Early Days In The Development Of Accelerators

W. Paul

Ladies and Gentleman!

The symposium today is dedicated to Robert R. Wilson. The subjects of the lectures cover a wide span from accelerator physics to beauty and science. Some people may be surprised by this but only those who are not familiar with the life of Bob Wilson, physicist and artist. As all his scientific life has been strongly coupled to particle accelerators, he himself would be the most appropriate speaker for the talk I am going to submit. But today, listening is his role.

Before starting, I have to apologize for concentrating on the part of the field that I am most familiar with, accelerators for fundamental physics. I restrict myself to the basic ideas and I will mention only names who played a major role in discovering the principles, leaving out my colleagues who brought the relevant devices to perfection, so that they are really useful for modern research.

What is an accelerator? If one consults a dictionary, accelerate means to increase the velocity of something. But dictionary editors normally are not familiar with the theory of relativity. Acceleration, as already formulated by Newton, means an increase of the momentum, the product of velocity and mass.

Having this in mind, W. W. Hansen (Ha 48), the late inventor of the electron linac, proposed to use the name mass aggrandizer, or -- after consulting the department of classical philology at Stanford -- ponderator, but we are still talking about accelerators.

Well, what are accelerators good for? All progress in the knowledge of matter comes by studying the interaction of its components with accelerated particles. This is done by three basic methods:

1. Scattering gives information about the structure
2. Particle spectroscopy or excitation of resonances elucidates the binding forces and
3. Energy transfer causes the production of secondary or new particles.

The study of the atom, the nucleus and the nucleon started immediately after the experimental technique of accelerating particles was developed for the relevant energy region. But these developments were strongly correlated with other techniques such as producing high voltages, generating radio frequencies and especially producing the necessary vacuum. Faraday, in studying the passage of electric currents through gases, was handicapped by the leather piston pump.

In 1860, Plücker and Hittorf in Bonn with the help of their glassblower Geissler reached 10^{-3} Torr and immediately detected the cathode rays. Around 1900 a vacumm of 10^{-5} to 10^{-6} was achieved, good enough for scattering of canal and electron rays. The diffusion-pump gave the necessary pumping speed for accelerators and without the modern ultra-high vacuum technique no storage ring would work and therefore no theoretician would publish papers on psis and upsilons.

The pioneering experiments for all the three tasks I mentioned were all performed around 1900. The first one was the generation of x rays by Röntgen in 1894, as an example for secondary particles.

After Heinrich Hertz (He 86) in 1886 had found that cathode rays are able to penetrate thin aluminum foils, his assistant Philip Lenard let the electrons out of the vacuum tube and observed that they had a defined range in air. In 1895, Lenard studied the effect of electron scattering in various gases as a function of pressure and accelerating voltage. He introduced the gas-kinetic conception of a cross section to particle physics, and found that the cross section decreases rapidly with the particle velocity. From this he concluded that the atoms contain constituents, which he called at first Dynamides. A few years later he identified them with electrons and calculated an upper limit for their diameter of 10^{-11} cm. He showed, in agreement with the Thompson model, that the atom is in the main empty.

His was the first experiment in which such measurements were performed with electrons artificially accelerated up to a few 100 thousand volts. For this experiment he was awarded the Nobel Prize in 1905.

Lenard was followed by Rutherford, who performed his famous scattering experiments, with alpha particles with even higher energies from radioactive decay, looking for the angular distribution of the scattered particles. He showed that the positive constituents of the atoms are agglomerated in a nucleus in the center of the atom. These two men, together with, Niels Bohr, are the fathers of the picture of the atom that we consider now as the reality.

A few years later, in 1913, James Franck and Gustav Hertz succeeded in exciting the atomic shell by bombardment with accelerated electrons, resulting in the consecutive emission of photons. The voltage generators at that time were electrostatic machines designed by Toepler and Wimshurst, namely the spark inductor with rotating rectifiers or Tesla coils.

All in all, it was an instrumentation well suited to the study of the structure of the atomic shell, but mostly these instruments did not exceed the 100-KeV region.

It is worthwhile to repeat that all the experimental methods which are still in use in particle physics: scattering of charged particles, energy excitation, production of secondary radiation, and the use of the secondary particles to the same purposes were already developed in a few years around the turn of the century (Figs. 1, 2).

In 1919 the great breakthrough in physics occurred. Rutherford demonstrated that the nitrogen nucleus could be disintegrated by natural alpha particles from radium. A new era was opened in physics. But the energy of some million eV of the alphas exceeded by far the energies available in the laboratory. These were limited not only by the voltage supplies but also by the discharge tubes with their corona discharges and insulation breakdowns. It looked hopeless at that time to build devices for sufficiently high voltages in order to study this new nuclear phenomena in greater detail with higher particle intensities. Still, in 1927 Rutherford expressed in a letter to his hope that artificial accelerators with adequate energy could be built discussing the various methods of generating high voltages (Ru 27). In the same paper he pleaded for the use of very high magnetic fields in nuclear physics, referring to experiments of Kapitza and Cotton, who reached 320 kilogauss at that time.

In 1928 Gamow showed that due to the laws of wave mechanics, a penetration of the nuclear potential barrier by charged particles seemed to be possible at energies of 500 KeV or even less. Several laboratories started immediately to develop the necessary accelerators. The first to succeed were Cockcroft and Walton in the Cavendish laboratory (Co 32). In 1932 they reported the successful disintegration of lithium by protons of about 400 KeV, using the voltage multiplying circuit invented in 1921 by Greinacher in Bern (Gr 21).

