History of the invention and development of accelerators (1922–1932)

A. P. Grinberg

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences, Leningrad
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The idea that for extended study of nuclear reactions natural fast particles should be replaced by artificially accelerated particles was first expressed by L. V. Mysovskiĭ in 1922. At that time under his guidance the first attempt was made to construct a high-voltage accelerator utilizing a potential difference of ~1 MV. In this review we describe all proposals and experimental developments of accelerators known from the literature and belonging to the first decade of these studies. This period has great significance in the history of the development of accelerators, since it was in this period that the basic principles of almost all presently operating accelerators were proposed and verified.

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It is well known that the discovery and first experimental studies of nuclear reactions took place in 1919. Ernest Rutherford and his colleagues carried out these studies by using as bombarding particles the α particles of natural radioactive elements, mainly RaC′ with energy ~7.7 MeV.

The idea that arose in the twenties that the α particles in these investigations should be replaced by artificially produced fast particles now seems so simple and obvious that its author is almost never mentioned. Nevertheless it marked a qualitative advance in the development of experimental nuclear physics. This landmark in the history of physics deserves more detailed discussion.

In this review we will set forth the history of the first decade of development of the accelerators which were created for research in nuclear physics. We describe the work of all inventors and scientists who took part in this first stage of accelerator development. This period turned out to be extraordinarily fruitful; during this time there were proposed and, in most cases, experimentally checked the main principles on which the operation of contemporary accelerators is based.

Lev Vladimirovich Mysovskiĭ (1888–1939). L. V. Mysovskiĭ was the first physicist to pose the problem of creating an accelerator of charged particles comparable in energy with natural α particles. He was one of several Russian physicists occupied with the study of radioactivity in the prerevolutionary period. In 1918 he took an active part in organization of the Radium Division of the State Radiological and X-Ray Institute in Petrograd. In 1922 the State Radium Institute in the Russian Academy of Sciences was organized. In this institute Mysovskiĭ headed the physics division.

In 1923 Mysovskiĭ and V. N. Rukavishnikov published a small article entitled "Acceleration of Positive and Negative Ions by the Field of a High-Frequency Alternating Current.[1] This paper was delivered at the session of the council of the State Radium Institute on July 24, 1922.[1)]

The work of Mysovskiĭ and Rukavishnikov contains not only the idea of the necessity of developing a source of artificial α particles, but also the proposal of an interesting accelerator design and the description of the first experiments with a model. They had in mind acceleration of helium ions, and perhaps also natural α particles, acting on them with an electric field with a potential difference of 1–2 MV. It was noted that the difficulty in solving this problem consists not so much in producing the high-voltage generator as in development of a vacuum tube which can operate at such a high field strength. Mysovskiĭ proposed a clever and simple idea which avoided the need for a feed-through insulator for introducing the high voltage into the vacuum tube.

As a high-voltage generator it was proposed to use a Tesla transformer whose secondary winding was placed in a glass tube pumped to a high vacuum. Another feature of this transformer was the fact that it was excited by a vacuum-tube high-frequency generator, i.e., it operated with coherent oscillations. One end of the secondary winding was grounded, and the crest of the high voltage was obtained at the other end. It was suggested that at this point it would be possible to obtain a high-frequency voltage of 1–2 MV relative to ground. The accelerating electric field was produced between this point and a grounded electrode placed as close to it as possible in the same vacuum tube.

The article by Mysovskiĭ and Rukavishnikov contains no illustrations. In Fig. 1 we have shown a schematic representation of the apparatus, corresponding to the description given in the article.[2)] In the first stage of the development no ion source was placed in the tube.

Further work of Mysovskiĭ's laboratory in the area of vacuum Tesla transformers is described in Rukavishnikov's dissertation[2] and in a review article by Mysovskiĭ.[3]

An attempt to construct a high-voltage generator very reminiscent of the vacuum transformer proposed by Mysovskiĭ was undertaken by C. C. Lauritsen and R.

[1)]V. N. Rukavishnikov (1895–1960) began work at Mysovskiĭ's laboratory in 1922. At that time he was a student of the Petrograd Electrotechnical Institute.

[2)]Additional information on the design of the vacuum transformers developed at the Radium Institute has been communicated by D. G. Alkhazov, who took part in these developments for a number of years, beginning in 1930.

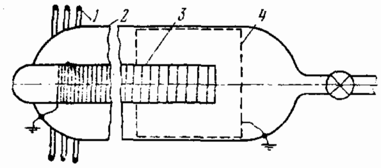

FIG. 1. Diagram of a vacuum Tesla transformer device (after Mysovskiĭ). 1—Primary transformer winding, 2—glass tube, 3—secondary transformer winding (1500 turns), 4—copper grid.

Bennett in 1928 at the California Institute of Technology. A brief description of this work appeared later.[4] The apparatus consisted of an evacuated glass cylinder of diameter 305 mm and length ~1.4 m, inside which was mounted a shorter cylinder with a secondary winding. The primary winding was placed outside the large cylinder. Experiments with this apparatus were discontinued, since it was difficult to outgas and the high-frequency power available was small.

Many years later the high-voltage generator proposed by Mysovskiĭ was again invented by D. H. Sloan, a colleague of E. O. Lawrence at the University of California in Berkeley. Sloan gave this apparatus its technically final form: The vacuum vessel was a large metal tank, and the transformer secondary winding was made in the form of a rigid coil of copper tubing fastened at one end, in which cooling water flowed.[5-7] A vacuum-tube generator with a power of 70 kW and a wavelength of 50 m was used to supply the power. Sloan obtained an accelerating voltage of ~600 kV in this apparatus.

In 1922 the idea of using artificially accelerated particles was suggested also by another Russian physicist, A. K. Timiryazev. In the lecture on the subject of atomic energy given at the Science and Technology Club in Moscow on February 15 and repeated on April 7 at the club of the Ya. M. Sverdlov Communist University, after describing Rutherford's experiments on disintegration of nuclei, Timiryazev said "It is possible that the so-called positive rays produced in electrical discharge tubes, when we learn to give them the same velocities as α particles, will assist us in disintegration of atoms. This is completely possible, but as yet we cannot be sure of it."[8]

Gustav Adolph Ising (1883—1960) (University of Stockholm). An important landmark in the history of the development of accelerators was the article by Ising, "A Method for Obtaining High-Energy Canal Rays" published in 1925.[9]

Gustav Ising, an eminent Swedish geophysicist, was a member of the Swedish Academy of Sciences from 1935, and was well known as a skilled designer of scientific apparatus, especially sensitive electrometers, galvanometers, and gravimeters of various types.[10]

Ising's scientific interests were diverse. Sometimes he published articles in fields not related to his main activity, for example on study of the magnetic properties of varved clay and on the theory of a possible mechanism for orientation of birds during migrations.

The article in which Ising proposed a new method of accelerating charged particles was of this type, standing by itself. In this article two basic ideas for indirect acceleration methods, i.e., methods not requiring large potential differences, were proposed for the first time—multiple use of the same comparatively small potential difference for communicating to a particle a large kinetic energy, and synchronism (resonance) between the appearance of a particle at a given place in the apparatus and the appearance of an accelerating field at the same place.

In contemporary language the apparatus invented by Ising is called a linear resonance accelerator. A series of drift tubes were placed in a evacuated vessel. To these drift tubes in turn was fed a voltage pulse arising when a spark jumped across a spherical gap. The necessary time sequence of arrival of the pulse at the drift tubes was achieved by giving the wires connecting the tubes to the spark gap different lengths: The wire to each succeeding tube was longer than that to the preceding tube by a definite, calculated amount.

Ising noted that the accelerator proposed by him was more suitable for acceleration of ions than electrons. Ising's proposal contained no errors, and was realizable. In his article Ising wrote that he hoped soon to have the possibility of beginning experiments. However, for a number of years no reports appeared regarding Ising's attempts to build a linear accelerator. Only in 1933 in a lengthy review "High-Voltage Methods of Distintegrating Atoms"[11] (in Swedish) did Ising return to this subject. He wrote (page 173): "Directly after publication of the principle, an accelerating tube was prepared for the purpose of carrying out a preliminary trial of this idea. Instead of canal rays, electrons from a hot filament were utilized. One of the students working with the author performed some experiments, but they were soon abandoned, partly as a result of difficulties in obtaining a vacuum, and partly because he was engaged at the same time in other work. In addition, the author must acknowledge that at that time he was unnecessarily skeptical in evaluating the practical possibilities of the method, particularly in regard to the beam intensity. One reason is that it was possible to obtain only a relatively low repetition rate of spark discharges; a second, even more important reason is that a large loss of particles at the walls was expected, as a result of which the number of particles would fall off roughly exponentially as the number of drift tubes increased." Later Ising points out that one could hope to obtain a more intense beam is the accelerator electrodes were supplied with a high-frequency voltage; however, oscillations with very short wavelength (several tens of meters) would be required, so that it would be very difficult to obtain a sufficiently large accelerating voltage.

It should be noted that two linear accelerators corresponding exactly to Ising's suggestion were constructed in 1934—1935 by Beams and Trotter at Virginia State University.[12,13] In the first accelerator, electrons were accelerated to 1.3 MeV, and in the second to 2.5 MeV. The authors did not cite Ising's work.

