Phasotrons and the phase stability principle *(to commemorate the 50th anniversary of the discovery of the phase stability principle)*

V. P. Dzhelepov and V. P. Dmitrievskiĭ

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The history of the development in Russia (formerly the Soviet Union) of accelerators of phasotron type following the discovery by Veksler and MacMillan of the phase stability principle is presented. The main emphasis is on the results of investigations associated with the creation of such accelerators, including some studies that were not published in journals at that time. Various theoretical aspects of the application of the phase stability principle that do not have analogs in operating phasotrons are considered. Possible further developments of the phase stability principle in resonance accelerators are noted. To give a brief illustration of the role of phasotrons in the development of nuclear physics, there is a discussion of the most important investigations made at the Joint Institute for Nuclear Research using the ordinary 680-MeV proton synchrocyclotron and a phasotron based on the same magnet with spatial variation of the magnetic field for the same energy. © *1995 American Institute of Physics.*

The discovery by Veksler[1] in 1944 and independently by MacMillan[2] in 1945 of the phase stability principle for particles in accelerators was universally seen by scientists working in the field of elementary-particle and nuclear physics as an outstanding scientific achievement of world status. It lifted the severe restriction on the limiting energy of ions that could be obtained using the cyclotron principle of acceleration of particles in a constant magnetic field at a fixed frequency of the accelerating electric field (which had been proposed and realized in the thirties by Lawrence[3]) and thus opened up the possibility of accelerating particles to effectively unlimited energies.

The phase stability principle eliminated the limitation in a very simple manner—by using modulation in time of the frequency of the accelerating voltage. For the acceleration of particles to more than 1 GeV, a magnetic field that grows in time is used.

One of the numerous applications of the phase stability principle is the creation of charged-particle accelerators of phasotron type, which are often called synchrocyclotrons.

The development, at the initiative of Kurchatov, of the first synchrocyclotron in the USSR was begun at the Laboratory No. 2 directed by Kurchatov at Moscow very soon after Veksler had discovered his principle. The decision by the government to commission the accelerator was made in August 1946. All work done in connection with this decision was classified as "top secret."

In 1947 a small accelerator section, headed by M. G. Meshcheryakov, the scientific director of the synchrocyclotron project, was organized at Laboratory No. 2.

In 1948, in order to push forward the work on developing the accelerator and preparing the program and apparatus for physics investigations with it, a special laboratory (directed by Meshcheryakov) was created; on grounds of secrecy, it was called the Hydrotechnical Laboratory (*Gidrotekhnicheskaya Laboratoriya*: GTL). One of the authors of this paper, V. P. Dzhelepov, was appointed Vice Director of this laboratory and Scientific Vice Director of the synchrocyclotron project. Our laboratory provided the physical basis for the accelerator, did the necessary work to model the acceleration process, and in collaboration with leading project organizations elaborated the accelerator project and the entire complex of necessary equipment.

The development of the rf system and the technical accelerator project as a whole was assigned to the laboratory of A. L. Mints, a well-known specialist in the field of high-power radio-frequency systems. A working trial accelerator, including an electromagnet with 5-m diameter of the poles, a vacuum chamber, dee system, and frequency buncher, was built by the special Construction Bureau of D. V. Efremov at the Elektrosila factory in Leningrad.

It was decided to build the Hydrotechnical Laboratory and accelerator 125 km from Moscow near the small village of Novo Ivan'kovo (later to become the town Dubna) on the bank of the river Volga a few kilometers from the first hydroelectric power station Volzhskiĭ Kaskad. In the first phase, the synchrocyclotron was to accelerate deuterons and α particles to energies 280 and 560 MeV, respectively, and later (after increase of the pole diameter to 6 m) protons to energy 680 MeV.

In this paper, we present a brief account of the theoretical developments of the phase stability principle made in connection with two accelerators:

• The ordinary synchrocyclotron with radially decreasing magnetic field built at Dubna in 1949 (Ref. 4).

• The phasotron (for the same energy 680 MeV), also built at Dubna, but with spiral variation and radially increasing mean magnetic field.

The second accelerator replaced the synchrocyclotron, which was worn out after 30 years of operation.

The new phasotron was developed under the scientific direction of V. P. Dzhelepov, V. P. Dmitrievskiĭ, and L. M. Onishchenko on the basis of the yoke of the synchrocyclotron's electromagnet. It was commissioned in 1984 (Ref. 5) and has parameters that are significantly better than those of the old synchrocyclotron—the current is several times greater, the intensity of the extracted proton beam is greater by a factor 20, the time stretching of the beam is better, etc.

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The principle of operation of both accelerators is based on resonance interaction of a high-frequency, frequency-modulated electric field with ions circulating around closed orbits in a stationary magnetic field.

In the presence of frequency modulation of the accelerating field in time, $f(t)$, it was obvious that in order to maintain the resonance condition $\omega=\omega_s$ of acceleration it is necessary to have the additional condition

$$\frac{d\omega}{dt}=\frac{d\omega_s}{dt} \tag{1}$$

to maintain the resonance in time. Here, $\omega_s=2\pi f$ is the angular frequency of the accelerating field, and ω is the angular frequency of the ions in the closed orbits in the given structure of the magnetic field. For an azimuthally symmetric magnetic field, $B(r)$, the closed orbits are the circles of radius r on which

$$\omega=\frac{ecB}{\sqrt{e^2B^2r^2+E_0^2}}, \tag{2}$$

where E_0 is the rest energy of the ion, and e is the charge.

