The history of the development of the cyclotron over fifty years (1930–1980)

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We examine the evolution that the magnetic resonance accelerator, or cyclotron, has undergone in 50 years. In the presentation we note the most essential points of development of these accelerators. We note individual instruments that have made possible further progress in the design of cyclic accelerators. We discuss the requirements imposed on contemporary accelerators.

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Let us go back half a century and examine the evolution undergone by the magnetic resonance accelerator, which has been named the "cyclotron."

This review examines the most essential events, as we see it, that have facilitated the conversion of a laboratory instrument made by the experimenter's hands into a very complicated engineering structure that has been employed on all continents of the world. We should note that the scope of the review naturally does not allow us to encompass all aspects involved with the development of cyclotron technology.

The first report on the principle of a cyclic resonance accelerator that does not involve ultrahigh voltage was published in 1930 by Lawrence and Edlefsen.[1]

In 1931 Lawrence and M. Livingston accelerated ions of molecular hydrogen to an energy of 80 keV in a cyclotron with a pole diameter of 100 mm. This instrument, which was built under laboratory conditions, and which now calls for a smile, became the prototype of contemporary cyclic accelerators.

In the same year, Lawrence and M. Livingston accelerated protons to an energy of 1.22 MeV in a more refined instrument. Here they showed that a change in the magnetic field by tenths of a percent leads to breakdown of the resonance condition. The authors presented in fundamental outline a method of correcting the inhomogeneities of the magnetic field by using iron elements inserted between the poles of the electromagnet and the covers of the accelerator chamber. They used the electric field of a condenser to deflect the charged-particle beam. The current in the beam at the final radius amounted to only 10^{-9} A, but the authors were already discussing the possibility of obtaining a current of the order of 10^{-7} A.

In 1932 the same scientists accelerated deuterons to an energy of 3.6 MeV in a more refined apparatus. In the same chamber in 1933, molecular hydrogen ions were accelerated to an energy of 4.8 MeV. Here the dees, or electrodes that created the accelerating high-frequency electric field, were elements of an oscillating circuit.

The first attempt to build a cyclotron in the Soviet Union was made in 1932. In the Leningrad Physicotechnical Institute in the laboratory of I.V. Kurchatov, M.A. Eremeev built a cyclotron with a pole diameter of 300 mm. The magnet, which was made from the core of a transformer, could not create a homogeneous enough magnetic field. The current in the beam of protons accelerated to 900 keV energy was of the order of 10^{-10} A.

In 1934, Lawrence and M. Livingston accelerated molecular hydrogen ions to 5 MeV in a chamber of 690 mm cover diameter, and in 1935 they obtained a current of 10^{-6} A in the deflected beam.

The year 1936 brought great advances, Lawrence and Cooksey[2] built a new chamber with a cover diameter of 700 mm, and accelerated deuterons to an energy of 5 MeV. By employing an electrostatic deflection system for the first time they extracted a charged-particle beam of 5 μA current from the chamber through a thin platinum window. The high-frequency generator, which was built as a self-excited push-pull circuit, supplied an ac power of the order of 25 kW. The potential difference between the dees amounted to 50–100 kV. The magnetic field was corrected by introducing iron disks between the poles of the electromagnet and the covers of the accelerating chamber.

Attention was first paid to the situation that the geometric center of the accelerating chamber does not coincide with the center of the orbits of the particles being accelerated. It was shown that this phenomenon can be eliminated by an additional correction of the magnetic field. An electrode to measure the beam current was placed in the chamber following the deflection system. One could set up in the same place a target for irradiation, which was cooled with running water.

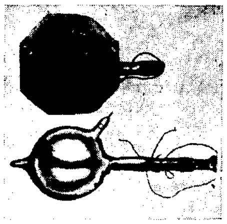

FIG. 1. Accelerator chambers of Lawrence's first cyclotron. Molecular hydrogen ions were accelerated to 80 keV (1930).

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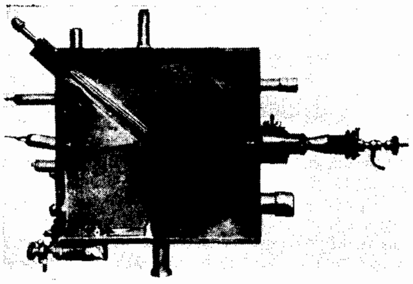

FIG. 2. Accelerator chamber of a cyclotron of Lawrence. Protons were accelerated to an energy of 1.22 MeV (1931).

Experiments with fast neutrons obtained by bombarding beryllium with deuterons were first performed in this cyclotron. The authors advanced the progressive suggestion of the expedience of extracting the beam in an evacuated tube through the shielding wall to a considerable distance from the cyclotron in order to reduce the background radiation of the apparatus itself.

In 1937 Lawrence and Cooksey[3] built a highly refined accelerator installation. The dee circuit had powerful water cooling. The chamber was fitted with reliable vacuum valves. There was an apparatus for measuring the potential across the dees. In the deflection system they employed for the first time a thin tip made of refractory metal to diminish the losses of the charged-particle beam entering into the condenser.

They employed for the first time a probe developed by R. Wilson with a sliding seal to measure the current of accelerated particles at any radius by observing the heating of the probe. One could attach a target for irradiation to this same probe. An airlock situated after the deflection system allowed one to insert and remove targets to be irradiated without breaking the vacuum in the accelerator chamber. The extraction of the charged-particle beam to the outside was performed through a thin metal foil attached to a cooled plate having many apertures. The authors obtained 8-MeV deuterons. The current at the final radius was as much as 100 μA.

The construction of this cyclotron was a great advance, since essentially it was the first instrument in world practice that was built on a high engineering technical level.

