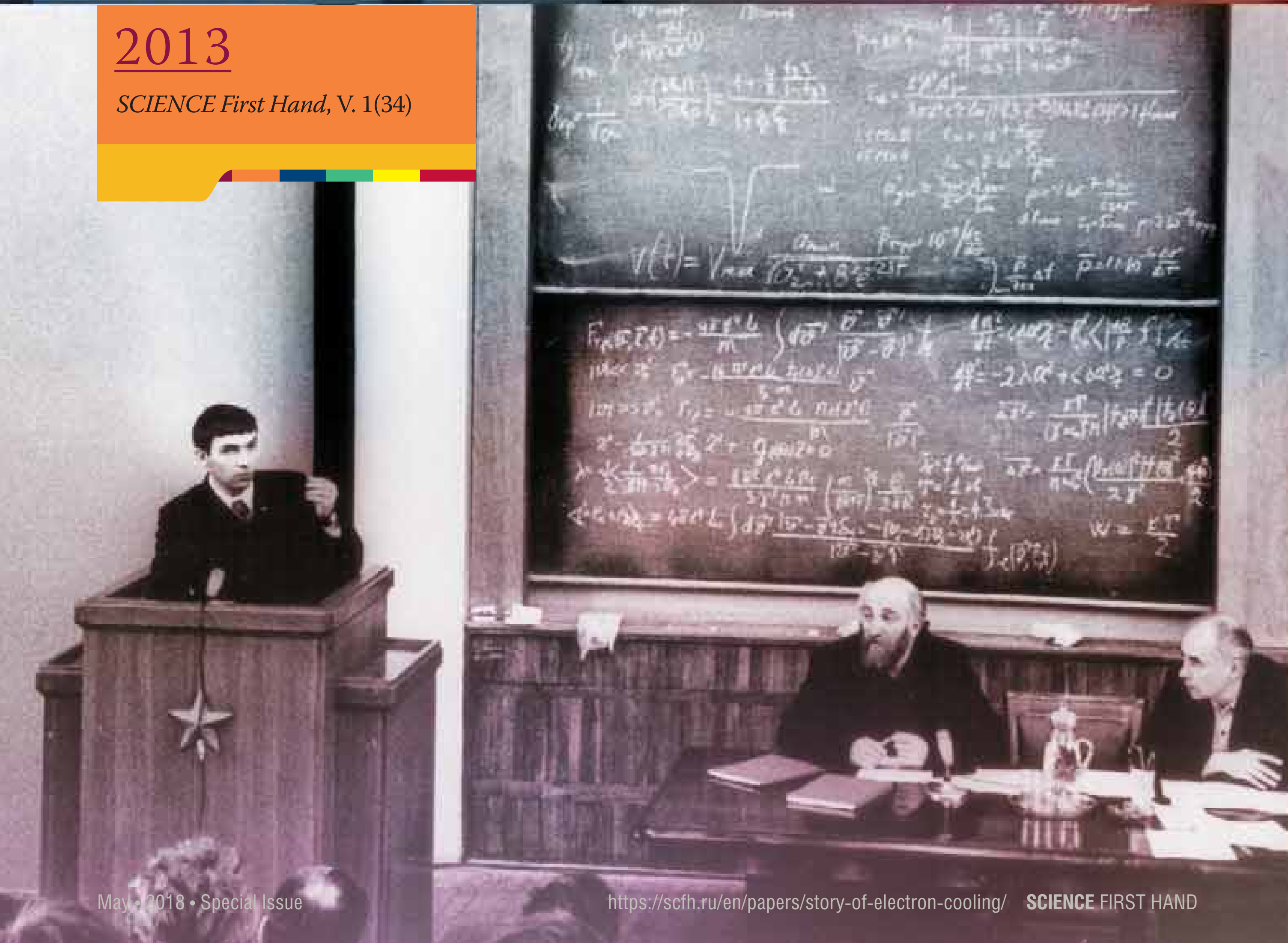
V.V. PARKHOMCHUK

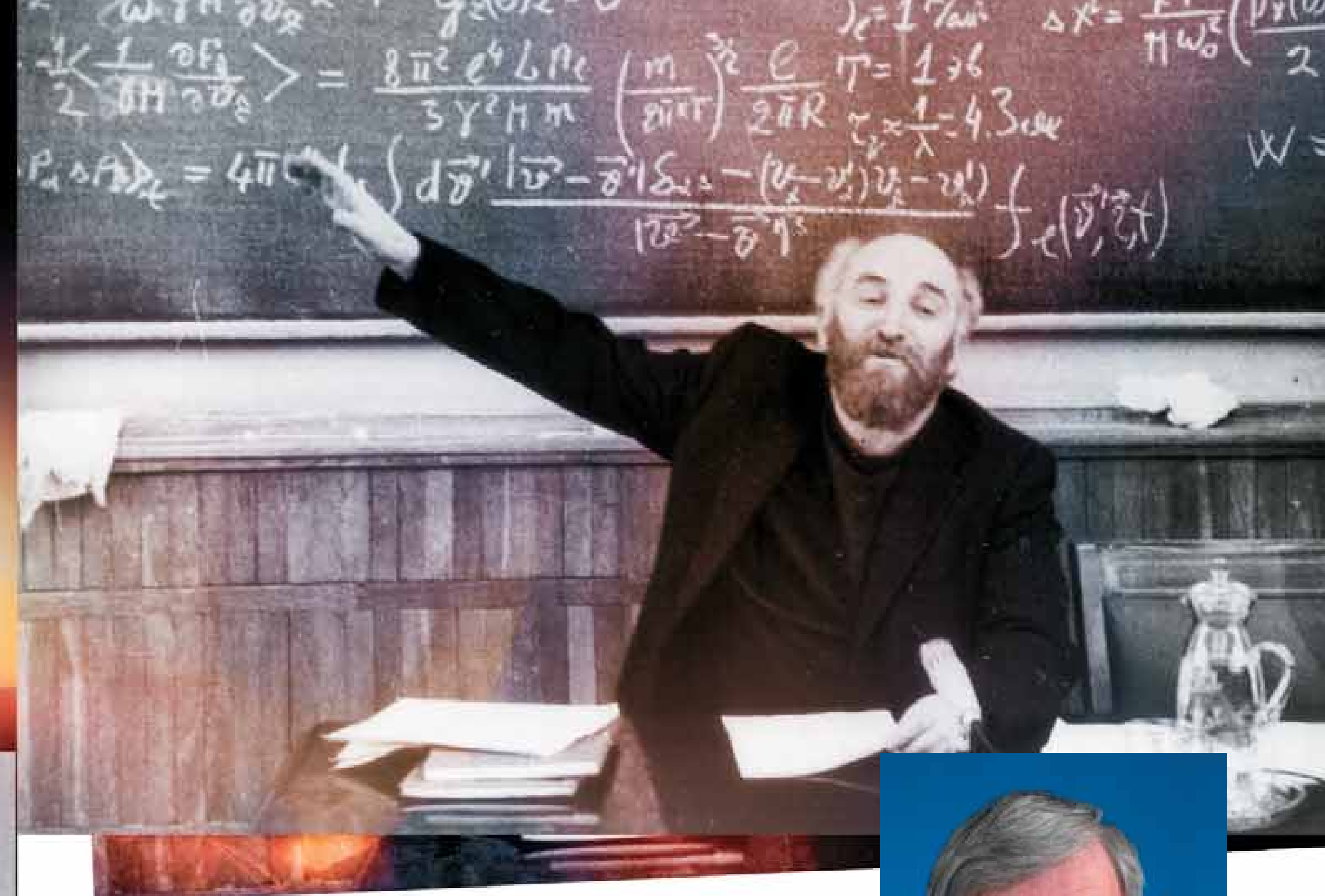
# THE STORY OF ELECTRON COOLING

*The method of electron cooling used in accelerators for ion beam focusing was proposed by G.I. Budker in 1966. However, the implementation of the method and creation of an operating facility had to wait. At that time, success on this way was not as obvious as it is now. Nevertheless, owing to the enthusiasm and efforts of researchers, the first accelerator based on this method was launched in 1971 at the Institute of Nuclear Physics of the Siberian Branch of the Academy of Sciences of the USSR. We publish the memoirs of one of the founders of the electron cooling method, V. V. Parkhomchuk, Corresponding Member of the Russian Academy of Sciences, who dwells on the development and evolution of this unique method*