It follows from (2) that to each radius there corresponds uniquely a definite frequency and total energy of the ion:

$$E=\sqrt{e^2B^2r^2+E_0^2}. \tag{3}$$

The condition (1) for a resonance ion can be written in this case in the form

$$K_s\frac{dE_s}{dt}=-\frac{E_s}{\omega_s}\frac{d\omega_s}{dt}, \tag{4}$$

where

$$K_s=-\frac{E_s}{\omega_s}\frac{d\omega_s}{dE_s}$$

is determined by the structure of the magnetic field and the energy at each radius, and the subscript s indicates the resonance ion. For such a magnetic field of the phasotron,

$$K_s=1+\frac{n}{1-n}\frac{1}{\beta^2}, \quad n=-\frac{r}{B}\frac{dB}{dr}, \tag{5}$$

where v is the velocity of the ion at the radius r, and $\beta=v/c$.

For magnetic structures with radially increasing mean induction,

$$K_s=1-\frac{n_1}{1+n_1}\frac{1}{\beta^2}, \quad n_1=\frac{r}{B}\frac{dB}{dr}. \tag{5$'$}$$

The condition (4) indicates the necessary increase of the energy to maintain resonance. Thus, after one revolution (the period of the rf accelerating field), the increase in the energy must be

$$\Delta E_s=\frac{dE_s}{dt}\frac{2\pi}{\omega_s}=-\frac{2\pi E_s}{\omega_s^2K_s}\frac{d\omega_s}{dt}. \tag{6}$$

If we denote the maximum increment of energy by the ion during one revolution by eV, the resonance frequency can be accelerated at the phase φ_s, provided that

$$\cos\varphi_s=-\frac{2\pi E_s}{eV\omega_s^2K_s}\frac{d\omega_s}{dt}=\text{const} \tag{7}$$

for an arbitrarily long time. At the same time, the criterion for selecting the accelerator parameters is the condition

$$0<\cos\varphi_s<1, \text{ i.e., } \frac{1}{K_s}\frac{d\omega_s}{dt}<0. \tag{8}$$

However, such a system, in which one particle can be accelerated in resonance, is not yet an accelerator. It is only the phase stability principle that transformed this system into an accelerator.

The physical meaning of phase stability for the phasotron regime of acceleration in the presence of a source of ions at the center of the magnet ($r=0$) consisted of the determination of a finite time interval in which ions, drawn off from the ion source, can oscillate stably in accordance with the phases of the rf field with mean increment of the energy greater than zero.

The determination of this time interval (τ), divided by the modulation period ($T=1/F_m$), was the subject of the first theoretical studies in 1947–48 on the use of the phase stability principle in the phasotron acceleration regime.[6,7]

The theory was based on the derivation and analysis of a phase equation under the assumption that the phase shift of an ion during one revolution is small, when it is possible to go over from a system in finite differences (microtron) to a system of differential equations.

The following obvious relations for a nonresonance ion were used:

$$\frac{2\pi}{\omega}\frac{dE}{dt}-\frac{2\pi}{\omega_s}\frac{dE_s}{dt}=eV\cos\varphi-eV\cos\varphi_s$$

$$\Delta\omega=-\omega K\frac{\Delta E}{E}, \quad \Delta E=E-E_s. \tag{9}$$

Since φ is the phase of the rf field at which the nonresonance ion crosses the accelerating gap, the phase shift during one revolution of the ion is

$$\frac{d\varphi}{dt}\frac{2\pi}{\omega}=\omega_s\frac{2\pi}{\omega}-2\pi, \quad \frac{d\varphi}{dt}=\omega_s-\omega. \tag{10}$$

For given structure of the magnetic field the time characteristics are known only for the resonance ion: E_s, ω_s, K_s; the system (9) under the conditions $\Delta\omega/\omega_s\leqslant 1$, $\Delta E/E_s\leqslant 1$, and $K=d\ln\omega/d\ln E=K_s$ can be transformed in the linear approximation into

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_s}\right)=\frac{eV}{2\pi}(\cos\varphi-\cos\varphi_s), \quad \frac{d\varphi}{dt}=\omega_sK_s\frac{\Delta E}{E_s}. \tag{11}$$

The equation $K=K_s$ follows from the validity of (2) and (3) for nonresonance ions if the transverse oscillations, which make a negligibly small contribution at the actually employed beam emittances, are ignored.

For analytic investigation of the solutions, the system (11) is written in the form of one second-order equation:

$$\frac{d}{dt}\left(\frac{E_s\dot{\varphi}}{\omega^2 K}\right)-\frac{eV}{2\pi}\cos\varphi=-\frac{eV}{2\pi}\cos\varphi_s,$$

$$\text{where } \dot{\varphi}=\frac{d\varphi}{dt}. \tag{12}$$

Under the condition of constancy of the coefficients, it follows directly from (12) that for small deviations of the phase of the nonresonance ion, $\varphi=\varphi_s+\delta$, $\delta\ll 1$, Eq. (12) can be written in the form

$$\frac{E_s}{\omega_s^2 K}\frac{d^2\delta}{dt^2}+\frac{eV}{2\pi}\sin\varphi\delta_s=0. \tag{13}$$

It follows from (13) that in the phasotron regime there are two stable phases $\pm\varphi_s$, which correspond to two signs of the coefficient $\pm K$ and which determine regimes with decrease (+) and increase (−) of the frequency of the accelerating field during the acceleration process.

An analysis of the efficiency of injection into the phasotron acceleration regime was made on the basis of a consideration of the first integral of Eq. (12). Under the conditions $E_s/\omega_s^2 K=\text{const}$, $\cos\varphi_s=\text{const}$, and $eV=\text{const}$ in the first phase oscillation

$$\frac{\pi E_s}{eV\omega_s^2 K}(\dot{\varphi}^2-\dot{\varphi}_0^2)=\sin\varphi-\sin\varphi_0-\varphi\cos\varphi_s+\varphi_0\cos\varphi_s. \tag{14}$$

Since the replacement of φ by φ_0 does not change Eq. (14), the stability analysis made for $(\varphi,\dot{\varphi})$ can be automatically extended to the region of initial conditions $(\varphi_0,\dot{\varphi}_0)$.

