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Development of techniques for the cooling of ions

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Contents

Abstract. The historical development of techniques for cooling charged particles is presented. It was G I Budker, the founder and first Director of the Institute of Nuclear Physics (INP) in Novosibirsk, who initiated the development of cooling methods as a means of improving the performance of colliding beams accelerators (now known as colliders). The electron cooling method proposed by G I Budker became the main subject of investigation at BINP. Today, many facilities — ranging from the LHC to those on a moderate university scale — use the electron cooling of heavy ions in nuclear and atomic physics experiments with highly charged ions. The stochastic cooling method proposed by van der Meer has become the primary tool for accumulating and cooling antiprotons.

Keywords: colliding beams, collider, beam cooling, electron cooling, storage ring, beam

1. Introduction

1.1 Origin of the colliding beam method

The successful development of research on electron–electron and electron–positron colliding beams accelerators gave evidence of the importance of radiative cooling for positron storage and achieving high luminosity. G I Budker, the founder and first Director of the Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences (INP SB RAS), had the highest esteem for the informative value of beam collisions as a new window to progressing elementary particle physics. In the 1960s, the institute staff designed and built the accelerators with colliding electron–electron (VEP-1 in Russ. abbr.) and electron–positron (VEPP-2, VEPP-4) beams. The latter two were later considerably modernized into VEPP-2000 and VEPP-4M, respectively, which are still used in high-energy physics research. But G I Budker continued to dream that the use of colliding proton–antiproton beams with an energy of several dozen GeV would allow the collision energy to be increased to much higher values than those attainable with the then standard method of beam collisions with stationary targets. The maximum energy of collision between a proton beam having the energy $E \gg Mc^2$ and an immobile particle of mass M is $E_{\text{coll}} = \sqrt{2EMc^2}$, compared with $E_{\text{coll}} = 2E$ for colliding beams. In other words, beam collision increases the effective energy by a factor of $\sqrt{2E/(Mc^2)}$ and thereby permits the size of accelerators to be reduced $\sqrt{2E/(Mc^2)}$ times, thus turning them practically into table-top devices (as said by G I Budker). Today, such an opinion sounds paradoxical bearing in mind that modern colliding beams facilities (now termed as colliders) may be nearly 100 km in circumference.

1.2 Radiative cooling of protons

More conservative-minded physicists argued that low beam density n, which is responsible for very weak luminosity L:

$$\frac{\mathrm{d}N_{\text{coll}}}{\mathrm{d}t} = f_{\mathrm{b}} N \sigma_{\text{coll}} n l_{\mathrm{b}} = L \sigma_{\text{coll}} \,,$$

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Table 1. Characteristics of colliders.

Year	Perimeter, km	Magnetic field, T	Proton energy, TeV	Decay time
1960	0.3	2	0.025	2 years
2017	26	8	7	18 h
2040 ?	100	16	78	0.5 h

where N is the number of colliding particles, $f_{\rm b}$ is the bunch collision frequency, $\sigma_{\rm coll}$ is the collision cross section, and $l_{\rm b}$ is the effective length of an oncoming bunch, would be the main obstacle hampering the application of the colliding beam technique. To implement it, an ion cooling method was needed, making it possible to increase a beam phase density by many orders of magnitude in analogy with radiative cooling for electrons and positrons. There was barely emission from heavy particles in a magnetic field at the energies available at that time. The radiative cooling time was defined as the time during which particles totally lost energy (certainly, they did not stop and their energy was recovered by virtue of the high-frequency fields of accelerating systems, while the transverse momenta decreased). This time was expressed as

$$\tau^{-1} = \frac{2}{3}\,\frac{e^4 c}{(Mc^2)^4}\, EB^2 \,, \tag{1}$$

where $e = 4.8 \times 10^{-10}$ is the proton charge, and B is the value of the magnetic field in the storage ring (in Gauss system of units). Table 1 presents parameters of storage rings, including the proton beam decay time obtained in the course of development of colliders. Clearly, radiative cooling is highly essential for the Large Hadron Collider with a proton energy of 7 TeV and will be even more important for future supercolliders as a factor directly determining high luminosity.

1.3 Electron cooling method

Ionization losses in matter could be of use for cooling ions, but their strong interaction with nuclei make this cooling mode inapplicable for protons and antiprotons. G I Budker proposed to cool a heavy ion beam using a pure (ion-free) electron beam moving at the mean particle speed [1]. Since the efficiency of interaction grows as the cube of the relative velocity of ions and electrons, it was deemed possible to rapidly enough cool heavy ions interacting with a parallel propagating electron beam, despite its several orders of magnitude lower density than the possible density of matter.

From 1967, INP SB RAS embarked on the construction of the EPOKhA cooler facilities (Russian abbreviation for 'Electron Beam to Cool Antiprotons") to validate and substantiate the principle of electron cooling. A test-bench was created to develop methods for recuperating an intense electron beam. For simplicity, the first facility had no special section for merging electron and proton beams. An electron gun with resonant electrodes was placed in a straight solenoid to suppress transverse angles in the electron beam, together with a receiving collector (Fig. 1).

At first, G I Budker dreamed to use a cooling electron beam of several hundred amperes [2]. However, mutual repulsion between electrons attributable to space charge effects precluded creating such intense beams. Therefore, it was decided to focus electrons by applying a 500–2000 G longitudinal magnetic field along their orbit using solenoids, as shown in Fig. 2.

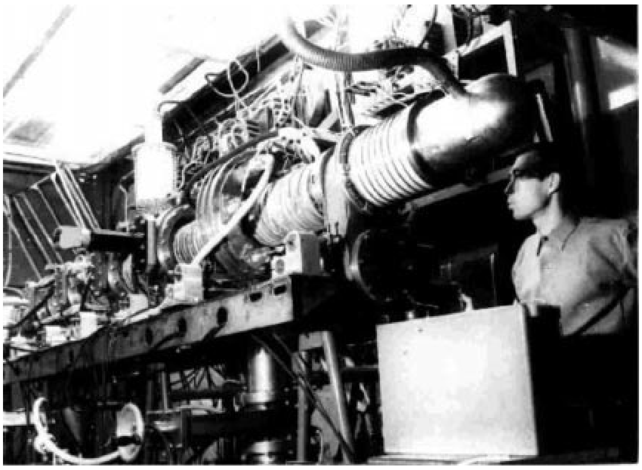

Figure 1. R A Salimov conducting experiments on a rectilinear test-bench for generating an intense electron beam.