2013

*SCIENCE First Hand*, V. 1(34)





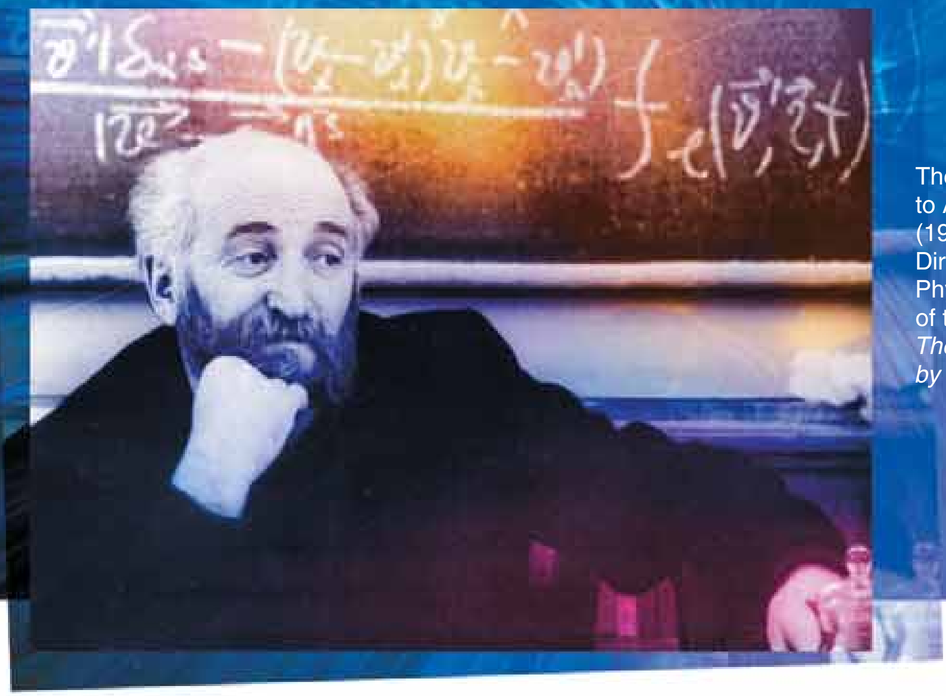
Half a century has passed since I heard about the colliding beams from G.I. Budker during his lecture at the fountain during the first summer school for academic competition winners among schoolchildren. At that time, in 1962, G.I. Budker was very enthusiastic and told us about the method of collisions of the opposing proton or electron beams, aimed at studying their structure. To simplify the story for schoolchildren, he compared particles with locomotives rushing toward each other almost with the velocity of light. After such a strong collision, all internal elements of particles (locomotives) fly apart, and it becomes possible to consider them individually.