It follows from (14) that the equation

$$\frac{\pi E_s}{eV\omega_s^2 K}\dot{\varphi}^2=\sin\varphi-\varphi\cos\varphi_s+C \tag{15}$$

in conjunction with

$$\frac{dE}{d\varphi}=\frac{eV\omega\cos\varphi}{2\pi\dot{\varphi}} \tag{16}$$

determines the interval of stable phases and the increase in the energy during the half-period T_f of the phase oscillations:

$$\Delta E=\int_{\varphi_1}^{\varphi_2}\frac{eV\omega\cos\varphi d\varphi}{\sqrt{\frac{eV\omega_s^2 K}{\pi E}}\sqrt{\sin\varphi-\varphi\cos\varphi_s+C}}=eV\cos\varphi_s\frac{\omega T_f}{2\pi}, \tag{17}$$

subject to the condition $\dot{\varphi}(\varphi_1)=\dot{\varphi}(\varphi_2)=0$; $T_f=\int_{\varphi_1}^{\varphi_2}d\varphi/\dot{\varphi}$.

Since $\omega T_f/2\pi$ is the number of revolutions of an ion in the half-period, the mean energy increment for all ions during one revolution is the same and equal to $eV\cos\varphi_s$. The constant C in Eq. (15) determines the amplitudes of the phase oscillations with which the ions oscillate in the potential well:

$$U(\varphi)=\varphi\cos\varphi_s-\sin\varphi \quad \text{for } K>0, \tag{18}$$

$$U(\varphi)=\sin\varphi-\varphi\cos\varphi_s \quad \text{for } K<0. \tag{19}$$

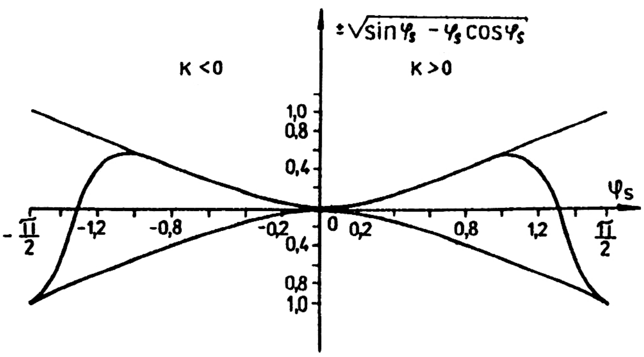

FIG. 1. The functions $L(\varphi_s)$ for $K>0$ and $K<0$.

The minima of these curves, corresponding to stable phase oscillations, are situated at $\varphi=\varphi_s$ $(K>0)$ and $\varphi=-\varphi_s$ $(K<0)$, and the maxima at $\varphi=-\varphi_s$ and $\varphi=\varphi_s$, respectively. The latter (the maxima) determine the maximum values of the constant C for $K>0$ and $K<0$:

$$C_{\max}=-\varphi_s\cos\varphi_s+\sin\varphi_s \quad (K>0),$$

$$C_{\max}=\varphi_s\cos\varphi_s-\sin\varphi_s \quad (K<0), \tag{20}$$

this following directly from (15) under the condition $\dot{\varphi}(\mp\varphi_s)=0$. It is natural that these values are equal, since the depth of the potential well $U(\varphi)$ is the same for both possibilities $(K>0, K<0)$. The second maximum deviation of the phase φ_2 can be calculated from the condition $\dot{\varphi}(\varphi_2)=0$:

$$\sin\varphi_2-\varphi_2\cos\varphi_s+\sin\varphi_s-\varphi_s\cos\varphi_s=0 \quad (K>0),$$

$$-\sin\varphi_2+\varphi_2\cos\varphi_s-\sin\varphi_s+\varphi_s\cos\varphi_s=0 \quad (K<0). \tag{21}$$

Thus, the second equation differs from the first only in the sign of the stable phase $\varphi_s=-|\varphi_s|$:

$$\sin\varphi_2-\varphi_2\cos|\varphi_s|+\sin|\varphi_s|-|\varphi_s|\cos\varphi_s=0. \tag{22}$$

The maximum value of $\dot{\varphi}$ is the same in the two cases and corresponds to the equilibrium phase $\varphi=\pm\varphi_s$:

$$\dot{\varphi}_{\max}=\omega_s\sqrt{\frac{2eVK}{\pi E_s}}\sqrt{\sin\varphi_s-\varphi_s\cos\varphi_s},$$

$$\dot{\varphi}_{\max}=\omega_s\sqrt{\frac{2eV|K|}{\pi E_s}}\sqrt{\sin|\varphi_s|-|\varphi_s|\cos\varphi_s}, \tag{23}$$

where $|K|$ and $|\varphi_s|$ are the absolute values.

Figure 1 gives the graph of this function in its dependence on φ_s for the interval $-\pi/2\leq\varphi_s\leq\pi/2$.

For phasotrons with unslotted structure of the magnetic field (continuous magnet), this region is decreased by the mechanism of loss of energy to the value zero in the first phase of oscillation in the region of negative values of $\cos\varphi$ ($\pi/2-\varphi_2$, $K>0$ and $-\pi/2-\varphi_2$, $K<0$), as follows directly from (21) and (22).