In the same year in Leningrad in the Radium Institute of the Academy of Sciences of the USSR, the first cyclotron instrument in the USSR and in Europe was built, with a pole radius of 1000 mm.[4] Within a year, it was put to use by I.V. Kurchatov, V.N. Rukavishnikov, D.G. Alkhazov, and M.G. Meshcheryakov. Deuterons were accelerated in this cyclotron to 6 MeV with a current in the accelerator chamber of the order of 40 μA.

In 1937 A.I. Alikhanov, I.V. Kurchatov, L.M. Nemenov, and Ya.L. Khurgin designed the largest cyclotron in Europe, with a pole diameter of 1200 mm. The cyclotron was to be introduced into use in January 1942, but this was prevented by the Second World War. The cyclotron was put into service at the end of 1946.[5]

In 1937 Alvarez *et al.* made the first attempt to remove the target being irradiated from the cyclotron. On the basis of the studies of Tuve and Lamar, Baker and M. Livingston built and tested the first capillary ion source for a cyclotron. Bethe published the first article on the theory of the cyclotron.

The year 1938 was especially fruitful in the development of accelerator technology. Employing an idea of Sloan, Dunning, and Anderson[6] first applied a quarter-wave coaxial vacuum resonance line in the cyclotron at Columbia University to transmit the high-frequency voltage to the dees. This refinement allowed them to eliminate the use of glass insulators, which restricted the magnitude of the voltage supplied to the dees. Alvarez obtained an interrupted beam of thermal neutrons upon modulating a deuteron beam incident on a beryllium target. Wilson and Kamen for the first time designed convincing experiments to test the theory of the cyclotron.

This year was extremely rich in theoretical studies. We should list here the fundamental studies of Rose on the theory of the cyclotron,[7] the study of Khurgin on the limiting energy of particles that can be accelerated in a cyclotron,[8] and the study of Wilson on electrostatic and magnetic focusing of the beam.[9]

Yet the most remarkable event of this year must be viewed as being the publication of the study of Thomas,[10] who showed that charged particles can be accelerated to considerably higher energies in a cyclotron if one creates a magnetic field with an azimuthal variation of sufficient depth, and which increases with increasing radius of the orbits of the ions being accelerated.

In the classical cyclotron an increasing magnetic field would lead to defocusing, and consequently to total loss of all the ions being accelerated. Thomas showed theoretically that the motion of the particles will be stable in the case that he treated, and will make possible resonance conditions for the duration of the entire acceleration process. Thomas' ideas were not developed at that time, since the creation of a magnetic field of the required form amounted to an extremely complicated problem. At that time even the correction of the magnetic field in the classical cyclotron gave rise to rather great difficulties.

The design and construction of the gigantic cyclotron with a pole diameter of 4.7 m for accelerating deuterons to 100 MeV, which was undertaken by Lawrence in the period before the war, distracted the attention of physicists from the original proposal of Thomas, while the outstanding discovery made independently by Veksler (1944)[11] and by McMillan (1945)[12] caused people to forget this remarkable study for more than ten years.

In 1939 Lawrence, Alvarez, *et al.* started construction of the largest cyclotron in the world, with a diameter of the poles of the electromagnet of 1500 mm.[13] The weight of the electromagnet was 200 tons. The design of the accelerator chamber differed considerably from the usual. Its main advantage consisted of the fact that the dees with the resonance lines could be removed from the accelerator chamber, while the chamber remained in the interpole space of the electromagnet. Thus this operation did not lead to disruption of the magnetic-field correction. The design of the resonance line of the cyclotron allowed them to adjust the position of the dees without breaking the vacuum. For the first time, the deflection system was set up inside a dee. Thus the system was shielded from "pickup" of the high-frequency voltage. McMillan and Salisbury perfected a capillary ion source for this instrument. In order to improve the efficiency of extraction of ions from the source, they employed a tab on the dees that increased the high-frequency potential gradient. This refinement allowed them to increase the current of accelerated particles by almost an order of magnitude.

The development of powerful high-vacuum pumps that had begun at about that time allowed them to install an oil-vapor diffusion pump of capacity 3000 L/sec to pump out the cyclotron. The accelerator chamber became so unwieldy that it had to be placed on a truck of special design. Before the beginning of World War II, deuterons were accelerated in this cyclotron to the record-setting energy of 22 MeV. The current in the extracted beam was 1 μA.

In 1940 Alvarez accelerated $^{12}C^{6+}$ ions to 50 MeV energy for the first time in world practice. This experiment began the studies of the interaction of multiply charged ions with matter. The intensity of the beam of accelerated ions at the final radius of the cyclotron amounted to 500 ions per minute.

In the same year Wilson[14] published a classical study in which he treated the problems of electric and magnetic focusing, ion production in the central region of the cyclotron, and shifting of the trajectories of the charged particles.

In 1943 a cyclotron of pole diameter 730 mm was projected in the Institute of Atomic Energy under the direction of I. V. Kurchatov, L. M. Nemenov, and A. A. Chubakov, and it was put into action in 1944. This was the first cyclotron in the USSR and in Europe that allowed extraction of the deuteron beam from the chamber to the exterior. This accelerator is also remarkable in that the first "cyclotron-generated" plutonium in Europe was obtained with it.[15]

In 1944 M. Livingston published data on a new instrument that was the best developed for its time. Outstanding results were obtained in a cyclotron of pole diameter 1050 mm. In developing the design of this cyclotron, Livingston studied the prior results of theoretical studies and the operating experience from all the existing instruments. He paid especial attention to the correction of the magnetic field. Variable capacitors with remote control were used for the first time for adjusting the frequency of the resonance circuit. The moveable short-circuiting elements of the resonance lines were fitted with spring contacts and were moved without breaking the vacuum. A rotating target was built and applied for the first time for receiving the powerful charged-particle beams. Most of the work of adjusting and controlling the accelerator was performed remotely from the central control console. In spite of the modest dimensions of the magnetic system of the accelerator, Livingston could accelerate deuterons in it to an energy of 15 MeV. The current in the extracted beam was 100 μA.