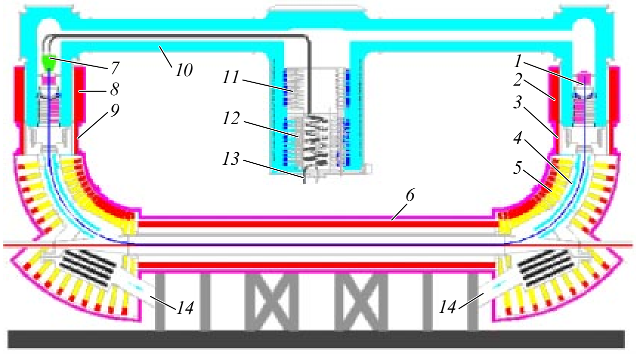

Figure 2. Schematic of the electron cooler designed for an electron beam energy of 300 keV. The electron beam from electron gun *1* is injected into the cooling section through the system of solenoids and toroids *2*, *3*, *5*, *8*, *9*, generating a longitudinal magnetic field, and electrostatic plates *4* making up for compensating centrifugal drift, to interact with the ion beam in the precise solenoid *6*. Then, the electrons are decelerated and enter collector *7* to be absorbed. High voltage along the co-axial line *10* is distributed between the electron gun and collector. High voltage is generated in generators *11*, *12*, *13*. High-power vacuum pumping systems are placed near toroidal chambers *14*.

1.4 NAP-M storage ring

It was initially proposed to exploit the VEPP-3 electron–positron collider as a testing facility. However, attempts to inject and accelerate a proton beam in VEPP-3 failed because of problems with vacuum and the aperture. Therefore, it was decided in 1972 to start the construction of a specialized proton storage ring (NAP-M) with electron cooling (Figs 3, 4).

To reduce expenditures, magnets with yokes formed from nonlaminated massive iron were used. The field in such magnets could be increased rather slowly (1–2 minutes), and a very high vacuum was needed to accelerate protons before their complete loss through scattering from the residual gas. In 1974, it became possible to start proton beam cooling experiments [2]. The very first ones yielded cooling times of 10–20 s, similar to those calculated in the plasma model of heat exchange between electrons and protons proposed by G I Budker, A N Skrinsky, and Ya S Derbenev [1, 4]. In this model, the electron beam had a temperature close to the cathode temperature of 1000 K, and the protons had to be cooled to electron temperature in the co-moving frame of

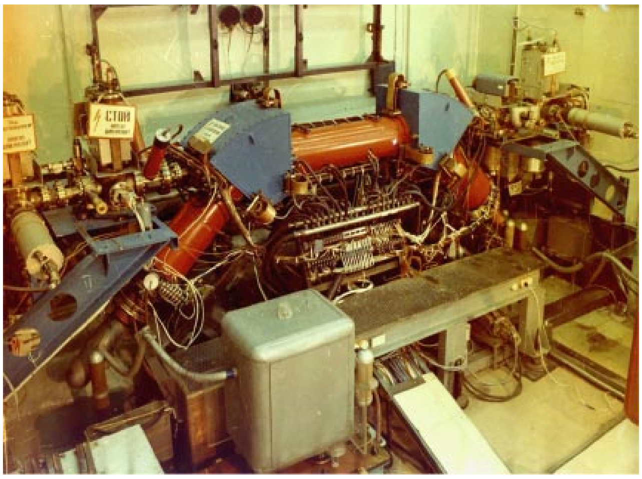

Figure 3. World's first electron cooling installation in the NAP-M proton storage ring.

Figure 4. External view of the NAP-M proton storage ring.

reference:

$$\langle V_\mathrm{i}^2 \rangle = \frac{m_\mathrm{e}}{M} \langle V_\mathrm{e}^2 \rangle \,. \tag{2}$$

The transfer to the laboratory reference frame from Eqn (2) yielded the relation for equilibrium angular spread θ_i of the ion beam after cooling:

$$\theta_\mathrm{i} = \theta_\mathrm{e} \frac{1}{43\sqrt{A}} \,, \tag{3}$$

where A is the ion atomic mass, $\theta_\mathrm{e} = V_\mathrm{e}/(\gamma V_0)$ is the spread of electrons, V_0 is the particle velocity in the collider, and $\gamma = 1/\left[1 - (V_0/c)^2\right]^{1/2}$.

2. Stochastic cooling

In 1972, van der Meer [5] initiated cooling research at CERN based on the use of broadband feedback for damping particle oscillations. In this method, a particle passing a pickup[1] generates a voltage pulse with an amplitude proportional to its deflection from the x-axis of the pickup; it then propagates through the plates (kicker) and experiences an 'impact' that decreases its oscillation amplitude. It seems possible to increase the deflection signal so as to totally suppress oscillations for the period of several revolutions. However, pickup thermal noises and the presence of other particles subjected to the impact create problems. If the voltage pulse duration $\tau_W \approx 1/W$, where W is the bandwidth of the feedback system, the number of particles experiencing the impact will be $N^* = N\tau_W/T_0$, where N is the total number of particles in the storage ring, and T_0 is the period of revolution or the bunch length (for a bunched beam). Thus, a decrease in the total energy of particle oscillations is expressed as

$$\frac{\Delta E}{E} = -2g + N^* g^2 \,, \tag{4}$$

where g is the total reduction factor of the particle's amplitude A for a single pass through the system $(A_{k+1} = A_k(1-g))$.

Clearly, optimal cooling occurs for $g \leqslant 1/N^*$, and the cooling time found from the van der Meer formula is

$$\tau_\mathrm{st}^{-1} = \frac{W}{N} \,. \tag{5}$$

When the number of antiprotons $N = 10^{11}$ and $W = 10^9$ Hz, the cooling time would reach 100 s.

Special pickups with reduced sensitivity had to be installed in the accumulation zone of the antiproton storage ring to ensure relatively slow drawing into the accumulation zone and fast cooling of the hot newly injected portion of antiprotons. Such a system makes possible frequent injection and rapid accumulation of antiprotons. In 1984, Simon van der Meer and Carlo Rubbia were awarded the Nobel Prize in Physics for the development of this cooling technique, realization of proton–antiproton colliding beams, and the discovery of the heavy field particles W and Z.