It follows from (17) that the energy increment ΔE by an ion in the first oscillation may vanish under the conditions

$$\Delta E \cong \int_0^{\pi/2} \frac{\cos\varphi d\varphi}{\sqrt{\sin\varphi - \varphi\cos\varphi_s + \sin\varphi_s - \varphi_s\cos\varphi_s}}$$

$$+2\int_{\pi/2}^{\varphi_{\max}} \frac{\cos\varphi d\varphi}{\sqrt{\sin\varphi - \varphi\cos\varphi_s + \sin\varphi_s - \varphi_s\cos\varphi_s}} = 0,$$

where $\varphi_{\max} < \varphi_2$ determines a new constant C for $\dot{\varphi}_0 > 0$ and

$$\Delta E \cong 2\int_0^{-\varphi_s} \frac{\cos\varphi d\varphi}{\sqrt{\sin\varphi - \varphi\cos\varphi_s + \sin\varphi_s - \varphi_s\cos\varphi_s}}$$

$$+\int_0^{\pi/2} \frac{\cos\varphi d\varphi}{\sqrt{\sin\varphi - \varphi\cos\varphi_s + \sin\varphi_s - \varphi_s\cos\varphi_s}}$$

$$+2\int_{\pi/2}^{\varphi_{\max}} \frac{\cos\varphi d\varphi}{\sqrt{\sin\varphi - \varphi\cos\varphi_s + \sin\varphi_s - \varphi_s\cos\varphi_s}}$$

$$=0 \quad \text{for } \dot{\varphi}_0 < 0. \tag{24}$$

The initial phase equal to zero in (24) is chosen because of the presence of the process of phasing of the ions after they have been drawn from the ion source (if there is no special device for drawing them off of puller type).

The doubling of the integrals in (24) corresponds to a double pass through the region of variation of the energy in a phase oscillation. There are two values of $\cos\varphi_s$ at which this effect either completely precludes the possibility of an energy increment, for the regime $\cos\varphi_s = 0$, or is completely absent: $\cos\varphi_s \cong 0.5$. The intermediate values of $\dot{\varphi}_0$ are calculated numerically from (24). The graphs of these functions for $K > 0$ and $K < 0$ are given in Fig. 1.

Thus, theoretically the capture efficiency in the phasotron is

$$\frac{\tau}{T} = \frac{2\omega_s\sqrt{2eV|K|}}{T\left|\frac{d\omega_s}{dt}\right|} L(\varphi_s), \tag{25}$$

where $L(\varphi_s)$ is taken from the closed region of the graphs of Fig. 1.

The theory is valid both for a radially decreasing induction of the magnetic field ($K > 0$) and for an increasing field ($K < 0$). However, it should be noted that an increasing mean magnetic field leads to negative values of K only under the condition $|n| > r^2/r_\infty^2$ in the region of the first phase oscillation $[r_\infty = c/\omega_0, \omega_0 = ecB(0)/E_0]$.

To test the theory, a model phasotron based on a magnet of diameter 90 cm was built in 1948 in Laboratory No. 2 (I. V. Kurchatov Institute). It was established experimentally using the model that the phase-stability effect does indeed exist, though some deviations from the developed theory were noted. Among the main deviations we must mention the existence of an intensity (of the scale of a few percent of the maximum current) in the $\cos\varphi_s > 1$ regimes and also a loss of intensity along the radius of the accelerator.

The two effects were found to be related, since the ions lost in one cycle, whose lifetimes exceeded the modulation period, could be picked up in subsequent cycles even in the absence of the phase stability conditions. A similar result was obtained in Ref. 8.

An important result of the modeling was the conclusion that one could use the phase stability principle under the condition of violation of constancy of the coefficients of the phase equation (14), including the condition $\cos\varphi_s = \text{const}$, on which the theoretical treatment was based.

On the commissioning and investigation of the characteristics of the 184-inch phasotron at Berkeley,[9] a first attempt was made to extend the theory of phase stability in the presence of slow (compared with the period of phase oscillations) variation of the parameters of the phase equation (14). The theory was based on the use of the invariance in time of the integral

$$J = \oint \frac{E_s}{\omega_s^2 K} \dot{\varphi} d\varphi$$

if there is adiabatic variation of the parameters during the time of the acceleration, this corresponding to conservation of the one-dimensional phase space in all the phase oscillations.

The authors of Ref. 9 considered the change of the integral for small phase oscillations for which

$$\dot{\varphi} = \dot{\varphi}_{\max}\sin\omega_f t, \quad \omega_f = \omega_s\sqrt{\frac{eVK\sin\varphi_s}{2\pi E_s}}.$$

In this case, in all phase oscillations

$$\frac{E_s}{\omega_s^2 K}\frac{\dot{\varphi}_{\max}^2}{\omega_f} = \text{const}. \tag{26}$$

Assuming that it is possible to use this relation for the separatrix values of $\dot{\varphi}_{\max}$, it is possible to introduce corrections into the function when taking into account the real experimental variations of the parameters during acceleration. This resulted in satisfactory agreement with the experimental data despite the lack of rigor in the assumption that it is possible to use small oscillations when considering the separatrices. Among the most important results of this theoretical study, we must mention the appearance of a flatter maximum of the function $L(\varphi_s)$ and a decrease in the limiting value of $\cos\varphi_s$ corresponding to zero intensity.

The 5-m synchrocyclotron was commissioned in December 1949 (Ref. 4), and in accordance with the project deuterons and α particles were accelerated to 280 and 560 MeV, respectively, and in 1953 (after increase in the diameter of the poles of the magnet to 6 m) protons with energy 680 MeV too (the intensity was $\approx 0.3\ \mu$A).[10] Figure 2 shows the general form of the 6-m synchrocyclotron.