Helium leak detectors were developed and put into use at about that time in the USA, and they highly facilitated the vacuum testing of apparatus having a large volume to be pumped out and numerous seals.

In 1947 the 1.5-meter cyclotron of the Institute of Atomic Energy of the Academy of Sciences of the USSR was put into action under the direction of L. M. Nemenov and A. A. Chubakov.[17] A deflecting system with an inhomogeneous electric field was used in this cyclotron. In addition to deflecting the beam of charged particles, it focused them in the horizontal direction. The studies that were performed of a deflecting system with a hyperbolic cross-section of the electrodes were subsequently made the basis for calculating similar systems in the USSR. Oppositely directed windings on the poles of the electromagnet were employed. These allowed the median surface of the magnetic field to be shifted

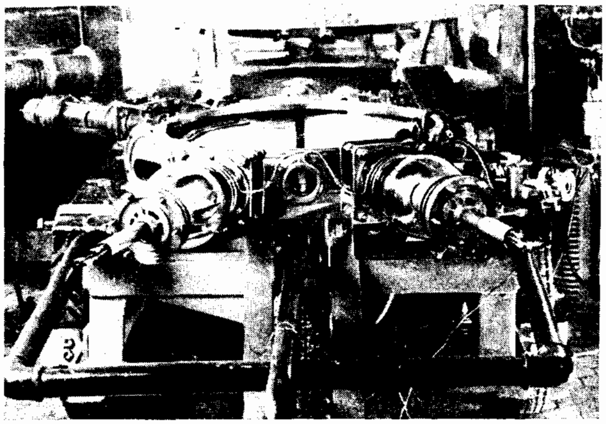

FIG. 3. Accelerator chamber of the cyclotron of the Institute of Atomic Energy (Moscow). The upper cover of the chamber has been removed (1943).

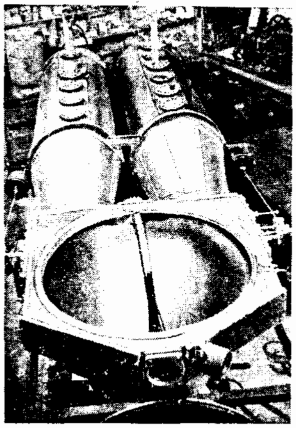

FIG. 4. Accelerator chamber with resonance lines and dees of M. Livingston. The upper cover of the chamber has been removed. Deuterons were obtained in this chamber with an energy of 15 MeV with a current at the final radius of 1 mA (1944).

without violating the conditions of resonance. This device considerably facilitated the correction of the magnetic field. The cyclotron was remotely controlled from a central console and had the best developed biological shielding in world practice.

In 1952 R. Livingston[18] described the largest cyclotron installation in the world, built at Oak Ridge (the diameter of the poles of the electromagnet was 2100 mm). It was used to obtain a record-setting proton energy of 24 MeV with a current at the final radius of 1 mA. The instrument was designed especially for working with internal targets. The electromagnet was C-shaped. In order to avoid sagging of the rods to which the dees were attached, a vertical variant of the arrangement of the chamber between the poles of the electromagnet was chosen, rather than the usual horizontal variant. The potential difference between the dees was 440 kV. In order to ensure electrical stability, a 1000-V dc negative bias was applied to the dees in addition. This was made possible by insulating the rods from the resonance-line tank. Livingston placed both rods in one common tank. In order to reduce the level of induced activity graphite shielding of the inner surfaces of the dees was applied for the first time. We should consider this cyclotron to be the first variant of the commercial-type instrument for preparing radioisotopes.

A report from Stockholm appeared in the same year. Atterling and Lindström[19] introduced into service a cycyclotron installation with 2250-mm poles of the electromagnet. The construction of this cyclotron had been started in 1945. The installation is actually an analog of the cyclotron of R. Livingston at Oak Ridge, except that the accelerator chamber was situated horizontally, while the electromagnet allowed them to obtain strong magnetic fields. Deuterons were accelerated in this cyclotron to 25 MeV with a current at the final radius of 100 μA. The cyclotron was designed for operating with internal targets, and was subsequently employed for studies with multiply charged ions.

In 1953 Walker and Fremlin[20] reported a new method of accelerating multiply charged ions, based on the idea that one can simultaneously accelerate in a cyclotron ions whose frequencies of revolution are odd integral multiples of the fundamental frequency. Thus, for example, one can simultaneously accelerate sextuply and doubly charged ions. The doubly charged ions lose electrons upon acceleration owing to "stripping" by the residual gas. The sextuply charged ions thus obtained are accelerated to the final radius. This method made it possible to accelerate $^{12}C^{6+}$ ions in the Birmingham cyclotron to an energy of the order of 120 MeV.

In 1955 Caro, Martin, and Rose published data on the Melbourne cyclotron. The proton energy varied from 2 to 12.5 MeV, while that for deuterons varied from 4 to 6.3 MeV. Here the magnetic field of the cyclotron was varied by using electrical coils. This was the first attempt to build a classical cyclotron with a regulable ion energy.

