8. Conclusion

To conclude, the most important SP-based methodical and physical studies were highly appraised and awarded State Prizes. The laureates and their works are as follows:

1959 — V I Veksler (JINR), F A Vodop'yanov, D V Efremov, L P Zinov'ev (JINR), A A Kolomenskii, E G Komar, A L Mints, N A Monoszon, V A Petukhov (JINR), M S Rabinovich, S M Rubchinskii, and A M Stolov — design and construction of 10-GeV synchrophasotron.

1983 — Yu K Akimov, V A Nikitin, B A Morozov, Yu K Pilipenko, L S Zolin, S V Mukhin, M G Shafranova, V A Kopylov-Sviridov, A A Kuznetsov (JINR), A A Vorob'ev (LINP), E L Feinberg (FIAN), and V A Tsarev (FIAN) — diffraction scattering of protons at high energies.

1985 — G P Zhukov, I F Kolpakov, A N Sinaev et al. — development and mass production of the CAMAC international standard-based automation system for scientific and technical studies.

1986 — Yu V Zanevskii et al. — development and application of nuclear physical methods and instruments for molecular biology studies.

1986 — N N Govorun, V P Shirikov et al. — development and application of computer software for engineering calculations and designing complex technical systems.

1988 — A M Baldin, P N Bogolyubov, V A Matveev, R M Muradyan, and A N Tavkhelidze — discovery of a new quantum number (color) and elucidation of dynamic patterns in the quark structure of elementary particles.

1992 — V S Alfeev, Z V Borisovskaya et al. — design and creation of cost-effective superconducting magnets for high-energy accelerators.

1996 — M D Bavizhev, V I Kotov (IHEP), A I Smirnov (PINP), A M Taratin, E N Tsyganov (JINR) et al. — development of new methods for handling particle beams with the help of bent crystals.

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From synchrophasotron to Nuclotron

A D Kovalenko

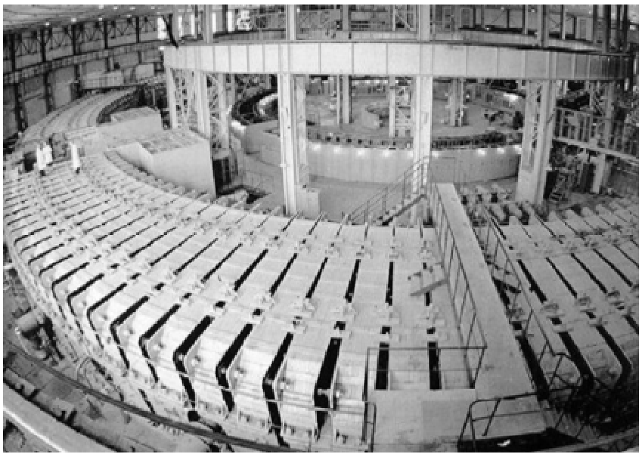
1. Introduction. The phase stability principle — the Gordian knot cut!

I have the honor of representing accelerator physicists, engineers, and technicians, in fact the entire staff of the Laboratory of High Energies (JINR) founded by V I Veksler, an outstanding scientist who made a major contribution to world science and international collaboration of scientists, at this solemn session celebrating the 100th anniversary of his birth. People of my generation, those born half a century after Vladimir Iosifovich and involved, as fate willed, in the construction of accelerators and the production and application of high-energy beams of charged particles, associate his name with the discovery of the principle of phase stability. To my mind, the atmosphere preceding this discovery is most exactly described in the memoirs of E L Feinberg. I cannot help quoting from the article entitled "Vavilov and his FIAN":

"... In the late 1930s, it was as clear as it is today that nuclear physics needed high-energy accelerators of particles.... Sergei Ivanovich (Vavilov — Auth.) understood that serious nuclear physics could not develop unless a large accelerator was available... As a result, a brave decision was made in 1940 to set up a 'cyclotron team' entrusted with studying the possibility of creating a cyclotron with a pole diameter of several meters and starting its designing... The cyclotron team was made up of 'verdant youth': Veksler, Vernov, Groshev, Cherenkov, and myself (i.e., Feinberg — Auth.). The problem was comprehensively considered in the course of ardent discussions, the sole result of which was the recognition of the enormous difficulty of solving it. The breakthrough came in February 1944 when Veksler, who had been thinking over acceleration matters amongst many other engagements he had in all those years, literally cut the Gordian knot by finding a way to surmount the relativistic barrier. He discovered the possibility of designing accelerators of a totally new class and thereby put world accelerator technology on a new path." [1]

The discovery of a way to overcome the relativistic barrier in the process of resonance acceleration of charged particles (i.e., the principle of phase stability) is known in the history of science as 'the discovery of the phase stability principle' by V I Veksler and E McMillan.