In 1956, when the Joint Institute for Nuclear Research was being set up, the 680-MeV synchrocyclotron became the basic facility of the Laboratory of Nuclear Problems (V. P. Dzhelepov was the director) of the JINR.

The accelerating system of the synchrocyclotron that was used was a half-wave resonance line with mechanical rotating buncher, which ensured frequency modulation of the accelerating voltage in the dee in the range 25.6–13.6 MHz at amplitude up to 15 kV (Ref. 11).

The synchrocyclotron was operated in this regime until 1979. By an improvement in the frequency characteristic of

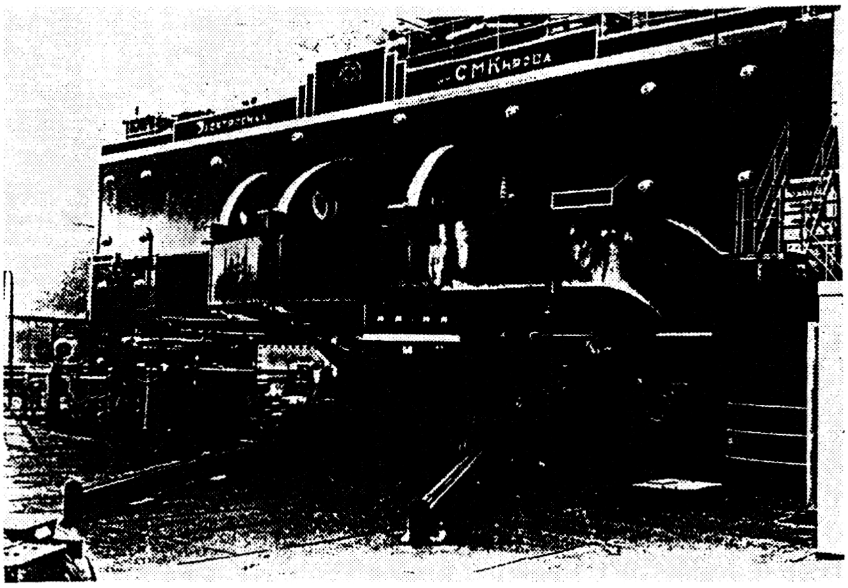

FIG. 2. General appearance of the JINR synchrocyclotron for proton energy 680 MeV.

the frequency buncher,[12] and also a certain optimization of the phase regime of acceleration, the intensity of the internal beam was raised to 2.3 μA in 1964.[13]

The accelerator was used to produce many beams of protons and neutrons (polarized and unpolarized) and $\pi^{\pm}$ mesons, and there was also a strictly focusing channel for μ-meson beams of various energies.

As a result of all this work, from the beginning of the sixties the 680-MeV synchrocyclotron became the leading accelerator in the world among the machines of its class.

During 30 years of operation of the accelerator, its beams were used in an extensive program of research in elementary-particle and nuclear physics in the region of intermediate energies. In many of these studies, results of a high world status were obtained. Fundamental discoveries were made in several studies.

We give some examples as an illustration.

There were experiments to test the general symmetry principles that form the basis of the strong interaction of particles. During the fifties and the beginning of the sixties, experiments on elastic scattering of nucleons by nucleons proved the charge symmetry of the nuclear forces at high energies, and the isotopic invariance of these forces was established in experiments on ion production in inelastic collisions of nucleons with nucleons. The results of study of elastic scattering of unpolarized and polarized nucleons by nucleons made it possible to carry out a phase-shift analysis of the data and determine the S matrix.

In 1951–53, the phenomenon of joint production of a heavy meson with a hyperon was predicted on the basis of theoretical arguments of Pontecorvo independently of Pais. The prediction was subsequently confirmed by direct experiments made using the cosmotron in the United States. However, using the synchrocyclotron at Dubna, Pontecorvo performed special experiments in order to observe production of Λ^0 particles following bombardment of carbon by protons with energy 680 MeV, which was quite sufficient for production of the particles. The experiments showed that Λ^0 particles are not produced under these conditions. This was an additional and strong argument in support of the validity of the hypothesis of joint production of the Λ^0 particle and a heavy meson.

In 1962, a delicate method led to the discovery of the very rare phenomenon of pion beta decay ($\pi^+ \rightarrow e^+ + \pi^0 + \nu_e$) and thus proved the validity of the law, predicted by theoreticians, of conservation of the vector current in the weak interaction.

The results of experiments on the capture of negative muons by helium-3 nuclei (1962) and by protons (1974) (gaseous hydrogen and helium-3 were used) proved convincingly the fundamentally important fact of the identity of the properties of muons and electrons in the weak interaction.

In 1976, an investigation of rare decays of muons in a magnetic spectrometer with a 4π detector yielded a bound on the probability of the $\mu \rightarrow 3e$ decay process that by several orders of magnitude was the lowest among the values then known: $R < 2 \cdot 10^{-9}$. This was strong evidence for the validity of the law of conservation of lepton numbers.

In 1957, there was the discovery of direct knockout of deuterons and, somewhat later, also ^{3}He and ^{4}He nuclei with momenta of order 1500–1900 MeV/c from nuclei by protons. This was direct evidence for the existence of density fluctuations—the formation of nucleon clusters in nuclear matter. Investigation of the interaction of pions with nuclei in 1963 led to the discovery of the phenomenon of double pion charge exchange, which was subsequently studied in detail.

New effects in meson physics were also observed by means of the μSR method. There was the discovery of the existence of muonium in condensed media (1965), the observation in the seventies of incoherent quantum diffusion of μ^+ mesons in solids, and more.

Important investigations were made in the field of nuclear spectroscopy. More than 100 new neutron-deficient radioactive isotopes were discovered, some of these were found to be very close to the boundary of proton stability of the nuclei, and there were more discoveries in this vein.

