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Half a century of electron cooling development at BINP SB RAS

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Contents

Abstract. We outline the history of the method of forming ion beams by interaction with an electron beam. The method of forming this beam and the features of its application are called 'electron cooling.' Described is the development of this method from the initial idea presented by its author, the first director of the Institute of Nuclear Physics (INP) in Novosibirsk G.I. Budker, to its implementation and dissemination in accelerator laboratories worldwide.

Keywords: antiproton storage rings, electron cooling (EC), electron guns, resonant optics, collectors, recuperation, solenoids, electron cooling system (ECS), magnets, electron magnetization, proton lifetime, particle temperature

1. Introduction

In May 1974, the first effect was recorded: a shift in the ion beam when switching on an electron beam, which accompanied the ion beam in one of the four straight sections of the antiproton synchrotron storage ring model (NAP-M). Fifty years have passed since then, and the method of affecting the ion beam, known as 'electron cooling' (EC), has become one of the most convenient and effective ways to optimize the parameters of an ion beam circulating in a synchrotron. The history of the EC method, its development, and modern projects using EC are the subject of this article.

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2. How it all began

Andrei Mikhailovich Budker's[1] first discussions about electron cooling with A.N. Skrinsky began in 1965 with a discussion of how to obtain powerful proton beams. Aleksandr Nikolaevich became interested in electron cooling when he realized that this was a way to obtain colliding antiproton-proton beams (VAPP).

Andrei Mikhailovich actively supported this idea after three days of pondering. In 1966, Budker, after returning from a joint trip with A.N. Skrinsky to the USA, reported this idea (electron cooling and colliding beams in the VAPP project) at an international conference in Orsay [1].

In 1967, at the Institute of Nuclear Physics (INP), a start was made on active discussions of the physics of electron cooling and the design details of the cooling device. I.N. Meshkov was brought in, who soon completed his work on another of G.I. Budker's projects, Relativistic Stabilized Electron Beams, and switched to work on creating a setup with electron beam antiproton cooling (EPOKHA).

Initially, Andrei Mikhailovich favored quadrupole focusing for the electron beam, but since a high cooling-beam

[1] Budker's official given name and patronymic are Gersh Itskovich. But, as he told us, back in his first year in the army (after graduating from university in 1941, he volunteered to join the Red Army and served in the air defense in the Far East), he suggested that the soldiers 'for the sake of clarity' should call him Andrei Mikhailovich. So this full name stuck.

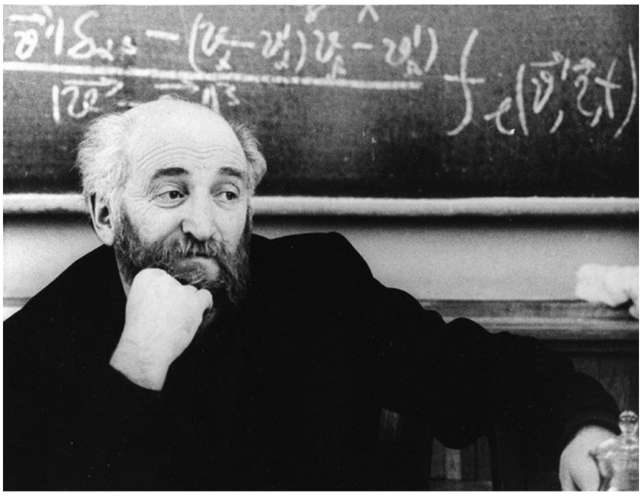

Figure 1. G.I. Budker at defense of dissertations in 1975.

current was required, A.N. Skrinsky and I.N. Meshkov convinced him that a longitudinal magnetic field better suited the task at hand: additional transverse velocities are not excited.

3. We will build our own new project to collide antiproton-proton beams

It was not long before a start was made on the design and manufacture of the Facility Prototype, consisting of an electron gun with resonant optics and an electron collector, which were placed in a three-meter solenoid with a uniform magnetic field containing devices for diagnosing the electron beam. Late in 1968, experiments on the prototype began. They were actively attended by physics students Vasilii Parkhomchuk and Viktor Fainshtein, whom I.N. Meshkov invited from the first-year group of the Physics Department of NSU, where he conducted physics seminars.

Soon, Andrei Mikhailovich, 'at the suggestion' of A.N. Skrinsky, invited R.A. Salimov to take part in electron cooling; at that time, R.A. Salimov was engaged in 'cold plasma' and was deservedly recognized as a talented experimenter.

Experimental studies on the prototype were intense and interesting. The main elements of the future electron cooling system (ECS) were developed and tested, namely the gun, the collector, and the solenoid transport system, which provide unique characteristics of the electron beam; low transverse electron velocities at high beam intensity [2] and electron deceleration at the collector with a low (less than 10^{-3}) level of electron loss [3]. They did not forget about electron beam diagnostics either [4]. Specialists from the All-Union Electrotechnical Institute from the laboratory of V.I. Perevodchikov significantly helped to solve the problem of electron beam energy recuperation.

At the same time, the design and production of the working version of the EPOKHA ECS was underway.

Being developed in parallel was the project to collide antiproton-proton beams with an antiproton storage ring (VAPP-NAP), whose active developer was N.S. Dikanskii [5]. Theoreticians did not lag behind either: the group was led by Ya.S. Derbenev and D.V. Pestrikov. And this entire 'army' was led by A.N. Skrinsky [6].

The first working EPOKHA ECS was built and tested in 1970 [7]. It remained to find a proton beam to be cooled. They tried to launch protons into the colliding electron-positron beam (VEPP-3) storage ring, which had already been built and was in the launch stage. They tried to inject protons from a Van der Graaff electrostatic accelerator, but the lack of a proton beam diagnostic system turned out to be a serious obstacle. At this time, the INP decided to focus all efforts on colliding electron-positron beams: the VEPP-3 and VEPP-4 colliders. Use was made of only magnets and vacuum chambers from the NAP synchrotron. This is how the 'antiproton accumulator–model' (NAP-M) appeared.