In that period this extremely successful collaboration of experimental and also theoretical physicists with engineers started. In the course of developing step by step more and more powerful accelerators, they achieved not only higher energies but also higher intensities, greater stability, and energy precision as well. As Stan Livingston, one of the great accelerator pioneers, wrote: "Physicists converted to engineers and vice versa forming this powerful club of machine builders," talking nowadays only in terms of giga or tera volts and storage rings with currents of many amperes. Let me start now a review of this development:

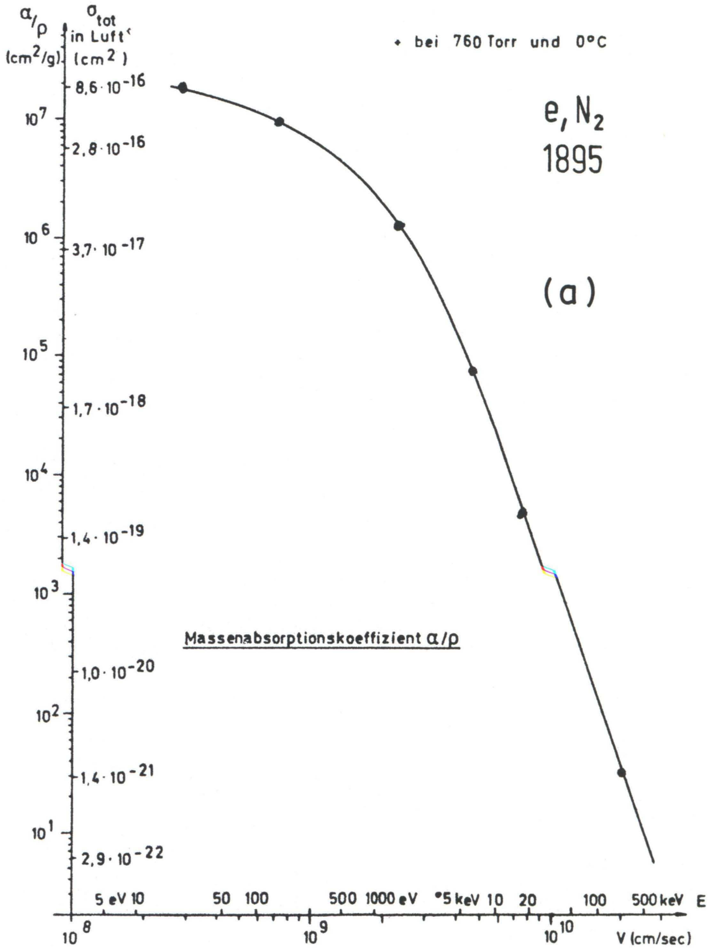
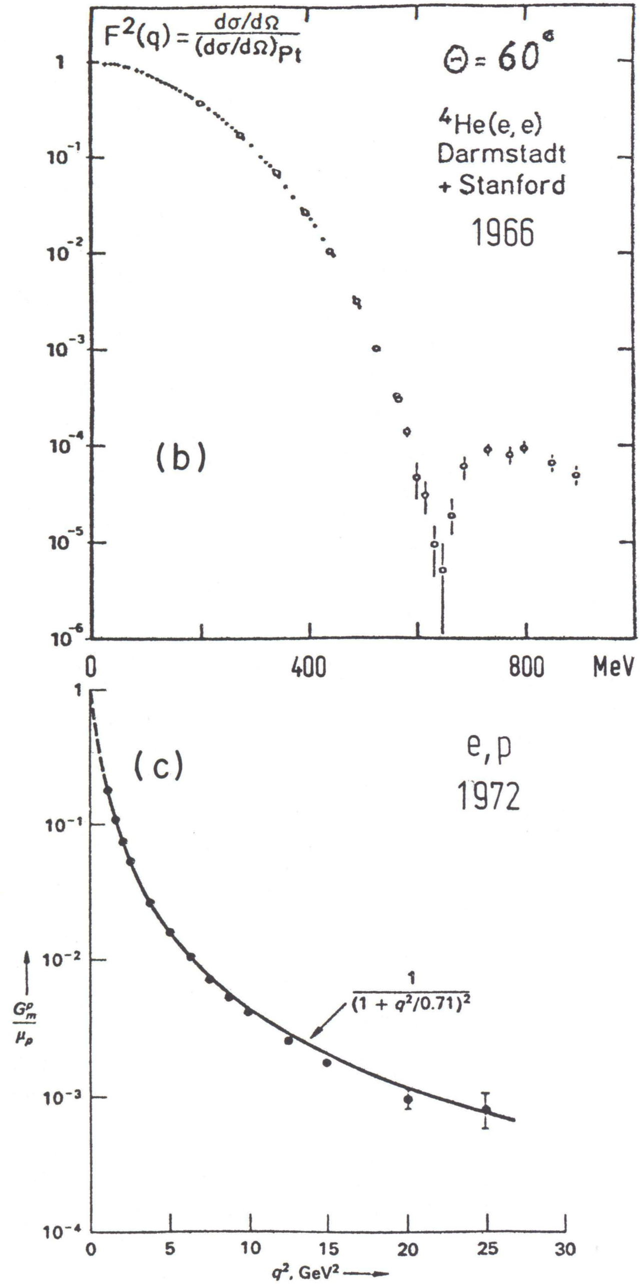


Fig. 1. Energy dependence of the cross section for elastic electron scattering. (a) atom: charge distribution in nitrogen (Lenard 1895); (b) nucleus: electric form factor (charge distribution); (c) proton: magnetic form factor (magnetic moment distribution).



F²(q) = dσ/dΩ / (dσ/dΩ)Pt
Θ = 60°
⁴He(e, e)
Darmstadt
+ Stanford
1966
(b)
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0
400
800
MeV
(c)
e, p
1972
1 / (1 + q²/0.71)²
G^p_m / μ_p
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
5
10
15
20
25
30
q², GeV²