Even at that time, the capabilities of accelerators of elementary particles were so high that the effective mass of accelerated electrons increased by a factor of

On March 25, 1975 V.V. Parkhomchuk defended the Candidate's thesis entitled *First experiments on electron cooling*. The people at the table were the members of the thesis council, G.I. Budker and L.M. Barkov. V.V. Parkhomchuk recalls: "G.I. Budker was very much excited by the implementation of his idea. He commented almost each sentence of my presentation. On the blackboard, I wrote formulas for the cooling rate and presented an experimental result: the time of cooling of the proton beam in my experiments was 1 s."
*The photograph was made by V.V. Petrov (BINP SB RAS)*

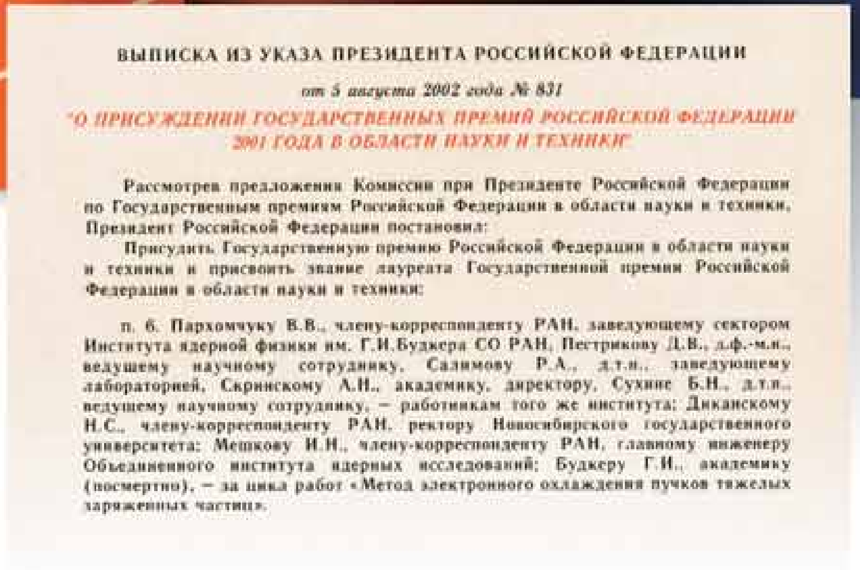
*Key words:* charged particle accelerators, colliding beams, electron cooling

Vasilii V. PARKHOMCHUK – Corresponding Member of RAS, Doctor in Physics and Mathematics, Head of Laboratory at the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences (BINP SB RAS). Winner of the State Prize of the Russian Federation. Author and co-author of over 160 academic publications



The idea of electron cooling belongs to Academician G. I. Budker (1918—1977), the founder and first Director of the Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences. *The photograph was made by V. V. Petrov (BINP SB RAS)*


Always being the first one: for participation in the All-Siberia academic competition in physics and mathematics for schoolchildren in 1962, Vasilii Parkhomchuk was awarded with the first prize in physics.
Almost forty years after that, he was among the authors of the method of electron cooling, who were awarded in 2001 with the State Prize of the Russian Federation in science and engineering for the contribution to development of science



ВЫПИСКА ИЗ УКАЗА ПРЕЗИДЕНТА РОССИЙСКОЙ ФЕДЕРАЦИИ

*от 5 августа 2002 года № 831*

"О ПРИСУЖДЕНИИ ГОСУДАРСТВЕННЫХ ПРЕМИЙ РОССИЙСКОЙ ФЕДЕРАЦИИ 2001 ГОДА В ОБЛАСТИ НАУКИ И ТЕХНИКИ"

Рассмотрев предложения Комиссии при Президенте Российской Федерации по Государственным премиям Российской Федерации в области науки и техники, Президент Российской Федерации постановил:

Присудить Государственную премию Российской Федерации в области науки и техники и присвоить звание лауреата Государственной премии Российской Федерации в области науки и техники:

п. 6. Пархомчуку В.В., члену-корреспонденту РАН, заведующему сектором Института ядерной физики им. Г.И.Будкера СО РАН, Пестрикову Д.В., д.ф.-м.н., ведущему научному сотруднику, Салимову Р.А., д.т.н., заведующему лабораторией, Скринскому А.Н., академику, директору, Сухине Б.Н., д.т.н., ведущему научному сотруднику, – работникам того же института; Диканскому Н.С., члену-корреспонденту РАН, ректору Новосибирского государственного университета; Мешкову И.Н., члену-корреспонденту РАН, главному инженеру Объединенного института ядерных исследований; Будкеру Г.И., академику (посмертно), – за цикл работ «Метод электронного охлаждения пучков тяжелых заряженных частиц».

thousands in accordance with the relativity theory, and it was clear that the collisions of rapidly moving "heavy" electrons with "light" electrons of the motionless target were much less effective than the opposing collisions of high-energy "heavy" particles.

The first prize in physics awarded to me for the participation in the All-Siberia academic competition in physics and mathematics among schoolchildren and the diploma signed by G. I. Budker and A. A. Lyapunov inspired me to choose physics as my profession. Like any boy, I thought that such experiments with "locomotives" looked funny, so I got into physics and stayed there for the rest of my life.

The physical-mathematical school, Novosibirsk State University, and Institute of Nuclear Physics finally made me a Ph.D. student of G. I. Budker. It was then and there that I started to study electron cooling. We tried to find an experimental verification of the new idea of the focusing of beams consisting of heavy particles, which was formulated by G. I. Budker. The team involved in the development of this method included many researchers who were already famous at that time: Academician G. I. Budker, Academician A. N. Skrinsky, senior researcher Ya. S. Derbenev, Head of Laboratory N. S. Dikanskii, senior researcher I. N. Meshkov, researcher D. V. Pestrikov, Head of Laboratory R. A. Salimov, and researcher B. N. Sukhina.

It was not easy to develop a viable setup, but we managed to make this idea work. These activities were later highly appreciated: in 2002, we were awarded with the State Prize of the Russian Federation.

