beams of low energy, which then interact in the straight section with cooled positron beams travelling in parallel with the same velocity, could be used for the generation of antiatoms. In this case, it seems reasonable to carry out the final cooling of the positron beam and its maintainance in that state also with the help of electron cooling [39]. The experiments on the interference of the states for antiatoms thus obtained [37] will enable one to make the comparison of the properties of atomic, and antiatomic matter within the «Lamb» accuracy.

CONCLUSION

At present, electron cooling is no longer a «high art» only in accelerator physics. As already said above, electron cooling installations are already either built, under construction, or designed in many laboratories throughout the world. There is reason to hope to see in the near future fundamental results from experiments of the types described above, and even, perhaps, results from some completely unexpected experiments.

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