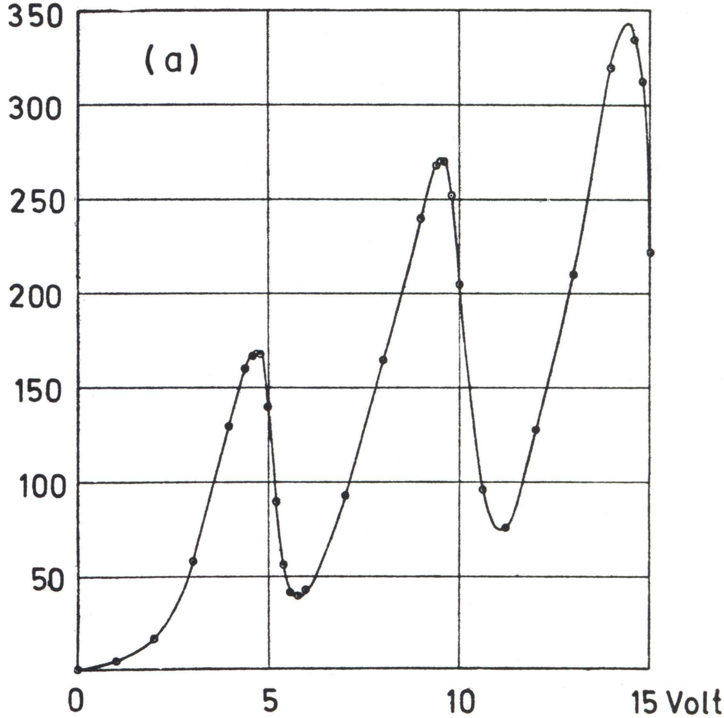
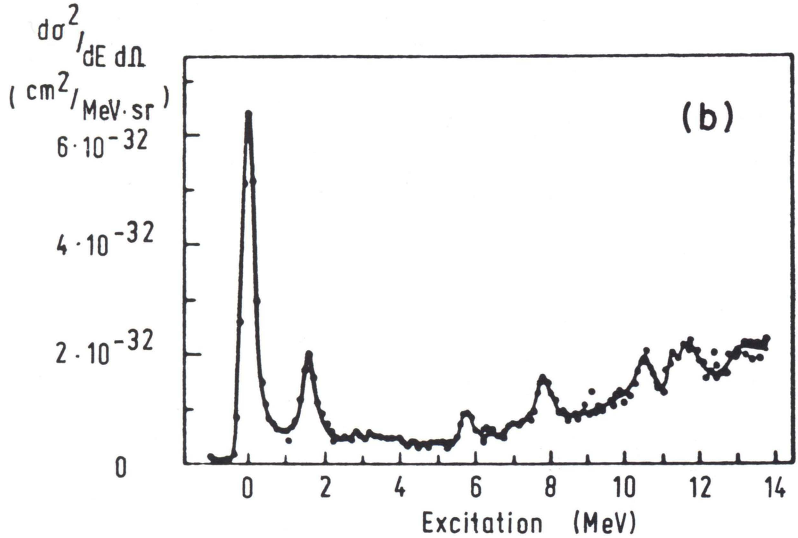


Fig. 2. Excitation of energy levels by electron impact. (a) Hg atom 1913; (b) nucleus 1962; (c) proton 1972.



Spectrum of electrons scattered at 180° from ^{25}Mg, with E_1 = 55.9 MeV.

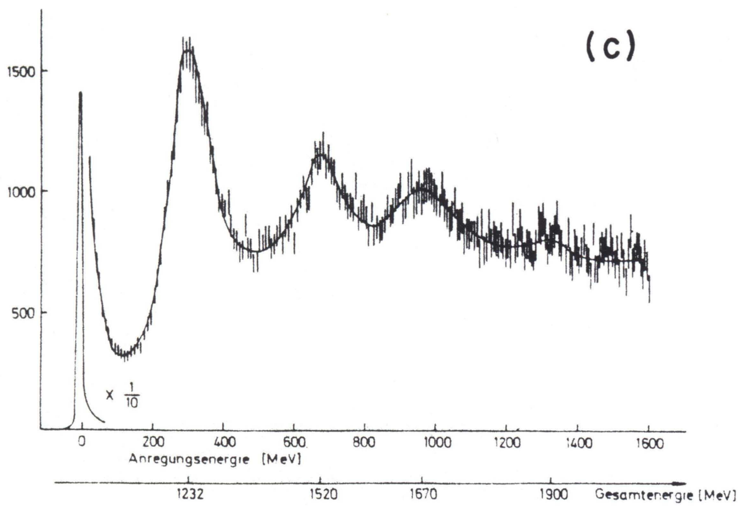


Fig. 3. The greenhouse of a university. H.A. Bethe and B. McDaniel in the accelerator tunnel at Cornell University.

It would take too long a time to go into all the details. Therefore I would like to concentrate on some of the basic ideas of the various types of accelerators which are listed in the table below. They were developed in many relatively small university laboratories, often sponsored by industry and often stimulated by the lack of the sums of money or technical resources, which seem to be indispensable for us. Today accelerator physics and engineering is concentrating more and more in very few large laboratories in the world, with their own standards of precision and perfection. A new device has to work at the first attempt. Due to the large sums of money involved, only well-founded techniques are used; at least the risk must be calculable. But discounting very rare cases, new ideas and new techniques need their time for ripening. They grow best, not in the framework of a national project, but in the greenhouse of a university. A typical example of this is shown in Fig. 3. The growth of energy of accelerators is shown in Fig. 4.

Types of Accelerators

I.	Direct Voltage Acceleration	
	Electrostatic Generators	1670
	Voltage multipliers	1932
II.	Induction Accelerator	
	The Betatron	1921-1940
III.	Resonance Acceleration	
	In electric high frequency fields	1924
	Linear Accelerators	1928
	Cyclotron	1930
IV.	Synchrotron Acceleration	
	Synchrotron	1945
	Synchro-Cyclotron	1946
	Isochron-Cyclotron	1955
	Strong-focusing optics	1950-1952
V.	Storage rings	
	Intersecting beams	1943,1956
	Cooling	1966-1968
VI.	Coherent Acceleration	
	Collective effects	Budker 1956
	Plasma accelerators	Veksler 1956

I. Direct Voltage Acceleration

In this type of accelerator, electrons or ions (in the old diction: cathode and canal rays) are accelerated in a discharge tube by an applied high voltage. They are limited in energy and current by the voltage generator and the electrical insulation strength of the tube as well.