The discovery of the phase stability principle eliminated the major limitation on the production of charged particle beams of *infinitely high energies* under laboratory conditions. Indeed, comparison of the proton energy (≈ 100 MeV) reached in cyclotrons, i.e., cyclic resonance accelerators of the 'pre-Veksler era', and that expected after commissioning of the CERN Large Hadron Collider (LHC) (7,000,000 MeV) makes it clear that such must have seemed like '*unbelievably high energies*' to accelerator physicists of that time, the more so since the energy of colliding protons in their center-of-mass system amounts to $E_{\text{c.m.}} = 14$ TeV, i.e., the equivalent energy of a proton hitting a fixed target will be around 5×10^7 MeV. It has been more than once stated in recent years that the LHC is the last hadron collider built on the Earth. I do not think so. There is a widely discussed project of another LHC accelerator facility, the 2×500 GeV electron–positron International Linear Collider (ILC), the idea of which is supported by the world community of particle physicists. Russian scientists are taking an active part in this project, and JINR has proposed locating such a complex in the vicinity of Dubna. Now that we are celebrating the anniversary of Veksler's birth, it is an opportune time to ask: "Is there a reasonable upper limit that is realizable, in principle, on the energy of a 'hand-made' proton accelerator?" There was a time when the author of these notes let his imagination run only as far as considering a conceptual design of the Pevatron, [2] a 1-PeV (10^{15} eV) proton synchrotron/collider based on a new type of cost-effective superconducting magnetic system. The Pevatron would ensure, in the collider mode, an equivalent interaction energy of $\sim 2 \times 10^{21}$ eV in a fixed target system, in excess of the maximum particle energy of $\sim 3.0 \times 10^{20}$ eV recorded in cosmic rays that reach our planet. To recall, I V Veksler began his scientific carrier in high-energy physics from the investigation of cosmic rays.



Ring magnet of the 10-GeV proton synchrophasotron.

2. Project 'KM' — synchrophasotron and its modernization

The development of the synchrophasotron, a machine known under the code name KM (Russ. abbr. of 'Kol'tsevoi Magnit', i.e., ring magnet in English), and its successful commissioning in Dubna in April 1957 were events of a world-wide importance. The appearance of the 10-GeV proton accelerator actually gave a start to high-energy accelerator physics and brought JINR to the forefront of these investigations for a certain period in the history of science, as highlighted in the previous report by Prof. V A Nikitin. The most remarkable element of the world's largest accelerator was, to be sure, a ring electromagnet 208 m in circumference weighing 36,000 tons and fed from a pulsed power supply system. Even now, this magnet produces a great impression on those entering building No. 1 of the Laboratory. Many other systems of the synchrophasotron, such as the HF one, the vacuum chamber and its pumpdown, were also based on the most advanced technologies of that time. The synchrophasotron was 'built to last' and remained in operation from 1957 till 2003.

In the 1970s, the proton accelerator was successively modernized to become the first accelerator of relativistic nuclei; the upgrade program was initiated by A M Baldin who took over the position of LHE director in 1968. The Laboratory suggested and implemented new methods for the production of multiply charged ions in particle sources, constructed a new injector (the LU-20 linear accelerator), developed systems for extracting accelerated proton beams and nuclei from the Synchrophasotron in two directions (including a new experimental area, building No. 205), and made many other modifications. Unique polarized deuteron beams with a momentum of up to 4.5 GeV/c and secondary beams of polarized neutrons were obtained. The mean annual

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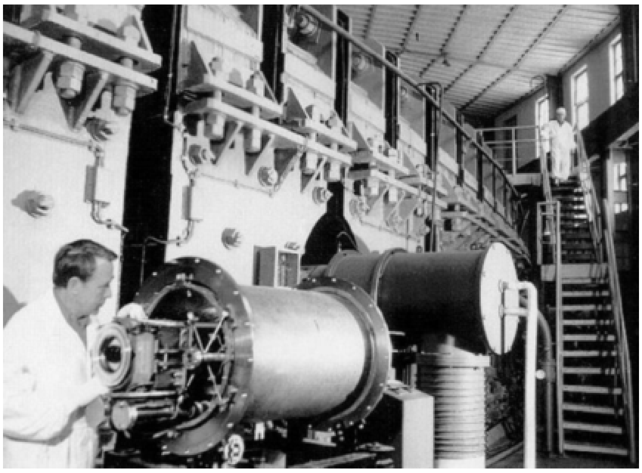
[1] Feinberg E L *Epokha i Lichnost'. Fiziki: Ocherki i vospominaniya* 2-e izd. (*Epoch and Personality. Physicists: Essays and Reminiscences* 2nd ed.) (Moscow: Fizmatlit, 2003) p. 233.