Its development also required a lot of work. Work on assembling the NAP-M together with the EPOKHA ECS and the Van der Graaff proton injector was completed in 1973, and the launch of the complex of facilities began. The correcting magnets at the ends of the dipole magnets could not be obtained from the INP workshops, and, at first, the proton beam was guided using pieces of permanent magnets placed on the vacuum chamber at the locations of the future correctors. The position of the proton beam was observed on fluorescent probes at the end of long straight vacuum tubes. By choosing the correct position of the permanent magnets, it was possible to place the beam orbit at the center of the vacuum chamber at the end of the gap. That was how a closed proton orbit was produced. This speeded up the manufacture of all eight correcting magnets: the successes of the physicists stimulated the engineers in the INP workshops.

It was time to start accelerating protons, but the program generator for the task of matching the magnetic field values and the RF voltage frequency got stuck in the sixth laboratory. We were in a hurry to start accelerating protons in order to check the operation of unlaminated electromagnets. It was decided to use a timer controlled 32-pole step relay as a function generator. The magnetic field value was measured by a Hall sensor with signal delay correction by voltage from a turn on the pole of the synchrotron magnet. The turn was connected in series to one of 32 variable resistors, and the signal from the resistor was fed to the RF-voltage frequency control unit. By adjusting the knob of the resistor, through which acceleration was currently taking place, we were achieving a frequency shift to the next step. This was a 'piecewise' converter of the Hall sensor signal to the RF-voltage frequency. It was not long before we managed to accelerate protons from an injection energy of 1.5 MeV to 65 MeV. Feeling that we would soon abandon the control unit, our colleagues from the sixth laboratory 'pounced' and gave us the coveted program generator controlled by an ODRA computer. After that, we successfully accelerated protons to the required energy, stopping the acceleration while retaining the proton beam.

It was possible to start experiments with cooling, but then it turned out that the introduction of an electron beam even with a current of 50 mA instantly killed the proton beam. The investigation into the loss of the beam dragged on for several months until it was found that the ion pumps distributed along the electron beam were to blame. In the cells of the ion pumps, ionization of the residual gas occurred. The resulting ions acquired high energy, being born in a field with a potential of 6 kV (the voltage on the plates of the ion pump), and in collisions with the pump plates 'picked up' an electron from them, turning into a fast hydrogen atom. Such an atom could fall into the electron beam, losing its electron, and at a sufficiently high energy fly off to the wall of the vacuum chamber. These lost electrons were retained by the magnetic field of the ECS solenoid and produced a negative potential to cause the death of the circulating protons. Distributed ion pumps were a great invention at that time, and such an effect was unexpected for us. After a trial shutdown of the ion pumps, the proton beam suddenly ceased to die, and in May 1974 we saw the first positive manifestations of electron cooling.

4. First experimental studies of electron cooling

The first evidence of electron cooling at NAP-M in May–June 1974 was recorded from the time dependence of the proton beam current curve. For the optimal electron beam energy, the proton beam had a rather long lifetime. Of course, the forced shutdown of the ion pumps entailed a strong deterioration of the vacuum and the beam lifetime was only 100 s, but for the first experiments this was sufficient. However, when the electron energy was detuned from the optimum, the proton beam was 'carried away' to the deflected energy and was lost in a few seconds.

The method of electron cooling, proposed and implemented at the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences in Novosibirsk under the leadership of A.M. Budker, was first presented at the All-Union Conference on Charged Particle Accelerators in November 1974 [8, 9].

After reconstructing the vacuum chamber and improving the stability of the electron energy of the ECS and the quality of the magnetic field of the NAP-M, the cooling decrements increased significantly (above 1 s^{-1}), and the lifetime of the proton beam ranged up to 20,000 s [10–13]. Such rapid cooling was determined by the magnetization of transverse electron motion [6] and the effect of 'flattening' of electron velocity distribution [14]. After electrostatic acceleration in the electron gun, the transverse velocities of the electrons persisted, and the longitudinal spread became 'almost zero' due to energy conservation:

$$eU_0 + \frac{kT_{\text{cathode}}}{2} = \frac{m(V_0 + \Delta V)^2}{2} . \quad (1)$$

This results in a small velocity spread in the co-moving frame of reference:

$$\Delta V = \frac{kT_{\text{cathode}}}{2mV_0} , \qquad E_k = \frac{(kT_{\text{cathode}})^2}{4eU_0} . \quad (2)$$

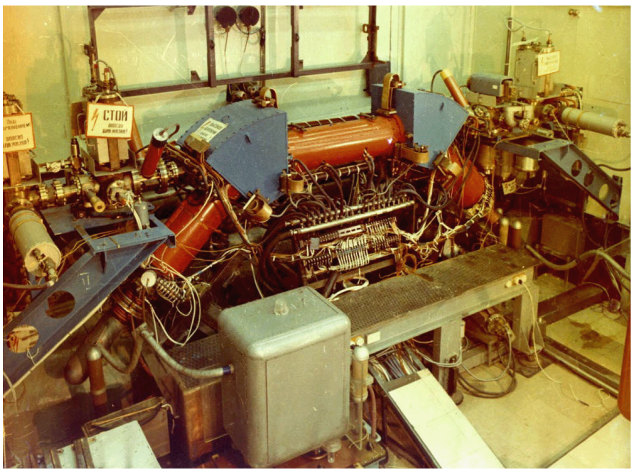

Figure 2. World's first electron cooling system in the NAP-M storage ring, 1974.

Of course, for a cathode temperature $kT_{\text{cathode}} = 0.1$ eV and acceleration to an energy of 35 keV, the thermal spread became fantastically small and corresponded to a temperature of approximately 1 K. This situation was very different from the model of a ball in all directions of velocities, which was used by G.I. Budker [1]. In a magnetized electron beam, the cooled ions actually interact not with a cloud of free electrons but with small Larmor circles slowly moving along the magnetic field [6]. This sharply increases the heat exchange between hot ions and electrons. In intense electron beams, the electron temperature also depends on their density (see formula (3) below).

As a result, ultrafast electron cooling of a 65-MeV proton beam was achieved with a cooling time of less than 60 ms. The beam diameter was reduced from several cm to 0.2 mm, and the electron energy spread from 2×10^{-3} lowered to 1.2×10^{-6}.

