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The investigations carried out by means of charged particle accelerators, based on the phase stability principle discovered by **V.I.Veksler** and **E.M.McMillan**, have resulted in radical changes in our picture of the microcosm: new laws of nature and physical principles have been discovered.

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THE HISTORY OF THE PROTON SYNCHROTRON

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ABSTRACT
The history of Vladimir Iosifovich Veksler's discovery of the phase stability principle and its technical realization by him, his disciples and collaborators from various Soviet scientific and engineering institutions is outlined. The account covers the period from 1944 to 1957.

In 1944, Veksler discovered a new method for the acceleration of relativistic charged particles that permitted obtaining high-energy charged particles unattainable in accelerators existing at that time.

To protect his priority for this discovery, he registered a claim for an authorship certificate at the Committee on Inventions and submitted a paper to the journal Doklady Akademii Nauk SSSR theoretically substantiating the possibility of coherent acceleration of relativistic charged particles moving in a circular trajectory in a varying magnetic field by means of high-frequency electric fields.

The paper titled "A New Method of Accelerating Relativistic Particles" appeared in Doklady Akademii Nauk, 1944, vol. XIII, No. 8. This was the first publication on phase stability.

Since all claims to inventions containing new proposals with the possibility of significant engineering application were classified, Veksler's claim was destined to the same fate. The Lebedev Physical Institute was informed accordingly. After publication of the paper, Veksler faced unpleasantness, but thanks to the efforts of Vavilov, Director of the Lebedev Physical Institute, the matter was smoothed over, for he convinced that it was necessary to protect the priority of this important discovery for our country.

This conclusion was furthered when it became known that the outstanding US scientist MacMillan declared that he had reported on an analogous method of accelerating charged particles at a conference in the United States in 1945, but the paper was not published.

Serious work on the theory of moving particles in accelerators by means of phase stability began in 1948 under the leadership of Veksler. Participating in this work were M.S.Rabinovich, A.A.Kolomensky and other members of the Lebedev Physical Institute Theoretical Department, headed by Academician I.E.Tamm.

At the International Symposium on Charged-Particles Accelerators, organized by CERN in 1956 in Geneva, Veksler presented a paper titled "Coherent Principle of Acceleration of Charged Particles" in which he set forth the main principles of phase focusing and substantiated the possibility of using it to construct a circular-orbit accelerator of charged particles to obtain intense beams of high-energy particles.

Veksler's disciples — M.S.Rabinovich, A.A.Kolomensky, B.M.Bolotovsky, E.L.Burshtein, L.V.Kovrizhnykh and I.V.Yankov — presented four papers at the symposium. In them, they developed the theory of motion of relativistic particles under conditions of coherent acceleration by high-frequency fields. Twenty papers on accelerators were presented by members of the Soviet delegation: G.I.Budker, V.V.Vladimirski, E.G.Komar, A.L.Mints, K.E.Sinelnikov and their colleagues.

The main impulse for beginning the development of accelerator engineering in post-war Soviet Union was Kurchatov's proposal in 1946 to the highest governmental level that a powerful accelerator of charged particles at an energy of 500 MeV be constructed to solve problems related to the creation of an atomic weapon. This proposal was approved by the government. Beria was appointed to oversee the program. The Ministries of Electric Industry and Medium Machine Building were entrusted with the construction task. In the middle of 1946, a special division for the construction of the 500-MeV Synchrocyclotron was created in the Ministry of Electric Industry. It was headed by K.N.Meshcheryakov. Subsequently this division served to organize and finance the construction of all accelerators in the USSR. At present, accelerator engineering development in the Russian Federation is in the competence of the Central Administration of Fundamental problems of Nuclear Physics and Controlled Thermonuclear Fusion. It is headed by A.A.Vasilyev.