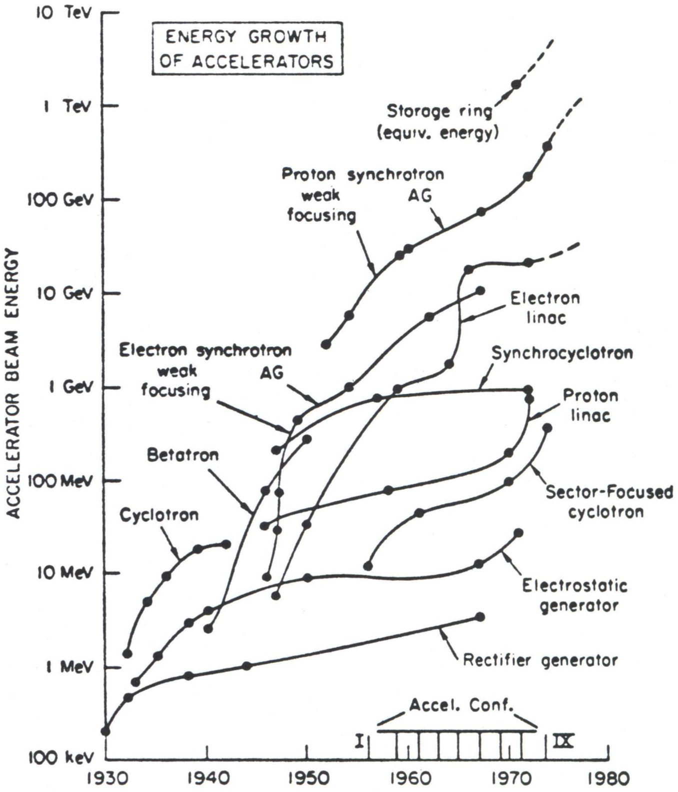


Fig. 4. Energy growth of accelerators.

The Electrostatic Generator

All electrostatic generators have their origin 300 years ago, when O. von Guericke in 1671 built the first friction electricity machine. In the following decades many improvements were made; a generator of special curiosity was the charge water drop or water vapor generator, constructed by Armstrong in 1845 (Ar 45) (Fig. 5). It was based on the observation of Faraday (Fa 43) that vapor emitted from a nozzle is electrically charged by friction. The water droplets were discharged on a metal plate, leaving the insulated steam vessel charged in the opposite sign.

Very common machines used in many laboratories until the 1920's were the induction generators, introduced by Toepler (Toe 65) and brought to perfection by Holtz, Wimshurst and Villard (Vi 11). They were quite powerful and in a multiplate version driven with an electromoter gave voltages up to 250 kilovolts at a current of 1 milliampere. Such a generator is shown in Fig. 6.

The most successful device is the belt generator developed by R. J. Van de Graaff (Gr 31). As a Rhodes scholar in Oxford (1928) he became aware of the necessity of high-voltage supplies for nuclear physics. Back in Princeton he succeeded in 1931 in reaching 1.5 megavolt with his relatively simple and cheap machine. In this generator an endless insulating belt transports charges to a spherical conductor. Looking through old books I found its prototype already commercially built in 1893 by R. Busch (Bu 93) (Fig. 7). In order to be independent from the room humidity, the driving cylinders were heated from inside and thereby also the belt. Even a very modern belt (the laddertron) was anticipated (1876) by A. Righi in Bologna. In order to avoid discharges along the belt, he constructed it from metal and insulating strips alternately linked together.

Van de Graaff's success immediately brought him the support of K. T. Compton, president of MIT, and a project was started, gigantic for that time. Two belt generators for 7.5 MeV each, but of opposite charge, were planned with a discharge tube between and an observation laboratory inside one of the terminals (Fig. 8a). The apparatus was installed in a huge hangar but never reached the full voltage. Figure 8b shows one of the impressive discharges between the voltage terminals and the metallic walls of the hangar. Another group--Tuve, Hafstad, and O. Dahl (Tu 35)--at the Carnegie Institution of Washington was more modest. They produced in 1933 a proton beam of 600 KeV and performed the first nuclear physics experiment with a Van de Graaff generator. In 1935 they reached 1.3 MeV with a beam current of 750 μA (Fig. 9). Van de Graaff's group at MIT followed soon with a revised version of their former ambitious project, reliably achieving 2.75 MeV. It was successfully used for research for many years.

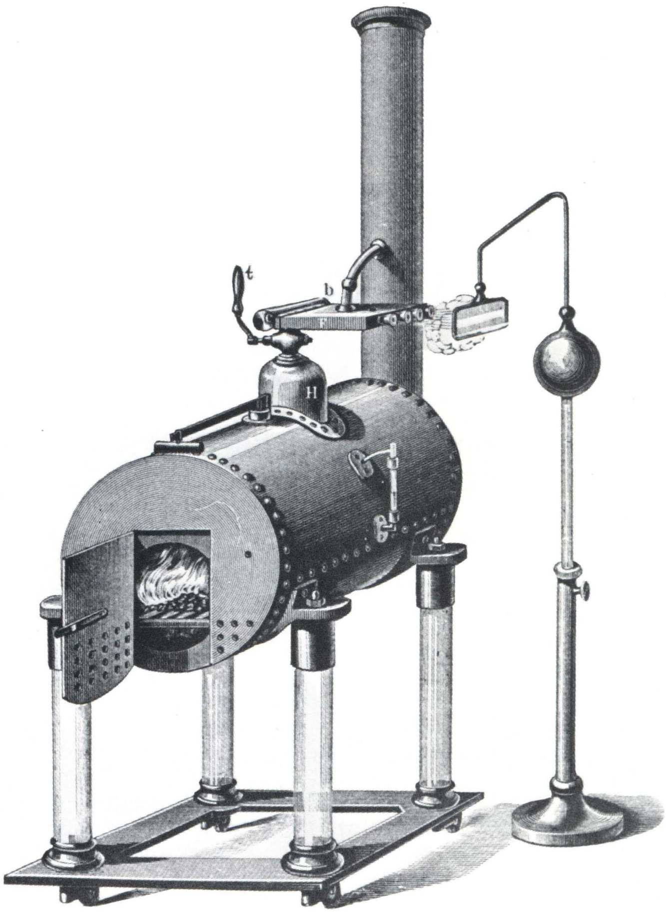


Fig. 5. High-voltage generator using charged water droplets
(Armstrong 1843).