5. Development of diagnostics of a cooled beam

Several types of special devices had to be developed to analyze compressed proton beams. The most useful one was an ionization profilometer involving a thin magnesium vapor jet scanning the cross section of the proton beam. Such a profilometer easily determined the profile of the proton beam if its diameter was much larger than the thickness of the magnesium vapor jet, about 1 mm. The main thing was that it was possible to measure the density of the proton beam in the dynamics as the amplitude of proton oscillations decreased and they fit into the magnesium vapor jet. As this took place, the ionization signal increased [12].

For a higher compressed beam, a device was developed involving beam scanning with a five-micron quartz thread. To make such a thin thread, use was made of a method described in an old book on experimental physics. The end of a quartz column was melted in the flame of a glass-blowing burner and shot with a homemade crossbow into a thick duralumin tube. During the flight, the flowing quartz formed a thin thread. The duralumin tube, pasted inside with black velvet, was divided along its generatrices into two halves, and the quartz thread glistening on the velvet was removed. A duralumin frame attached to a steel string was used for scanning. The thread was attached to the free sides of the frame. In the neutral position, the thread was at the center of the vacuum chamber, but when two electromagnets located on opposite sides of the vacuum chamber were turned on, it could be held by one of them in one of the two extreme positions. When the magnet holding the frame was turned off, the thread crossed the proton beam and stuck to the second (turned on) magnet. The signal arising from its passage through the beam was recorded by scintillation sensors based on protons scattered by the thread. During a standard string flight, about 10% of the proton beam was lost, which allowed the proton beam profile to be measured repeatedly with gradually decreasing intensity [12].

A Schottky pickup was used to measure the energy spread. At that time, Russia did not have sensitive spectrum analyzers, and we had to make a supersensitive detector with a double heterodyne. The output signal was fed to the ADC and recorded in the computer memory. It was necessary to understand the fast Fourier transform procedure and write a program for our computer [12]. Our system did not work very quickly, but it allowed us to process signals by accumulating a hundred measurements to obtain a sufficiently smooth

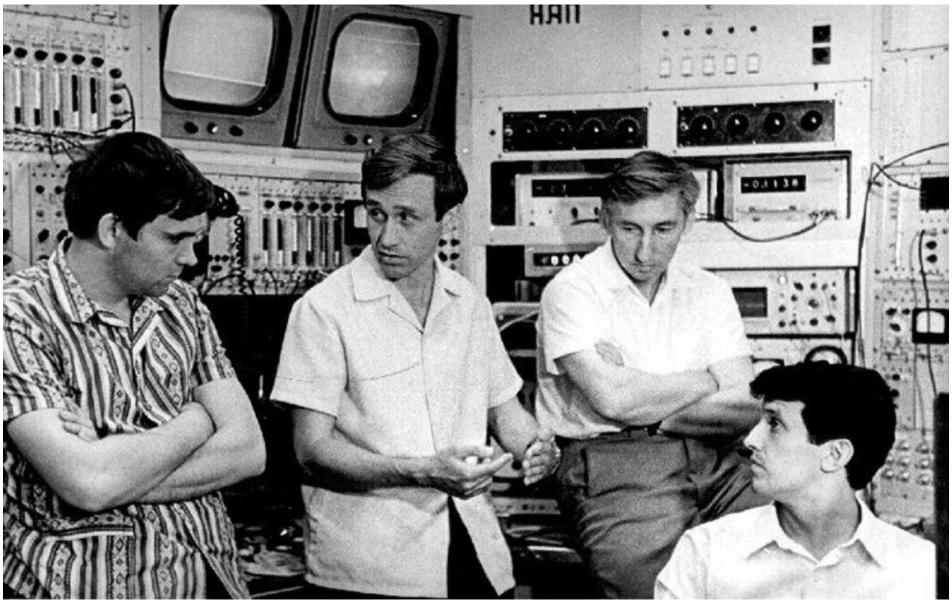

Figure 3. Small headquarters for studying electron cooling that is too fast. From left to right: postgraduate student V.V. Parkhomchuk, Academician (since 1970) A.N. Skrinsky, PhD in Physics and Mathematics I.N. Meshkov, head of the laboratory and PhD in Physics and Mathematics N.S. Dikanskii.

Figure 4. Academician (since 2016) V.V. Parkhomchuk, Academician (since 1970) A.N. Skrinsky, Academician (since 2019) I.N. Meshkov, Academician (since 2011) N.S. Dikanskii.

Schottky signal of the cooled beam. We saw in the spectrum that, after cooling, the spatial charge significantly modified the Schottky spectrum, and the signal was two longitudinal waves running along and against the proton motion [13, 15, 16]. The Schottky spectrum turned into two peaks around the proton revolution frequency.

Further research revealed the possibility of cooling until a proton beam ordered in the longitudinal direction appeared. Later, this formation of crystalline ion beams came under study at many foreign synchrotron storage rings equipped with ECSs ('electron coolers'). However, it was not possible to obtain a reliable ordered proton beam for a long time, until in 2007 a Japanese-Russian team (Kyoto University–JINR) demonstrated an ordered structure no worse than an ionic one [17].

The electron cooling developed at the INP came to be known as the 'magnetized Russian.'

6. Setup for measuring friction force in single-flight mode

The results were interesting, and it was decided to build a setup with a strong magnetic field for a detailed study of the friction force of a high-density electron beam. The setup was called MOSOL (model of a solenoid) [14]. In this setup, protons moved in an intense electron beam, and the effects of the space charge of the electron beam were suppressed by a strong magnetic field. The results obtained with this setup laid the foundation for the development of new ECSs at the INP.

The MOSOL setup had an electrostatic accelerator of negative hydrogen ions with an energy of about 1 MeV, a charge-exchange target on magnesium vapor installed in front of a three-meter solenoid with an electron beam, and a precision spectrometer at its output that ensured accurate measurement of the ion energy.

The facility was designed for a detailed study of the friction force and the influence of various factors on it: deviations in velocity from the average electron velocity, electron beam density, and the role of the values and sign of the ion charge and the magnitude of the magnetic field. And most of these tasks were successfully completed.