## How can the ion beam be focused?

To observe a sufficient number of reactions during the collision of particle beams, these beams should be fairly dense. The main obstacle for beam focusing is the transverse velocity of the beam owing to the high initial temperature of the beams and, correspondingly, the high velocity of thermal motion.

It is known that electrons and positrons moving with acceleration (e. g., along a circular trajectory, as it happens in ring accelerators) emit electromagnetic radiation (the so-called synchrotron radiation), which makes them lose a large fraction of their energy, resulting in a rapid natural cooling of the electron beam and, correspondingly, in beam compression. This cooling technique could not be used for heavier particles (protons and ions) because synchrotron radiation becomes sufficiently intense only at particle motion energies of tens of teraelectron-volts, which could not be provided in the 1960s.

The essence of the cooling method proposed by G. I Budker was based on the idea that the proton beam and electron beam moving next to each other with almost identical velocities start to interact by means of electromagnetic forces. Owing to this interaction, their temperatures become equalized, i. e., the energy of thermal motion is transferred from the proton beam to the colder electron beam. As the proton mass is greater than the electron mass almost by a factor of 2000, the velocity of thermal motion of the proton beam and, correspondingly, its angular scattering are much smaller than those of the electron beam: $T=(m_e{*}V_e^2)/2=(M_pV_p^2)/2$, the velocity $V_p$ of the particle having a greater mass by a factor of $M_p/m_e$ 2000 should be smaller by a factor of 40 (in the corresponding system) at the time when the particle temperature becomes equal to the electron temperature during cooling.

1978. Pioneers in science: Academician A. N. Skrinsky in the panel control room of the antiproton accumulator discusses the newly found phenomenon of super-rapid electron cooling with young researchers V. V. Parkhomchuk, I. N. Meshkov, and N. S. Dikanskii

1998. Former pioneers are now top officers: members of the Russian Academy of Sciences V. V. Parkhomchuk, A. N. Skrinsky, I. N. Meshkov, and N. S. Dikanskii are participants of the conference on electron cooling at the Joint Institute for Nuclear Research (Dubna)

## First success

To verify the method, it was decided to construct a full-scale model of an antiproton accumulator (with the ring perimeter of 47 m) and perform experiments on electron cooling. We started to put this idea into practice in 1971.

We designed and fabricated the setup in the workshops of the institute and experimentally checked the elements of the pioneering accelerator with electron cooling. Using a special testbench, we generated an electron beam and studied its properties: density, charge, temperature, and all other factors that could affect the cooling process.

My first experiment was aimed at measuring the electrostatic potential of the electron beam by using a light sphere suspended on a long filament. This almost school-level experiment (with spreading of light bands in an electroscope) actually failed in reality. We could clearly see deflections of the sphere on the laboratory table. When the sphere was placed into vacuum, however, the friction against air, which "calmed down" the sphere motion, drastically decreased, and the sphere started to swing so intensely owing to the setup vibrations that we could hardly see the filament. Therefore, we had to invent special dampers to stabilize the filament.

After all elements of the setup were assembled, we started our attempts to obtain cooling, which were not successful for the first several months for various reasons: first, because the vacuum was not sufficiently deep; then because of problems with oscillations in our electron circuits. It was only our enthusiasm, faith to the idea, and whole-hearted desire "to make a flea wear a horseshoe," i.e., to achieve proton beam cooling, that allowed us to overcome the various problems that we faced.

Once, when the internal ion pump was accidentally switched off, we suddenly saw that the beam lifetime increased, and I immediately recalled our experiments with the measurements of the electron beam field by using a sphere suspended on a filament. It turned out that the hot ions from the pump charged the electron beam, and the high value of the electric field "kicked out" protons from the accelerator instead of cooling them. Soon after that we modified the evacuation system and were happy to see that we did obtain cooling.

It took several years to reach this result. During this period, we did not publish a single paper; if it were today, under the conditions of the current system of grants, we would be fired. At that time, however, we, Ph.D. students, reported our achievements, the academic secretary of the Institute of Nuclear Physics, S. Popov, tried to reassure us; he told us: "OK, wait a little bit; as soon as you get the cooling, you will be able to publish your results."

This was a complicated problem, in terms of both science and engineering. The fact that this problem could be solved was not as obvious at that time as it is now, several decades later. For this reason, probably, nobody in the world was so courageous as to start these activities. It was only owing to the intuition of the older generation of scientists and enthusiasm of the younger researchers of the Institute of Nuclear Physics that many problems of design of an operational setup were solved and we finally succeeded.

Thus, the Antiproton Accumulator NAP-M (M stands for model) was commissioned in 1974, and the first results on electron cooling were obtained. This important scientific achievement was highly appreciated by the Russian and foreign academic community.

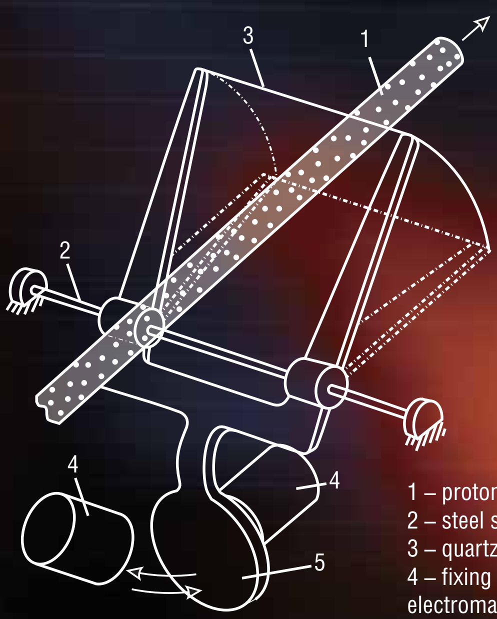
## New ideas

Two years later, in 1976, we had another important breakthrough: we found the so-called *rapid electron cooling*.