The important of Ising's work was emphasized by E. O. Lawrence in his Nobel lecture.[14] Ising's article was the starting point for R. Wideröe, who carried out the first successful experiment with a small linear accelerator,[15] and Wideröe's article in turn impelled Lawrence to the idea of the cyclotron at the beginning of 1929.

Gregory Breit (1899) and **Merle Antony Tuve** (1901) (Department of Terrestrial Magnetism, Carnegie Institution, Washington). The group led by Breit began its nuclear-physics program in 1926. Two directions were explored: 1) creation of a compact Tesla transformer of several million volts and an appropriate vacuum tube,[16,17] and 2) acceleration of electrons in a toroidal electric field, i.e., without use of high voltage (see ref. 16, page 209).

The first direction was explored by the group for several years. They were quickly able to obtain a potential difference of ~3 MV with a Tesla transformer placed in transformer oil; by using oil at a pressure of 35 atm they obtained[18] ~5 MV. A number of tubes were built. These were multisection glass tubes whose design was based on an idea of W. D. Coolidge (see below). In 1930 a 15-section tube for 1.4 MV was described.[19] The first accelerated particle beam was obtained in January 1930 and consisted of electrons with energy ~1 MeV;[20] by the end of the year the electron energy had been raised to ~2 MeV.[21] In 1931 a beam of protons with energy ~1 MeV was obtained.[22]

In the summer of 1931 it became clear that the Tesla transformer was not a promising high-voltage generator for nuclear research. Tuve's group (after 1930 Breit was no longer involved in these developments) jointly with Robert Van de Graaff began construction of an electrostatic generator with a sphere of 2 m diameter.

The second direction of the work of the group, in contrast to the first, appeared to be an endeavor to which little effort was devoted. No promising results were obtained. After tests lasting three weeks, the work was discontinued. It can be supposed, however, that some later workers, in attempting to make an induction electronic accelerator, borrowed the idea of such an accelerator from this pioneering work, since the scientific world was informed of the basic idea of the new method of electronic acceleration by means of a brief publication[16] (it is true, in a medium of limited distribution).

We note that Joseph Slepian had invented the induction electron accelerator already in 1922.[23] However, he did not publish his proposal in the periodical literature, and at that time, as a rule, the patent literature did not come to the attention of physicists. Therefore Slepian's invention remained unknown and apparently had no influence on the development of accelerators. In particular, the Washington group may not have known of Slepian's idea. The first citation of his patent appeared only in 1939 in a review chapter of a book by A. Bouwers well known in its time.[24] We will have more to say about Slepian's proposal below.

Let us return to the work of the Breit-Tuve group. The apparatus built by them had the following form.[16,25] An iron-free system of windings was connected to a high-voltage capacitor through a spark gap. On discharge of the capacitor, a magnetic field with an extremely high value of dH/dt was produced, namely $\sim 3 \times 10^9$ Oe/sec. This corresponded to an increase in electron energy of ~500 eV/turn. According to a calculation made by the authors, an accelerated electron located in an almost uniform magnetic field should move in a collapsing spiral and at the end of the acceleration, hitting a target with a radial coordinate of ~3 mm, should have an energy of 1.5–2 MeV. Electrons were injected into the chamber with an energy of ~50 keV and r_{init} = 35 mm. The process was repeated approximately once a second. The glass vacuum chamber of diameter ~76 mm was continuously pumped. In the theoretical portion of the work it was established that axial focusing of the accelerated electrons was necessary, and therefore the coils were designed so that the magnetic field strength fell off slightly from the center to the periphery in the working region.

The observed x rays were very weak and irregular. The authors made no further tests. Nevertheless, on the basis of our contemporary understanding of the processes occurring in an induction accelerator, we can consider that the apparatus was correctly built, so that the failure of the tests was due only to insufficient persistence of the experimenters.[3)]

Joseph Slepian (1891) (Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania). In contrast to the induction accelerator of the Washington group, in the accelerator proposed by Slepian[23] the functions of the magnetic field were separated: One magnetic system produced a guiding magnetic field, and a second system produced an inducing field. Slepian discussed two versions of the design of the accelerator, both being distinguished by the fact that the guiding magnetic field was constant with time. It is now well known that this form of induction accelerator can be used successfully only with use of a magnetic system with strong focusing.[26]

The design which Slepian favored had the following form. The magnetic system for production of the alternating magnetic flux consisted of an H-type electromagnet with a continuous central core (without an air gap) of square cross section. Coaxial with this core was placed a glass vacuum chamber in the shape of a doughnut of approximately elliptical cross section. The guiding magnetic field is produced by means of permanent magnets in the form of sectors located above and below the chamber. The trajectory of the accelerated electron has the form of an expanding spiral. The source of electrons was a hot filament mounted on the inner wall of the doughnut. The target was located near the outer wall. In the uniform and constant guiding field the electron hits the target after a comparatively small increase in energy in comparison with the initial energy (since $p_f/p_i = r_f/r_i$, where p is the electron momentum and r_f and r_i are respectively the radial coordinates of the target and filament.[4)] To overcome this basic difficulty, Slepian proposed to give the permanent magnets a special shape such as to make the guiding magnetic field nonuniform. However, he failed to notice that with the location proposed by him for the north and south poles of the permanent magnets the guiding magnetic field in the different parts of the vacuum-chamber cross section would have a different (opposite) direction, and in the vicinity of the chamber axis, $H = 0$. Of course, under these conditions the accelerator could not work.

The main positive content of the patent description of Slepian lies in the very idea of accelerating electrons by a toroidal electric field. We note that Slepian posed for himself an extremely difficult problem in regard to the final electron energy—in his x-ray tube the electrons had to be accelerated to ~100 keV. It is not

[3)]Success of the experiments may have been prevented by the absence of a grounded semiconducting covering on the inner walls of the chamber. Without such a covering the glass charges up and the strong electric field can unacceptability distort the electron trajectory; in addition, the electrons must be injected in short pulses.

[4)]In the case where there is no shaped electron injector in the form of an electron gun with sufficiently high anode voltage, the initial momentum p_i will be extremely low and the final electron momentum p_f will be correspondingly low.

known whether Slepian attempted to put his idea into practice.

Albert Bouwers (1893–1972) (Philips Research, Eindhoven, Holland). A very interesting induction electron accelerator was invented by A. Bouwers in 1923. However, he reported this only in 1939 (see ref. 24, page 83). Somewhat earlier a patent disclosure was made[27] in which Bouwers and Van den Berg set forth the idea of the accelerator. At the present time this apparatus is called a linear induction accelerator. A diagram showing its arrangement is given in Fig. 2.

William David Coolidge (1874–1975) (General Electric Research Laboratory, Schenectady, New York). In many of the studies cited above there are no direct indications that the authors considered the accelerated ions or electrons as a tool for nuclear research. Nevertheless, this intent of the developments is frequently clear from indirect indications or subsequent remarks of the authors. There are also other studies, however, in which the methods of obtaining fast electrons have been developed for another purpose, namely to obtain energetic x-ray beams. Of course, these studies also had great significance for the development of accelerators of more general application.

Of the early studies devoted to creation of superhigh-voltage x-ray tubes, the most important are those of W. D. Coolidge. In 1926 he suggested the idea of a cascade x-ray tube. Before Coolidge, the maximum voltage which it was possible to apply to a vacuum tube was 300 kV. Coolidge suggested placement of tubes equipped with thin windows for entrance and exit of the electrons, one after the other.[28] This design was the first step toward provision of a specified uniform potential distribution along the tube. This distribution is a most important principle which is utilized in all contemporary superhigh-voltage accelerator tubes.

In 1927 with a three-stage tube Coolidge obtained a beam of electrons emerging from vacuum into the atmosphere with a record energy[29,30] of ~900 keV. The source of high voltage was an induction coil with an interrupter (inductor).

Fritz Lange (1899) **and Arno Brasch** (1904–1963) (Physics Institute, University of Berlin). This group (initially it also included C. Urban) in 1926 set itself the goal of obtaining fast cathode and canal rays by means of high voltage applied to a vacuum tube and by this means investigating the disintegration of nuclei.[31-34] They began their program by studying the possibilities of using atmospheric electricity (lightning) as a source to supply the vacuum tube. These studies were carried out in the Swiss Alps near Lugano in the period from 1927 to April 1931. In the summer of 1928 Urban perished tragically from a lightning strike.

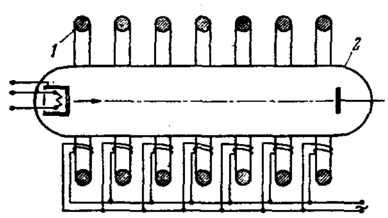

FIG. 2. Diagram of x-ray tube device with linear induction accelerator for electrons (after Bouwers). 1–Laminated iron core with winding (inductor), 2–evacuated glass tube.

This group developed several versions of the design of pulsed vacuum tubes. One of the first tubes maintained an alternating voltage of 1.2 MeV.[32a] In the mountain laboratory they prepared for tests a tube intended to support a pulsed voltage up to 5 MV.