To eliminate problems with magnetic field nonuniformity, the studies were conducted at low electron energies, i.e., at low electron and ion velocities. Particular emphasis was placed on the correction of magnetic field distortions. This had the effect that the transverse electron velocities associated with the transverse components of the magnetic field turned out to be much lower than the effective electron velocities, which coincided with good accuracy with the longitudinal spread of their velocities in the electron beam.

Experimental measurements of the longitudinal electron temperature T_{long} showed that it was satisfactorily described by formula (2.8) in the preprint Ref. [14, p. 9]:

$$kT_{\text{long}} \approx \frac{(kT_{\text{cathode}})^2}{4eU_0} + 2e^2 n_{\text{e}}^{1/3} \,. \qquad (3)$$

The first new effect discovered was quite impressive: the friction force of negatively charged ions was significantly greater than that of positively charged ions (Fig. 5). It was quickly realized that this was due to the kinematics of electron scattering on ions: negatively charged ions reflect electrons at low impact parameters back and forth along the magnetic field, while protons attract them, causing them to accelerate and slip past the proton without energy transfer.

The maximum friction force for protons and negative ions was experimentally found to depend linearly on the magnitude of the solenoid magnetic field (Fig. 6): having equal values at a field of 1 kG, the maximum friction force for negative ions increases with the field 2.5 times faster than for protons.

Proceeding from the results of measurements, taking into account the value of the magnetic field and the flight time of the MOSOL ECS, an empirical formula was proposed:

$$F = -\frac{2\pi n_{\text{e}} e^4 Z^2 V}{m_{\text{e}}(V^2 + V_{\text{eff}}^2)^{3/2}} \ln \frac{\rho_{\max} + \rho_{\text{L}} + \rho_{\min}}{\rho_{\text{L}} + \rho_{\min}} \,, \qquad (4)$$

where V is the ion velocity, Z is its charge, n_{e} is the electron beam density, m_{e} is the electron mass, V_{eff} is the spread of electron velocities associated with the longitudinal and transverse motion of electrons in the magnetic field of the solenoid and the electric field of the electron beam, $\rho_{\max}$ is the greatest impact parameter, ρ_{L} is the Larmor rotation radius of electrons in the solenoid field, and $\rho_{\min} = Ze^2/V^2$ is the smallest impact parameter.

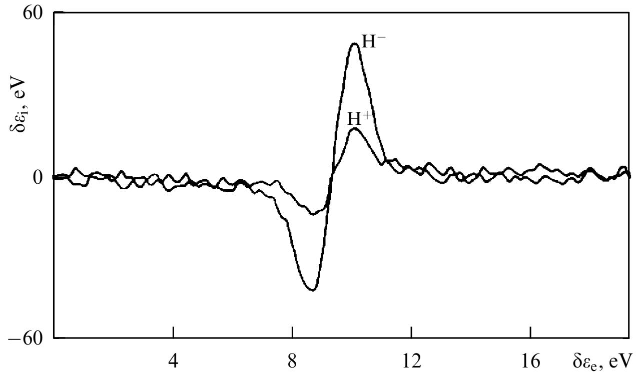

Figure 5. Dependence of H^- and H^+ ion energies on electron energy, $B = 4$ kG; electron beam current is 3 mA.

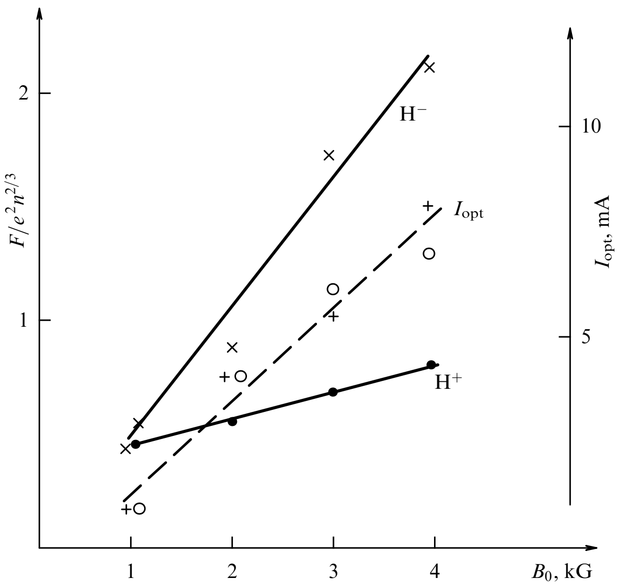

Figure 6. Effect of magnetic field on magnitude of maximum friction force for $H^-(\times)$ ions and $H^+(\bullet)$ protons; I_{opt} is optimal value of electron current (mA) at highest cooling rate for $H^-(+)$ and $H^+(\circ)$ ions.

As we have seen, negative ions cool significantly faster, and the cooling time in such an electron beam is roughly 7 μs.

It is pertinent to note that the temperature of a strongly magnetized electron beam is so low that the plasma theory, which is the basis of the theory of electron cooling, cannot be used to describe so cool an electron beam. Therefore, constructing an accurate theory of electron cooling for ion velocities $V \leqslant [e^2 n_{\text{e}}^{1/3}/m_{\text{e}}]^{1/2}$ is a major problem that still remains to be solved.

The MOSOL facility and experiments with it are described in greater detail in the preprint Ref. [15].

7. We will help abroad

Soon after the first successful experiments on NAP-M, the results of which were presented at the All-Union Accelerator Conferences of 1974–1976 with participation of foreign colleagues, we began to travel to physics laboratories in Europe and the USA: we were invited to give reports on the electron cooling method and, most importantly, the experimental results achieved. I.N. Meshkov ‘got’ to conduct four such seminars in Switzerland, in March 1977 at CERN, and

Figure 7. Commissioning of ECS for SIS-18, 1998. GSI Laboratory, Darmstadt, Germany. V.N. Kazakov, S.N. Bocharov, B.M. Smirnov, V.V. Parkhomchuk, P. Spadtke, M. Steck, B.H. Wolf, B. Franzke, N. Angert.

three in Germany, on September 24–25, 1987 at GSI[2] and MPIC,[3] and on November 1, 1989 at the Forschungszentrum Juelich GmbH, Juelich Research Center (limited liability company).