In the same year Thornton *et al.* at the University of California[21] built a cyclotron with a pole diameter of 2250 mm. The instrument was designed for producing monoenergetic neutrons in the energy range from 2 to 30 MeV. The cyclotron was capable of accelerating protons from 2.6 to 14 MeV, deuterons from 5.2 to 12.5 MeV, and tritium ions from 7.7 to 8.3 MeV. The magnetic field was corrected with electrical coils arranged on the covers of the chamber.

Information came at the same time from the Los Alamos Laboratory about a cyclotron with a pole diameter of 1050 mm. The energy of the accelerated ions varied for protons from 3.5 to 9 MeV, for deuterons from 7 to 17.5 MeV, and for tritium ions from 10.5 to 12 MeV.

But the most noteworthy feature of this cyclotron was that it employed a modification of the azimuthal variation of the magnetic field as proposed by Thomas. Three 50° iron sectors were arranged on each cover of the vacuum chamber. This arrangement made focusing possible, starting at small radii of acceleration, and increased the axial stability of the beam. In the same way a certain decrease in the threshold potential on the dees was achieved. In order to decrease the divergence of the extracted beam upon passing through the stray field of the magnet iron wedges of a special shape were employed. This was a prototype of the magnetic channel. The magnetic field of the cyclotron was corrected with special electrical coils lying both in the vacuum chamber and in the gaps between the poles of the magnet and the covers of the accelerator chamber. A current of accelerated ions of 2 mA was obtained at the final radius of this cyclotron. The extracted-beam current was 100 μA. This instrument could not yet be called an isochronous cyclotron, since the phase losses of the current were still very large, but an attempt to employ Thomas' idea was at hand.

With the invention of magnetic quadrupole lenses, the problem of focusing and transporting the beam was greatly simplified. The targets under study and the detecting apparatus were set up at sites shielded by protective walls at considerable distances from the cyclotron.

In 1955 planning was started in the USSR for the largest cyclotron in the world with a pole diameter of 3000 mm(U-300). It was designed for accelerating heavy ions for synthesis of transuranium elements. The accelerator was put into service under the direction of G.N. Flërov at Dubna in 1961.[22]

Starting in 1953–1954, studies in the field of nuclear physics began to develop intensively in the countries of the socialist alliance. The German Democratic Republic, the Polish People's Republic, the Socialist Republic of Rumania, and the Czechoslovak Socialist Republic applied to the government of the Soviet Union with a request for installing cyclotrons for them. These cyclotrons were required to be reliable in operation, relatively simple to employ, and to have sufficiently effective biological shielding. A typical design of such a cyclotron, the U-120, was built by the associates of the NIIÉFA and the associates of the Institute of Atomic Energy.[23] These cyclotrons were brought into operation in the period 1957–1958, and made it possible to obtain the necessary experience in operating such installations and in performing experiments in nuclear physics.

In 1955 at the Geneva conference, Lawrence reported on experiments performed on electron models to design a cyclotron having an azimuthal variation of the magnetic field. Experiments performed on a model having the poles of the magnet in the shape of a cloverleaf convincingly showed the possibility of building a cyclotron with a constant frequency of the accelerating voltage. This would allow one in principle to accelerate charged particles to the energies obtained in modern synchrotrons, but with far larger particle currents. We can consider the date of publication of Ref. 24 to be the second birth of Thomas' remarkable idea.

A study by Kerst and Simon[25] published in the same year merits attention. Here the possibility was studied for the first time of employing in cyclic accelerators magnetic fields whose intensity varies periodically, both in azimuth and along the radius. The advantage of using such fields in cyclotron-type accelerators consists of the possibility in principle of increasing the limiting energy for protons up to 1000 MeV.

In 1957 in the Institute of Atomic Energy a very effective heated-cathode source of multiply charged ions[26] was developed and brought into use.

In the same year E.M. Moroz and M.S. Rabinovich suggested using stationary magnetic fields with spatial variation.[27]

Also in the same year 1957 a report was published on the starting of a classical cyclotron in the Institute of Nuclear Physics of the Czechoslovakian Academy of Sciences.

In 1958 the NIIÉFA jointly with the Institute of Atomic Energy completed the design of a production model of the most highly developed classical cyclotron with a pole diameter of 1500 mm (the U-150). The cyclotron allowed deuterons to be accelerated to an energy of 20 MeV. Four of these cyclotrons were built. Two of them allowed the ion beam to be extracted into a special station with biological shielding situated 25 meters from the accelerator chamber of the cyclotron. One of them was installed at Alma-Ata and was put into use in 1956.[28] The second one was put into operation in the same year under the direction of N.N. Krasnov in the Physico-Energetic Institute (Obninsk). Subsequently this accelerator was improved and mainly served for production of isotopes.

A design published in 1958 by Blosser *et al.*[29] of a four-sector cyclotron with azimuthal variation of the magnetic field merits attention.

In 1959 R. Walton *et al.* first applied a computer to calculate the dynamics of motion of the accelerated particles.

The four-sector cyclotron of Heyn installed in Delft in 1958[30] should be considered to be the first cyclotron with azimuthal variation of the magnetic field that had no substantial phase losses of the ion beam. Protons were accelerated in it to an energy of 12 MeV.

Based on the theory of the phase motion and spatial stability developed in Dubna, Harwell, and Oak Ridge in the period 1953–1958, a working model of a large steep-spiral isochronous cyclotron with six spirals attached to the covers of the accelerator chamber was built at Dubna in 1959 under the direction of V.P. Dzhelepov and V.P. Dmitrievskiĭ[31] on the basis of a U-120 cyclotron. In this model deuterons were accelerated to an energy of 13 MeV with a high-frequency voltage on the dees of only 5 kV. Phase losses were not observed with the model. The acceleration regime was isochronous.