Subsequently Lange and Brasch stopped their experiments with atmospheric electricity and turned to use of man-made high-voltage equipment. At that time the most powerful pulsed high-voltage generator in Europe was the Arkad'ev-Marx generator with maximum voltage 2.4 MV installed at the laboratory of the AEG transformer plant. In 1930 the new vacuum tube assembled from alternating metal and dielectric disks and rubber gaskets and mounted in a tank with transformer oil was able to operate at the full voltage of this generator. X rays with maximum energy 2.4 MeV were obtained.[32b] Subsequently protons with energy up to 900 keV were obtained.[33]

Ernest Rutherford (1871–1937) (Cavendish Laboratory, Cambridge University). At the beginning of the 1920s the main center of research in the field of experimental physics continued to be the Cavendish Laboratory headed by Rutherford. How did the transition from natural α particles to artificially obtained fast particles occur at this laboratory? We have the account of Niels Bohr, who in his recollections of Rutherford[35a] reported that for a period of several years (beginning approximately in 1924–A. P. G.) Chadwick urged Rutherford that the laboratory be occupied with construction of an appropriate charged-particle accelerator. However, Rutherford resisted this–he did not wish to "start such a large and expensive undertaking." Bohr explains this position of Rutherford's by the fact that "previously, astonishing progress had been made by him with very modest experimental equipment."

Somewhat later, in 1962, Chadwick himself had something to say on this question. Beginning in 1962, sometimes jointly with Rutherford, from time to time he undertook attempts to observe the existence of the neutron. In a letter sent to Rutherford in September 1924, Chadwick wrote: "I believe that we should engage in an extended search for the neutron. I am confident that I have an effective experimental arrangement..." In 1962, in a paper given at the Tenth International Congress on the History of Science at Ithaca, New York, Chadwick explained that, in writing these words, he had in mind bombardment of heavy atoms by fast protons. "I supposed that a voltage of at least 200 kV was necessary for acceleration of the protons. However, we did not have the necessary transformer and, in spite of the active interest of Rutherford, we did not have funds to carry out this extravagant plan... For a year or two I stood my ground... and attempted to find means of using a Tesla transformer for acceleration of ions in a discharge tube. I did not have the proper conditions and experience to carry out such things."[35b]

In 1927 a 24-year-old scholar from the University of Dublin, E. T. S. Walton, arrived at the Cavendish Laboratory in connection with the award to him of the 1851 Exposition scholarship, the biggest scholarship at that time in Great Britain. At Cambridge Walton occupied himself with development of indirect methods of acceleration of charged particles, i.e., methods not requiring use of high voltage. In contemporary language, Walton attempted to build a betatron and a linear resonance accelerator for ions.[36,27]

The basic ideas of these two accelerators, as we have said above, had been proposed previously in Slepian's patent and in Ising's article. However, Rutherford and Walton did not know about these studies or about the work of Breit's group.

At the end of 1927 Walton told Rutherford his idea of accelerating electrons by means of a circular electric field and expressed the desire to work on development of this method.[5)] Rutherford gave his consent. After some time Walton became convinced that there was not much hope for rapid completion of work on an induction electron accelerator, and began to think about other methods of particle acceleration. He arrived at the idea of a resonance linear accelerator with drift tubes. After making preliminary calculations and showing these to Rutherford, he obtained Rutherford's permission to begin experiments. It was proposed to accelerate cesium ions. In these experiments he utilized drift tubes whose two open ends were covered with wire grids, since it was admittedly essential that inside the tubes the electric field be completely absent. Walton points out that he made the same error as Ising: The use of grids on the drift tube openings resulted in removal of the focusing action of the accelerating gap.

His source of high-frequency voltage was a primitive LC generator with a spark gap. Walton considers that poor quality of this type of high-frequency generator was one of the main causes of failure of his experiments with the linear accelerator.

Walton did not publish his idea of the linear resonance accelerator, thinking that first he should obtain positive experimental results.[6)]

In regard to the attempts to build an iron-free betatron, Walton has described it in a detailed article.[38] In this article he presented an important theoretical result—the condition for radial stability of electron motion in an axially symmetric magnetic field, described in the most general form. It was shown that radial oscillations of the electrons about a fixed orbit should be observed.

It is possible that Walton would have carried his experiments with the induction accelerator to a successful result in spite of the modest facilities available.[39] However, Rutherford soon asked him to switch to another accelerator project which promised success much sooner than the first one.[37]

At the end of November in 1927 at the annual meeting of the Royal Society, Rutherford as usual delivered the presidential address.[40] This speech is often cited as the first expression of the idea that it was necessary to replace α particles by artificially obtained fast particles. As is clear from what we have said above, this statement does not correspond to reality. However, Rutherford in his speech formulated the problem for the more distant future. He said: "For a long time I have wanted to have available for research intense sources of atoms and electrons having individual energies much greater than the energies of α and β particles emitted by radioactive materials. I hope that I will still be able to see this wish fulfilled, but it is obvious that it will be necessary to overcome many experimental difficulties before this is accomplished even on a laboratory scale." This hope of Rutherford's was fated to come true only to a small degree, and only in respect to α particles: At the end of 1935 Lawrence's group in their first large cyclotron (with pole diameter 70 cm) accelerated α particles to an energy of 11 MeV;[41] this energy did exceed, although not by a large margin, the energy of the most energetic natural α particles.

The first working high-voltage accelerator in Rutherford's laboratory turned out to be an accelerator built by a former employee of the firm Metro-Vickers, A. Alibon. He supplied the laboratory, probably at the beginning of 1928, with a powerful 0.5-MV Tesla transformer belonging to this firm. In a specially prepared glass vacuum tube connected to this transformer, electrons were accelerated to 300 keV.[39,42]

In November 1928 G. A. Gamow came to the Cavendish Laboratory. He discussed with J. D. Cockcroft the results of a quantum-mechanical calculation of the probability of passage of a charged particle through a potential barrier. The theory predicted that this probability increases sharply with increasing energy of the particle, but even for protons with a comparatively modest energy the probability of penetration into a light nucleus turned out to be not too small.

This unexpected result brought about a radical change in the approach to the problem of obtaining fast particles. It turned out that there was no need to work to obtain charged particles with energies approaching those of natural α particles: The particles (and especially protons) can have significantly lower energy, but nuclear transformations can be successfully observed if the number of particles is sufficiently great.

Cockcroft made detailed calculations and reported his results in a memorandum given to Rutherford. Here he noted that even for a proton energy of only 100 keV one could hope to observe the result of penetration of protons into boron nuclei, and for lithium nuclei the conditions were even more favorable.[37,43] Cockcroft suggested that construction be started on a proton accelerator. Rutherford quickly consented. Cockcroft was soon joined by Walton. They worked about three years on building two versions of their accelerator. The story of this work will be continued later in the article in the section devoted to Cockcroft.

Rolf Wideröe (1902) (Technical High School, Aachen, Germany). Late in 1928 an article appeared which played an important role in the development of indirect acceleration methods. The author, R. Wideröe, presented in this article the content of his dissertation, which was presented on October 29, 1927. The author discussed two accelerators—a linear resonance accelerator and a cyclic induction accelerator.[15] Wideröe considered his linear accelerator to be a development of the suggestion of Ising; he arrived independently at the idea of the induction accelerator (he later indicated that he invented it in the autumn of 1922,[44] when he was a student at the Technical High School in Karlsruhe).

The development of the linear accelerator was carried to a successful conclusion. It is true that

[5)]This and the subsequent information on the initial period of Walton's work at the Cavendish Laboratory are contained in his letter dated April 29, 1975. I am deeply grateful to Professor Walton for this detailed letter.

[6)]Up to this time it has been possible to encounter in the literature only a fleeting metnion of Walton's linear accelerator. Cockcroft [36] noted that this was a primitive accelerator of the type which was later developed successfully by Lawrence and Sloan.

Wideröe's experimental apparatus was a minimal variant of such an accelerator: It contained only two accelerating gaps. The theory of such an accelerator was discussed, including questions of the law of increase of drift-tube length as a function of the number of the tube, the role of the finite length of the accelerating gap, and the energy spectrum of the particles at the accelerator output.

With an amplitude of the accelerating high-frequency voltage 20 kV, singly charged ions of potassium and sodium were accelerated to 40 keV. The energy of the ions was determined from their deflection in an electrostatic field.

In the theoretical part of the section on the cyclic induction accelerator, very important results were obtained. It was established that the electron accelerated by the action of an alternating magnetic flux possessing rotational symmetry can move in a circle of constant radius. Such a trajectory is significantly more satisfactory than a spiral. It was shown that the circular trajectory (the equilibrium orbit) is a circle coaxial with the inducing flux and satisfying the following condition: The average induction $\bar{B} = \Phi(r_0)/\pi r_0^2$ is equal to twice the induction at the points of a circle of radius r_0. This condition—the so-called 2 : 1 condition or betatron condition—is the basis of the theory of the contemporary induction accelerator—the betatron. In his article[15] Wideröe did not discuss the second very important condition, without which the acceleration of electrons in the betatron is impossible,—the condition of stability of the electron motion. As has been mentioned above, the stability condition was obtained by Walton at about that time.[7)]

Wideröe's experimental apparatus was designed to accelerate electrons up to ~6 MeV. Many design features of this apparatus are retained in the contemporary betatron. The alternating magnetic flux was produced by means of an electromagnet with an air gap, with a laminated core of silicon steel. (However, the winding of the electromagnet was supplied not by an alternating current but by current pulses.) The glass vacuum chamber had the shape of a doughnut. The electrons were given a relatively high initial energy of ~30 keV, and the electron beam was shaped in an electron gun. To spill the accelerated electrons from the equilibrium orbit, a special winding supplied by voltage pulses was provided.