In 1982, INP researchers undertook experiments to study this method based on the NAP-M storage ring using a 65-MeV proton beam [6]. Cooling time proved to be 150 s. Experiments on stochastic cooling of a carbon ion beam with an intensity of 2×10^9 particles and energy of about 2.5 GeV per nucleon were carried out using more sophisticated equipment in the framework of the nuclotron-based ion collider facility (NICA) project (Dubna, 2011). The spread in momenta for the carbon ion beam was found to decrease from 1.5×10^{-4} to 0.7×10^{-4} in 27 s [7].

3. Electron cooling kinetics

The traveling of a charged particle in a gas of sufficiently cold electrons is accompanied by electrostatic interactions with energy transfer onto electrons closest to the particle, given that the process is considered in the beam reference system. The flight of a particle having charge Z with speed V at an impact parameter ρ from an electron gives rise to an additional momentum acquired by electrons:

$$\Delta p = \frac{2Ze^2}{\rho V} \,. \tag{6}$$

Accordingly, the total energy transferred to the electrons from an ion covering distance s determines the friction force:

$$Fs = \left[\int_{\rho_\mathrm{min}}^{\rho_\mathrm{max}} \left(\frac{2Ze^2}{\rho V} \right)^2 \frac{1}{2m_\mathrm{e}} \, n_\mathrm{e} 2\pi\rho \, \mathrm{d}\rho \right] s \,, \tag{7}$$

where the collision parameters ρ_max, ρ_min define the field of applicability of the simple Born approximation in Eqn (7),

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[1] A system of sensitive electrodes measuring particle axial deviation and sending the signal to a kicker (a device reducing particle oscillation amplitude).

and n_e is the electron beam density. Integrating over impact parameters yields friction force

$$F = \frac{4\pi e^4 Z^2 n_e}{m_e V^2} \ln \frac{\rho_{\max}}{\rho_{\min}} \,, \tag{8}$$

where $\rho_{\max} = V\tau_{\text{flight}}$ is the maximum impact parameter depending on interaction time τ_{flight}, and $\rho_{\min} = 2e^2 Z/(mV^2)$ is the minimum impact parameter at which the excited electron speed is comparable to the velocity V of the oncoming particle. Electrons possess intrinsic velocities, which necessitates convolution between the resultant friction force and the electron velocity distribution. The 'Coulomb' analogy helps in understanding the behavior of the friction force in such a situation. Coulomb forces show a quadratic dependence on the coordinates. Inside a uniformly charged sphere, the force increases linearly from the center along the radius; outside the sphere, the force decreases quadratically with distance from the sphere. Furthermore, the friction force linearly increases, when electron velocities are uniformly distributed inside a sphere of radius V_e, as the particle velocity increases in the range $|\mathbf{V}| < V_e$, and then decreases as $1/V^2$:

$$F(\mathbf{V}) = -\frac{4\pi e^4 Z^2 n_e \,\mathrm{Ln_C}}{m_e} \begin{cases} \dfrac{\mathbf{V}}{V_e^3} \,, \\ \dfrac{\mathbf{V}}{V^3} \,, \end{cases} \tag{9}$$

where $\mathrm{Ln_C}$ is the Coulomb logarithm. Energy loss fluctuations are as important as energy losses themselves, $F(V) = \langle \Sigma \Delta E \rangle / s$, averaged over the covered distance s. In each collision at the impact parameter ρ, an electron acquires energy from an ion:

$$\Delta E = \frac{2Z^2 e^4}{m_e \rho^2 V^2} \,. \tag{10}$$

The probability of a collision with the impact parameter equal to ρ per unit time is defined as

$$\mathrm{d}W = 2\pi\rho \,\mathrm{d}\rho n_e V \,. \tag{11}$$

It follows from expression (8) describing the relationship between the electron energy and the impact parameter that

$$2\pi\rho \,\mathrm{d}\rho = \frac{2\pi Z^2 n_e e^4}{m_e V^2 E^2} \,\mathrm{d}E \,. \tag{12}$$

In other words, the probability of an energy loss jump per unit time is expressed as

$$\frac{\mathrm{d}W(\Delta E)}{\mathrm{d}E} = \frac{2\pi Z^2 e^4 n_e}{m_e V \Delta E^2} \,. \tag{13}$$

Time-averaged losses can be obtained from the integral

$$\begin{aligned} \frac{\mathrm{d}E}{\mathrm{d}t} &= -\int_{\Delta E_{\min}}^{\Delta E_{\max}} \Delta E \,\mathrm{d}W(\Delta E) = -\frac{2\pi Z^2 e^4 n_e}{m_e V} \int_{\Delta E_{\min}}^{\Delta E_{\max}} \frac{\mathrm{d}E}{E} \\ &= -\frac{2\pi Z^2 e^4 n_e}{m_e V} \ln \frac{\Delta E_{\max}}{\Delta E_{\min}} \,, \end{aligned} \tag{14}$$

fully coinciding with the expression for the friction force, bearing in mind that $\mathrm{d}E/\mathrm{d}t = FV$, and energy losses are defined by the impact parameter squared: $\ln(\Delta E_{\max}/\Delta E_{\min}) = 2\ln(\rho_{\max}/\rho_{\min})$. The spread in energy is described by the equation

$$\begin{aligned} \frac{\mathrm{d}\Delta E^2}{\mathrm{d}t} &= -\int_{\Delta E_{\min}}^{\Delta E_{\max}} \Delta E^2 \,\mathrm{d}W(\Delta E) \\ &= -\frac{2\pi Z^2 e^4 n_e}{m_e V} \Delta E_{\max} \,. \end{aligned} \tag{15}$$

The parameters of ion–electron collisions are determined by collision kinematics.

For nonrelativistic collisions, one has $\Delta E_{\max} = 2m_e V^2$ and $\Delta E_{\min} = Z^2 e^4/(m_e \rho_{\max}^2 V^2)$, while the time of interaction with the electron beam gives $\rho_{\max} = V\tau_{\text{flight}}$.