[2] Kovalenko A D "VLHC based on cooled iron intermediate field superconducting magnets," in *Intern. Conf. on High Energy Accelerators. HEACC'03. Tsukuba, Japan, March 2003.*



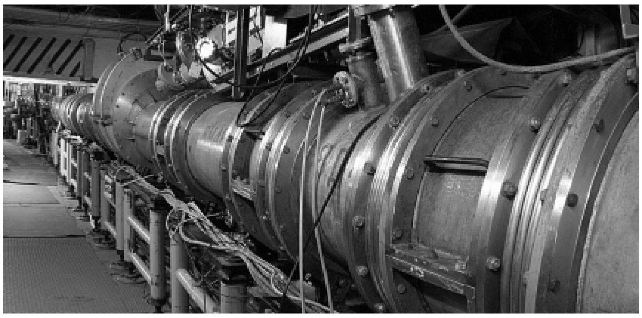
Superconducting dipole magnet of the Nuclotron in the synchrophasotron hall.

running time of the LHE accelerator facilities between 1970 and 1990 exceeded 4,000 hours.[3]

Synchrophasotron modernization provided a basis for further experiments in Russia in the field of relativistic nuclear physics with the employment of light-nucleus beams (up to sulphur, $A = 32$). One of the most important results of these studies was the establishment of the limiting fragmentation boundary (~ 3.5 A GeV) determining the outset of the asymptotic regime in relativistic nuclear collisions. However, further development of this new area of research required a broader range of masses of accelerated particles (up to uranium), enhancement of maximum beam energy, and improvement of some other accelerator parameters really unattainable with the synchrophasotron. Understanding this fact in the early 1970s prompted the idea of a new specialized facility for accelerating relativistic particles, called the Nuclotron.

3. Nuclotron — a new technology of superconducting synchrotrons

In the early 1970s, the world's leading research centers started practical development of superconducting technologies and their application in basic facilities — that is, charged particle accelerators. JINR LHE also found itself working on the idea of designing a Nuclotron, a strong-focusing superconductor accelerator of relativistic nuclei. A realizable Nuclotron concept was being worked out throughout 1973–1983 in parallel with the development of techniques for the fabrication of superconducting magnets under laboratory conditions. These efforts resulted in an original technology for manufacturing rather simple and reliable superconducting magnetic systems for synchrotrons with 1.8–2-T fields capable of operating at a cycle repetition rate of up to 1 Hz, which to this day has not yet been reached in other laboratories. The magnets have a ferromagnetic yoke with poles providing the necessary field configuration and an exciting winding from a hollow superconducting composite cable cooled by a two-phase helium flow to 4.5 K. The photograph illustrates the progress reached in the magnetic technology for high-energy accelerators. The two realized ideas — that is, the strong-focusing principle and application of the phenomenon of superconductivity in magnetic systems for generating a high-density current in their exciting windings — made it possible to substantially reduce the magnet's dimensions and decrease the linear weight of the accelerator ring by more than 500 times! A quite novel element of the Nuclotron is a hollow superconducting cable characterized by low dynamic heat release and minimal degradation of critical current in the rapidly alternating magnetic field. The magnet was assembled from standard commercial components, e.g., composite superconducting NbTi filaments 10 μm in diameter. Operating prototype magnets of the new accelerator were available in the early 1980s, which made it possible to proceed to designing all the other systems.



Nuclotron: accelerator ring section adjoining the beam injection site.