The effect of these seminars was impressive. In the laboratories listed above and many other ones in Europe, Japan, and the USA they began to build Electron Coolers (i.e., ECSs). As I.N. Meshkov would recount, upon returning home after his second trip (1987), in the International Department of the USSR Academy of Sciences in Moscow, a young lady employee who accepted his report on the trip asked: "Did you go to CERN for an internship?" — to which he immediately replied: "Quite the reverse, to make an internship for them!"

From 1979 to 1993, 11 ECSs were constructed and launched.

After 1991, funding for science in the Russian Federation decreased sharply, and earning money from foreign contracts became a necessity to continue research.

The first experience of such a contract was gained by the Physicotechnology Center — a branch of the INP (FTC INP) — organized by A.N. Skrinsky and I.N. Meshkov in Lipetsk. Apart from a large program for the implementation of accelerator technology in metallurgy and mechanical engineering, the FTC carried out basic research using accelerators. In particular, two joint experiments were performed with the E.K. Fedorov Institute of Applied Geophysics to study ionospheric plasma using electron beam injection from a gun launched on a geodetic rocket. In parallel, possessing the technology for designing and manufacturing electron-beam devices, the FTC fulfilled a contract with CERN, supplying an electron gun and an electron collector for the electron cooling system of the Low Energy Antiproton Ring (LEAR) ion synchrotron storage ring. With these devices, the LEAR electron cooler worked as well as our EPOKHA ECS. It was not long before the first physical experiment was conducted at LEAR to measure the lifetime of iron ions [18].

[2] Gesellschaft für Schwere Ionen forschung (Darmstadt), Society for Heavy Ion Research.

[3] Max-Planck-Institut für Kernphysik (Heidelberg), Max Planck Institute for Nuclear Physics.

In the difficult year of 1993, we were forced to close the FTC INP, which that year graduated two PhDs in technical sciences and two PhDs in physical and mathematical sciences, one doctor of physical and mathematical sciences, and one corresponding member of the Russian Academy of Sciences.

One of the first contracts involved making an ECS for the SIS-18 synchrotron at GSI [19].

Electron cooling began to develop actively at GSI immediately after its successful tests at the INP. German physicist Markus Steck (Fig. 7, at the center, above the letter G) visited Novosibirsk in the summer of 1987 to study in detail the experience gained at the INP. Upon his return to GSI, he supervised the development of an electron cooling system in the ESR.[4] The Center was actively pursuing research with accelerated heavy ions. When the intensity of the ion beams became insufficient, it was decided to install into the main SIS-18 accelerator an ECS ordered from the INP. For us, storing heavy ions was new. The task called for ultra-high vacuum and a new level of vacuum hygiene for us, but it was very interesting. And all our employees engaged in this work with enthusiasm. The setup required using a large number of Durite hoses to cool the solenoid sections. We picked the cleanest Durite hose and made special clamps to seal them. And when we brought the ECS to GSI, their workers cut everything off with a knife and installed a smooth radiation-resistant German hose with German clamps on the ends. This cooler still successfully stores heavy ion beams [19].

During the ECS assembly, Chinese students assigned to GSI were actively photographing all the parts. Markus Steck joked: "Look, Vasilii, they'll photograph everything and make a cooler for themselves." To which the answer came: "Now we know how to make a cooler even better."

In 2000, a large delegation from China headed by director of the IMP[5] came to the INP to work out an agreement on the INP's participation in the development of heavy ion research at the IMP. The agreement included not only two coolers for the CSRm and CSRe storage rings (Fig. 8) [20], but also a

[4] Experimental Storage Ring.

[5] Institute of Modern Physics in Lanzhou.

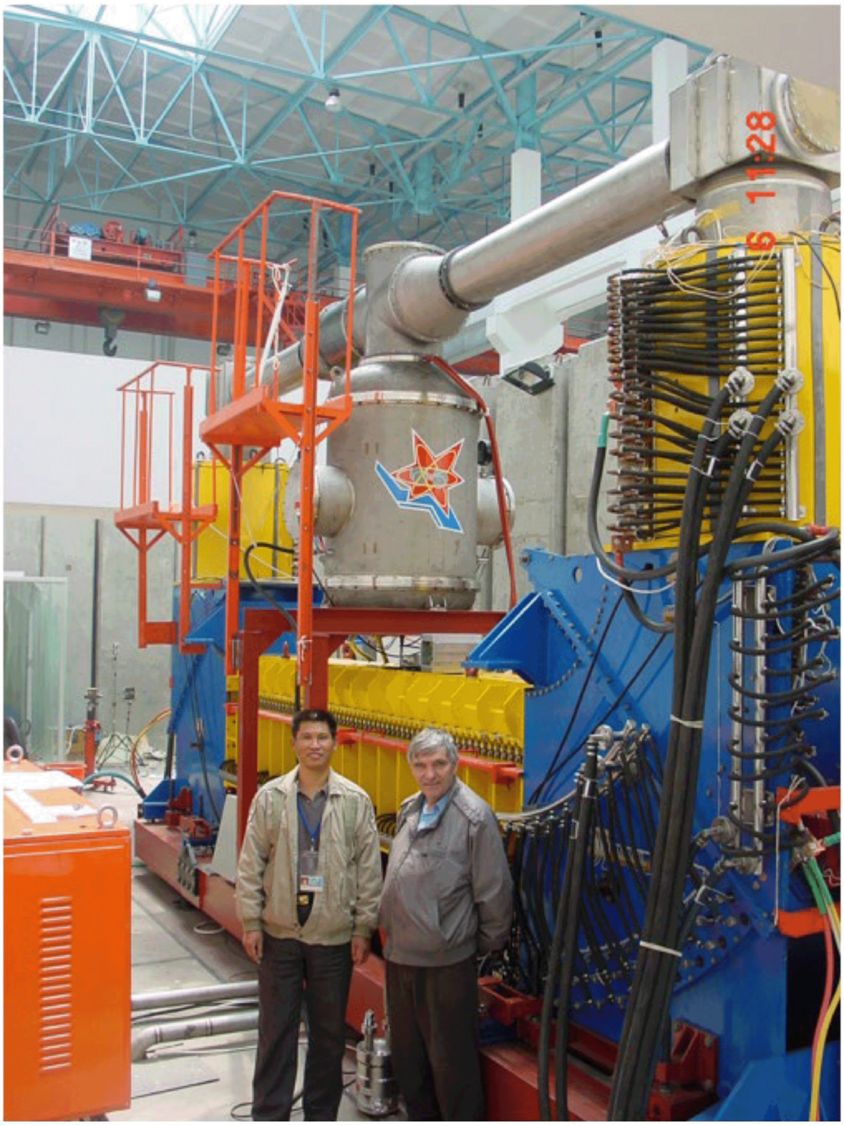

Figure 8. Director of Institute of Modern Physics Wenlong Zhan and V.V. Parkhomchuk in front of 300-keV ECS facility for CSRe storage ring, Lanzhou, China, 2000.

source of polarized hydrogen atoms. In the new ECS, the solenoids were made from coils adjustable in angles, and the electron gun could produce an electron beam with a density reduced on its axis to suppress recombination with the stored ion beam.