Wideröe's main mistakes, as a result of which electron acceleration could not be obtained, were the absence of a semiconducting grounded coating on the inner walls of the vacuum chamber and the injection of electrons from an external source. The electron trajectory in a constant or relatively slowly rising magnetic field cannot have the form of a straight line segment which then transforms into a circle of constant radius.

Leo Szilard (1898—1964) (Physics Institute, University of Berlin). In the literature several patents of Leo Szilard on various accelerators are cited.[45,46] As it subsequently turned out, we should discuss not the patents, but the patent disclosures, since for one reason or another no patents were issued on these disclosures. This means that there were no patent descriptions of these inventions published by the patent offices of the corresponding countries, so that an acquaintance with the inventions could be obtained only by receiving material from the inventor himself. Szilard did not publish his ideas on accelerators in the periodical literature. Thus, we are discussing work which for a long time remained unknown and therefore had no effect on the development of accelerators. Nevertheless, it is evident that they are interesting for the history of science. A familiarity with these studies makes it possible to obtain an ideà of the level of development of certain branches of science at that time and permits one to see what the inventive mind could create on the basis of the knowledge accumulated by science and technology up to that time. Such information is interesting also as an illustration of the phenomenon of simultaneous discoveries, well known in the history of science. In addition, the proposals of different authors, which are for the most part identical, cannot fail to differ in their technical details, and these variants of the solution are sometimes interesting not only in their historical aspect.

In 1972 the collected works of Szilard[47] appeared in a book.[8)] A special section of the book reproduces selected patent disclosures from a number preserved in Szilard's scientific archives, and some of his patents. There is also an impressive list of all the patents obtained by him.[9)] It is curious that among Szilard's patents disclosed by him in the period 1927—1930, that there are eight patents whose co-author is A. Einstein.

The first invention of Szilard in the field of accelerators is described in a disclosure given at the Berlin patent office at the end of 1928.[49] In this disclosure a linear resonance accelerator is proposed. Szilard was undoubtedly not acquainted with Ising's article. We note that at that time Szilard, who was teaching in the University of Berlin, was occupied with physics research not related to nuclear physics, namely thermodynamics and x-ray physics.

Szilard's linear accelerator is distinguished by the following features. There are no drift tubes. The high-frequency electrodes are plane grids. The distances between neighboring grids are increased in accordance with the increase in particle velocity. To shorten the total length of the accelerator it is proposed to divide it into two sections and in the second section to use a very-high-frequency field. This idea of Szilard's anticipates what was put into practice many years later in construction of ion linear accelerators.

A second disclosure of Szilard, recorded at the

[7)]In a later article [44] Wideröe states that in Aachen he theoretically studied the problem of stability of the motion and in the summer of 1925 he obtained an expression for the frequency of stable oscillations of the electrons about a fixed orbit.

[8)]I am very grateful to Dr. B. Dibner (USA), who kindly sent me this book.

[9)]We cannot avoid mentioning one of the very interesting items of this section: Szilard's disclosure for a nuclear reactor is published in its initial form for the first time. Five years before the discovery of the fission of uranium, Szilard describes a hypothetical reactor with a neutron chain reaction, introduces the concept of critical mass, and gives an approximate calculation of this quantity. [48] In the same disclosure it is proposed to obtain artificially radioactive isotopes of all elements up to very heavy elements by utilizing the bombardment of an element by neutrons instead of the bombardment by charged particles which has been used up to that time. It should be kept in mind that this was written before Fermi and his colleagues began their experiments in Rome on bombardment of various elements by neutrons.

German patent office at the beginning of 1929,[50] contains descriptions of two different accelerators—a magnetic resonance accelerator now known under the name cyclotron, and an induction cyclic accelerator.

In the description of the first accelerator, it is pointed out that in the nonrelativistic case the period of rotation of a charged particle in a constant magnetic field is a constant quantity independent of the particle velocity, which permits it to be accelerated by means of a high-frequency electric field of constant frequency. It was noted that the field strength in this accelerator must be to a high degree constant with time. The particle trajectory will be an expanding spiral. In Szilard's proposed accelerator design there are no dees, i.e., no particle-drift regions, as also in his linear accelerator.[49] The accelerating system consists of an even number of radially placed grids (for example a system of six grids is discussed); all grids with odd numbers are connected to a single terminal of the high-frequency generator, and all grids with even numbers to the other terminal. The generator frequency is chosen in accordance with the requirement that the particle traverse each sector between the grids in a time equal to half the period of the generator. In the reproduction of the disclosure[50] Figs. 1 and 3 are missing; apparently the originals of these figures have been lost. Therefore it is difficult to say how it was proposed to accomplish the injection of the ions. Probably external injection was intended. This variant has been put into practice in cyclotrons only in recent years, since it is much more complicated than the usual method.

Szilard undoubtedly arrived at the idea of the cyclotron independently of the other inventors of this accelerator.[10)]

The second accelerator proposed in the disclosure[50] was intended for acceleration of electrons. A circular electric field is used as the accelerating field. The vacuum chamber has the form of a toroid of approximately elliptical cross section. The source of electrons is simply a hot filament (i.e., there is no electron gun). The circular electric field is produced by means of a closed iron core equipped with winding supplied by alternating current. The guiding magnetic field is produced by a long solenoid which encloses the entire apparatus and is fed by a constant current. Thus, the accelerator described in the disclosure, like Slepian's accelerator, is a prototype of the ring phasotron with induction acceleration. It is shown that a radial electric field can also be used as the guiding field.

The electrons move in an expanding spiral, hit an anode, and give rise to a beam of bremsstrahlung. It was noted that use of a guide field constant in time permits a bremsstrahlung beam with a high duty cycle to be obtained. As already mentioned, this mode of operation of an induction accelerator was actually achieved only many years later.[26]

Finally, the disclosure contains the important remark that for axial focusing of the electrons it is necessary to use a magnetic field whose strength falls off from the center to the periphery.

In speaking of the patent disclosures of Szilard on accelerators, we cannot omit mention of the most interesting of them, although it belongs to a time somewhat later than the period discussed in this review.

Regarding this disclosure, except for the name of the invention, which contains no information (this name was published in the patent journal[52]), only fragmentary information was previously known. It was reported that in this disclosure Szilard proposed the principle of modulation of the frequency in a resonance accelerator and described the phenomenon of phase stability.[53,54]

For some unknown reason Szilard did not provide a complete specification of his invention in the time prescribed by patent law, and in the same patent journal it was reported that this disclosure is considered as not having occurred.[55]

The text of the disclosure is reproduced in Szilard's collected works.[56] This disclosure describes two cyclic electron accelerators. One of them, designated by the author "asynchronous transformer for particles," as in the previous disclosure of Szilard,[50] is an induction accelerator with a guiding magnetic field constant in time. The strength of the guide field falls off with increasing radius. The author poses the problem of creating conditions under which the spiral electron trajectory will occupy the narrowest possible region in radius. He proposes an extravagant solution of this problem, consisting of application of a ring magnet system with triangular sector plates producing a periodic azimuthal variation of the magnetic field.[11)] We now know that in a system of this type strong focusing of the accelerated particles occurs.

One additional feature of Szilard's induction accelerator is the use of two hollow C-shaped electrodes with an azimuthal extent of $\sim 180^\circ$. As a result the accelerating electric field acts on an electron only at the two gaps between these electrodes. It is pointed out that this arrangement is used to obtain axial electric focusing of the electrons.

The accelerated electron beam is extracted from the chamber by means of an electrostatic deflector. A more complicated induction accelerator is also proposed, in which the same laminated iron core provides field to several ring chambers of the type described. Electrons accelerated in one chamber are successively transferred to all the remaining chambers.[12)]

The second part of the disclosure[56] contains a description of a cyclic electron accelerator with the same structure of a guide field constant in time as in the first part, but with replacement of the toroidal accelerating field by a high-frequency field. The author calls this accelerator a synchronous transformer for particles. The high frequency is produced in the gaps between the C-shaped electrodes.

[10)]The German physicist Max Steenbeck, who was a foreign member of the USSR Academy of Sciences, published in 1964 a note [51] in which he reported that he developed the cylotron idea in 1927. In the following year he prepared for publication an article in which, in particular, he discussed the question of the desynchronization of the particle in a cyclotron as a result of the relativistic increase of its mass. This article was never sent to press.

[11)]In Mann's book this part of the disclosure [56] is given incorrectly. He writes as if Szilard's H(r) is a rising function and as if the sector structure of the pole tips was proposed just to produce this distribution (see ref. 53, page 98).

[12)]We note that much later a betatron was described with one core and two chambers, with transfer of the electrons from one chamber to the other. [57]

Since the period of revolution of the electron gradually changes in the different turns of the spiral trajectory. Szilard proposes to use a high-frequency voltage with slowly changing frequency. It is proposed that the necessary frequency modulation is achieved by means of a variable capacitor connected to the circuit. The capacitance varies periodically on rotation of toothed disks incorporated in the capacitor.

In the disclosure it is noted that in resonance acceleration by a high-frequency field with a modulated frequency the phenomenon of phase stabilization of the accelerated particle arises, and a qualitative description of the phase oscillation of the particle is given, together with a graphical explanation. It is also noted that the amplitude of the accelerating high-frequency voltage cannot be chosen arbitrarily.