More detailed information about these and other studies made using the synchrocyclotron at the JINR up to 1978 can be found in the special reviews of Ref. 14, which give references to the original publications.

During systematic investigations with the synchrocyclotron of μ-mesic atomic and molecular processes in hydrogen isotopes (1964–1977), the phenomenon of resonance production of μ-mesic deuterium molecules (sharp increase in the rate of their production with the energies of the $d\mu$ atoms) was discovered, and in 1979, in experiments with a deuterium–tritium mixture, it was also established for the first time that the rate of production of $dt\mu$ molecules $\lambda_{dt\mu}$ exceeds $10^8\ s^{-1}$ and exceeds by a factor of almost 100 the rate for $dd\mu$ molecules. Simultaneously, it was found that the rate λ_{dt} of isotopic exchange of muonium ($d\mu+t\rightarrow t\mu+d$) is also large and has a value $\sim 2.9\cdot 10^8\ s^{-1}$ (Ref. 15). The experimental data on $\lambda_{dt\mu}$ and λ_{dt} agreed well with the values predicted by the Dubna theoreticians and supported their comment that under these conditions with allowance for the calculated probability $\simeq 10^{-2}$ of attachment of muons to ^{4}He nuclei the muon could realize about 100 dt synthesis reactions and release an energy $\sim$2 GeV during its lifetime.[16]

This discovery revived the by then flagging interest in the West and in the United States in muon catalysis and was a second birth of it and initiated the development of experimental and theoretical investigations of the problem in many nuclear centers of the world, especially in connection with searches for new energy and neutron sources, and later in connection with the possibility of studying various delicate effects like the polarization of the vacuum or the interaction of the lightest nuclei in pure spin states at very low velocities of the relative motion of these nuclei.

It should be noted that in 1967 a second ordinary synchrocyclotron with magnetic field decreasing toward the edge, as in Dubna, was built at the branch of the V. P. Konstantinov Physicotechnical Institute of the USSR Academy of Sciences at Gatchina. This is the largest synchrocyclotron in the world. The diameter of the pole of the magnet is 6.85 m, and the weight of the magnet is 7600 tons. With it, protons are accelerated to energy 1000 MeV (Ref. 17). The beams of this accelerator have also been used in many investigations, and results of high scientific importance have been obtained, especially in the field of nucleon–nucleon and elastic proton–nucleus scattering, the study of the properties of condensed matter by the μSR method, muon catalysis, etc.

The next stage in the use of the phase stability principle in phasotrons was the application of a radially increasing mean induction of the magnetic field. The presented theory of phase oscillations is not associated with the transverse stability of ions in the acceleration process, as a consequence of which it remains valid for arbitrary structures of the magnetic field: $n \gtreqless 0$.

After the proposal to use in accelerators azimuthally inhomogeneous magnetic fields[18]—sector and helical[19,20]—the problem of transverse stability was solved for a large class of structures.

For mirror-symmetric structures of magnetic fields with zero values of the transverse components in the median plane, the form of Eqs. (2) and (3) is unchanged, since

$$\omega=\frac{2\pi\beta c}{L}=\frac{ec\oint B_z ds}{EL}=\frac{ec\hat{B}}{E}, \tag{27}$$

where $L=2\pi\hat{r}$ is the length of a closed orbit in the periodic field structure, $\oint B_z ds=\hat{B}L$, $E=\sqrt{p^2c^2+E_0^2}$, $p=(e/2\pi c)\oint B_z ds$, and ds is the element of the closed orbit.

Thus, the expressions (2) and (3) are unchanged if $B=\hat{B}$ is the mean induction on the closed orbit, and $r=\hat{r}$ is the mean radius of the closed orbit.

A significant difference in the nature of the phase motion for magnetic fields with radially increasing mean induction of the field is in the values of the parameter K (5′).

If

$$n_1=\frac{\hat{r}}{\hat{B}}\frac{d\hat{B}}{dr}<\frac{\beta^2}{1-\beta^2}$$

in the range of acceleration radii, then the frequency of the accelerating field will be decreasing ($d\omega_s/dt<0$); if the opposite inequality holds, it will be increasing ($d\omega_s/dt>0$). If in the acceleration range the equation $n_1=\beta^2/(1-\beta^2)$ holds, corresponding to a critical energy, phase stability is lost.

For a long time (in contrast to synchrophasotrons), theoretical consideration was not given to the possibility of passage by the beam through the zone of critical energy in the phasotron acceleration regime because of the fact that in all the operating phasotrons a critical energy did not occur. However, this problem arose in connection with the development during the seventies of phasotrons at Columbia University in the United States[21] and in the Laboratory of Nuclear Problems of the JINR, Dubna[22] with radially increasing mean induction of the magnetic field, in which, as calculations showed, it is possible to obtain a much higher intensity of the accelerated beam than in ordinary phasotrons.

Stability of the axial oscillations in such magnetic fields is achieved by variation of the magnetic field. However, one can create the necessary variation only beginning with radii that exceed the vertical gap between the ferromagnetic elements.[20]

Examination of the stability problem showed that it can be solved in two ways.

1. By arranging that the radii of the first revolutions of the ions after they are drawn from the ion source are in the region of vertical stability.

2. By creating in the region of small radii a magnetic field whose induction decreases in magnitude and then goes over to an increase ("bump of the magnetic field") on violation of the phase stability in the region of the first phase oscillation.

The first method was realized in the phasotron of Columbia University. The second was realized in the new phasotron of the Laboratory of Nuclear Problems at the JINR at Dubna.