In such a gun (Fig. 10), it is possible to form a practically tubular electron beam to reduce the recombination of electrons with stored ions. In addition, four independent sectors of the control electrode allowed the electron beam to be modulated independently. In this case, it is possible to see how the selected part of the beam moves along the three remaining parts. This allowed observations of electron beam rotation under the influence of its space charge. The stored ions of the residual gas also influenced the beam movement by compensating for the space charge. Such an electron gun first appeared at the ECS for the COSY synchrotron (see below).

The interaction between CERN and the INP began with the work of the FTC on the production of the electron gun and collector for LEAR (Figs 11, 12). Having studied the experience of the INP ECS in Germany and China, CERN decided to order a new electron cooling system to upgrade the LEAR antiproton ring to the LEIR ion storage ring. They were especially attracted by the ultra-high vacuum in our ECS due to electrostatic bends in the toroidal part of the magnetic

Figure 9. System for adjusting position of magnetic coils to achieve magnetic field rectilinearity at a level of better than 10^{-5}.

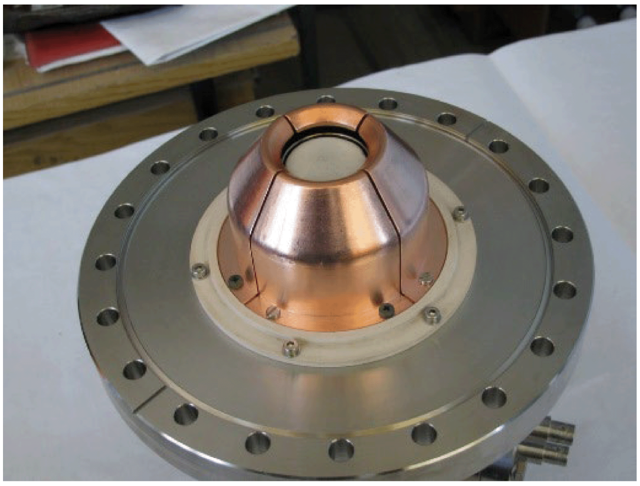

Figure 10. Electron gun with four independent sectors for modulating local intensity of COSY electron beam.

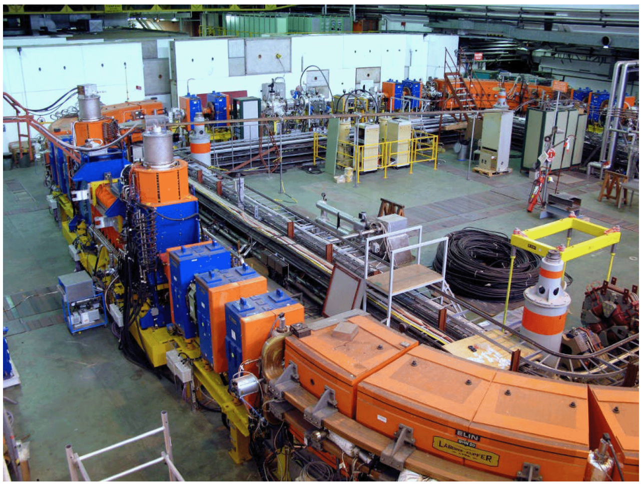

Figure 12. ECS in the LEIR ring (Low Energy Ion Ring), 2005.

system. These plates made it possible to capture into a collector the electrons scattered from it after their reflection from the gun to make the relative loss during recovery less than 10^{-6} in lieu of 2×10^{-3} with a corresponding improvement in vacuum due to desorption suppression. Since 2005, LEIR has been successfully providing high-quality ion beams [21] for the LHC.

The next major work stage was the making of a high-voltage cooler for the COSY synchrotron at the Research Center in the city of Juelich (FRG). The main problem of this task was connected with the specified electron energy of the COSY ECS of up to 1.5 MeV (Fig. 13, 14).

The cooling section was designed in a traditional style, but, due to the high voltage, the electron gun and collector were placed on a high-voltage column in a sealed vessel filled with SF_6 gas. The electron beam was transported to the cooling section and returned to the collector by a solenoid magnetic system with transverse magnetic and electrostatic

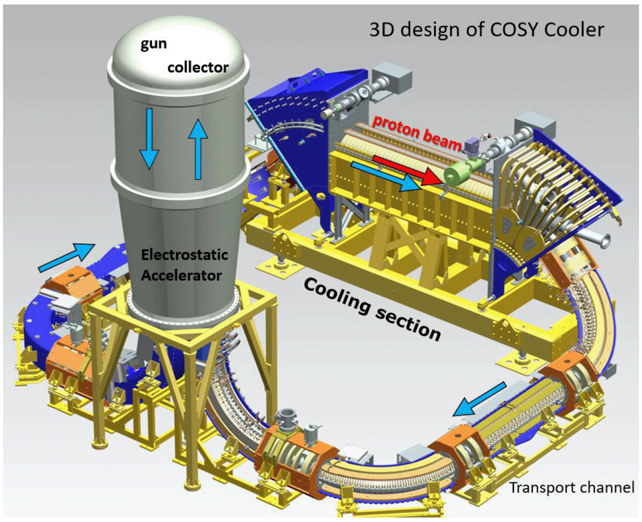

Figure 13. ECS for COSY (COoler SYnchrotron) synchrotron, 2015 [22].