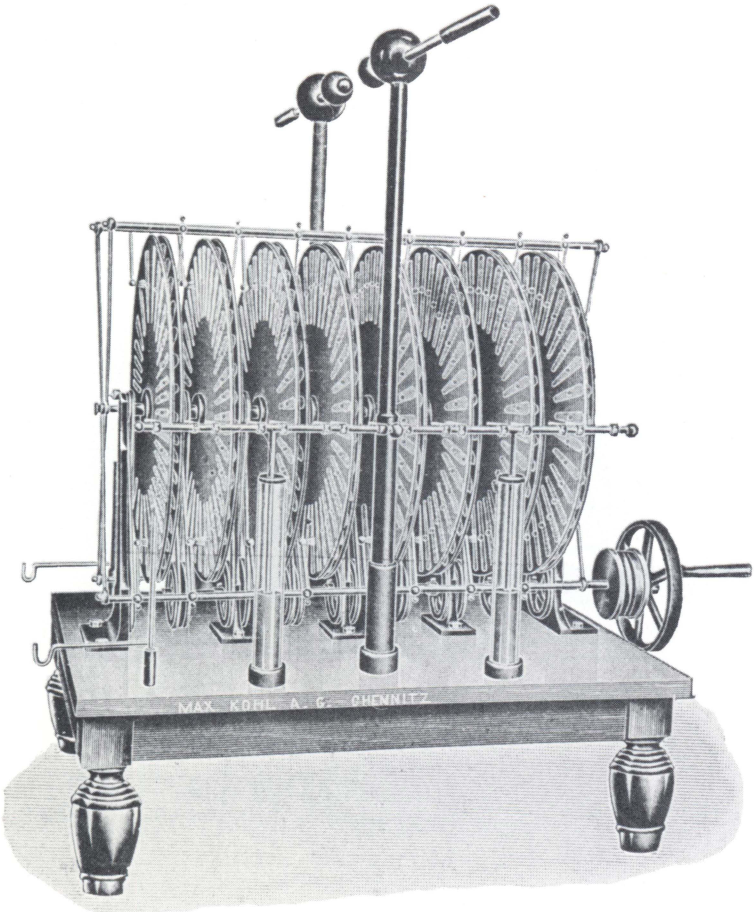


Fig. 6. Electrostatic generator of the Toepler type, disc diameter 90 cm.

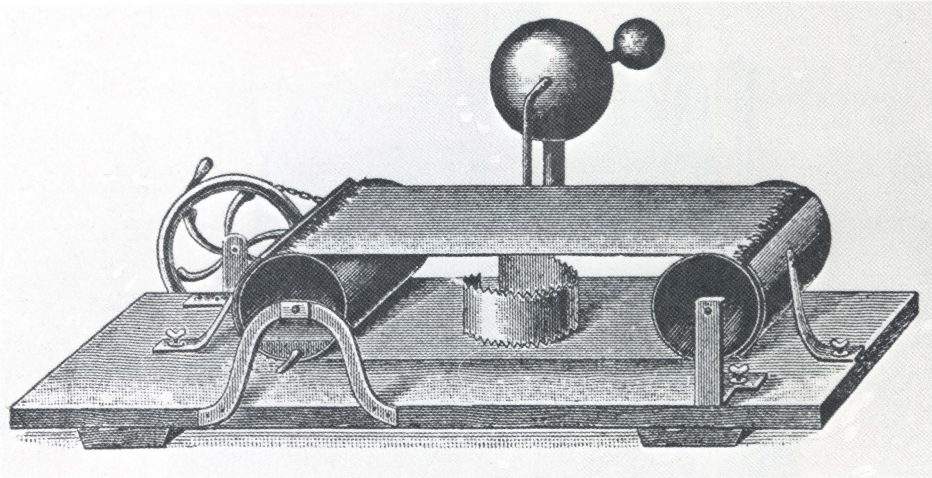


Fig. 7. The commercial belt generator by R. Busch 1893.

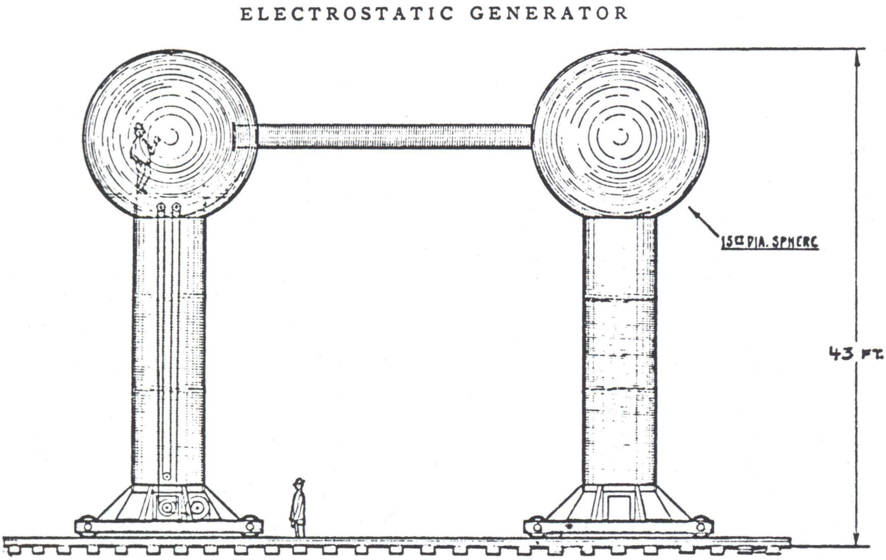


Fig. 8a. Sketch of the 2 x 7.5 MV "Round Hill" generator.