It turned out that the physics of the process is much more versatile than we thought before: electrostatically accelerated electrons have a much smaller scatter in the streamwise direction than in the transverse direction. This fact was observed experimentally in measuring the friction force (force of interaction of protons and electrons, leading to the energy loss by protons) as a function of the difference in the velocities of the electron and proton beams.

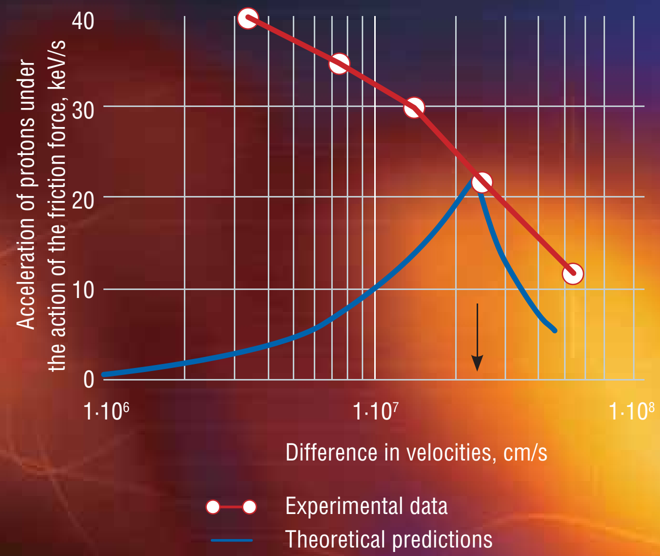
I still keep the plot of the friction force versus the difference in velocities, where I put the measured points, and they differed more and more from the predictions of our leaders. Trying to understand how this was possible, we found the reason for the "cold" character of streamwise motion.

In addition, another effect was observed: if electrons are "magnetized," i.e., freely move along the force lines of the magnetic field and rotate around them, then the proton perceives them as particles that have no transverse velocity (the effective temperature of magnetized electrons was

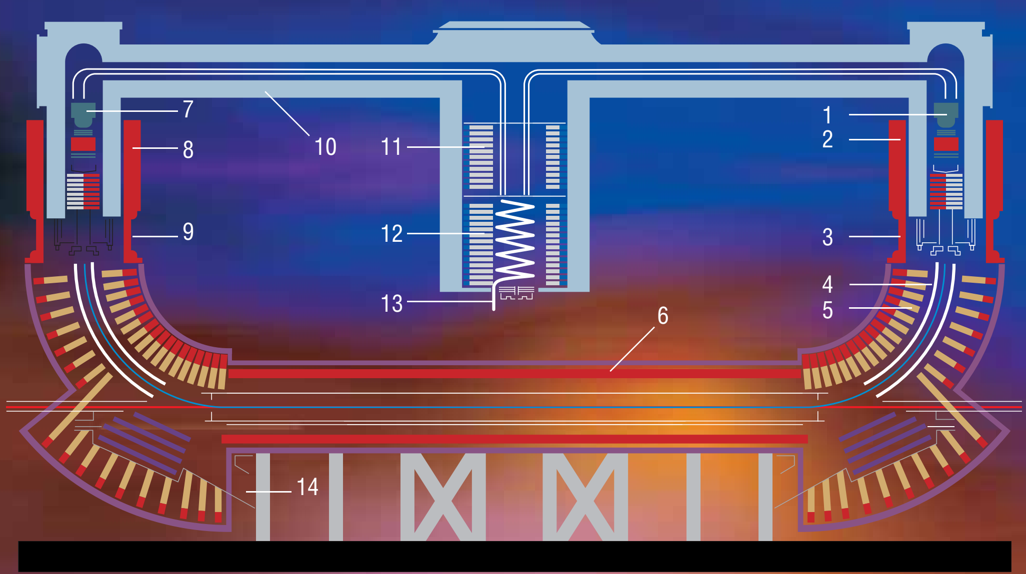



1 – proton beam;
2 – steel string;
3 – quartz filament;
4 – fixing electromagnets;
5 – armature

A simple but effective device for measuring the profile of the beam of accelerated protons. A quartz filament with a cross-sectional area of several microns crosses the beam. By measuring the intensity of particles scattered by the wire, One can perform precision measurements of the density distribution of protons over the beam cross section




In studying the interaction of proton and electron beams, it turned out that the initial theoretical assumptions about the force acting on protons do not agree with experimental results. A comparison of these data made it possible to detect and explain the phenomenon of super-rapid electron cooling