The project "Reconstruction of the synchrophasotron magnetic system to the superconducting one of the Nuclotron" was approved in December 1986. One hundred dipole and 66 quadrupole cryomagnetic modules were industrially manufactured and tested between 1987 and 1992. Mounting work for the Nuclotron was completed in January 1993 and the first test run undertaken in March. At this anniversary time, the Nuclotron is making its 36th run. Its magnetic cryostat system 251.5 m in perimeter is located in a tunnel surrounding the synchrophasotron basement. An adequate infrastructure was developed at LHE to cool the magnets down to the operating temperature of 4.5 K; it comprises the necessary technical and technological means for the storage of gaseous helium, and its cooling, liquefaction, and transportation. The Nuclotron, a 6 A GeV synchrotron, is a high-tech facility that remains unique even today.[4]

The commissioning of the Nuclotron coincided with the passage of this country to a market economy, a difficult period for JINR and science at large. The operating time of the LHE accelerator complex decreased almost 4-fold, from 4,000 to 1,000 hours per year) due to reduced budget funding. Moreover, the lack of beam extraction from the new accelerator restricted the possibility of fully exploiting the Nuclotron for physics experiments and required simultaneous operation of both the Nuclotron and the synchrophasotron. This, in turn, did not allow the meagre funds to be concentrated on completing the requisite work. This period

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[3] The reader is referred to relevant review articles for more details about the synchrophasotron; see, for instance, Semenyushkin I N "Dubnenskii sinkhrofazotron. Ot protonov k relyativistskim yadram i polyarizovannym deitronam" ("The synchrophasotron of Dubna: from protons to relativistic nuclei and polarized deuterons") *Pis'ma Fiz. Elem. Chastits At. Yadra* **1** (6) 80 (2004) [*Phys. Part. Nucl. Lett.* **1** (6) 353 (2004)]

[4] The superconducting system of the Nuclotron is described at greater length in the work by Smirnov A A, Kovalenko A D "Nuclotron — a superconducting accelerator of nuclei at LHE, JINR (creation, operation, development)" *Pis'ma Fiz. Elem. Chastits At. Yadra* **1** (6) 11 (2004) [*Phys. Part. Nucl. Lett.* **1** (6) 296 (2004)].

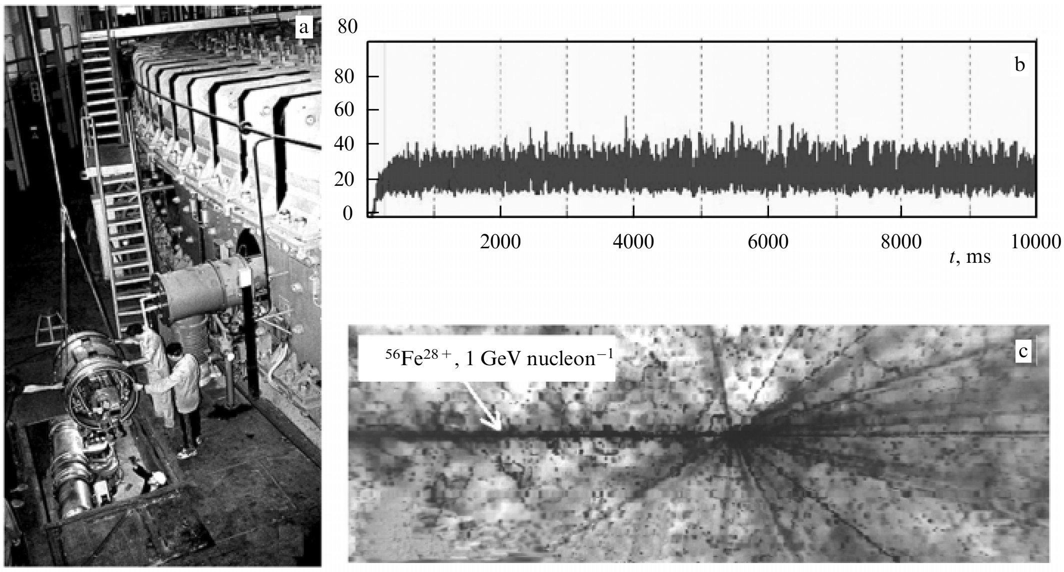


Figure 1. Nuclotron: (a) assembly of elements for the beam extraction system, (b) current signal of the extracted beam at the monitor, and (c) interaction between relativistic iron nucleus and photoemulsion nucleus.