The 500-MeV Synchrocyclotron was constructed in Dubna in record time and put into operation on December 19, 1949. At this time, theoretical and experimental work began on the design of a 10-GeV proton synchrotron. In the process of elaborating the project, Veksler delivered a number of lectures on accelerators to those participating in this work and organized many seminars in the Lebedev Physical Institute at which lively discussions took place.

The first model of an accelerator with phase focusing was developed in the Ukrainian Physics and Engineering Institute under the leadership of A.I.Leipunski and V.A.Petukhov. The electromagnet of this accelerator was fed directly from 50-Hz mains. At this repetition rate, the accelerating voltage frequency had to change in accordance with the changing velocity of particles in the annular electric magnet. This was achieved by means of mechanical variation of the frequency of a master oscillator. Its oscillatory circuit contained a condenser the rotor plate of which made it possible to secure the required law of frequency change by means of a large number of auxiliary condensers. The rotor of the condenser rotated synchronously with the changing magnetic field in the electromagnet. The master oscillator was developed in Laboratory no. 11 of the Lebedev Physical Institute. This laboratory was establiched by A.L.Mints.

A model of the proton synchrotron at an energy of 180 MeV was constructed in the Lebedev Physical Institute. This work was headed by V.A.Petukhov. A 0.7-0.8 MeV injector was provided by the Ukrainian Physics and Engineering Institute. The electromagnet and its power supply were constructed by the factory "Electrosila". The radio-engineering equipment — a system of high-frequency supply of accelerating electrodes and control of the accelerating process — was developed in the Radio Engineering Laboratory of the Academy of Sciences, USSR, under the leadership of A.L.Mints.

In parallel with the theoretical and experimental work conducted in investigating the particle acceleration process on the model, a number of organizations performed scientific research and design work necessary for elaborating a working project.

The working project had to provide solutions, in addition to construction work, to the following two main tasks:

(1) create a periodically changing magnetic field at a given trajectory with required parameters and (2) provide accelerating high-frequency field on the path of moving particles with parameters necessary for effective acceleration, develop a system of control of the acelerating process, and monitor particle motion in the accelerator vacuum chamber.

The first task was tackled in the Scientific Research Institute of Electrophysical Apparatus organized for this purpose. It was headed by E.G.Komar. In this institute, project and technological documentation was elaborated for systems of the annular electromagnet, its power supply and vacuum chamber. The second task was handled in the Radio Engineering Laboratory of the Academy of Sciences under the leadership of A.L.Mints. There were developed radio-engineering systems providing the required value and accuracy of the high-frequency accelerating field frequency to match the magnetic field intensity of the orbit of motion of the accelerated particles, control of the injection and acceleration process, monitoring of beam position in the chamber and measurement of beam intensity. A number of design and research institutes elaborated projects for the construction of buildings, technology of assembling the main equipment, and designed and fabricated various equipment for the proton synchrotron.

Veksler was the scientific leader for constructing the proton synchrotron. Mints was the chief technologist. A.P.Lepilov was the construction chief and all organizational and financial problems were handled by K.N.Meshcheryakov.

The most labor-consuming work in constructing the proton synchrotron was construction of the main building, the control and power-plant building, and also placing the concrete ring and assembling the annular electromagnet on it. For assembling the electromagnet and other equipment, Mints proposed and had constructed a special ring crane that rotated on tracks laid along the perimeter of the building.

When construction of the proton synchrotron began, the Dubna settlement was already in existence. It had been built for those working on the synchrocyclotron. Comfortable cottages, a small hotel, a club with cinema hall, a hospital, and repair services provided conveniences for those living in the settlement. Particular attention was paid to safeguarding nature in constructing the settlement. And today pine trees grow on the sidewalks and next to the cottages. Veksler lived in one of these cottages.

Before the Verbilki-Dubna railroad line was built, it was necessary to use the narrow, dangerous Dimitrov-Dubna road. A group from the Radio Engineering Laboratory almost suffered disaster here as they sped to a conference on the proton synchrotron urgently called by Beria. The automobile with five leading members of the laboratory, including Mints, overturned while traveling at 100 km per hour. Fortunately, no one was seriously hurt. Two suffered only minor injuries.