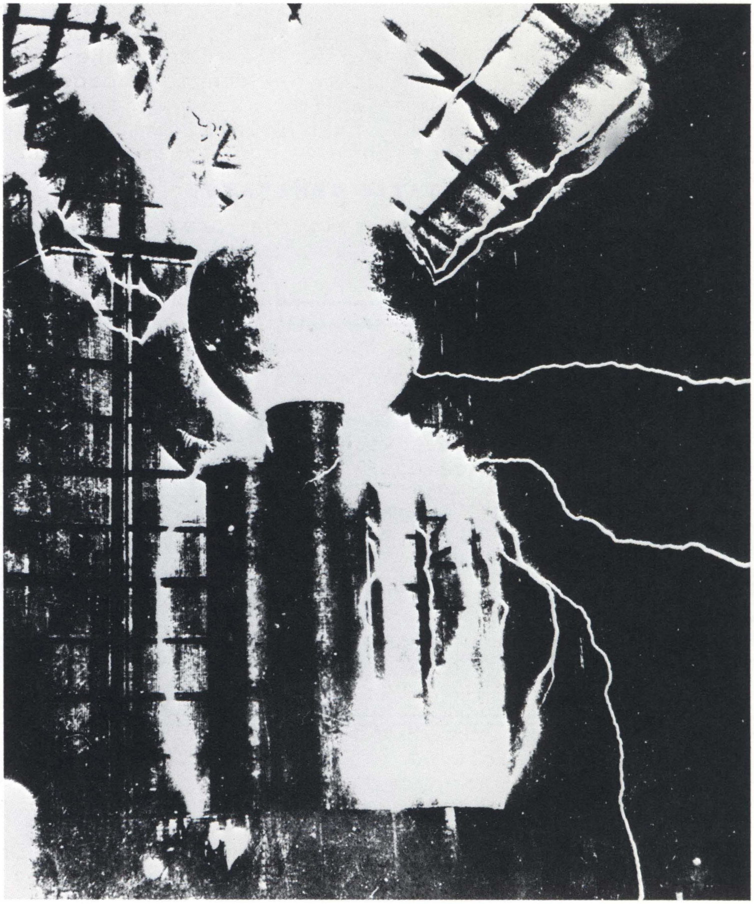


Fig. 8b. Discharges between the voltage terminal and the hangar walls.

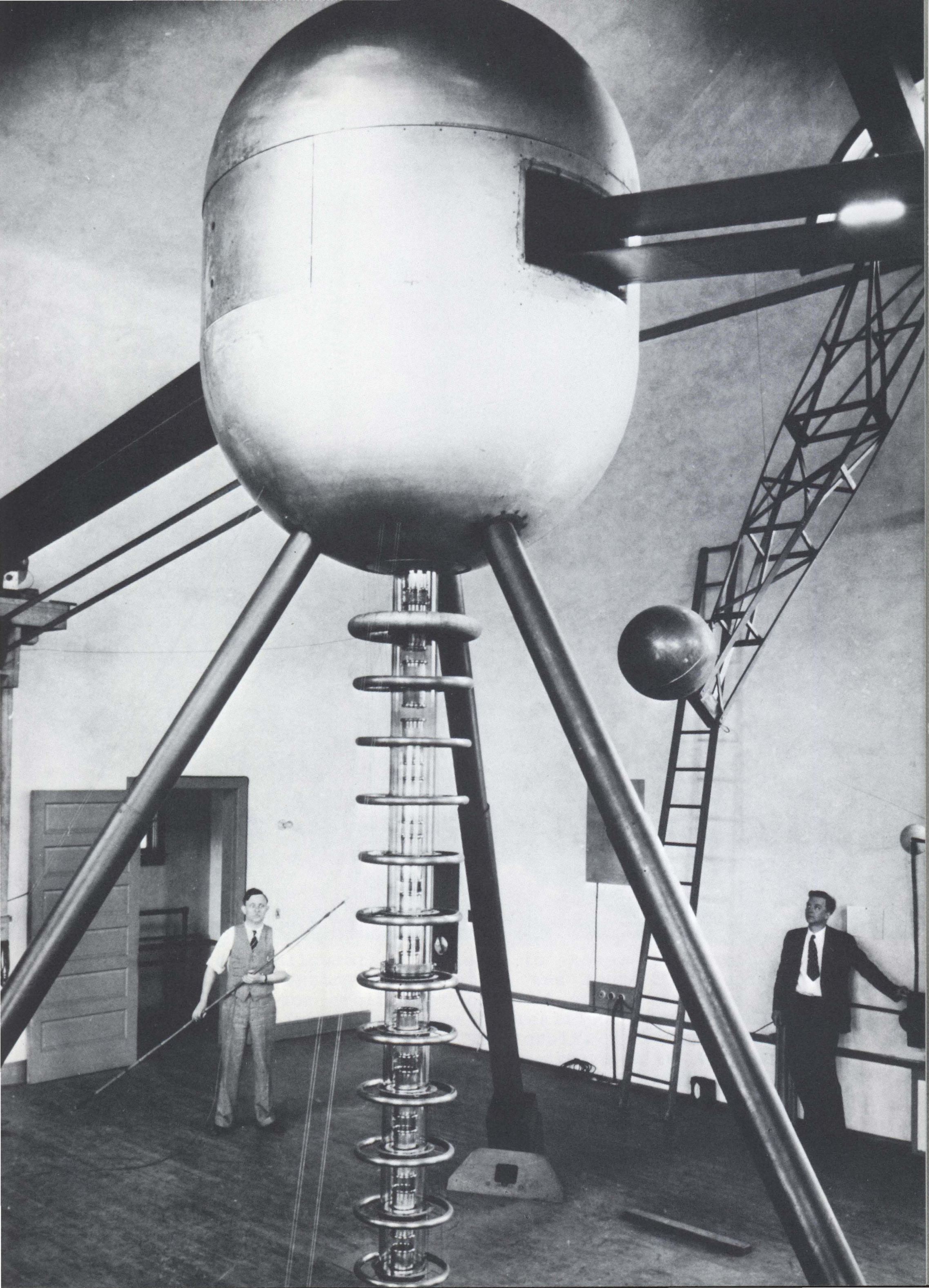
The annoying dependence of these generators on the atmospheric conditions was overcome by Herb, Parkinson and Kerst by installing the generator in a pressure vessel (He 35), which at the same time allowed higher voltages due to Paschen's law of voltage breakdown. But this technique also was anticipated in 1885 by Hempel in Dresden (He 85), who studied the performance of a Toepler induction generator in an iron pressure tank filled with dry air up to 6 atm. Even the driving electromotor was placed in the vessel. He found a significant increase in the achieved current, and better insulation properties. He also investigated the behavior of different gases such as H_2 and CO_2.