All of the new ideas contained in the second part of the disclosure[56] were later rediscovered by other inventors and found their embodiment in the synchrotron, phasotron and ring phasotron, and the principle of phase stability is embodied in most contemporary accelerators.

In 1934, of all of the numerous accelerators of various types with indirect acceleration which are now known, only the cyclotron was known and in successful use. Cyclotron technique developed rapidly, it was long before its possibilities were exhausted and its use in accelerators of other types is still increasing. There were no publications setting forth the ideas on the principles of these accelerators (except for accelerators of the induction type for electrons). In this background the numerous findings of Szilard are a striking example of the rich creativity of an inventor who clearly was in advance of his time by many years. At the same time this is an illustration of the infrequent and casual publication of his ideas. As a result no one could make use of them.

Charles Christian Lauritsen (1892–1968) (California Institute of Technology, Pasadena, California). Lauritsen's group had available a low-frequency high-voltage apparatus (a cascade connection of four transformers) with an effective voltage of 1 MV. The group developed several original versions of accelerator tubes.

In the first stage these were x-ray tubes. The first tube was built in 1928.[58] It was made of glass and could be operated at voltages up to 750 kV (rms). Electrons were obtained as the result of cold emission. The entire accelerating potential difference was applied to one gap (of length 1–2 cm). Thus, this group was able to exceed by more than a factor of two the previous record for working voltage for a single-gap evacuated tube.

In the second tube, electrons were obtained either by cold emission of thermionic emission.[59] In continuous operation the tube worked at 600 kV rms. Later a porcelain tube was built for about the same voltage.[60] It was subsequently rebuilt and used to accelerate He^+ ions and deuterium up to 1 MeV with a beam current up to 30 μA.[61]

Many investigations of nuclear reactions were carried out by means of these accelerators.

In addition to tubes for which the source of high voltage was a cascade transformer, a tube was designed to work with a Tesla transformer. The secondary winding of this transformer was wound inside the tube. All of this apparatus was placed in transformer oil. A pulsed voltage up to 750 kV was obtained on the high-voltage electrode.[4]

Robert Jemison Van de Graaff (1901–1967) (Princeton University, New Jersey). In 1928 at the time of the work on his dissertation in Townsend's Laboratory at Oxford, Van de Graaff had the idea for design of an efficient and powerful high-voltage electrostatic generator. Rutherford's presidential address published in 1928[40] further strengthened Van de Graaff's intention of developing the generator.

For a long time there had been proposals for various types of electrostatic generators based on the principle of multiple (or continuous) transport of charge to the inside of a hollow electrode, whose potential is therefore increased. Among these designs were some in which the transport of the charge was accomplished by means of a conveyer belt.[62]

Van de Graaff perfected this generator with extraordinary success. In his version charge is deposited on a moving dielectric belt by means of the corona discharge from a point. The first working model of the generator was built by Van de Graaff at Princeton University in the second half of 1929. This model consisted of a metallic sphere mounted on a vertical pyrex tube. The silk tape was put into motion by a small electric motor. Voltages up to 80 kV were obtained on the sphere.[62,63] Van de Graaff then built a larger generator which was placed in a vacuum tank, since the idea arose that in a high vacuum the conditions for operation of an electrostatic generator would be much more favorable than in air. With this model it was possible to obtain voltages up to 50 kV, but this development was abandoned as a result of a number of difficulties associated with obtaining and maintaining the vacuum.

Van de Graaff was distinguished not only by his inventiveness, but also by his extensive knowledge and deep physical intuition. He easily imagined what kind of investigations could be carried out if a sufficiently powerful accelerator were available. In a letter to Karl Compton dated March 20, 1931 he wrote: "Uniform beams of protons at voltages which we can expect as the result of work now going on can be useful for simple experiments of a fundamental nature. Among them might be the study of the action of their collisions with uranium and thorium. These nuclei are unstable, and it would be interesting to see whether a proton incident with high velocity would produce a rapid disintegration. On the other hand, it is possible that the proton would be captured by the nucleus, which would open the possibility of producing new elements with atomic number greater than 92."

"Near the other end of the periodic table is lithium. Now suppose that a ^{7}Li nucleus is hit by a proton which makes available the additional component for formation of a second α particle. Consideration of Aston's curve and Einstein's law shows that a nuclear reaction of the following type can occur: $^7\text{Li} + {}^1\text{H} \rightarrow 2{}^4\text{He} + 16$ MeV."[64] We can only express our astonishment that all this was written as early as 1931.

In June of 1931 Van de Graaff began to construct a third model of the generator, intended for operation in air at atmospheric pressure. This model was a combination of two identical generators with charges of opposite sign. The spheres had a diameter of 61 cm. Between spheres he obtained a constant potential difference of up to 1.5 MV[65] at a current of 25 μA. This voltage was twice any constant voltage previously obtained.

The idea of using an electrostatic generation as a component part of a high-voltage accelerator was picked up by many physicists. The first such group was that of Tuve and his colleagues at the Carnegie Institution. In 1931 they began construction of the first large generator with a conductor[17] of diameter 2 m. At about the same time the decision was made to build a giant double generator at the Massachusetts Institute of Technology (Round Hill), designed to obtain a potential difference up to 10 MV.[13)]

It is difficult to overestimate the role played by accelerators with electrostatic generators in diverse investigations in nuclear physics. The well known advantages of these accelerators has led to the fact that they, and particularly their second-generation charge-exchange accelerators—are extensively used in physics laboratories all over the world up to the present time.

Ernest Orlando Lawrence (1901—1958) (University of California, Berkeley). In 1925 Lawrence finished the experimental part of his dissertation at Yale University, New Haven, devoted to the photo-effect in potassium vapor, and received the degree of Ph.D. Beginning on August 17, 1928, Lawrence occupied himself with the duties of Associate Professor in the Physics Department at the University of California.

Several years before, Lawrence had been at the laboratory of Breit and Tuve at the Carnegie Institution in Washington and had learned about their developments of vacuum tubes and high-voltage sources. Tuve advised Lawrence to work on accelerators. Lawrence believed that obtaining fast particles by means of high voltage was a limited and unpromising method. He suggested that there must be some indirect approach for acceleration of particles.

On going to the University of California, Lawrence decided, following the example of Rutherford's laboratory, to do research on nuclear reactions and began to consider seriously the question of the method of obtaining accelerated charged particles with an energy of ~1 MeV. Sometime in April 1929, while looking over current journals in the library, Lawrence found Wideröe's article[15] in a German electrical engineering journal. His knowledge of German was poor, but from the figures he immediately understood the idea of the linear resonance accelerator.[14] He understood that repeated acceleration and the resonance principle provided a good answer to the problem with which he was occupied. On that same day he made a number of calculations relating to the design of a resonance linear accelerator, found that a linear accelerator in which protons could be accelerated to ~1 MeV would become an extremely long device (several meters), and attempted to find methods overcoming this deficiency. He found that use of a magnetic field to bend the trajectory of the accelerated particles and retention of the same resonance method of particle acceleration by means of a high-frequency field made it possible to produce in principle a very simple and compact accelerator. The only doubt arising in Lawrence's mind was whether the mean free path of a proton in vaccum could be made sufficiently long. After some period of continuing to think about his accelerator Lawrence noted that the relativistic dependence of the particle mass on velocity could result in desynchronization of the acceleration. Thus, in the spring of 1929 Lawrence independently invented the magnetic resonance accelerator, later called the cyclotron.

However, a year passed before Lawrence, heavily loaded with teaching duties and supervision of his eight graduate students, found it possible to start experiments. At the beginning of 1930, the first of his graduate students, Niels Edlefsen, turned out to be relatively free, since he had finished the experimental part of his dissertation (devoted to study of the photoionization of the vapors of alkali elements) before the year had passed and was waiting to receive his degree in June. He agreed to carry out preliminary experiments on resonance acceleration of protons.

Edlefsen used for these experiments the largest electromagnet which he could find in the department. This was an electromagnet with a vertical gap and with poles ~100 mm in diameter. The maximum magnetic-field strength in the gap was 5.2 kOe. Edlefsen built several very primitive glass chambers. His first chambers had the form of a flat bulb with silvered portions of the internal surface which played the role of dees. The chamber was equipped with a hot filament, a tube for introduction of hydrogen, and a probe for collection of the accelerated ions. All of the vacuum seals were made with Picein.

The chambers of this type cracked on evacuation. Therefore a chamber of another type was prepared: Onto two copper dees on whose windows were stretched wire grids, glass plates were fastened with Picein cement in such a way that a vacuum chamber was formed. This was an arrangement distinguished by its ungainly appearance.[14)]

In April 1930 Edlefsen obtained with this chamber results which, he considered, showed that he had been successful in observing resonance acceleration of hydrogen ions.[68]

Lawrence discussed his invention with many physicists. However, his first statement on this subject, which became widely known, was his address at the meeting of the National Academy of Science at Berkeley on September 19, 1930. The content of this report was soon published.[69] In this brief note he set forth the principle of operation of the cyclotron and pointed out that preliminary experiments were encouraging.[15)]

[13)]Each of the two conductors of this generator had a diameter of ~4.6 m. The limiting voltage actually obtained between the spheres was 5.1 MV with a total load current [66] of 1.1 mA, but the vacuum tube, which was developed at the same institute in 1937, could only operate up to 2.5 MV. [67]

[14)]Edlefsen's chambers are in the Kensington Scientific Museum in London.