In the same year Yu.A. Zavenyagin, R.A. Meshcherov, E.S. Mironov, L.M. Nemenov, and Yu.A. Kholmovskiĭ[32,33] accelerated deuterons in a magnetic field having azimuthal variation to an energy of 24 MeV in the reconstructed cyclotron of the Institute of Atomic Energy. The variation of the magnetic field was generated by three sectors. The depth of modulation of the field amounted to ±15%. The shape of the magnetic field was corrected with electrical coils.

These studies were continued in 1960.[34] The limiting energy of deuterons accelerated in the 1.5-meter cyclotron amounted to the record-setting value of 32 MeV. The regulation of the energy of the ions being accelerated was carried out in the range of magnetic field induction from 5 to 17 kG. The currents in the extracted beam were as much as 70 μA.

In 1962 V.P. Dzhelepov, V.P. Dmitrievskiĭ, B.M. Zamolodchikov, and V.V. Kol'ga proposed the idea of building a new type of accelerator—a ring cyclotron with hard focusing.[35] The theoretical development and the experimental study of the dynamics of the particles that were performed on an electron model of the accelerator showed the actual possibility of building a cyclotron of energy 800 MeV for protons.[36]

In 1962 the Institute of Nuclear Physics (Krakow) reported on the operation (from 1957) of a classical cyclotron with a pole diameter of 480 mm. The ion source of the cyclotron had a vertical design.

A report followed in early 1963 on the starting at Oak Ridge (USA) of the most highly developed isochronous cyclotron with a regulable ion energy.[37] The diameter of the poles of the accelerator was 1930 mm. The number of sectors was three, with one dee of 180° extent. The cyclotron made it possible to accelerate protons to an energy of 75 MeV, and deuterons to 40 MeV. The current in the extracted beam was 100 μA. Numerous electrical coils served for correcting the magnetic field. Hydraulically clamped contacts were employed in the resonance system. The cyclotron building incorporated an original plan of the stations and a well planned system for extracting the beams. This accelerator was the basis for the subsequent design of isochronous cyclotrons, and has been the best isochronous accelerator in world practice over the course of many years.

It was reported in 1963 that an isochronous cyclotron with a pole diameter of 2250 mm had been put into operation in Karlsruhe (West Germany).[38] The cyclotron was designed for accelerating deuterons to the fixed energy of 55 MeV. The structure of the magnetic field was produced by three sectors, each of 60° extent. Three dees were installed in the valleys. The resonance circuit included three coaxial lines. Each dee could be removed individually from the accelerator chamber. The high-frequency voltage was 40 kV. Owing to the presence of the three dees, a particle received an energy gain of 240 keV per revolution. Ten electrical coils were employed to correct the magnetic field. The location of the dees in the valleys made a minimal gap between the poles of the magnet possible. Deuterons were accelerated in this cyclotron to an energy of 50 MeV. The current inside the accelerator chamber amounted to about 2 mA, and 10 μA in the extracted beam. The ion source had a vertical design. Without question, the many ideas embodied in the design of this accelerator are original, but they greatly complicate the construction.

In the same year Willax[39] reported on a completed design of a "meson factory" consisting of two stages. The first stage, or injector, was an isochronous cyclotron from the Philips firm, which accelerated protons to an energy of 70 MeV. The second stage was a ring isochronous cyclotron, which accelerated the protons to an energy of 500 MeV. In order to increase the depth of variation of the magnetic field of the ring cyclotron, the usual magnetic system was converted into a divided-sector system. This magnetic structure made it possible to solve the problem of creating a highly efficient accelerating system by using four resonators situated in the space between the magnets. Here the energy gain per revolution was 2.4 MeV. The design made a strong impression, yet difficulties which the authors would encounter in building it were already clearly apparent.

The year 1964 was marked by an original study by G.N. Vyalov, Yu.Ts. Oganesyan, and G.N. Flërov. For the first time in world practice, the authors proposed an original extraction of the charged particles by a charge-transfer method. This was done in the two-meter isochronous cyclotron at Dubna.

In 1965 a report was published on the building in Milan (Italy) of a three-sector isochronous cyclotron with a pole diameter of 1660 mm, in which protons were accelerated to an energy of 45 MeV.

In the same year an isochronous cyclotron was put into service at Harwell (England). The pole diameter of the cyclotron was 1780 mm. The variation of the magnetic field was carried out with three spiral sectors. Protons were accelerated in this accelerator to an energy of 50 MeV. Multiply charged ions were also accelerated.

A publication by Blosser (1969) on a Michigan (USA) three-sector isochronous cyclotron with a pole diameter of 1700 mm merits especial attention. Protons were accelerated in it to an energy of 56 MeV. Owing to phase selection of the beam and outstanding stabilization of the parameters of the accelerator, unique characteristics were obtained in the extracted beam (an emittance of the order of 77 mm · mrad and an energy inhomogeneity of 2×10^{-4}).

In this same year V.P. Dmitrievskiĭ[40] reported on the development of a design for a monoenergetic cyclotron with unique parameters. The maximum proton energy was 80 MeV, and 60 MeV for deuterons, 120 MeV for ^{3}He, and 180 MeV for ^{6}Li. The current in the extracted beam was of the order of 100 μA. The energy scatter in the extracted beam was 1×10^{-4}. The range of continuous variation of energy was 1 : 4.

In 1965 Li ions were accelerated in the cyclotron of the Institute of Atomic Energy (Moscow) for the first time in world practice.[41]

A proposal was published in 1967 at the 7th International Conference on High-Energy Accelerators (Cambridge) of two-cycle acceleration of multiply charged ions in a single cyclotron with intermediate charge-transfer of the ions.[54] This proposal was first realized at Oak Ridge in 1972.[55] The realization of this proposal allows one to increase the limiting energy for ions in an accelerator by a factor of $(Z_2/Z_1)^2$, where Z_1 is the charge of the ion before charge-transfer and Z_2 is the charge of the ion after charge-transfer.