The self-motion of electrons is responsible for diffuse shocks changing particle momentum. Disregarding particle velocity near equilibrium position (in view of the large mass of a particle) and taking account of Eqn (4) give the following expression for the particle 'heating' rate:

$$\begin{aligned} \frac{\mathrm{d}\Delta p^2}{\mathrm{d}t} &= \int_{\rho_{\min}}^{\rho_{\max}} \Delta p^2 2\pi\rho \,\mathrm{d}\rho n_e V_e f(\mathbf{V}_e) \,\mathrm{d}^3\mathbf{V} \\ &= \frac{4\pi e^4 Z^2 n_e \,\mathrm{Ln_C}}{V_e} \,, \end{aligned} \tag{16}$$

where $f(\mathbf{V}_e)$ is the electron velocity distribution function.

The equation for small oscillations ($V \ll V_e$) of an ion having mass M with respect to the equilibrium position, taking into consideration the friction force and the restoring force of the storage ring focusing system, can be written out as

$$\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + \frac{4\pi e^4 Z^2 n_e \eta \,\mathrm{Ln_C}}{M m_e} \frac{\mathrm{d}x}{\mathrm{d}t} + \omega_x^2 x = 0 \,, \tag{17}$$

where ω_x is the oscillation frequency around the equilibrium position in the degree of freedom x, and η is the share of the cooling section in the ion beam orbit.

Evidently, the solution of Eqn (17) has the form

$$x(t) = A \exp(-\lambda t) \exp(-\mathrm{i}\omega t) + B \exp(-\lambda t) \exp(\mathrm{i}\omega t) \,, \tag{18}$$

where $\lambda = 2\pi e^4 Z^2 n_e \,\mathrm{Ln_C}/(M m_e V_e^3)$ is the damping rate, and $\omega = (\omega_x^2 - \lambda^2)^{1/2}$ is the friction-modified oscillation frequency. As a rule, $\lambda \ll \omega_x$, and the frequency remains practically unaltered, but oscillation amplitude attenuates with time:

$$x(t) = A_0 \exp(-\lambda t) \exp(\mathrm{i}\omega t + \varphi_0) \,. \tag{19}$$

4. Cooling by magnetized electrons

The first NAP-M experiments seemed to confirm not only an electron cooling effect but also the cooling kinetics described in Section 3 (see also Ref. [4]). Cooling was achieved at an electron energy of 65 MeV and a current close to 0.3 A.

The cooling time (around 4 s) obtained in early experiments proved to the very close to the expected value (Figs 5–7). But this was only th beginning of our history. The improved rectilinearity of magnetic lines of force, higher vacuum, and accurate adjustment of mutual positions of the beams resulted, however, in an unexpected 10–20-fold

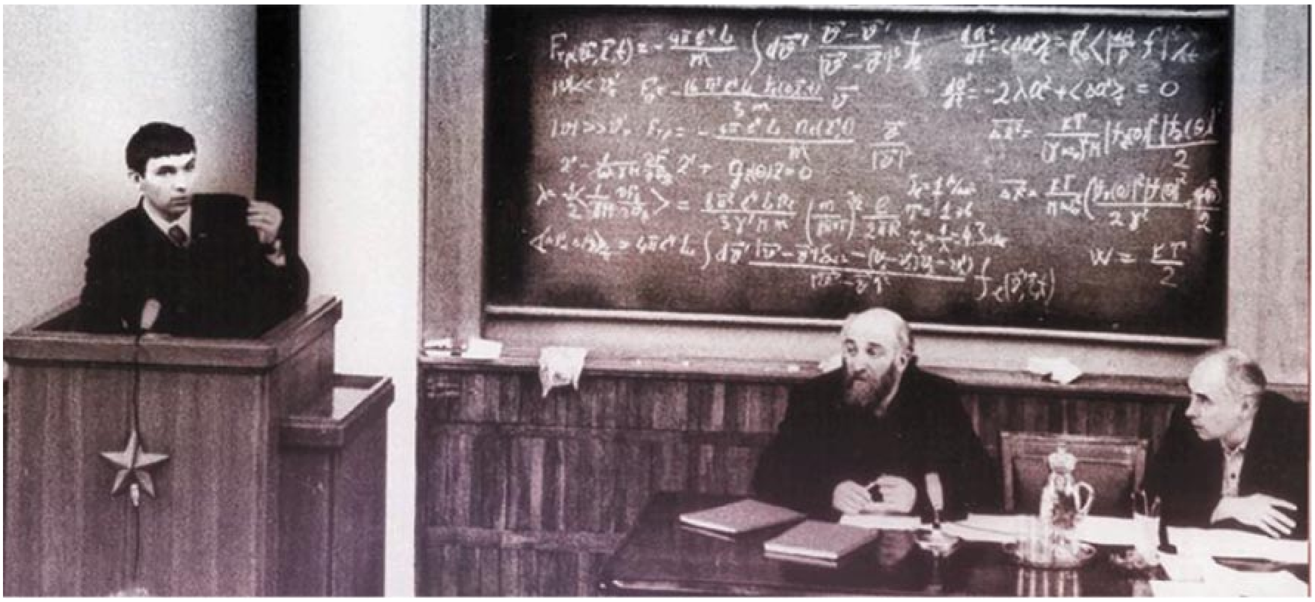

Figure 5. Meeting of the INP Scientific Council chaired by G I Budker (sitting in the center) with the secretary L M Barkov (right). V V Parkhomchuk (standing at the lectern) defends his PhD theses on "The first electron cooling experiments" (1975). The board displays cooling rate formulas. Photo by V V Petrov, INP SB RAS.

Figure 6. Team of participants in the first cooling experiments (from left to right): I N Meshkov, B N Sukhina, D V Pestrikov, V N Ponomarev, V V Parkhomchuk, and N S Dikansky (demonstrating a photo with a decreased proton beam size after effecting the electron cooling, as recorded with the use of a magnesium vapor jet) (1975).

acceleration of cooling. It turned out that the electron beam in the co-moving coordinate system was characterized by a much smaller spread in velocity, while the longitudinal magnetic field 'magnetized' the transverse movement of electrons and thereby excluded their transverse velocities from the interactions [6, 9 –11].