After the war, Van de Graaff's generators became for many years the standard accelerator not only in nuclear physics, but also in many other fields of research and industry where they are still standard today. The most impressive installations are under construction in Oak Ridge and Daresbury for heavy-ion research. They are designed for 30 MV voltages and housed in 70 m high towers. These generators will work according to the tandem principle. In such a device one starts with negative ions which are accelerated to the voltage terminal. In a gas flow or a metal foil, electrons are stripped off, the sign of the ion charge is changed and the particles are accelerated back to ground, gaining in that way double the energy. This method was applied to Van de Graaff generators in 1955 but was already invented thirty years earlier. In 1932, in a paper *Method for Multiplying Canal Ray Energies for Nuclear Disintegration*, Gehrtsen (Ge 32) reported on an experiment in which protons were accelerated to a tube electrode. Inside the tube they became neutralized by gas collision in order to avoid their deceleration in running against the subsequent opposite voltage. They were charged again and accelerated in a second step with the same voltage gaining double the energy. Gehrtsen's Ph.D. student Peter, in a subsequent paper (Pe 36), reported that he applied this method five times obtaining a 300-KeV proton beam of the order of nanoamps with a 60 KeV dc power supply. Dempster (De 32) in Chicago, independently reported also on such a device on a smaller scale. H. I. Kallmann (Ka 33) in the same year worked with multicharged ions, changing the charge between accelerations. (Later, in 1949, he introduced photomultipliers to nuclear physics.)

Other groups approached the problem of getting high voltages in different ways. I bring to your attention the experiment of Breit and Tuve in 1928 using Tesla coils. They were quite successful after putting the coil in an insulating coil under a pressure of about 40 atmospheres. In a letter to *Nature* (Br 28), they reported to have reliably reached 5 megavolt with a repetition rate of 60 cycles/sec and 10 μ sec pulse length.

In 1932 Brasch and Lange (Bra 31) used a powerful Marx generator. For the first time they were able to accelerate electrons up to 2.4 MeV. The pulse current was extremely high, about 1000 amps with a 10 sec pulse length and a repetition rate

Fig. 9 . Belt generator built by Tuve, Hafstad, and O. Dahl, 1933.



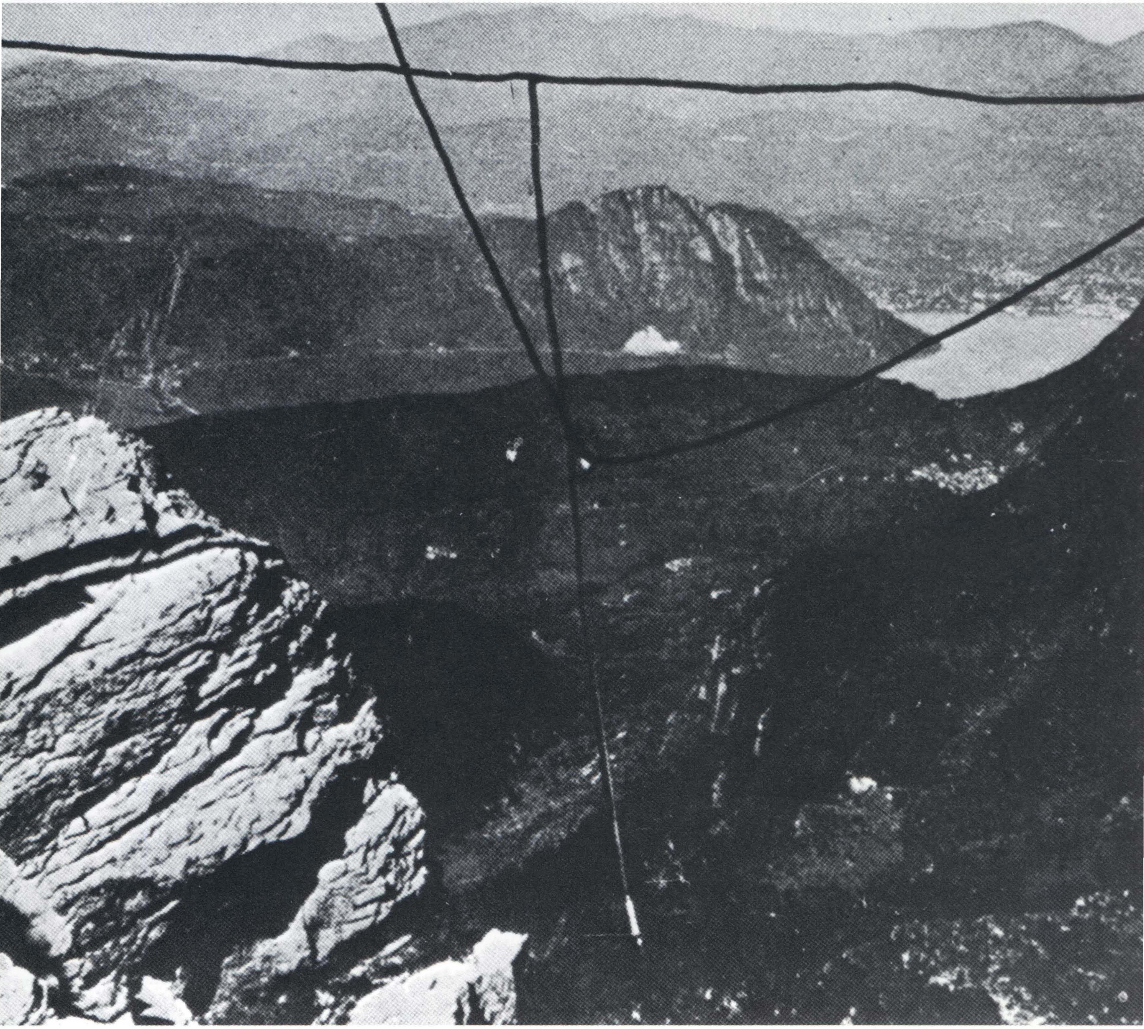


Fig. 10. The "antenna" installed at Monte Generoso by Brasch and Lange, 1930.