A four-sector isochronous cyclotron with a pole diameter of 2120 mm was put into service in 1968 at Grenoble (France). Protons were accelerated in this cyclotron to an energy of 60 MeV. The ions $^{14}N^{5+}$, $^{16}O^{6+}$, $^{20}Ne^{6+}$, and $^{40}Ar^{6+}$ were also accelerated. The cyclotron was designed for nuclear physics studies, and also for operation in conjunction with a mass spectrometer.

A three-sector isochronous cyclotron with a regulable ion energy also began to operate in the same year at Bonn (West Germany). The diameter of the poles of the magnet was 2000 mm. Protons were accelerated in this cyclotron in the energy range from 14 to 30 MeV. In addition, the heavy ions $^{12}C^{4+}$ were accelerated to 85 MeV and $^{14}N^{5+}$ to 100 MeV. The cyclotron is employed for spectrometric studies, time-of-flight studies, operation in conjunction with a mass spectrometer, and isotope production.

A three-sector isochronous cyclotron with a regulable ion energy was put in service in 1969 in the Institute of Nuclear Studies at Julich (West Germany). The diameter of the poles of the electromagnet is 3300 mm. The accelerator has three dees. The design of this cyclotron is analogous to the accelerator installed at Karlsruhe (West Germany) in 1963, but it permits regulation of the energy of the ions being accelerated. Protons were accelerated in this cyclotron in the energy range from 22.5 to 45 MeV, deuterons from 45 to 90 MeV, ^{3}He from 67 to 185 MeV, and ^{4}He from 90 to 180 MeV. The accelerator is employed for nuclear physics studies, isotope production, and in the field of applied chemistry.

An accelerator complex was created in 1971 at Dubna under the direction of G.N. Flërov.[42] It consists of two cyclotrons (the classical U-310 cyclotron and the isochronous U-200 cyclotron). Ions accelerated in the first cyclotron were injected into the second one. A charge-transfer device was installed in the second cyclotron to increase the charge on the ions. This led to a substantial increase in the energy of the ions being accelerated. The system was built for studying the interaction of heavy ions with matter and synthesis of new transuranium elements. A 1.5-meter, three-sector, isochronous cyclotron with a regulable ion energy was put into service in 1972 for the first time in the Soviet Union at the Institute of Nuclear Physics (Alma-Ata) under the direction of A.A. Arzumanov and L.M. Nemenov.[43] Protons were accelerated in the cyclotron from 7 to 30 MeV, deuterons from 14 to 25 MeV, and α-particles from 29 to 50 MeV, with extracted beam currents up to 50 μA. Helium-3 ions were accelerated in the energy range from 18 to 62 MeV. The operation of the cyclotron was carried out entirely by remote control. The accelerated ion beam was transported to an experimental room 25 meters away. The isochronous cyclotron was built on the basis of the 1.5-meter classical U-150 cyclotron.

In the same year a paper was published by V.P. Dmitrievskiĭ, V.V. Kol'ga, and N.I. Polumordvinova,[44] who theoretically showed the possibility of a substantial separation of the orbits in a cyclotron having spatial variation of the magnetic field. Under certain conditions this method can enable a 100% extraction of the beam from the cyclotron. In 1974 this method was tested experimentally on an electron model of a cyclotron.[45]

In 1973 a four-sector isochronous cyclotron with a pole diameter of 2670 mm was put into service in Maryland (USA). It allowed acceleration of protons to the record-setting energy of 100 MeV.

In this same year an isochronous cyclotron that accelerated protons to 80 MeV was put into service at Louvain (Belgium), and construction was completed at Groningen (Netherlands) of a four-sector isochronous cyclotron with a pole diameter of 2800 mm, in which protons were accelerated to 70 MeV.

In this same year the National Institute of Radiological Studies (Japan) put into service an isochronous cyclotron with a regulable ion energy. The cyclotron had a magnet pole diameter of 2150 mm. The variation of the magnetic field was brought about with four spiral sectors. Protons were accelerated from 8 to 70 MeV, deuterons from 16 to 43 MeV, and helium ions from 32 to 86 MeV. The accelerator is mainly used for isotope production and neutron therapy.

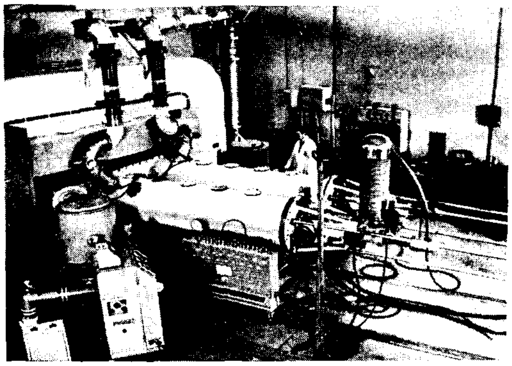

FIG. 5. Overall view of the Kazakhstan (Alma-Ata) isochronous cyclotron (1971). One can see the divided sectors and resonators in the intervals between them (1974).

The outstanding event of 1974 was the putting into service at Zürich (Switzerland) of the first cyclic meson factory in the world (SIN), the design for which was reported at Geneva in 1963. Protons were accelerated to an energy of 590 MeV. The beam currents were as much as 100 μA.

In 1975 construction was completed in Indiana (USA) of a ring isochronous cyclotron with divided sectors, which allowed acceleration of protons to an energy of 200 MeV (the final acceleration radius was 3300 mm). The accelerator complex included two preliminary cascades (a high-voltage tube and an injector cyclotron) in addition to the ring cyclotron.