The main difficulty in the realization of the first method was the need to place iron masses (shims) in the dee accelerating system. This made it necessary to develop strong insulators and created certain difficulties in their exploitation.

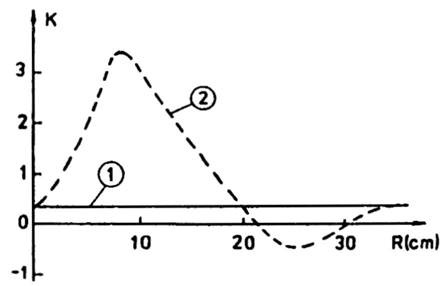

FIG. 3. Graph of variation of the parameter K in the central region of the new JINR phasotron for proton energy 680 MeV.

The second method led to a need to investigate the phase stability principle in the region of instability in the presence of strong variations of the parameters in the region of the first phase oscillation and also in the presence of radial instability near $n=0$ (restrictions on the first harmonic in the structure of the field).

Figure 3 is a graph of the variation of the parameter K (curve *2*) in the central region of the JINR phasotron. Curve *1* is calculated in the absence of a "bump."

Naturally, for such a variation of K (presence of two vanishing values of it), the classical theory does not hold. However, numerical calculations carried out in the Laboratory of Nuclear Problems for different structures of the magnetic field demonstrated the possibility of using the phase stability principle even under such nonstandard conditions. The efficiency of capture was found to be close to the separatrix value after the region of instability had been passed.[23]

The 680-MeV phasotron of the JINR has been operated in such a regime since 1984 (Ref. 5).

The internal structure of the magnetic system of the new accelerator is illustrated in Fig. 4. One can see the iron shims, which have the shape of Archimedean spirals placed on the disk of the lower pole of the electromagnet. Similar shims are placed on the disk of the upper pole. Together they create the necessary spatial variation of the field. Growth of the field strength by 30% from the center, where it is 1.2 T, to outermost orbits is mainly guaranteed by the shape of the iron disks to which the helical shims are fixed.

The radially increasing magnetic field made it possible to reduce by a factor of almost 3 the interval of frequencies of the accelerating rf voltage compared with the previously operated synchrocyclotron, to increase by a factor 3 the voltage on the dee (from 15 kV to 45 kV), and to use a homogeneous half-wave line in the resonance system. This made it possible, in the complete range of frequencies, to have a voltage on the buncher that does not exceed the voltage on the dee.

The maximum intensity of the internal beam of the phasotron was fixed at the level 9.2 μA (Ref. 24), this being approximately 4 times greater than in the previously operated synchrocyclotron; the extraction coefficient is larger by a factor 10 than the previous one, the beam stretching is better, and the intensity of the stretched beam is more uniform.

In this accelerator, a whole series of channels for particle beams, including a beam of surface muons, has been created (Fig. 5); these are used for nuclear-physics investigations. There has also been built a six-cabin physicoclinical complex in which physicists of the Laboratory of Nuclear Problems in collaboration with specialist radiologists of the On-

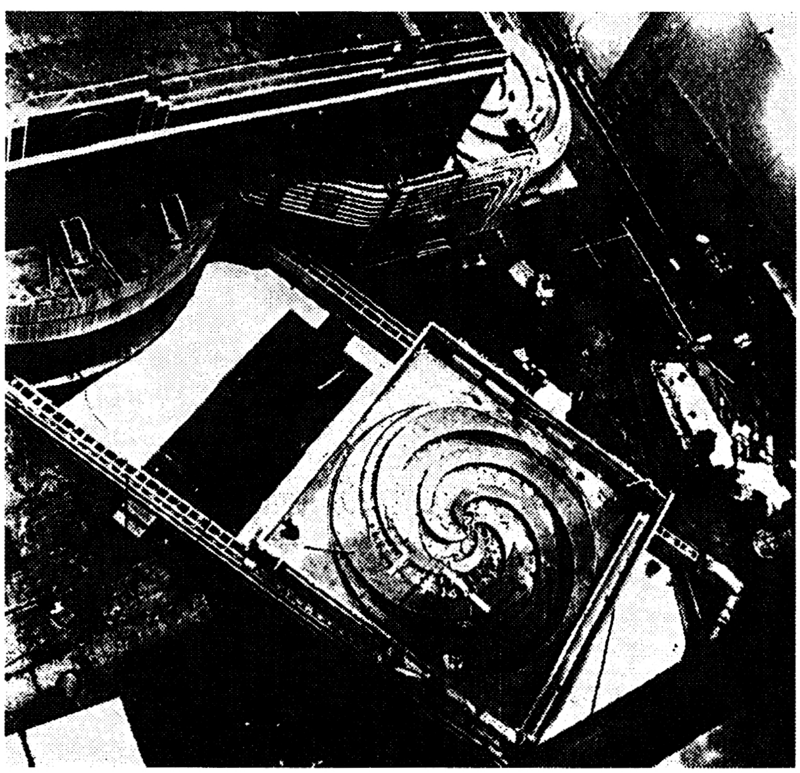

FIG. 4. The magnetic system of the JINR phasotron.