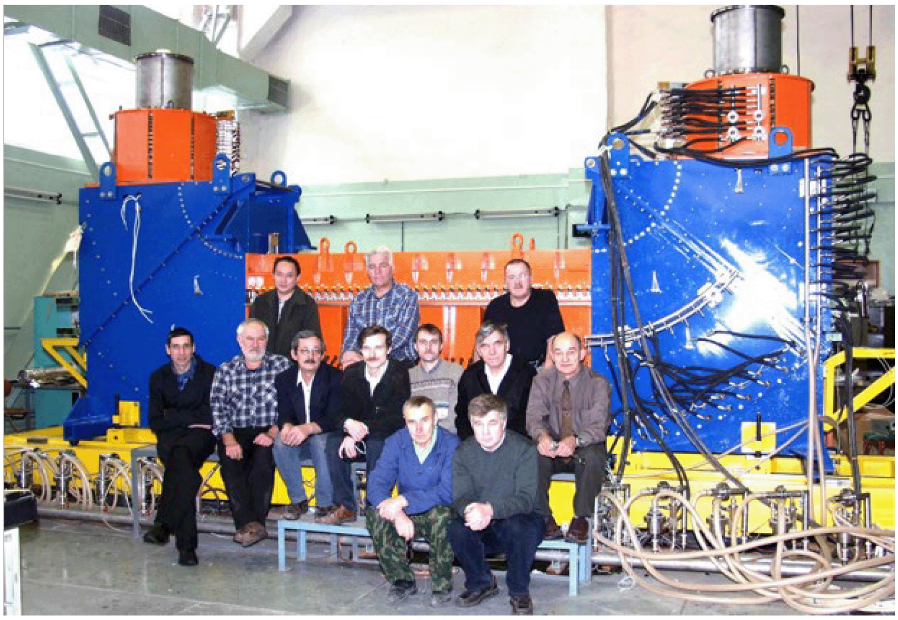

Figure 11. INP team before sending to CERN the ECS for LEIR, 2004. Bottom row: N.A. Ardzhanov, A.D. Goncharov; second row: A.N. Lomakin, V.M. Panasyuk, B.A. Scarbo, V.B. Reva, A.V. Bublei, V.V. Parkhomchuk, N.P. Zapyatkin; third row: V.A. Vostrikov, V.M. El'tsov, G.N. Ezhov.

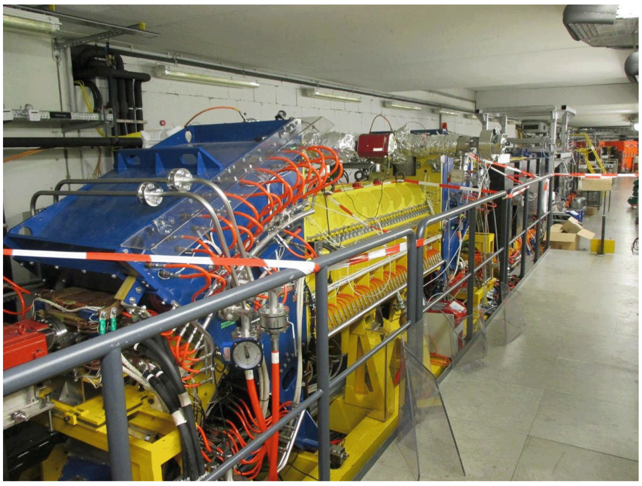

Figure 14. Cooling section in COSY synchrotron ring.

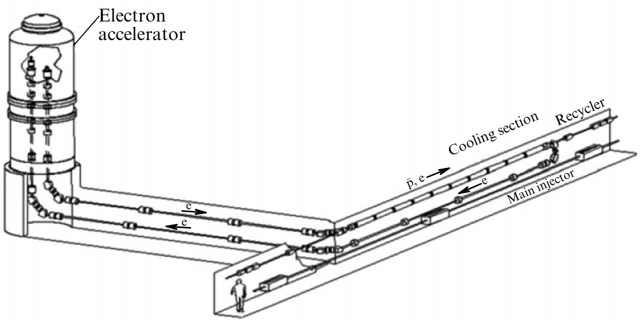

Figure 15. Fermilab ECS diagram [23].

field correctors [22]. Since 2015, the COSY ECS has been successfully operating in various experiments, including simulation of FAIR project nodes.

8. Landing group from Novosibirsk

The success of the COSY ECS was preceded by the history of the first high-voltage ECS at the Recycler synchrotron, the antiproton storage ring of the Tevatron accelerator complex at Fermilab, USA. When the opportunity to freely travel abroad arose in the late 1980s, many Soviet scientists took advantage of it. One of these opportunities led to the formation at Fermilab of a group of young accelerator physicists from the Budker Institute of Nuclear Physics, Novosibirsk. The leaders of the group, S.S. Nagaitsev and V.A. Lebedev, actually defined the tasks of the group's work and carried them out: the development of an ECS for the storage of antiprotons and the formation of their bunches subsequently injected into the collider.

Commissioning the ECS in 2006, approximately 5 years after the start of the second run (Run II), allowed the antiproton storage rate to be improved and the average luminosity of the collider to be more than doubled.

The Fermilab ECS had a maximum electron energy of 4.2 MeV, which made it possible to cool antiprotons with an energy of 8 GeV (Fig. 15). These electron and antiproton energies still exceed the energies of all previously existing and currently operating ECSs by more than a factor of two. The experience of the Fermilab ECS

Figure 16. NICA Booster ECS installed in straight section of the synchrotron.

is still used today by groups at the Budker Institute of Nuclear Physics and JINR.

9. Electron cooling system of NICA accelerator complex

In 2006, the Joint Institute for Nuclear Research (JINR, Dubna) began discussing a project for an ion collider for experimental research in the field of superrelativistic nuclear physics. Two years later, presented at the EPAC08 conference in Genoa was the project for the Nuclotron-based Ion Collider fAcility (NICA) accelerator complex at JINR [24]. The NICA complex included three synchrotrons: Booster, Nuclotron, and the two-ring Collider. [6] And a start was made on project development and the manufacture of equipment.