It was reported in the same year that protons had been accelerated to an energy of 75 MeV in the isochronous cyclotron at Osaka (Japan).

Without question, a major event of this year was the report of the construction at Vancouver (Canada) of the isochronous cyclotron "TRIUMF".[46] The aim of attaining a highly efficient extraction of the charged-particle beam led to the creation of an original design of a six-sector isochronous cyclotron with a pole diameter of 17 m. Negative hydrogen ions were accelerated in the cyclotron with a magnetic field induction of only 5 kG. A charge-transfer target was set up at the final radius of the accelerator, and after passing through it, practically the entire beam was extracted from the accelerator chamber. Hydrogen ions were accelerated in this cyclotron to an energy of 520 MeV.

In recent years (1978) the same group has been considering a project of building a three-stage accelerator, which will allow accelerating protons to 8.5 GeV. The injector will be "TRIUMF", from which protons accelerated to 450 MeV will enter a ring isochronous cyclotron of 10-meter radius with 15 sectors. Protons accelerated to 3 GeV are admitted to the following ring accelerator of 20 meter radius with 30 sectors, where they are accelerated to an energy of 8.5 GeV. It is proposed that magnets of the second and third stages should have superconducting coils. The accelerating system of the ring cyclotrons consists of resonators analogous to those of the accelerator at Zürich.

In 1977 A.V. Stepanov *et al.*[47] published data on the compact isochronous cyclotron with pole diameter 1030 mm that was built in 1974 at the D.V. Efremov NIIÉFA and was designed to accelerate hydrogen and helium ions over a broad energy range. The structure of the magnetic field is three-sectored and "weakly spiral." The ion source is of the axial type. The beam is extracted with an electrostatic deflecting system and a radially focusing magnetic channel.

In 1978 the three-sector isochronous cyclotron U-240, which is the largest in the USSR and has a regulable ion

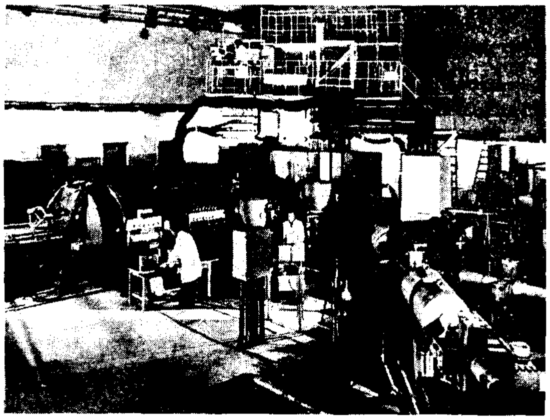

FIG. 6. Overall view of the isochronous cyclotron U-240 (1977).

energy, was put into service at Kiev under the direction of Yu. G. Basargin, A. F. Linev, and R. N. Litunovskiĭ. The diameter of the poles of the cyclotron is 2400 mm. Up to the present time the regimes of service with an extracted beam up to an energy of 80 MeV for protons have been completely worked out. The cyclotron is outfitted with the most modern apparatus for diagnostics and study of the beam quality, as well as with the pertinent automation.

In this same year a 1.5-meter three-sector spiral isochronous cyclotron with a regulable ion energy was put into service in the I. V. Kurchatov Institute of Atomic Energy under the direction of N. I. Venikov.[48] The shape of the magnetic field is corrected with 18 pairs of electrical coils. Nine pairs of pickup electrodes are installed in the accelerator chamber for monitoring the isochronicity of the regime. Slit focusing diaphragms are set up on the dees. The energy of the accelerated ions is regulated over a broad range. Protons are accelerated to an energy of 35 MeV, ^{3}He ions to 70 MeV, and deuterons to 30 MeV. The best intensities in world practice are obtained in the beam for such ions as $^7Li^{3+}$, $^9Be^{3+}$, $^{12}C^{4+}$, $^{14}N^{5+}$, and $^{16}O^{6+}$.

A three-sector isochronous cyclotron with a regulable ion energy has been put into service at Calcutta (India). The diameter of the pole pieces is 2240 mm. Protons are accelerated from 6 to 60 MeV, and deuterons from 12 to 65 MeV. The current of the extracted beam is 100 μA.

An isochronous cyclotron with divided sectors has been started at the Hahn-Meitner Institute of Nuclear Studies (West Berlin). The pole diameter is 3800 mm. The injector is a 6-MeV electrostatic generator. Protons are accelerated to 50 MeV, Ne to 200 MeV, and Ar to 200 MeV.

In this same year scientific collaborators at Dubna and in Czechoslovakia developed and built an isochronous cyclotron with a regulable ion energy on the basis of the classical U-120 cyclotron. The cyclotron allows one to accelerate protons from 12.5 to 40 MeV, deuterons from 8.4 to 20.3 MeV, and $^3He^{2+}$ ions from 16.9 to 54.4 MeV. Protons have been accelerated to 40 MeV in a cyclotron with a pole diameter of 1200 mm with a regulable ion energy for the first time in world practice.[49]

One of the largest complexes for accelerating multiply charged ions (Ganil) is being built at Caen (France).[50] The accelerator will have three stages: the first is a small cyclotron; the second is an isochronous cyclotron with divided sectors of diameter 6900 mm. After stripping, the ions are injected into the third stage, an isochronous cyclotron analogous to the second stage. The complex enables acceleration of C ions to 100 MeV/nucleon, Kr ions to 50 MeV/nucleon, and U ions to 8 MeV/nucleon. It is expected that the accelerator will be put into service in 1982.