A number of diagnostic tools had to be developed to register cooling. The most important one was a proton beam

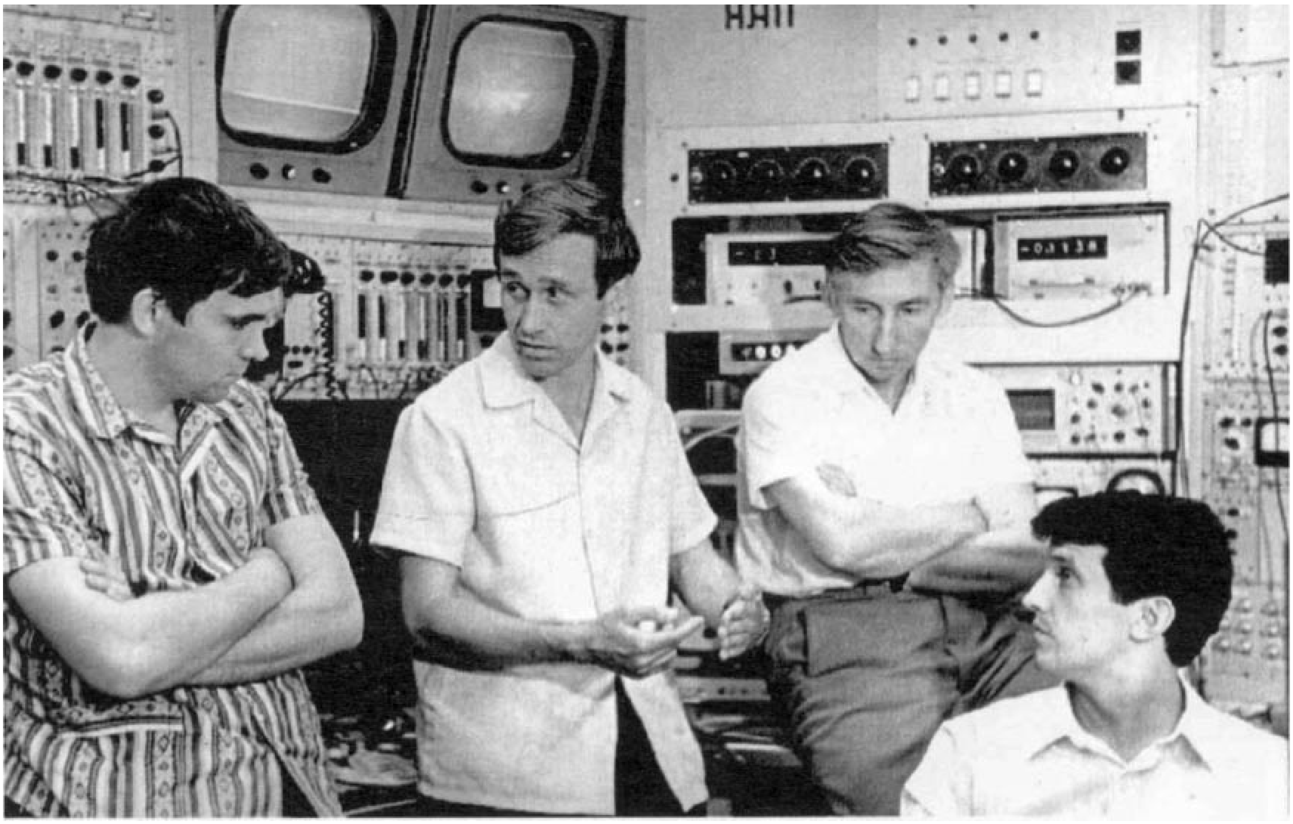

Figure 7. V V Parkhomchuk, A N Skrinsky, I N Meshkov, N S Dikansky (from left to right) discussing why the proton beam is cooled so rapidly (1975).

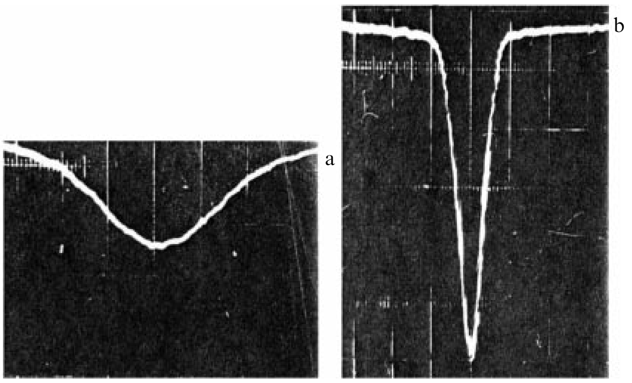

Figure 8. Proton beam profiles measured before (a) and after (b) electron cooling. Measurements were done by scanning with the use of a thin magnesium vapor jet over the proton beam cross section.

profilometer operating with a thin magnesium vapor jet (Fig. 8) [8]. This device made it possible to measure proton beam density in the distribution center with a millisecond resolution; it was utilized in subsequent fast electron cooling studies.

It proved possible to cool a proton beam to 1 K in NAP-M. The cooling was accompanied by interesting phenomena associated with the suppression of temperature fluctuations by electrostatic interactions in the beam [12], as exemplified most vividly by a change in the shape of its thermal noise spectrum. Fluctuations along the beam began to spread faster than cold ions themselves; moreover, two space charge waves were apparent, one running in the direction of beam travel, and the other opposite to it. Accurate measurements showed that the longitudinal temperature for a small number of beam particles was much lower than that predicted by the intrabeam scattering theory. Appreciable heating could be observed only in the presence of a large number of particles. Thereafter, such phenomena were documented to occur in many facilities. The transition of an ion beam into a quasicrystalline state remains an intriguing topic.

5. Magnetization cooling facility for studying the friction force

Detailed studies of the cooling kinetics with the aid of a magnetized beam were carried out using a special setup for direct measurement of the force of friction without a storage ring. A 1-MeV H^- ion beam from an electrostatic accelerator passed over a 3-m long cooling section with an electron beam energy of about 500 eV. Figure 9 presents a photograph of the MOSOL facility (Russian abbreviation of 'solenoid model') that served to measure the friction force in a strongly magnetized electron beam. The ions moved faster when the electron beam energy was slightly higher than that of the ion beam. Conversely, the slower movement of electrons caused ion deceleration. Practically the same behavior of the beam system can be observed in any electron cooler.