Constructors, designers and fabricators of the technological equipment faced great difficulties due to the scale of construction as well as to the unique technical requirements regarding equipment parameters.

The annular electromagnet weighs about 35,000 tons and its average diameter is 60 meters. To assemble the electromagnet, it was necessary to construct a concrete foundation that would provide placement stability over many years. To assemable and adjust the electromagnet, special mechanical, electrical and optical measuring instruments and devices were designed and fabricated.

A special 140,000 kVA power sub-station was built to feed the electromagnet. A voltage of 11 kV, produced by alternating-current generators, is converted by means of 96 power ignitrons to periodic current pulses of I_{max} = 13 kA, varying in time by the law required for effective acceleration. The electromagnet winding, consisting of insulated copper bars passing along the entire perimeter of the electromagnet, weighs 600 tons.

The main designers of the electromagnet and its power supplies were E.G.Komar, N.A.Monoszon, A.M.Stolov, M.A.Gashev and N.S.Streltsov.

The high-voltage ignitrons were designed and fabricated by the Lenin All-Union Electrotechnical Institute under the leadership of T.A.Suetin.

Scientific workers of the Radio Engineering Laboratory of the Academy of Sciences, USSR, developing radio-engineering and electronic control systems of the proton synchrotron, were confronted for the first time with technical problems that had to be solved to achieve the operating regime of the proton synchrotron. It was necessary to create a powerful accelerating high-frequency field with a frequency variable by a factor of more than 7 times that would synchronously and with a high degree of accuracy ($1 \cdot 10^{-3}$) follow the change in magnetic field intensity in the proton synchrotron vacuum chamber. To control the acceleration process, it was necessary to provide switching-on and -off of the injector and elements of the accelerating system with an accuracy of ±10 μs, which corresponds to $\pm 4 \cdot 10^{-3}$ oersted. Since magnetic fields in various blocks of the electromagnet differed in magnetic field intensity during change, distributed systems of probes in the median plane of the electromagnet gap were provided.

A measuring electromagnet block, connected in series with the main electromagnet, was introduced in the electronic control system. Probes required for controlling the frequency of the master oscillator and forming pulses for the control of the acceleration process were placed in the measuring electromagnet gap. In the 50-70 GeV proton synchrotron of IHEP, the use of such measuring magnets made it unnecessary to place numerous probes in the main electromagnet. The system developed by L.L.Kuzmin for monitoring the position of the beam in the vacuum chamber and measuring the parameters of the beam of accelerated particles made it possible to obtain the most effective regime of the acceleration process. Radio-engineering and electronic control apparatus were the muscles, brain and eyes of the proton synchrotron.

The main designers of the radio-engineering and electronic control systems were A.L.Mints, S.M.Rubchinski, M..Veisbein, F.A.Vodopyanov, A.A.Vasilyev, I.Kh.Nevyazhski, V.A.Uvarov, Yu.M.Lebedev-Krasin. The powerful output cascade with pre-amplifier was produced in the Leningrad "Comintern" factory.

Two buildings were built to house the proton synchrotron equipment. Their total volume exceeds 300,000 cubic meters. In these two buildings, it was necessary to fit and connect into a single technological system a tremendous amount of electrical engineering devices, radio-engineering apparatus, vacuum equipment, measuring and monitoring apparatus, systems controlling and monitoring the accelerator. A large network of electric cable and piping was designed and constructed for this purpose. The overall length of wiring was more than 1,000 km.

Thus, the Laboratory of High Energies was created.

After the construction and assembling work was completed, work began on putting into operation individual systems of the accelerator. Under the overall leadership of Veksler, this work was organized and performed by V.A.Petukhov, L.P.Zinoviev, K.V.Chekhlov, N.I.Pavlov and their colleagues. Technical work was performed by an assembly organization under the supervision of A.A.Efimov. In this period, work proceeded practically around-the-clock.