[15)]Seven months after Lawrence's paper, C. G. Smith submitted a patent disclosure on the design of a miniature x-ray tube in which it was proposed to accomplish acceleration of the electrons by means of a uniform high-frequency electric field of constant frequency in a trans-

Serious and systematic development of Lawrence's idea was begun in the summer of 1930 when he assigned this work to graduate student M. S. Livingston.[14,73] The problem assigned was to accelerate protons to ~1 MeV.

Livingston undertook this work in spite of the skepticism of many professors of the physics department who considered that, because of various practical difficulties, it would not be possible to construct a working device.

Livingston's first experiments were carried out in the same electromagnet (with poles of diameter ~100 mm). He found that the resonance effect observed by Edlefson in reality did not involve cyclotron acceleration of hydrogen ions.[74]

Glass vacuum apparatus was traditional in laboratory practice. Livingston at first followed this tradition. However, he could not make a satisfactory vacuum chamber out of glass. He then designed a ring-shaped brass chamber. It contained one dee, whose support was provided by a glass insulator. To supply the dee he used a high-frequency generator employing one 10-watt tube. The wavelength of the generator could be varied over a wide range, from 30 to 180 m. High-frequency voltage with an amplitude up to 2 kV relative to the grounded chamber could be obtained on the dee.

By November 1930 Livingston succeeded in obtaining narrow peaks of ion current i in a curve i(I), where I is the current in the electromagnet winding.[16)] At first H_2^+ ions with energy 13 keV were obtained with an accelerating voltage $V_a = 160$ V. Then the same chamber was placed in the gap of a larger electromagnet where it was possible to obtain a field with strength up to 13 kOe, and on January 2, 1931 H_2^+ ions were obtained with energy 80 keV. Accleration of ions to this energy could be observed also on reducing the value of V_a to 980 V. This meant that the ions made at least 41 turns in the vacuum chamber.[78]

In his thesis Livingston[79] gave plots of i(H) and $\lambda_{res}(H)_{res}$ which indicate complete agreement of the experimental data with the theory (these plots are reproduced in the book of Livingston and Blewett[80]). Thus, this first operating cyclotron brilliantly confirmed experimentally the achievability of Lawrence's idea.

In the first stage of development of the cyclotron, Lawrence did not discuss the need of focusing the accelerated particles. However, it was clear that a problem existed of obtaining a sufficiently large ion beam current at the accelerator output. Lawrence considered that it was necessary to provide a strictly uniform magnetic field and the same kind of electric accelerating field. He suggested that the existence of even small transverse components of the electric field in the accelerating gap would lead to deflection of the accelerated particles from the specified orbit plane, as a result of which they would hit the dees and be lost. Therefore Lawrence suggested to Edlefsen and later to Livingston to mount wire grids on the windows of the dees.

At the time of the experiments on the cyclotron with pole diameters 100 mm carried out by Livingston in the spring of 1931, facts were established, to a certain degree accidentally, for which Lawrence immediately found an explanation—he showed that the shape of the electric-field lines in the gap between the dees without grids provides axial electric focusing of part of the accelerated ions, and the barrel-shaped magnetic-field lines with rotational symmetry provide axial magnetic focusing of the ions.[74,81] In the first detailed article on the cyclotron[82] the elementary theory of these focusing actions is given.

In June 1931 Livingston put into operation the second cyclotron. An electromagnet of Armco iron with a horizontal gap and pole diameter 230 mm was specially built for this accelerator. A new brass chamber, also with one dee, had a square shape. In this cyclotron H_2^+ ions and protons with energy ~500 keV were obtained (July 1931) with a beam current of more than 0.1 μA and ~0.01 μA, respectively.[83]

Subsequently the pole diameter was increased to 280 mm. Protons were obtained with energy 1.22 MeV (with a beam current 10^{-9} A).[41,82] This was a record: No one had been able to accelerate protons to such an energy. With this beam, experiments with nuclear reactions were carried out for the first time in Lawrence's group.[84]

Doubts as to the great possibilities of the cyclotron method of acceleration no longer remained. Lawrence began an untiring search for funds and equipment for construction of the next, still much larger cyclotron. At the Federal Telegraph Company he found a 74-ton electromagnet with a pole diameter of 1.4 m, built in 1919 for a telegraphic radio transmitter with a Poulsen arc. The magnet was presented to Lawrence and in October 1931 installed in an old wooden building near the physics building of the university. This building soon became known as the Radiation Laboratory.

Pole tips 70 cm (27.5 inches) in diameter and a two-dee chamber were prepared for the magnet. The cyclotron was put into operation in 1932.[41,85,86] Immediately H_2^+ ions of energy 3.6 MeV were obtained.

At the end of 1937 a new chamber with a diameter of 940 mm (37 inches) was built,[87] and in 1939 in a new building—the Crocker Laboratory—the last of the classical Berkeley cyclotrons began to operate, with a pole diameter of 1.52 m (60 inches).[86] It was equipped primarily to obtain a high neutron flux, which was intended to be used for medical purposes.

The first working cyclotron which appeared outside Berkeley was a small cyclotron built at the initiative of I. V. Kurchatov in the Leningrad Physico-technical Institute in 1933 by M. A. Eremeev. The electromagnet

verse uniform magnetic field. [70] In this apparatus, in contrast to the cyclotron, the high-frequency field acts on the accelerated particles over the entire extent of their trajectory (there are no dees). Smith noted that resonance acceleration of an electron will occur for any initial phase of the electron. This crossed-field arrangement subsequently found wide application in mass spectrometers of the omegatron type. [71]

In Lawrence's case, he submitted a patent disclosure on the cyclotron method of acceleration only after carrying out reliable experiments. [72]

16)At this time (November 1930) the French physicist Jean Thibaud (1901–1960) was carrying out his first experiments with the cyclotron method of particle acceleration. These experiments were not crowned with success, and the first report of his cyclotron, of diameter 20 cm, and in which he could obtain protons with energy 425 keV, was made by Thibaud only in June 1932. [75-77] He stated that after learning about Wideröe's work he arrived at the cyclotron idea independently of Lawrence.

with an H-shaped core and horizontal gap had a pole diameter of ~25 cm. The square chamber with one dee was similar to the corresponding chamber of Livingston.[82] The cyclotron was designed to provide protons with energy ~1 MeV. A weak beam of protons with energy ~530 keV was actually obtained.[89,90]

In 1932 on the initiative of L. V. Mysovskiĭ the Scientific Council of the State Radium Institute in Leningrad decided to build a cyclotron. It was decided that the pole diameter of the cyclotron would be 1 m. Such a large cyclotron existed nowhere at that time—the largest cyclotron at Berkeley had a pole diameter of 70 cm.

Preparation of the magnet (with a vertical gap) was begun in 1932. The weight of the electromagnet was 28.4 metric tons. The cyclotron was put into operation in 1936.[91,92] This was not only the first large Soviet cyclotron, but also the first accelerator of this type in Europe.

Plans for construction of a large cyclotron at the Leningrad Physico-technical Institute were made in 1933. Construction of this cyclotron with a pole diameter of 1.2 m, close to completion, was interrupted by World War II and it was put into operation only in 1946.[93]

In the United States the first cyclotron outside Berkeley appeared in 1935. It was built by Livingston at Cornell University, Ithaca. This was a cyclotron 406 mm in diameter, in which protons were accelerated to 2 MeV.[94] The number of laboratories wishing to have a cyclotron at their disposal grew rapidly. By the end of 1938 there were nine working cyclotrons and more than 15 under construction.[87]

As already mentioned, artificial α particles with at least the energy of natural α particles were obtained at the end of 1935 in a cyclotron of 70 cm diameter; this machine produced α particles with an energy of 11 MeV and a beam current of ~0.1 μA.[41] 17) The problem posed by Rutherford of obtaining particles significantly higher in energy than natural α particles was solved in 1939 after start-up of the second large cyclotron at Berkeley with a diameter of 1.52 m: Protons of 8 MeV were obtained, deuterons of 16 MeV, and α particles of 32 MeV.[88]

In 1939 Lawrence was awarded the Nobel prize in Physics for invention and development of the cyclotron.[14] In 1943 he was elected an honorary member of the Academy of Sciences of the USSR.

We have mentioned several times that the various indirect methods of acceleration were proposed in the earliest stages of accelerator development. However, the transition from plans to intensive and systematic development of indirect acceleration methods appeared only in 1930 when Lawrence began to work in that field. He used the "star method"—he directed development simultaneously in several directions. He assigned his graduate student Sloan to development of a linear resonance accelerator of the type described by Wideröe. Another direction was the development of the cyclotron.