The employment of such a simple test-bench enabled us to come to a much better understanding of the nature of the friction force and the mode of its measurement. Results of these measurements constitute up to now the scientifically sound basis of many our studies with the application of the electron cooling method [13]. Newly designed measuring devices guarantee fairly good rectilinearity of magnetic lines of force (deflection of less than 10^{-6} rad from the straight

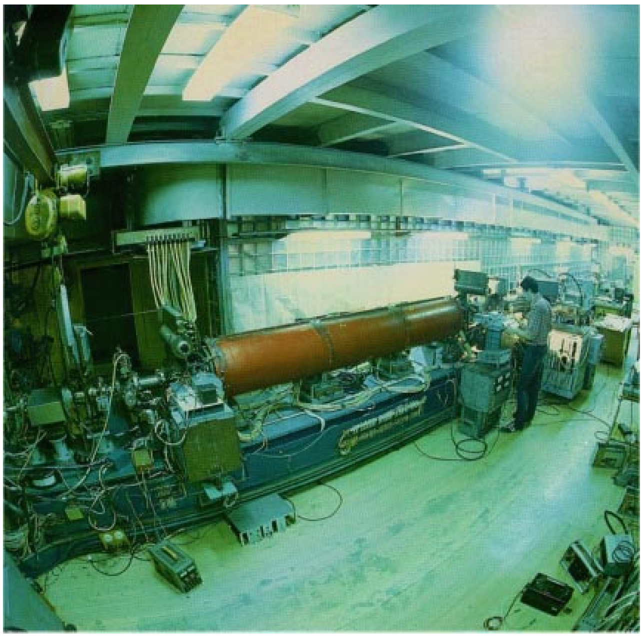

Figure 9. MOSOL facility for the study of excessively magnetized electron cooling [13].

direction). It was shown that a strong magnetic field suppressing electron drift can be applied to generate electron beams having high density and low temperature. The equivalent cooling time did not exceed a few microseconds.

Governmental funding of electron cooling research was reduced significantly in the early 1990s. To continue the work, we had to actively search for financially reliable users for our high-tech electron cooling techniques outside of Russia. The first project of this kind was the cooler system for the SIS-18 synchrotron of GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany, where the experimental storage ring (ESR)-based electron cooler had by that time been exploited for several years. German physicists were perfectly aware of the value of our cooler systems for the enhancement of the performance of their synchrotron. True, there were sceptics who argued that recombination would hardly substantially increase the beam intensity of highly charged ions. Experiments on bismuth ion (Bi_{209}^{+67}) accumulation showed that in the absence of cooling the intensity could not be higher than one injection step with a 0.05-mA current filling up the entire accessible aperture of the synchrotron. In contrast, the current curve under cooling appeared as a multistep one, with each consecutive step increasing by 0.05 mA. The high efficiency of our coolers convinced the sceptics of the advantages of electron cooling for modern ion synchrotrons (Fig. 10).

But already at the time of constructing the cooler for SIS-18, the experiments on the Celsius facility at the University of Uppsala, Sweden showed that the high intensity of the accumulated beam being cooled affected its

Figure 10. Electron cooler for the SIS-18 synchrotron (GSI, Germany). Standing behind the INP lettering are members of the INP SB RAS team commissioning the cooler system; those behind the GSI lettering are the GSI acceptance team. Fourth from left: V V Parkhomchuk, one of the authors of the present article; standing to his right is H J Specht, Director of GSI (1996).

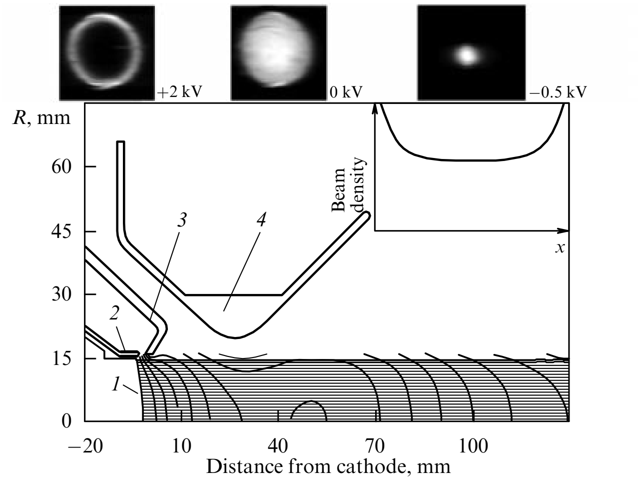

Figure 11. Schematic of an electron gun with a controlled beam profile: *1* — cathode, *2* — ring on the cathode to smooth its angle, *3* — profile-controlling electrode, and *4* — electron gun anode. Top: three beam profiles measured at potential values of 2, 0, and −0.5 kV. The inset to the top right corner shows the characteristic beam density shape obtained by computer-aided calculation.

stability. A large part of the instabilities were those attributable to vacuum chamber impedances. Feedback systems proved highly efficient for coping with such instabilities. However, the Celsius facility experienced considerable losses of the proton beam under electron cooling conditions in the absence of readily apparent coherent signals that could suppress the losses via a feedback-driven mechanism. This phenomenon, called 'electron heating' by Dag Reistad — head of the Gelsius team, was reminiscent of effects of meeting oncoming beams in storage rings. Its interpretation in terms of the model of mutual plasma oscillations in the beams over the cooling section provided a basis for the assumption of electron density reduction in the midst of the electron beam.

The development of such oscillations can be suppressed by lowering the density in the center of the electron beam with its rise at the aperture edges. This does not appreciably decrease the large-amplitude cooling rate but markedly heighten the instability threshold. Figure 13 displays electron beam profiles generated at different voltages at the control electrode [13].

Near the edge of the cathode, the standard Pierce electrode is torn away from cathode potential; the potential being positive, emission from the beam edges increases

Figure 12. Electron cooler for LEIR before dispatch to CERN and a group of its developers from INP SB RAS: front row: N A Arzhanov (left) and A D Goncharov; sitting in the second row (from left to right): A A Lomakin, V M Panasyuk, B A Skarbo, V B Reva, A V Bubley, V V Parkhomchuk, and N P Zapyatkin; standing in the third row (left to right): V A Vostrikov, V S El'tsov, and G N Ezhkov (2004).

substantially, while the space charge suppresses emission in the center of the cathode, thus making the beam hollow.

Another specific feature of a new generation of electron coolers is the application of an electrostatic field in the section of toroidal convergence of electron and ion beams to compensate for the centrifugal drift.