To achieve the design parameters, the accelerator complex is equipped with electron and stochastic cooling systems. In particular, employed are two ECSs: a low-voltage system for electron energies up to 50 keV in the Booster [24] and a high-voltage system up to 2.5 MeV in the Collider [25, 26].

The low-voltage ECS (Fig. 16) was installed in the Booster ring and put into operation in 2018. Several adjustment sessions of the NICA Booster were carried out using the ECS, and cooling of the $^{56}Fe^{14+}$ and $^{124}Xe^{28+}$ ion beams was achieved (Figs 17, 18).

Using formula (3) and assuming that the electron motion is determined primarily by the drift rotation with electron beam velocity V_l in the accompanying magnetic field B,

$$V_l = c\,\frac{E_{\mathrm{r}}}{B} = c\,\frac{2\pi e n_{\mathrm{e}} a_{\mathrm{e}}}{B}\,, \tag{5}$$

where E_{r} is the radial field of the beam space charge and a_{e} is the radius of the electron beam cross section, a minimum cooling time of 70 ms can be obtained for a magnetic field of 750 G. Naturally, by increasing the longitudinal field, we can increase the optimal current and decrease the cooling time. Of course, this increases the power spent on feeding the ECS solenoid.

Direct use of electron cooling in colliders calls for the making of high-voltage systems of approximately the same type as for the COSY synchrotron [22]. The high-voltage ECS of the NICA Collider [25, 26] is designed to service both rings and is currently at the stage of beginning installation at the Collider and completing the manufacture of its most intricate elements. The system will cool the beams both during storage

[6] The names 'Booster,' 'Nuclotron,' and 'Collider' are written with a capital letter, since they are proper names.

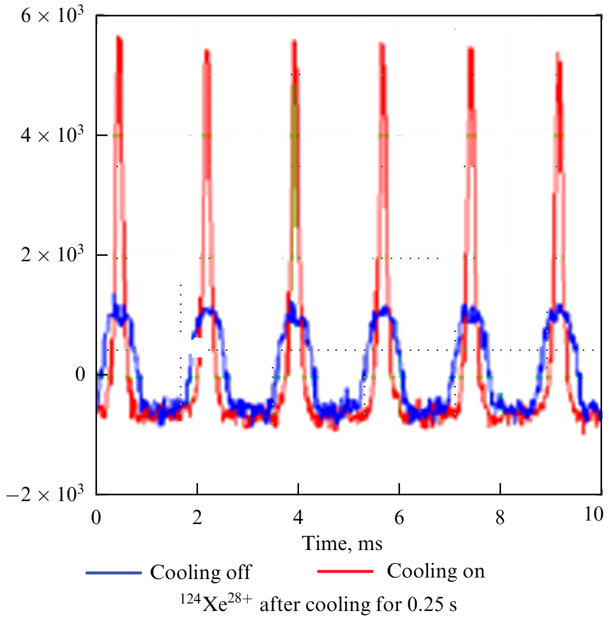

Figure 17. Bunched $^{124}Xe^{28+}$ ion beam in NICA Booster measured with FCT[7] prior to and after cooling for 250 ms.

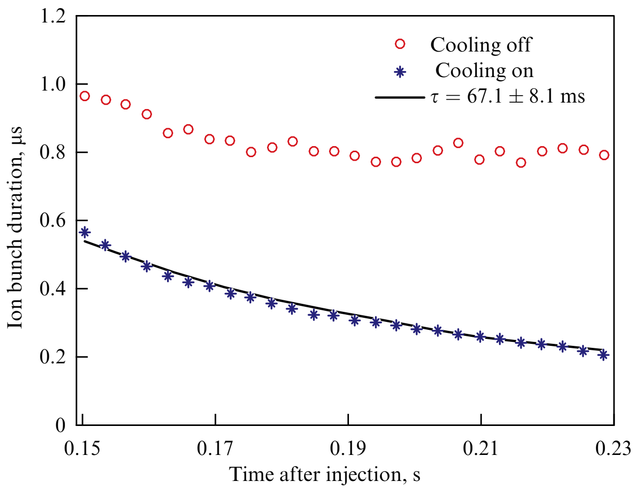

Figure 18. Evolution of ion bunch duration, also measured with FCT with and without EC; cooling time of less than 70 ms was obtained.

and directly during experiments. Since it is necessary to simultaneously cool two ion beams moving towards each other, the system contains two cooling sections and consists of two practically independent high-voltage ECSs. Each them, by analogy with the cooler of the COSY synchrotron, has its own tank with a high-voltage system, transport channels and a cooling section. Almost all subsystems of the ECS, including all magnet power supplies, are also independent.

Early in the development, an option with one electron beam was considered: when passing through the cooling section of the first ring, it cools its ion beam, and then, after turning by 180°, enters the cooling section of the second ring to cool the second beam. However, this approach has serious, and not only technical, difficulties: there is still no certainty that two ECSs connected by a common electron beam would not introduce feedback of the ion beams.

[7] Fast Current Transformer (FCT).

Figure 19. Collider's ECS has two cooling sections with electron beams moving in straight sections towards each other to cool ion beams in NICA collider in upper and lower rings.

Therefore, it was decided to organize two independent electron beams.

The cooling sections of the two ECSs are arranged one above the other and are approximately 6 m long. Many technical solutions for this ECS were borrowed from the design of the COSY high-voltage cooler described above, but some of the solutions invited serious modifications arising from the specific features of this system. In particular, the high-voltage system and the cascade transformer feeding it were significantly redesigned, since simple scaling of the COSY high-voltage system to a voltage of 2.5 MV did not allow obtaining the required parameters. In addition, the distance between the counter-propagating ion beams in the cooling sections is specified by the design of the collider itself and is only 320 mm, which called for a significant change in the design of the cooling section and the abandonment of the solution tested in the previously developed ECSs INP [29].

10. Conclusions

Electron cooling is widely used in synchrotron storage rings of proton and ion beams to significantly improve their parameters. More than two dozen electron cooling systems have been built in the world over the past 50 years. During this time, many specialists — talented engineers and physicists — have grown up at the G.I. Budker INP and a great deal of experience has been gained in the development and application of ECSs.

The authors express their appreciation to all participants in this remarkable process.

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