Very heavy particles were chosen to be accelerated in the linear accelerator, in order not to require too high a frequency of the accelerating field for a total accelerator length which appeared acceptible at that time. By December 1930 the first results were reported: Ions of Hg^+ were accelerated to 90 keV in an accelerator in the form of a glass tube containing 8 tubular electrodes.[95] A few days later a report was made of a linear accelerator containing 21 tubes. Hg^+ ions were accelerated to ~200 keV.[96]

The next model of this type contained 30 electrodes, and for a high-frequency voltage of 42 kV (λ = 30 m) Hg^+ ions with energy 1.26 MeV were obtained.[97,98] Finally, at the end of 1932 mercury ions of energy 2.85 MeV were obtained in a linear accelerator of total length 1.85 m and containing 36 electrodes.[99,100]

The construction of these accelerators involved overcoming many difficulties and required superior experimental technique. The predictions of the theory of the linear resonance accelerator were completely confirmed by experiment. Further experiments with acceleration of mercury ions were abandoned, since for the energies achieved, ~14 keV/nucleon, these ions were completely unsuitable as nuclear projectiles. Somewhat later at Berkeley, lithium ions were accelerated in a similar apparatus.[101,102] An ion beam with energy ~1 MeV was obtained (for a beam current of 10 μA). This energy is also insufficient for excitation of nuclear reactions.

Soon after the first operation of the linear resonance accelerator, Sloan became interested in the direct action accelerator suggested to him, with a resonant high-frequency transformer as the source of high voltage (this accelerator has already been mentioned[5-7] in connection with the work of L. V. Mysovskiĭ and V. N. Rukavishnikov). This development rapidly led to a practical result—under Livingston's guidance a high-power x-ray installation of 800 kV was built for the hospital of the Medical School of the University of California.[103]

Sloan also proposed a method of converting his apparatus with a resonance transformer into a proton accelerator.[7,5] For this purpose it was proposed to mount in a vacuum tank a system of drift tubes, part of which were connected to the grounded tank, and the remainder to the high-voltage end of a transformer secondary winding.18)

Independently of the group at Berkeley, Thibaud[105,106] in 1931 worked for a while on development of the linear accelerator described by Wideröe. His apparatus was designed to accelerate the lightest ions (H^+, H_2^+) and also mercury ions. He succeeded in accelerating mercury ions to 145 keV in a tube with eleven accelerating gaps.

It was only after World War II, as a result of the impressive advances in microwave technology, that proton linear accelerators with drift tubes—descendants of Wideröe's linear accelerator—were built. The first

17)At this time the beam current of ions accelerated in a cyclotron was significantly smaller than the average currents obtained in direct-current accelerators.

18)In a detailed article [7] describing Sloan's apparatus, it was stated that in a following article written by Sloan and J. J. Livingood the results of work with a proton accelerator of this type would be presented. However, the promised article did not appear. A resonance linear accelerator of ions, very similar to that described by Sloan, was built much later at the Institute of Physics and Chemistry Research in Japan. [104]

accelerator of this type built, which was developed by Lawrence's colleague Louis Alvarez, was capable of producing protons with a record energy of 32 MeV, significantly higher than obtained up to that time in cyclotrons.[107,108]

Christian Gerthsen (1894) (Physics Institute, University of Tubingen, Germany); **Arthur Jeffrey Dempster** (1886–1950) (University of Chicago). An original method of direct acceleration of ions was proposed in 1932 independently by Gerthsen[109] and Dempster.[110] The idea of this device was as follows. A particle beam passes successively through a series of chambers with electrodes connected to the same dc voltage source in such a way that the chambers with an accelerating field alternate with the chambers in which the electric field is retarding. In the first accelerating chamber the ions receive their first increase in energy. If a part of the ions is in some way neutralized at the entrance to the next retarding chamber, these particles will pass through this chamber without loss of energy. Before entering the second accelerating chamber it is necessary again to convert the neutral particles (at least part of them) into ions with the same sign of charge, so that in this chamber they will receive a new increase in energy, and so forth.

Dempster obtained a doubling of the energy of protons ($W_p = 45$ keV). Evidently he made no further attempts to improve this accelerator.

Gerthsen and his co-workers built an experimental apparatus for acceleration of protons. Neutralization and charge exchange of hydrogen ions was accomplished in gas chambers containing air at a low pressure. It was noted that the cross section for charge exchange falls off with increasing energy of the particle, so that the proton energy achievable is limited.

Gerthsen's apparatus also contained also two charge-exchange chambers. Protons with energy up to 180 keV were obtained.[111] Later, in working with this apparatus, it was noted that the spectrum of protons contained a group with increased energy.[112] This was explained by the fact that some protons in the first charge-exchange chamber are converted not into neutral atoms, but into negative hydrogen ions. For these particles all three gaps are accelerating.

These experiments are interesting in that for the first time in accelerator technology they utilized charge exchange of ions as a means of increasing energy of accelerated particles. Much later, when intense negative-ion sources and efficient charge-exchange devices were developed, this idea found wide application in charge-exchange electrostatic accelerators and in linear accelerators of multiply charged ions. Some special types of accelerators based upon multiple charge exchange of ions have also been proposed.[113,114]

Georgiĭ Il'ich Babat (1911–1960) (Laboratory of the "Svetlana" Factory, Leningrad). In 1932 Babat and I. P. Polevoĭ attempted to construct a traveling-wave linear accelerator. This original proposal of Babat appeared well before the corresponding technical feasibility.

Babat and Polevoĭ used a smooth waveguide in the form of an evacuated copper tube with an internal diameter of 5 cm and a length of ~2 m. In this tube traveling waves could arise if $\lambda < 10$ cm. At that time there were no generators capable of producing electromagnetic oscillations with such a short wavelength. The authors attempted to use a high-voltage spark discharge as a microwave generator (the method of P. N. Lebedev). However, the power of the centimeter waves obtained was negligible, so that there could be no further consideration of using them for acceleration of electrons.[115,116]

As is well known, only during the second world war were high-power centimeter-wave generators—magnetrons and klystrons—produced for radar needs. The first working linear electron accelerator with traveling waves[117] was built on this principle in 1946.

John Douglas Cockcroft (1897–1967); **Ernest Thomas Sinton Walton** (1903) (Rutherford's laboratory, Cambridge University, England). As we have mentioned above, this group began to construct a high-voltage proton accelerator in 1928. The first apparatus, designed to produce a dc voltage of 300 kV, used the well known rectifier circuit with two kenotrons connected in series.[118] Homemade continuously pumped kenotrons were used. There was one accelerating gap in the glass vacuum tube. Experiments were carried out with protons accelerated to an energy not exceeding 280 keV with a beam current of $\sim 2\ \mu$A (the first experiments performed in March 1930). Attempts to observe γ radiation in bombardment by these protons of various targets, including lithium, were not crowned with success. The result would have been different if α particles had been detected in these experiments. However, at that time Cockcroft and Walton did not plan such observations.

In the middle of 1931 the need arose to move the accelerator to another room with a much higher ceiling. It was decided to make use of this to increase the proton energy substantially, since it was supposed that the failure of the first experiments was due to insufficient energy of the accelerated protons.

As far as the high-voltage generator was concerned, it was assumed that this problem would be solved by means of some voltage-multiplication scheme. Such schemes had been proposed by several inventors; the first publication was in 1919.[119-122] The apparatus required employs capacitors and rectifier tubes as its main components.

Prior to the work of Cockcroft and Walton, no working high-voltage apparatus of this type had been built. Cockcroft and Walton developed a cascade generator—a voltage-quadrupler circuit. It is a successful development of the circuit of Greinacher.[19)]

The apparatus again used homemade continuously pumped kenotrons with battery-operated filaments. Each kenotron could hold off a maximum voltage of 400 kV. The capacitors were designed for the same voltage. In this way the cascade generator could provide voltages up to 800 kV.[125]

The glass accelerator tube of total height 1.83 m contained two short accelerating gaps. The maximum proton energy was 710 keV and the beam current was

19)Independently of Cockcroft and Walton, a cascade generator was developed in 1932 by A. Bouwers at the Philips Company in Holland, initially for x-ray equipment. [123,124] The basic circuit of the generator was the same, but the capaciters and kenotrons were arranged differently.

up to 10 μA. The beam passed through a thin mica window into the atmosphere.

In April 1932 a short note[126] appeared which informed the scientific world of the successful achievement of a long established goal: production of a nuclear transmutation with artificially accelerated fast particles. It was shown that the following nuclear reaction was produced:

$$^7\mathrm{Li} + p \rightarrow 2\,^4\mathrm{He} + 17\ \mathrm{MeV}^{20)}.$$

In these experiments fast α particles appeared already at a proton energy of ~120 keV; the number of α particles rose rapidly as the proton energy was increased.[127]

Subsequently several investigators showed[128-130] that with a sufficiently high proton-beam intensity and high sensitivity of the method of observing α particles, the disintegration of lithium by protons is observed at still much lower proton energies, down to 8 keV! Thus, Cockcroft had made no mistake in his memorandum given to Rutherford in 1928.

In 1951 Cockcroft and Walton were awarded the Nobel prize in physics for their pioneer work in transformation of nuclei by artificially accelerated particles.

As is clear from the foregoing, by 1932 and even earlier many laboratories had the necessary equipment to carry out studies of nuclear reactions. It is not surprising therefore that the historical experiment of Cockcroft and Walton with lithium was very soon repeated in various parts of the world and in various accelerators:21) by Gerthsen in a charge-exchange accelerator,[109] by Lawrence and co-workers in the cyclotron,[84] by Lange and Brasch in a high-voltage accelerator with pulsed voltage,[34] by Kirchner in a high-voltage accelerator with a rectifier,[31] and by K. D. Sinel'nikov and his co-workers in a cascade accelerator.[132]

This marked the beginning of a period of extraordinarily intensive use of accelerators in various countries for various studies in nuclear physics.