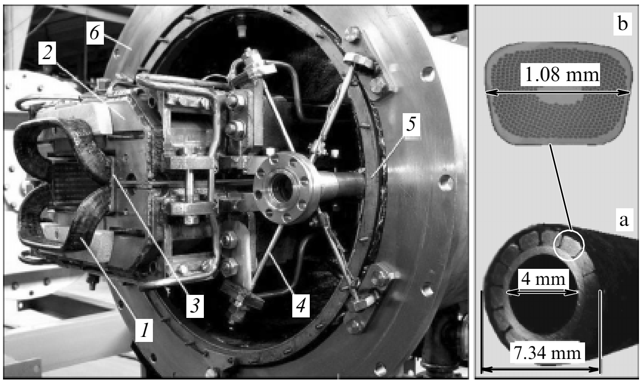
lasted from 1993 till 2003. Nevertheless, selfless efforts of accelerator specialists and the entire laboratory staff made possible a number of scientific and technical achievements that surpass the highest world levels. By way of example, the group led by E D Donets discovered the 'electron string' phenomenon and utilized it to run in a new mode the CRION, an electron-beam source of multiply charged ions. This work has led to the production of Ar^{16+} and Fe^{24+} beams.

A system for slow resonant beam extraction from the Nuclotron was designed and completed. Thus, beam extraction from the superconducting synchrotron was achieved for the first time in the world, and some record-breaking parameters were obtained. Specifically, the time expansion was increased to 10 s, whereas in the synchrophasotron this parameter did not exceed 0.5 s. Successful acceleration and extraction of beams of relativistic argon and especially iron ions demonstrated conclusively the advantages of the superconducting synchrotron over conventional facilities. Figure 1 displays (a) the snapshot relating to the assembly of elements for the system of beam ejection into the Nuclotron tunnel, (b) the time structure (expansion) of the extracted beam, and (c) a photograph taken through a microscope objective, which imprints an interaction event between an iron nucleus with an energy of 1 GeV per nucleon and a photoemulsion nucleus, obtained in the Nuclotron-based Becquerel Collaboration unifying the efforts of physicists from JINR, the P N Lebedev Physical Institute, RAS and other institutions.

A wide choice of accelerated beams and the possibility of rapidly switching from one operation mode to another, in particular, to vary the energy and intensity of extracted beams, account for the prolonged 'beam time' of the Nuclotron. In 2002–2006, its annual running time reached 2000 hours. This was actually the maximum possible performance of the LHE accelerator complex, permitted by the JINR budget and growing cost of electric power. However, physicists needed more than twice as much operation time. The total number of scheduled experiments amounted to 20, despite the rigorous selection of priority studies.

Worthy of mention is the considerable progress made by LHE after commissioning the Nuclotron in the further development of fast-cycling superconducting magnet technology for new high-energy proton and ion synchrotrons. One of the main results of this work is the more than two-fold decrease in dynamic heat release in Nuclotron-type dipole and quadrupole magnets. It is being carried out in cooperation with the Center for Heavy Ion Research (GSI) in Darmstadt, Germany, and supported by the European Union in the framework of the FP6 Program. The ultimate goal of studies conducted at LHE is the development of basic elements of the superconducting magnetic system comprising dipole and quadrupole magnets for the new SIS100 synchrotron, one of the main components of the accelerator complex being projected at Darmstadt for investigations with high-energy heavy ions and antiprotons. This complex, known as the Facility for Antiproton and Ion Research (FAIR), unites the efforts of many countries, including Russia.

A number of new types of superconducting cables and magnets surpassing those of the Nuclotron in terms of the



Prototype superconducting dipole magnet for work at a cycle repetition rate of 10 Hz: *1* — single-layer superconducting winding made from a unique high-current hollow cable (cross sections of the cable and the composite wire are shown in the right photos (a) and (b), respectively), *2* — magnet yoke, *3* — gap between the winding cooled to 4.5 K and the yoke (80 K), *4* — magnet suspension in the cryostat, *5* — intermediate heat shield, and *6* — external vacuum vessel of the cryostat.

cycle repetition rate, maximum field strength, and other important parameters were proposed in the context of the further development of the Nuclotron complex at JINR. By way of example, a dipole magnet with a single-layer winding from a tubular superconducting cable was designed and tested; the critical current in this cable was twice that in the original Nuclotron SC cable, the cross sections of both being identical. A special superconducting composite wire with a trapezoid cross section was first used for the purpose; it was made at the A A Bochvar Research Institute of Inorganic Materials following our technical specification. The magnet winding, having a temperature of 4.5 K, is in point thermal contact with the magnet yoke, the temperature of which may be as high as 50 – 80 K. This magnet has unique parameters, for example, it can be operated at a cycle repetition rate of up to 10 Hz with minimal heat release at 4.5 K.