Little attention was paid to radiation safety. In this connection, the following incident comes to mind. It was necessary to quickly examine a certain network element in one of the channels under the control building and there was no special camera to do this at our level. A group of leading personnel gathered around the well through which it was necessary to descend to enter the channel. They were discussing the problem when Veksler approached and upon learning what the trouble was, asked for overalls and prepared to enter the well. Of course, we did not permit him. I often recall this incident.

After putting into operation and checking the individual systems, we were ready for the overall start-up of the accelerator. First, it was necessary to achieve a quasi-betatron regime that would indicate conformity of the magnetic field intensity in the electromagnet gap to the technical requirements of the injection regime. The quasi-betatron regime was obtained on March 15, 1957.

Then began work on conducting the beam in the accelerator vacuum chamber over the entire magnet cycle. In the last decade of March, 2-GeV particles were obtained and on April 10, 1957, protons with an energy of 8.3 GeV were obtained for the first time anywhere.

By this time, the Laboratory of High Energies was already a part of the Joint Institute for Nuclear Research, the director of which was D.I.Blokhintsev.

Now began painstaking work in increasing the energy and intensity of the beam, which required improving the characteristics of all of the proton synchrotron systems.

Before obtaining 8.3-GeV protons on the proton synchrotron, the United States held the record in obtaining the highest proton energy. There was the proton synchrotron "Cosmotron" with an energy of 3 GeV at Brookhaven Laboratory and the "Bevatron" with and energy of 6 GeV at Radiation Laboratory in Berkeley. Since 1957 the world record in obtaining the highest proton energy on accelerators belonged to the Soviet Union. This lasted until CERN obtained 25-30 GeV on its accelerator.

Veksler's discovery of the phase stability principle in circular orbit accelerators of charged particles marked the beginning of fruitful development of this field at home and abroad. From acceleration of particles in weak-focusing magnetic fields, accelerator designers went over to strong-focusing magnet systems. This made it possible to significantly decrease the weight of the electromagnet and, accordingly, the cost of constructing an accelerator and its operation and maintenance.

The introduction of superconductors made it possible to use small-sized magnet systems and increase the maximum energy of accelerated particles.

The idea arose of creating a cybernetic accelerator as proposed by A.L.Mints, A.A.Vasilyev, V.A.Petukhov and A.M.Rubchinski. A model of the cybernetic accelerator at 1 GeV was constructed by Vasilyev in the Radio Engineering Institute. The diameter of the chamber was only 2 cm, which permitted the use of miniature electromagnets.

Work began on creating accelerators with intersecting beams, which would enable obtaining superhigh-energy particles.

As early as 1956, at the symposium on accelerators in CERN, M.Sands spoke about the expediency of constructing cascade accelerators. This proposal is now being realized in constructing accelerators at an energy above 1 TeV.

The Committee on Lenin Prizes in Sciences and Engineering under the Soviet Council of Ministers awarded in its decision dated April 22, 1957 the

Lenin Prize for work in constructing the 10 GeV proton synchrotron. Those awarded were: V.I.Veksler, L.P.Zinoviev, D.V.Efremov, E.G.Komar, N.A.Monoszon, A.M.Stolov, A.L.Mints, F.A.Vodopyanov, S.M.Rubchinski, B.M.Bolotovsky, A.A.Kolomensky, V.A.Petukhov and M.S.Rabinovich.

At present, the Laboratory of High Energies headed by A.M.Baldin are successfully carrying on the creative heritage of Veksler. New ideas are developed and realized on the proton synchrotron.

We wish the members of this laboratory further success in their scientific work.

This paper is dedicated to the bright memory of Lenin Prize Laureate, Academician Vladimir Iosifovich Veksler.