The first coolers took advantage of magnetic compensation for centrifugal drift in the convergence section, where electrons moved along an arc of a circle in the direction of a toroidal magnetic field. The electrons being lost were reflected from the collector to be involved in a drift motion that was twice as strong and reached the walls of the vacuum chamber, where they induced gas emission through desorption. The use of the electric field enabled these electrons to move along the main beam and return to the collector after they were reflected from the cathode potential; this reduced beam losses more than a 1000-fold. It also promoted the accumulation of highly charged ions. Both capturing and stripping ions in the residual gas greatly reduced the beam's lifetime. Bombardment by lost electrons caused enhanced desorption from the walls of the vacuum system (even modern vacuum pumps fail to do so with such a gas flow). A 1000-fold reduction in the loss current helped to solve such a vacuum problem. The introduction of an electron current improved vacuum performance due to additional pumping by the electrons themselves. Successful operation of the cooler at the SIS-18 synchrotron motivated researchers from the Institute of Modern Physics (IMP) in Lanzhou, China to order from INP SB RAS two electron coolers for the new Cooler Storage Ring (CSR) consisting of the main ring (CSRm) and experimental ring (CSRe). A schematic of the electron cooler, projected for an energy of 300 keV (voltage of 300 kV), at the CSRe is presented in Fig. 2.

The success of the electron cooling systems installed in China [15] dispelled the doubts of CERN researchers about the workability of our coolers, and one more facility (Fig. 12) was ordered in 2003 for the heavy-ion injection facility Low Energy Ion Ring (LEIR). An important characteristic of LEIR is the requirement for a high vacuum: 10^{-12} Torr. The cooler was delivered to Geneva on 17 December 2004 and put into operation in the summer of 2005. The first successful experiments on electron cooling of oxygen ions were carried out at the end of 2005 [16].

6. International cooperation

The development of the electron cooling method in the USSR aroused great interest in the world's accelerating centers. Many participants in the *Xth International Conference on High-Energy Particle Accelerators* held in Protvino [9] visited INP SB RAS in Novosibirsk after conference terminating to see its colliding beams and electron cooling facilities. The construction of the Initial Cooling Experiment (ICE) facility was started at CERN to master the electron cooling method. The Fermi National Accelerator Laboratory in Batavia, Illinois, USA decided to create a facility for cooling protons. The University of Uppsala, Sweden used magnets of the device intended for measuring the muon g–2 factor (CERN) to construct the Celsius electron cooler.

Vast experience with electron cooling permits INP SB RAS to participate in the development of conceptual projects for many laboratories all over the world. In 2005, our team developed an electron cooling facility for the Relativistic Heavy Ion Collider (RHIC) to be operated by the Brookhaven National Laboratory, USA.

G I Budker dreamed of creating a facility for studying antiprotons in Siberia. In the late 1980s, it was decided to implement this project based on the proton–proton collider under construction at that time in Protvino. However, the systemic crisis in the USSR put an end to the antiproton beam project in this country. In 1983, Fermilab commissioned the Tevatron collider facility with an energy of proton and antiproton beams of up to 1 TeV. To enhance the luminosity of the collider, its Recycler storage ring was equipped with the most powerful high-voltage electron cooling system (4.3 MV) [17]. Former INP employees S S Nagaitsev, A V Shemyakin, A V Burov, A V Lebedev, and V D Shil'tsev were active participants in this project but already in the capacity of Fermilab researchers [17, 18].

The most ambitious project for electron cooling of gold ions at an energy up to 100 GeV per nucleon was developed in the Brookhaven National Laboratory. This project requires the generation of an electron beam with the energy of 50 MeV and the current peak of about 1 A [19]. It was planned to build a linear superconducting accelerator–recuperator in which electron bunches will return their energy to the linac after interaction with ions in the cooling section.

A very interesting facility for work with cooled antiproton beams, the Low Energy Antiproton Ring (LEAR), created at CERN, made it possible to strongly decelerate antiprotons, down to a complete stop and the formation of a neutral antihydrogen atom [20]. This facility was exploited in precision experiments designed to compare properties of matter and antimatter. Moreover, CERN continues such investigations with the new Antiproton Decelerator (AD) [21]. LEAR is now converted into the LEIR ion storage ring equipped with an electron cooling system designed at INP in 2006; this machine provides injection of highly charged lead ions for realizing ion–ion colliding beams at the Large Hadron Collider (LHC). The ALICA (A Large Ion Collider Experiment) detector at LHC is used to study heavy ion collisions at ultrahigh energies.

Great effort will be needed to develop a cooling system for the FAIR complex (Facility for Antiproton and Ion Research) at GSI in which several 40-kV to 4-MV coolers will be installed to ensure the desired luminosity of devices with rare ions and antiprotons. A distinctive feature of this project is the generation of exotic nuclei and their detailed investigation in collisions with antiprotons and electrons. Cooling is indispensable to keep these future facilities working. Parameters of the cooling, both electron and stochastic, must be very high, which implies the necessity of new ideas for the development of cooling techniques.

INP SB RAS is developing, jointly with J Gutenberg University (Mainz, Germany), an idea of the electron cooling system with voltages of up to 8 MV using gas turbines for the high-voltage terminal and solenoids along the accelerating column [22].

INP SB RAS greatly contributed to the creation of ion storage rings with electron cooling, CSRm and CSRe, at the Institute of Modern Physics (China), which are now extensively used in many research projects on atomic physics of partially ionized ions having electrons at atomic levels and on rare ions resided far away from the line of stability. A decision has been made to build a new ion facility with intense ion beams in southern China [23].

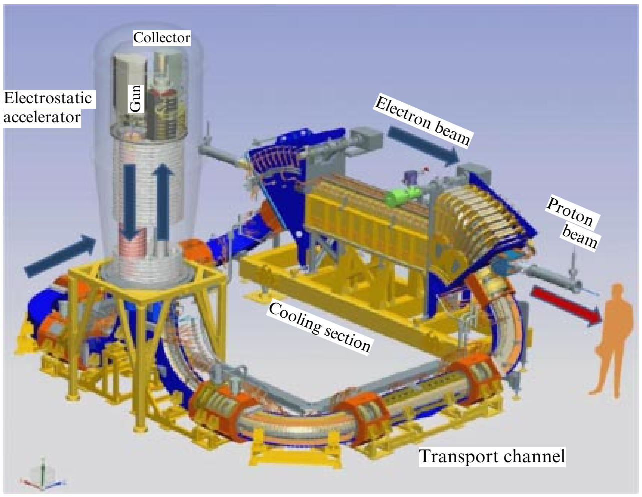

Figure 13. Schematic of an electron cooling system for COSY.