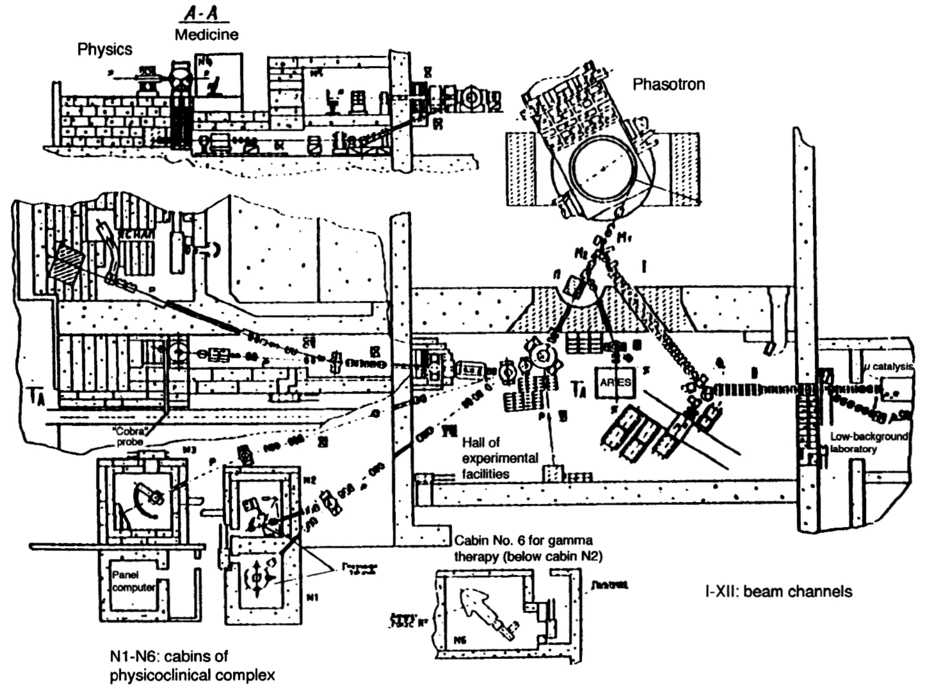

FIG. 5. Channels of the particle beams of the JINR phasotron.

cology Center of Russia treat cancer patients with beams of high-energy particles.[25]

The significantly higher intensities and better quality of the beams from the new phasotron, compared with the previous synchrocyclotron, make it possible, on the one hand, to perform previously impossible experiments and, on the other hand, shorten the time of operation of the accelerator needed to obtain the experimental data in all experiments.

A significant program of investigations has already been carried out with the new accelerator. We merely mention some of the most important results.

A very difficult experiment to look for a rare effect—transition of muonium into antimuonium ($\mu^+e^-\rightarrow\mu^-e^+$)—has been carried out. The process is strongly suppressed, since the lepton numbers of the particles that participate in it change at once by two units. As a result of the experiments, a new bound, the lowest yet, was established for the probability of this process.[26]

In experiments on muon catalysis, new data, important for the theory, have been obtained in the previously unstudied interval of pressures from 0.4 to 1.5 kbar at temperatures up to 300 K on the rates of production of $dd\mu$ and $pd\mu$ molecules and also on spin effects in resonance production of mu-mesic deuterium molecules.[27]

In experiments aimed at studying by the μSR method the magnetic properties of polycrystalline high-temperature superconductors, the depths of penetration into them of magnetic fields have been determined, and also the dependences of these depths on the temperature.[28] The results of the experiments make it possible to carry out a comparison with existing theoretical calculations and to establish the extent to which they adequately reflect the experiment.

In investigations using a large magnetic spectrometer (ARES) with a 4π detector in 1991, a new upper bound for the probability of the $\mu^+\rightarrow e^+e^+e^-$ decay process was obtained: $R<3.6\cdot10^{-11}$.[29] This result improves by a factor 50 the estimate obtained in 1976 in experiments using the synchrocyclotron. The same experiments yielded an estimate of the partial probability of the allowed decay $\pi^+\rightarrow e^+\nu_e e^+e^-$, which is due to the presence of structure in the pion. It was found that this probability is $R_{SD}\simeq4.6\cdot10^{-10}$ of that of the $\pi^+\rightarrow\mu^+\nu_\mu$ decay.[30]

The main aim of presenting in this paper the most valuable and varied scientific results obtained in the experiments using the JINR phasotrons is the desire to demonstrate how broad were the possibilities for investigations in nuclear physics made available to physicists by the accelerators of this type based on the phase stability principle.

Classical phasotrons with magnetic field decreasing to the outermost orbits were constructed in different years in various countries: in the United States at Berkeley (the first phasotron in the world, 1946), at Chicago (1950), at New York (1950), in Switzerland at CERN (1957), and, as we noted, in 1967 in our country at Gatchina. Many valuable and important scientific results were obtained with these accelerators.

Today, examining all these events through the magnifying glass of time, we can state without any exaggeration that in world science accelerators of phasotron type were associated with an entire epoch of fruitful development of particle and nuclear physics in the region of what are now called intermediate energies.

In saying this, we should not forget that the Veksler–MacMillan phase stability principle was found to be very comprehensive, and it also made it possible in the second half of this century to build accelerators of the synchrophasotron and synchrotron type with particle energies that are tens, hundreds, and thousands of times greater than in phasotrons. This created vast prospects for studying the structure of matter at a previously unattainable subhadronic (quark) level and led to results that greatly enriched our knowledge of the world of microparticles and the laws of their production and interaction.

But this is the subject of a different paper.

CONCLUSIONS

The wide use of the phase stability principle in different types of resonance accelerators has not exhausted all its possibilities. It can be used in the case of adiabatic as well as in the case of rapid (compared with the period of the phase oscillations) changes of the parameters and even, in individual cases, in the case of local violations of phase stability. Investigation of such regimes can greatly extend the domain of application of the Veksler–MacMillan principle.

The results, briefly presented as examples in this paper, of the main physics investigations carried out using the JINR phasotrons (the ordinary one and the one with spatial variation of a radially increasing magnetic field) make it possible to obtain a clear picture of the important role that has been played by accelerators of this type (based on the phase stability principle) in establishing new knowledge in the field of modern elementary-particle and nuclear physics.

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