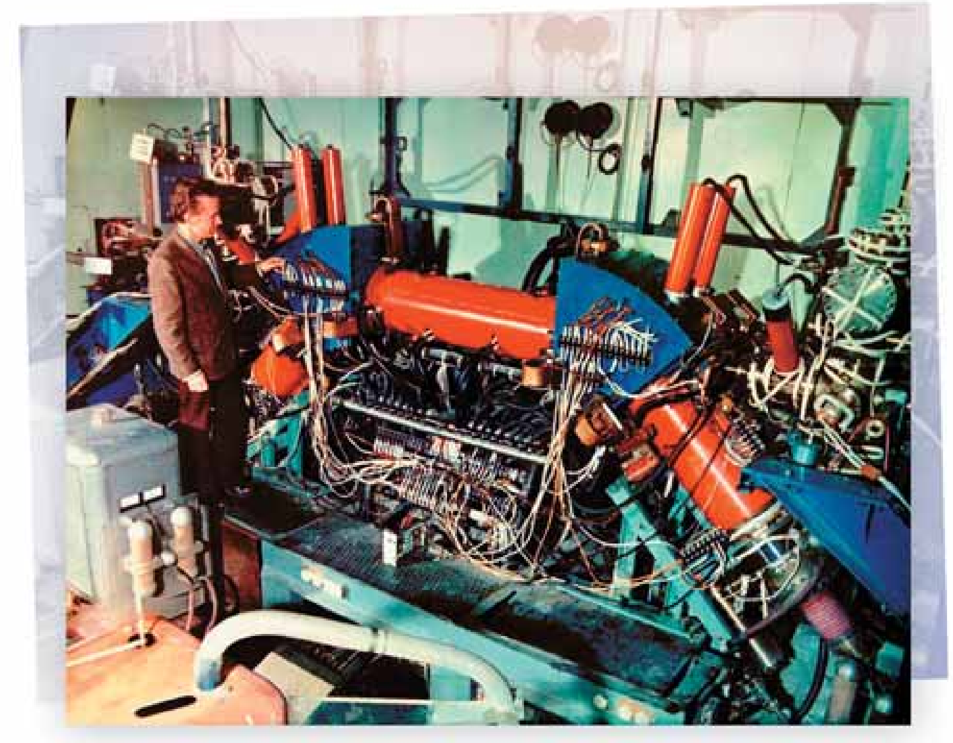

Cooling system with an energy of 350 keV:

1 – electron gun;
2 – main magnet of the gun;
3 – additional magnet of the gun;
4 – electrostatic deflectin system;
5 – toroidal magnetic deflecting system;
6 – main magnet;
7 – collector;
8 – main magnet of the collector;
9 – additional magnet of the collector;
10 – elegas(SF6) feeder;
11–12 – rectifiers;
13 – power input;
14 – vacuum pumps

The electron cooler has a fairly simple structure. The electron beam is generated by an electron gun having a specially shaped cathode. After that, the beam is accelerated and directed to the channel of the main accelerator with the help of a deflecting system. Then the electron beam is directed outward (with the help of the same deflecting system), and electrons are collected in a collector







1976. The heart of the HAP-M system is the EPOKHA setup based on the electron cooling method and one of its founders, V. I. Kudelainen

close to 1 K instead of 1000 K), and the cooling process proceeds faster by a factor of hundreds. In other words, owing to their motion in a magnetic field, the electrons are colder than they actually are. The calculations of the kinetics of the cooling by magnetized electrons, which were performed by Ya. S. Derbenev and A. N. Skrinsky, allowed us to get a better understanding of rapid cooling and deliberately update the setup in a needed manner.

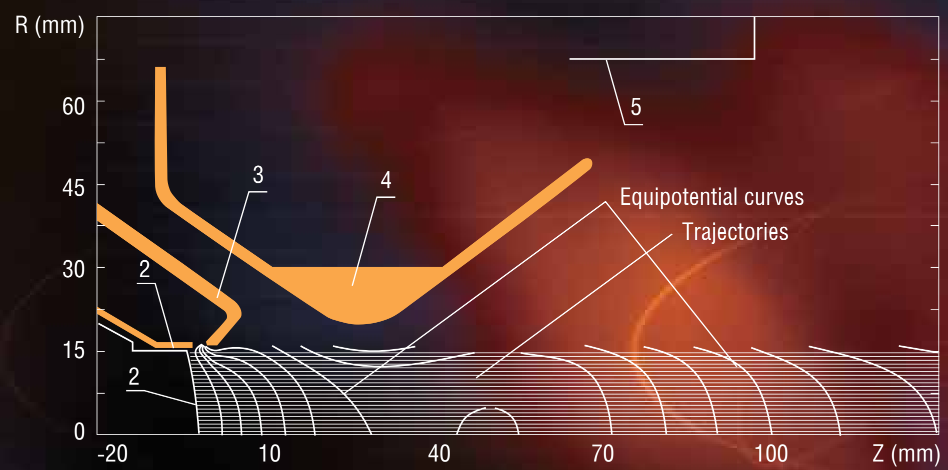
As a result, we managed to obtain deeply cooled proton beams with unique parameters: the angular divergence was the same as that provided by a high-quality laser, smaller than a fraction of a milliradian, and the size of the cooled beam at the effective temperature of transverse motion of protons of the order of 1 K was several fractions of a millimeter.

It was convenient to measure the transverse size of the beam by a thin quartz filament with a micron diameter. To create such a filament, we fabricated an arbalest that was used to shoot an arrow with a quartz stick on the spike, which was melted at the end. When the shot was made, an ultrathin filament was generated, which could be found on an absolutely black surface because of its luster. My wife's velvet evening dress was found to be the best surface for filament searching. After several months, my wife felt indignant to discover the absence of her dress, but soon I was forgiven owing to the scientific importance of the results obtained.

In ion beams with such a low temperature, we can observe a phenomenon similar to crystallization of liquids: correlations between the motion and relative positions of ions increase. Back at the time when I defended my Doctor's thesis (in 1985) and reported the possibility of observing "crystalline" beams, my opponent A. N. Lebedev noticed that it might be difficult to maintain the structure of such a beam moving in an accelerator when passing from a one-dimensional crystal to a more realistic three-dimensional crystal.