As we know, there are two ways for increasing the energy of ions being accelerated in a cyclotron: increase in the final acceleration radius, and increase in the magnetic field intensity. Accelerator technology at first took the first path by increasing the dimensions of the pole pieces of the magnet. Further increase in the dimensions has led to an extreme mass of the electromagnet and to an enormous power supply for the coils. The operation of such instruments has become extremely costly.

In recent years scientists of many countries have studied the question of using electromagnets with superconducting coils in order to increase the magnetic field intensity. This solution of the problem allows one to diminish substantially the dimensions of the electromagnets and to make their operation less costly. Economic calculations have shown that use of such magnets seems profitable, in spite of design difficulties and of the expensive coils.

In 1978 two reports were given at the 8th International Conference on Cyclotrons and Their Application (Bloomington, Indiana, USA) on isochronous cyclotrons with superconducting coils.

H. G. Blosser[51] reported on a three-sector isochronous cyclotron with superconducting coils for accelerating heavy ions (Michigan, USA). The diameter of the poles of the cyclotron is 1420 mm. The maximum magnetic field intensity is 58 kOe, and the minimum 49 kOe, with a mean field of 43 kOe. The mass of the coil (Nb, Ti) is 8 tons. Only the coils are situated in the cryostat at the temperature of liquid helium. The $^{12}C^{5+}$ ions will be accelerated to 800 MeV, $^{20}Ne^{6+}$ to 900 MeV, $^{40}Ar^{8+}$ to 800 MeV, and $^{78}Kr^{8+}$ to 410 MeV. The accelerator will be started in 1980. It is proposed to employ this cyclotron subsequently as an injector for a large divided-sector accelerator.

At this same conference, a group of scientists reported on a four-sector isochronous cyclotron with superconductive coils at Chalk River (Canada).[52] The diameter of the poles of the electromagnet is 1386 mm. The maximum magnetic field intensity is 60 kOe, the minimum is 50 kOe, and the mean field is 43 kOe. The mass of the coils (Nb, Ti) is 10 tons. The injector for the cyclotron is a 13-MeV electrostatic generator. *The* cyclotron is designed for accelerating heavy ions from Li (50 MeV/nucleon) to U (10 MeV/nucleon). Only the coils of the magnet placed in a cryostat are cooled to liquid-helium temperature. It is expected that the accelerator will be put into service in 1981.

One of the largest isochronous cyclotrons in the world for accelerating heavy ions, the U-400, was put into operation in 1979 under the direction of G. N. Flërov and Yu. Ts. Oganesyan.[53] The diameter of the poles of the electromagnet is 4000 mm. In contrast to similar accelerators, the mean magnetic field of the cyclotron is very large: 20–22 kOe. The beam is extracted from the cyclotron by charge-transfer of the ions in an internal target. A current is obtained up to 3×10^{13} particles/s for $^{40}Ar^{4+}$ and $^{40}Ca^{4+}$ accelerated to an energy of 5.5 MeV/nucleon.

It is proposed subsequently to employ the U-400 cyclotron as an injector for an isochronous cyclotron with divided sectors and superconducting coils. The final acceleration radius is 5500 mm. This complex will enable acceleration of ions in the range from He to U at an energy of the accelerated ions from 256 to 50 MeV/nucleon.

Currently about 100 cyclotrons have been reported and are being employed on all the continents of the earth. In addition to studies in nuclear physics, cyclotrons are widely used for solving applied problems (production of radioactive isotopes, implantation of dopants into semiconductors, preparation of filters, etc.), and also in medicine for therapy.

In closing, I must not fail to take up the factors that have facilitated the development of cyclotron technology. Primarily, these have been the ever greater demands on accelerators from physicists studying the interaction of charged particles with matter. The development has also been facilitated by the numerous theoretical studies that have revealed new potentialities of the cyclotron.

Industry has been called upon ever more often to participate in the building of accelerators. The outstanding advances of radioelectronics have allowed the building of instruments that seemed but a fantasy in the recent past. The perfection of computers has advanced the boundaries of study of particle dynamics. Calculations that took years have come to be performed in weeks. The advent of semiautomatic and automatic devices on-line with a computer, has made it possible to solve the complicated problem of the laborious processes of shaping and measuring magnetic fields within periods that can be envisioned. Electronics has given rise to reliable methods of stabilizing accelerator parameters, and to devices for diagnostics and for studies of beam quality. All this is equipped with modern automation. The development of ion optics has allowed solution of the problems of focusing and transporting extracted beams at a completely new level. Thus, evidently, the advances in accelerator technology are inseparable from the technological revolution that has taken place in recent decades.

What requirements must be imposed on newly built accelerators?

It would seem that a new accelerator must differ qualitatively from its predecessors and must make it possible to expand studies, both in the field of fundamental and of applied sciences.

The fundamental requirements imposed on a contemporary accelerator are: the greatest attainable energy of the accelerated ions and intensity of the extracted beam, minimal energy scatter of the ions in the extracted beam, and a prescribed emittance of the beam depending on the nature of the studies being performed. One must be able to regulate the energy of the ions being accelerated over a broad range, and to accelerate both light and heavy ions from hydrogen to uranium.

The construction of an accelerator that simultaneously satisfies all these requirements is not practical. Therefore one must find a compromise solution in each individual case.

As we see it, in designing a new accelerator, one must proceed in a goal-directed fashion without creating a universal instrument. As a rule, universality complicates and increases the cost of the installation, and does not allow one to build an accelerator with unique parameters. Moreover, owing to their complexity, universal instruments operate less reliably. It is most rational to make a clearcut choice of the set of problems to be solved and to build a goal-directed accelerator. Analysis of the history of the development of the cyclotron offers a convincing proof of this.

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