Kirill Dmitrievich Sinel'nikov (1901–1966); **Anton Karlovich Val'ter** (1905–1965) (Ukrainian Physico-technical Institute, Khar'kov). The Ukrainian Physico-technical Institute (of the Supreme Council of the National Economy, Ukrainian SSR), created at the end of 1928 by separating group of scientists from the Leningrad Physico-technical Institute, soon became the only institute in the USSR in whose program one of the central places was occupied by research in nuclear physics.

The development of various dc accelerators at the Ukrainian Physico-technical Institute began in the first half of 1931. There were two groups—the Tesla-transformer group and the high-voltage laboratory, a total of about twenty persons led by K. D. Sinel'nikov and A. K. Val'ter.

As high-voltage sources for accelerators they developed a Tesla transformer, a shock-excited oscillator, and later a cascade generator. For each of these generators, high-voltage vacuum tubes were developed.

20)We note that prior to these experiments lithium was one of the few light elements which could not be disintegrated when natural α particles were used as nuclear-projectiles.

21)Here we have listed in chronological order only studies made in 1932.

The Tesla transformers were placed in oil, like those developed by Breit and Tuve, but they had the feature that the vacuum tube was located inside the secondary winding of the transformer. In a transformer without a tube it was possible to obtain voltages up to 2.5 MV. It was much more difficult to produce the vacuum tubes. More than a hundred tubes were made.[133] By the autumn of 1932 they were able to build a sectionalized vacuum tube of pyrex glass which worked for a long time at 1.7 MV. Later on, protons were accelerated in this tube.

The pulsed voltage generator, employing an Arkad'ev-Marx circuit, consisted of 36 very simple (homemade) capacitors and provided voltage pulses up to 1.5 MV. About 20 vacuum tubes were made. The last specimens were a refinement of the plate-tube of Lange and Brasch. These tubes withstood the full voltage of the pulsed generator. In a tube of this type an electron beam of energy 1.5 MeV was obtained. Attempts to accelerate protons turned out to be less successful and were soon abandoned.

All of these studies were carried out in only one year. On the basis of the results obtained the investigators concluded that for studies in nuclear physics it was necessary to have dc voltage sources which could provide a sufficiently high average current of the accelerated ions.

The first cascade generator was built at the Ukrainian Physico-technical Institute in the course of several months in 1932. It developed a voltage of up to 350 kV. In this apparatus at the beginning of October 1932 the result of Cockcroft and Walton[126] was repeated.

Later K. D. Sinel'nikov and A. K. Val'ter developed a cascade generator of a new type. In this generator the voltage increases linearly with the number of stages, while in the Cockcroft Walton scheme this effect could be obtained only with a substantial increase in the capacitance of the capacitors in each succeeding stage. The cascade generator of the new type consisted of a series connection of individual voltage-quadrupler circuits, each of which uses its own transformer and alternating-current generator, rotated by means of an insulating shaft. A cascade installation of two such units gave a dc voltage up to 700 kV and had a power of 5 kW. A tube for this voltage was also prepared. This apparatus was put into operation in 1933.[134]

At the Khar'kov Physico-technical Institute the tradition of accelerator development has been continued to the present day. In the prewar years the largest apparatus built at the institute was a giant electrostatic accelerator with a conductor 10.2 m in diameter which worked at 5 MV (without a tube). In a ten-meter vacuum tube, electrons were accelerated to 3.6 MeV.[135]

In the postwar years first-rate accelerators of various types were built at this institute, among them the only waveguide linear electron accelerator in Europe, with an energy of 2 GeV.

* * *

In the present review we have considered from the contemporary point of view the first decade in the history of accelerator development. In this short time as a result of the creative efforts of many investigators great progress was made: 1) A solution was obtained of the initially formulated problem—creation of an instrument suitable for study of nuclear reactions; 2) accelerators of various types were developed and put into operation; 3) a firm basis was established for the entire subsequent development of accelerators; in this sense the success in development of the cyclotron had particularly great significance.

Accelerators were not developed by the simplest logical scheme. It would seem natural that the well known and obvious approach would be followed first—acceleration of charged particles in a strong electric field; when development of this method encountered great difficulties, the search for indirect means would begin. In actual fact the indirect means were invented before a real requirement arose for them. The first practical developments of the indirect method of acceleration were also carried out very early. This was a correct insight into the main direction of accelerator development.

In almost all cases either the inventor himself or other investigators (who sometimes arrived at the same idea independently) made attempts to achieve the principle proposed. As far as we know the only accelerator which no one attempted to build during this period was the linear induction accelerator of Bouwers, the first accelerator of this type being put into operation by N. Cristofilos and his colleagues at the Lawrence Radiation Laboratory in Berkeley only in 1963.[136]

There were only two cases in which attempts to produce a working accelerator did not lead to success and a long period of time was required before the proposed idea was successfully realized: The first betatron was put into operation in 1940,[137] and the first waveguide linear electron accelerator in 1946.[117]

The causes of the delay were different: The betatron could have been made much earlier if a sufficiently complete theory combining the previously obtained results[15,16,36,82] had been developed. The waveguide accelerator could not be built before appearance of a new technology—high-power centimeter-wave generators.

The development and perfection of accelerators were naturally closely connected with the development of various branches of technology and industry. For example, L. V. Mysovskiĭ was unable to build a satisfactory apparatus with a Tesla transformer in vacuum; later when Sloan made such an apparatus, his success was due in a large degree to the fact that he had available high-performance vacuum pumps.

An interesting feature of the first stage of accelerator development is the fact that here we frequently encounter cases of independent and almost simultaneous inventions of the same device. A particularly clear example is the invention of the cyclotron (Steenbeck in 1927, Szilard in 1929, Lawrence in 1929, and Thibaud in 1929).

Of course, the subsequent fate of the invention was determined to a decisive degree by the individual characteristics of the inventor. Lawrence brilliantly demonstrated the necessary characteristics.

In retrospect it is always possible to note errors and missteps in the path taken for development of any field, and to evaluate which developments were on the main line of development and which were unproductive sidelines. In regard to the errors, the history of accelerator development chose a characteristic pattern. Many investigators were engaged in the solution of a problem. All of them proceeded from the same basic premise, which afterwards turned out to be erroneous: It was assumed that it was necessary to obtain accelerated particles whose energy was comparable with that of natural α particles. If the laws governing penetration of charged particles through a potential barrier had been known at the beginning, the problem of obtaining the necessary beam of accelerated particles would have produced no difficulties: Mysovskiĭ would easily have built a tube to obtain "canal rays" at a voltage, for example, of 50 kV and, by means of the scintillation method used long before by Rutherford, would have observed the disintegration of lithium by protons.

However, such a course of events would have changed nothing except that the "Cockcroft-Walton experiment" would have been carried out ten years earlier.

In spite of the error in the initially chosen path, it is likely that none of the developments in this path turned out to be superfluous or the labor expended in vain. The reason for this unusual situation is that the further course of development of accelerator technology was determined by the requirement of obtaining particles accelerated to ever higher energy, and in this second stage almost all of the previously obtained results were applicable.

In regard to the main direction and the sidelines, we can state the following. Even in the earliest stage of accelerator development it turned out that there was found not one but several successful solutions of the problem. Here it became clear that there was no solution which was clearly better than all of the others in all respects. This situation still exists in accelerator technology at the present time: Different accelerators turn out to be best for different purposes. This circumstance is responsible for the fact that almost all of the developments of the first decade have been on the main line of development—in any case, in the sense that the direct descendants of almost all of the accelerators of that time are working today in various laboratories. One might say that only the developments of Lauritsen's group were not on the main line of development.

We can perceive a direct connection, for example, between Ising's accelerator and the giant synchrotron at Serpukhov.

If we speak of the main principles on which the development of accelerators has been based, the working accelerators of all presently known types, after more than forty years of intensive development and amazing achievements, have their roots in the developments of the first decade.

The discovery of the principle of phase stability had the greatest significance for the development of accelerators. It was noted above that this principle was described in 1934 in a patent disclosure by Leo Szilard[56] and that Szilard's idea remained unpublished for a long time. In 1944 V. I. Veksler independently discovered phase stability and first gave its mathematical theory.[138] In the following year the same phenomenon was discovered independently by E. M. McMillan.[139] Publication of the articles of Veksler and McMillan marked the beginning of a new stage of accelerator development: First in two laboratories and then in many laboratories over the entire world construction was begun of various cyclic accelerators based on the principle of phase stability.

More recently several important new ideas have been proposed. First among these are the collective method of particle acceleration, the relativistic self-stabilized electron beam, and the colliding-beam method. The starting point for the collective method of acceleration is Veksler's article published in 1956.[140] At the present time various versions of this method are being studied and developed intensively. The idea of an accelerator based on use of a self-stabilized beam was proposed by G. I. Budker in 1952 (the article was published in 1956[141,142]). It later turned out that this suggestion was unachievable; however, Budker's work was responsible for a large number of important theoretical and experimental studies relating to the use of collective fields.

The colliding-beam method has been successful in recent years; it has received extensive use and has turned out to be invaluable for research in high-energy physics.

The creation of contemporary ring installations accelerating ions and electrons to energies of tens and hundreds of GeV would be impossible without use of strong focusing, which was invented in 1950.[143,144]

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