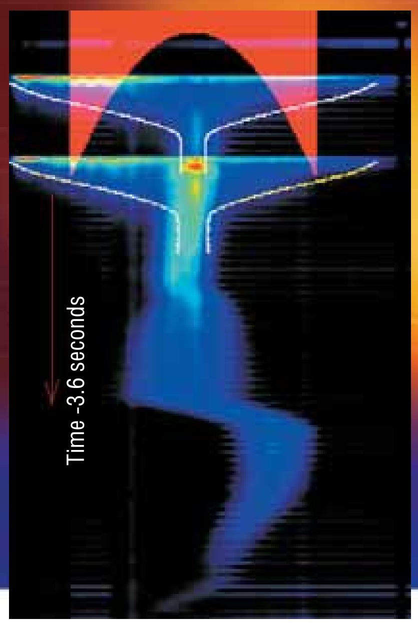
Now many foreign laboratories study such beam crystals and develop new configurations of magnetic systems for retaining the crystalline properties of deeply cooled beams. Unfortunately, the Russian participation in these activities is limited by rare visits of young researchers to take part in experiments in those research centers where our cooling systems were installed.

The method of electron cooling allows not only the focusing of proton beams; it is also applicable to the beams of heavier particles: ions. To avoid the loss of ions in recombination with electrons, the idea was to form an

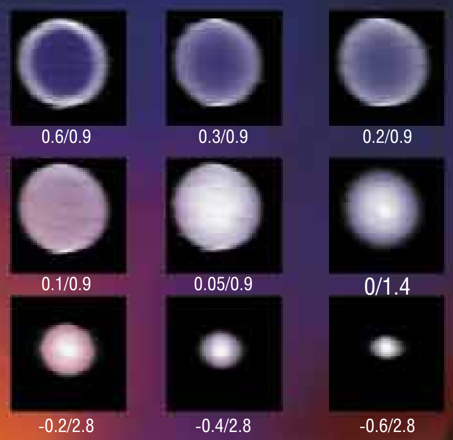



A modified electron gun can generate a hollow electron beam. Electrons emitted by the hot cathode (1) are accelerated in the electrostatic field generated by the anode (4). When voltages of certain magnitudes are applied to the screening electrode (2) and the control electrode (3), they can form beams with different profiles of electron density

Electron beam profile




The image obtained by a device for measuring the particle beam profile illustrates operation of the electron cooler mounted in the Large Hadron Collider. The vertical scale corresponds to the time interval of 3.6 seconds.
The red curve shows the profile of the electron beam whose density is much greater at the edge than in the beam center. The blue curve shows the beam of lead ions, which occupy the entire cross section of a chamber 50 mm in diameter after injection. The electron beam cools and rapidly compresses the ion beam to a diameter of 2 mm. Then there follows the next stage of injection to add ions to the beam. The beam, once again expanded, is subjected to another cycle of cooling and is compressed to a diameter of approximately 4 mm. After that, electron cooling is switched off, and the beam slightly expands




The electron beam profile can be changed by varying the voltages on the anode and control cathode.
If a negative potential is applied to the control electrode, the beam is focused; if a positive potential is applied, the beam expands until a hollow beam with an empty central part is formed

Another idea extending the capabilities of electron cooling is to divide the ring controlling the beam profile into four sectors. This idea was implemented in the novel cooler recently made for Germany

electron beam so that the electron density had the maximum value on the beam periphery, and the dense ion beam was accumulated in the central part with a small number of electrons.

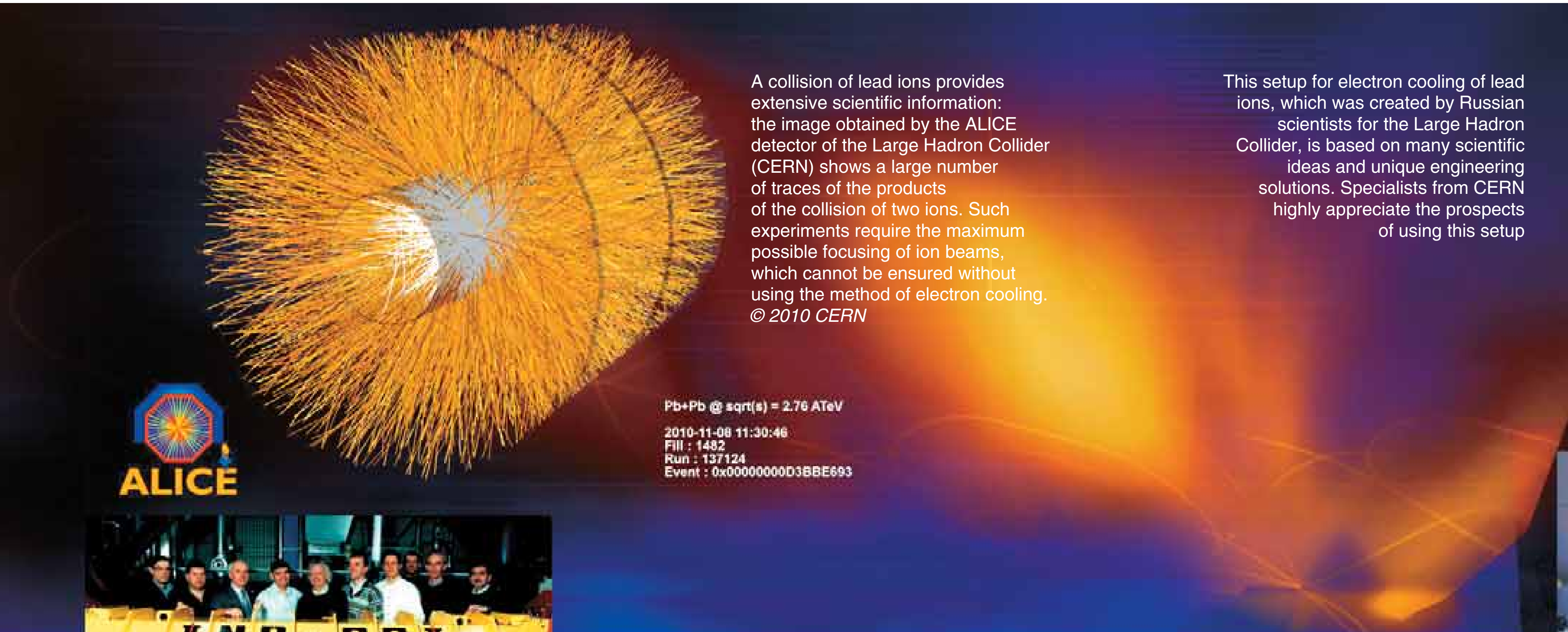
In implementing the idea of a hollow beam, we decided to create a segmented cathode whose center was heated to a smaller temperature and, correspondingly, emitted a lower number of electrons. After preliminary calculations and modeling, however, it turned out that such an electron gun was poorly controlled and inconvenient in operation.