An important objective of highly ionized ion experiments is to observe the beta decay of nuclei into states with bound electrons on atomic shells [24]. The energy of electrons bound on the atomic shells is much lower than that of free electrons, which opens up the beta decay channel for quite stable neutral atoms. Such phenomena are known to occur at very high temperatures in stars where atoms are devoid of their electron shells. Under deep vacuum and strong cooling conditions, ions live a few dozen hours, which facilitates observation of decays and the formation of new nuclei. These processes affect isotopic ratios in Nature. The data obtained help in better understanding details of nuclear synthesis in hot stars. Studies along these lines are among the priorities at GSI (Darmstadt) and IMP (Lanzhou), where precise measurements of the masses and lifetimes of various ions are performed.

The most powerful high-voltage (2 MV) cooling system was designed at INP SB RAS in 2013 for the COoler SYnchrotron (COSY) in Germany (Fig. 13) [25].

7. Engineering implementation of electron cooling

The maximum density of an electron beam in the rectilinear section of the ion orbit is needed for electron cooling. This requirement poses the question of electron beam divergence under the effect of its space charge. The defocusing length l_{def} is expressed as

$$\frac{1}{l_{\mathrm{def}}} = \sqrt{\frac{2\pi r_{\mathrm{e}} n_{\mathrm{e}}}{\beta^2 \gamma^3}} . \tag{20}$$

At electron beam density $n_{\mathrm{e}} = 10^8\ \mathrm{cm}^{-3}$ and an electron energy of 54 keV, the defocusing length is 37 cm, i.e., too short for the cooling of a 100-MeV proton beam. The simplest way to compensate for repulsion between electrons inside the beam is to generate a strong longitudinal magnetic field B in the cooling section. Then, the transverse electric field induces drift rotation of the electron beam about the axis with a speed increasing in proportion to the deviation from the beam center r (in the co-moving system of coordinates):

$$V_{\perp} = \frac{2\pi e n_{\mathrm{e}} r}{\gamma B} . \tag{21}$$

The sufficiency condition for the magnetic field is a low velocity of electron movement compared to that of ions with a deviation amplitude r: $V_{\mathrm{i}} = r\beta\gamma c/\beta_{\mathrm{c}}$, where β_{c} is the beta-function in the cooling section. Thus, a sufficient magnetic field is defined as

$$B = \frac{2\pi e n_{\mathrm{e}}}{\beta\gamma^2}\, \beta_{\mathrm{c}} . \tag{22}$$

For a nonrelativistic case of electron beam density $n_{\mathrm{e}} = 3 \times 10^8\ \mathrm{cm}^{-3}$ and $\beta_{\mathrm{c}} = 1000$ cm, the magnetic field induction $B = 2000$ G.

For a beam of radius $r = 1$ cm, the angular spread $\theta_{\perp} = r/\beta_{\mathrm{c}} = 10^{-3}$; it decreases tens and hundreds of times in the course of cooling. To fully realize the electron cooling potential, the angular spread in the direction of a magnetic line of force must be much smaller than that in the ion beam, even if it is cooled. It may be conjectured based on the experience gained thus far that solenoids with an angular spread in the direction of a line of force around 10^{-6} can be designed.

Electrostatic acceleration appears to be the simplest method for obtaining an electron beam of as low an energy as 5 MeV. In a strong longitudinal magnetic field, electrons travel along the lines of force and are adiabatically connected to them, meaning that the relationship between the size of the electron beam at the electron gun cathode and that in the cooling section are determined by magnetic fields, in conformity with the Bush theorem:

$$a_{\mathrm{ec}} = a_{\mathrm{e}} \sqrt{\frac{B}{B_{\mathrm{c}}}} , \tag{23}$$

where a_{e} is the electron beam radius in the cooling section, a_{ec} is that at the cathode, and B_{c} is the magnetic field at the cathode. Facilities for low-energy electron beams have a limiting field accompanying the beam from the gun to the collector of electrons.

The electron beam has power $eU_0 I_{\mathrm{e}}$, where U_0 is the electron gun voltage, and $I_{\mathrm{e}} = e n_{\mathrm{e}} V \pi a_{\mathrm{e}}^2$ is the electron beam current. An energy of $eU_0 = 54$ keV is needed to cool 100-MeV protons; the current of a beam having density $n = 3 \times 10^8\ \mathrm{cm}^{-3}$ and a radius of 1 cm is 2 A. A dump of such a beam causes a power of more than 100 kW to be released in the vacuum tube.

Recuperation of electron beam energy is based on the employment of two sources. The negative pole of the powerful one is hooked to the cathode and the positive pole to the collector, so that the total beam current traverses the source at a relatively low voltage. The negative terminal of the high-voltage source is attached to the cathode, while the positive one is connected to a grounded vacuum chamber; it determines the electron beam energy over the cooling section. Only a current of electron beam losses accounting for less than 10^{-4} of the main current flows through the high-voltage circuit. An inconvenience of such a system arises from the necessity to transfer high power onto the collector rectifier at a high potential. High-voltage systems comprise generators rotated by a ground-based dielectric shaft, cascade generators consisting of series transformers with insulated windings, compressed gas-fed turbo-generators, etc. [26].

8. NICA heavy-ion collider and the role of cooling

An ion–ion colliding beams accelerator at energies from 4 to 11 GeV/nucleon is currently under construction at the Joint

Institute for Nuclear Research in Dubna, Russia [26–28]. This facility is designed with the main purpose of studying the quark–gluon plasma near the phase transition point of nuclear matter. The physical conditions formed in heavy nuclei collisions are believed to roughly correspond to the state of matter in the Universe within a few microseconds after the Big Bang. The NICA complex will consist of a collider for ion–ion beams with an energy of 1–4.5 GeV/nucleon, and an injector based on a booster and the currently operating nuclotron. The main components ensuring high luminosity in the NICA, $L > 10^{27}$ cm^{-2} s^{-1}, are electron and stochastic cooling systems. The electron cooling system is already integrated into the future booster ring, while the construction of the high-voltage system is currently underway at INP SB RAS in Novosibirsk.

9. Conclusion

Systems for the cooling of particle beams are used in many accelerators to achieve high luminosity of colliders. The idea forwarded by G I Budker in 1966 continues to be translated into reality and finds wide application in the increasingly sophisticated facilities for investigations in elementary particle physics and nuclear physics. Great interest has unexpectedly been aroused in atomic and nuclear physics research with the utilization of precise cold ion beams.

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