4. NICA — Nuclotron-based flagship project of JINR

Under current conditions of strong competition between world research centers for attracting unique feasibilities of international collaboration of physicists, the prospects for the further development of LHE and its accelerator complex are directly dependent on the ability to bring forth a competitive ambitious physical problem that might be approached based on the existing Nuclotron facility, taking into consideration its ongoing technical modernization, and the availability of funds. In 2006, JINR elaborated a new NICA project aimed at searching for the mixed phase and the critical point of strongly interacting matter. Such a research is important for understanding physics of hadron and heavy ion interaction, the evolution of the Universe after the Big Bang, the origin of neutron stars, etc. A new basic facility that allows, in principle, optimally carrying out these investigations is a collider of relativistic heavy ions with an energy $\sqrt{s_{\mathrm{NN}}} \sim 7-9$ GeV in the center-of-mass system and sufficient luminosity. This energy range would be fully covered by the potential of an upgraded LHE accelerator complex. The main tasks of the NICA project include: (1) the development of the existing Nuclotron as a basic facility for the generation of intense ion beams in a range of masses from p to U and light polarized nuclei; (2) the design and construction of a heavy-ion collider with a maximum energy of $\sqrt{s_{\mathrm{NN}}} = 9$ GeV and average luminosity of 10^{27} cm^{-2} s^{-1}, and (3) the preparation of an experiment for the search for a mixed phase and construction of a multipurpose facility for the registration of ion collision processes. The conceptual scheme of the new complex is presented in Fig. 2. The working group of the NICA project is headed by A N Sissakian and comprised of S V Afanas'ev, V D Kekelidze, A D Kovalenko, A I Malakhov, I N Meshkov, V A Nikitin, A S Sorin, and V D Toneev. The project will be implemented stepwise. The first stage (2007 – 2009) includes the development of the Nuclotron, preparation of technical specification for elements of the NICA complex, and preliminary testing of prototype units of the accelerator and multipurpose interaction detector (MPD). The Nuclotron booster will be designed and commissioned at the second stage (2008 – 2012) in parallel with the completion of work on the NICA collider and MPD facility. The collider and the physical unit will be assembled in 2010 – 2013. The commissioning is scheduled for 2013. Construction of the Nuclotron-based NICA collider will be the third birth of the accelerator complex that originated in Dubna under the direction of V I Veksler. It will be the next important step towards the creation of unique conditions for the solution of still unresolved problems of high-energy physics.

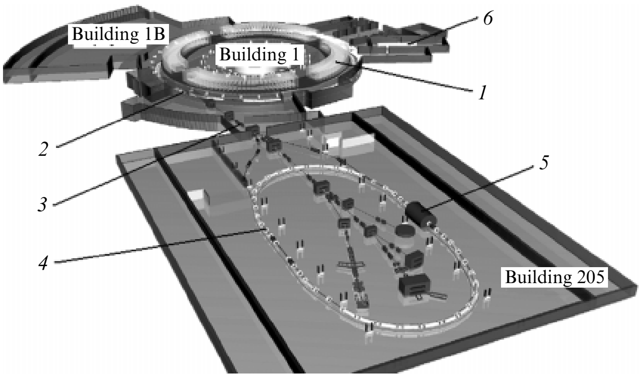


Figure 2. Conceptual scheme of the Nuclotron-based heavy-ion collider (NICA project): *1* — synchrophasotron, *2* — Nuclotron, *3* — existing channel for beam extraction from the Nuclotron to the main experimental hall, *4* — storage rings of the collider, *5* — MPD detector for recording interactions of oncoming particles, and *6* — areas for housing particle sources and pre-accelerator assembly of the complex.

5. Conclusion

A person is judged by the memory they leave behind, the legacy of their deeds and work. V I Veksler is remembered for his invaluable contribution to world science, for vivid pages he added to the history of this country and the city of Dubna. His former colleagues often remember him, although fewer and fewer people are alive to share these memories. The accelerator complex created under his direction is still in operation. It continues to be developed by Veksler's disciples, despite all the difficulties, past and present.

I had no occasion to meet Vladimir Iosifovich, but all my life and work in Dubna since the very first visit there for prediploma practical training in February 1967 have been linked to his scientific legacy. Up to 1974, I was involved in the realization of the cooperative method of an acceleration and thereafter in the development of the synchrophasotron and Nuclotron. But even earlier, some 10 years before my coming to Dubna, I had been deeply impressed by the announcement regarding the commissioning of the synchrophasotron. This event in many respects determined the course of my life and work.