One of our colleagues, A.N. Sharapa (unfortunately, he passed away prematurely) developed an electron gun with a special cathode shaped as a ring. In vigorous discussions about possible simplifications of this gun, the following idea was proposed: if we "tear away" the near-cathode focusing electrode (the so-called Pearson electrode) from the cathode and then apply a defocusing positive potential instead of the focusing negative potential, we can obtain a ring instead of a narrow beam.

Later on, it was this procedure that allowed us to generate beams with a nonuniform distribution of electrons.

### THE TARGET IS THE TUMOR

**Application of the electron cooling method was successful not only in physics of elementary particles. Extremely interesting results were obtained by this method in medicine, namely, in oncology. In conventional X-ray therapy, the maximum radiation level is reached when the beam enters the patient's body, but it noticeably decreases as the beam moves toward the tumor.**
**To compensate for this effect, the patient is irradiated from different sides; as a result, the tumor obtains the maximum amount of radiation, whereas health tissues are irradiated to a level below the dangerous limit, though this level is rather high as well.**
**If a high-energy ion beam is used, the situation is different. As the beam is decelerated in the patient's body, ionization is enhanced, and the maximum effect is observed in the tumor region. Owing to electron cooling, the size of the ion beam is small, and the beam can be easily focused and directed from various locations to the cancerous region. This procedure offers a possibility of concentrating high-density radiation only in the neoplasm and minimizing radiation in healthy tissues.**
**Experiments on treating patients with cancer by this method are performed at the Chinese Institute of Modern Physic (IMP, Lanzhou, China) on a large experimental ion setup with two systems of electron cooling designed and fabricated at BINP SB RAS. During the time of operation of this setup, hundreds of people have received a chance to extend their lives. The results of this treatment look very promising, and IMP launches a project of a specialized center for treating patients based on this method**




A collision of lead ions provides extensive scientific information: the image obtained by the ALICE detector of the Large Hadron Collider (CERN) shows a large number of traces of the products of the collision of two ions. Such experiments require the maximum possible focusing of ion beams, which cannot be ensured without using the method of electron cooling. *© 2010 CERN*


1996. Electron cooler in the SIS-18 synchrotron with the ring radius of 216 m at the Institute for Heavy Ion Research (Germany). This accelerator can accelerate ions up to a velocity of 90 % of the velocity of light. *The photograph* shows the team of Russian and German physicists participating in the development and fabrication of the cooler

This setup for electron cooling of lead ions, which was created by Russian scientists for the Large Hadron Collider, is based on many scientific ideas and unique engineering solutions. Specialists from CERN highly appreciate the prospects of using this setup

Electron cooling in one of the few examples of a Russian invention developed within the country to such a level that these works are still in demand. We can be proud of that: within several decades, we moved forward in scientific research and solved extremely complicated engineering problems, which allowed us to make the next step in the field of physics of elementary particles.

The Institute of Nuclear Physics developed and fabricated ion accumulators based on the electron cooling idea for Germany, China, and Switzerland. The institute was an active participant in the development of this method in Japan, Sweden, and the USA. The setup for the accumulation of ion beams in the Large Hadron Collider was also developed and fabricated at BINP SB RAS.

An important step forward is the setup of electron cooling for voltages up to 2 MV, which was recently created for a research center in Germany. Next year, it is planned to install it in the COSY synchrotron, which will substantially extend the capabilities of this accelerator.

A heavy-ion collider called NICA is under development in Russia, at the Joint Institute for Nuclear Research (Dubna); it is planned to use systems for cooling ion beams in this collider. BINP SB RAS has already designed such a cooler and is planning to start its fabrication in the near future.

The fact that Germany now has four electron cooling setups and Russia has none illustrates our eternal problem that the shoemaker's family wife goes barefoot: Still I hope that the electron cooling method will be used in our country for academic research and for applications in the near future.

Accelerator centers all over the world are interested in Russian technologies. The last (most advanced) setup of electron cooling was designed and fabricated at BINP SB RAS for the COSY research center (Julich, Germany)

*References*

*Budker G. I. Jeffektivnyj metod dlja dempfirovanija kolebanij chastic v protonnyh i antiprotonnyh kol'cah // Atomnaja jenergija. 1967. T. 22. S. 346–348.*

*Budker G. I. , Skrinskij A. N. Jelektronnoe ohlazhdenie i novye vozmozhnosti v fizike jelementarnyh chastic // UFN. 1978. № 124. S. 561–595.*

*Parhomchuk V. V., Skrinskij A. N. Jelektronnoe ohlazhdenie – 35 let razvitija // UFN. 2000. T. 170. № 5. S. 473–493.*

*Parkhomchuk V. V., Skrinsky A. N. Electron cooling: physics and prospective applications // Report on Progress in Physics, July 1991. V. 54. No. 7. P. 919–947.*

*Parkhomchuk V. V., Skrinsky A. N. Cooling methods for charged particle beams // Reviews of Accelerator Science and Technology, 2008. V. 1. P. 1–21.*