of 2/sec. The intensity of the x rays were so strong that behind 10 cm of lead a photographic film was still blackened. As far as I know, such devices are now used in experiments for collective acceleration.

Brasch and Lange (Bra 31) also tried a very unusual method of getting high voltages using thunderstorm electricity. For that purpose they stretched an isolated metallic net between two peaks 700 m apart on Monte Generoso at the Swiss-Italian border. This "electrode" collecting atmospheric electricity was connected at the ground to a discharge tube and parallel to a spark gap for measuring and limiting the voltage. They observed voltages up to 15 megavolt and 8 megavolt with a reasonable rate (Fig. 10).

The experiment was stopped in 1933 because one of the co-workers had a fatal accident at the experiment. Lange emigrated in 1933 to the Soviet Union, Brasch to the United States.

These experiments led to a blind alley but they were of great value for the development of discharge tubes. The technique of dividing the tube in many sections made of ceramics or resins and separated by metallic iris diaphragms has been in common use since that time.

II. The Betatron

Our next candidate is the Betatron or the accelerator of electrons by magnetic induction.

The idea to use the electric field around a time-varying magnetic flux for acceleration of electrons which are guided in a magnetic field has many fathers. S. Slepian in 1922 (Sle 22) took a patent on the idea, which was published in 1927, but he never made an experiment (Fig. 11). Breit and Tuve, at that time at the Carnegie Institution used high-frequency coils but were without success as they did not achieve stabilization of the electron orbit.

The first, who had in principle all the ingredients in his hands, was the Norwegian Rolf Wideroe. In 1923 as a very young student he was fascinated by the problem. He calculated the magnetic field configuration needed to keep the radius of electrons constant during acceleration and found the condition that the field at the orbit must be half of the average field within the orbit. Two years later he realized that in addition the electrons must be stable in the orbit. He came to the conclusion that the guide field must decrease with the radius according to a power law with a field index $n = (\Delta B/B_0)(r0/\Delta r)$ between 0 and 1. He did not publish his results at that time but one can still read it in his notebook (Fig. 12). His published experiments in 1928 (Wi 28) were not successful. As an electrical engineer he had no experimental experience with free

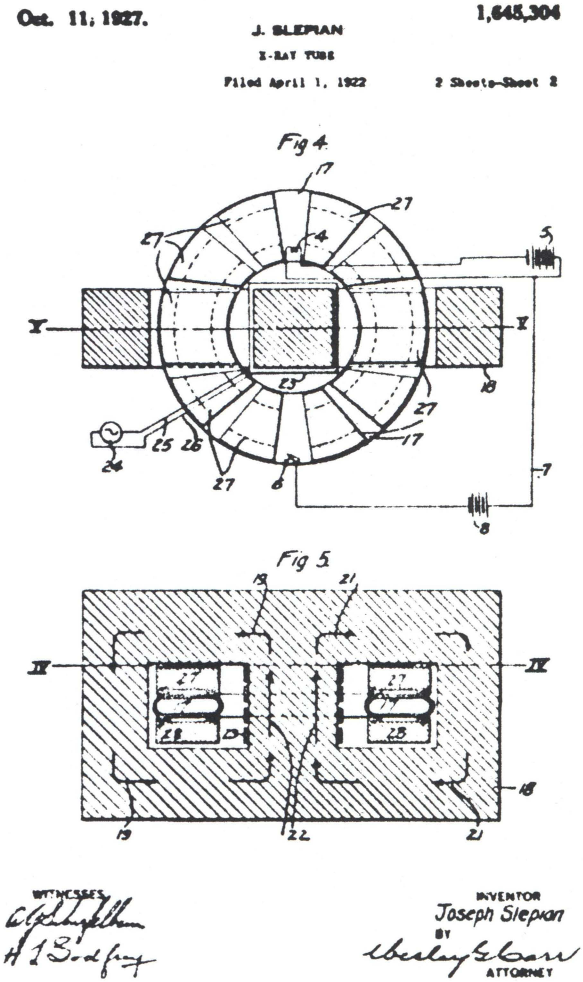


Fig. 11. Slepian patent: "X-Ray Tube," electron acceleration by induction, 1922.

electrons and surprisingly in the experiment he made no use of the field conditions he had calculated for the orbit stabilization. But it is worth mentioning that in his notebook he gave the parameters for a 100-MeV accelerator. In 1923, and for a 21-year old student, this is an astonishing feat.

In 1928 Rutherford stimulated Walton (Wa 29) to study the problem. He also found mathematically the focusing conditions. For the experiment he used a low pressure ring discharge as the electron source and failed. Such a Plasmabetatron, as we would call such a device today, was brought to some success by Budker and by Drees and Paul and others 30 years later, but it turned out not to be very useful for the purpose envisaged.

In 1935 M. Steenbeck at the Siemens Company also took up the problem of acceleration by magnetic induction. Knowing the Wideroe 1:2 conditions, he formulated the magnetic focusing condition for electrons on the stable orbit: $0 > n > 1$, as Wideroe already knew. An experimental set up was built. He certainly observed accelerated electrons, but with extremely low intensity (Ste 35,43), due to the fact that he did not preaccelerate the electrons before injection into the orbit.

The first successful induction accelerator was built by Donald Kerst in 1940 (Ke 40). He was just the better, more steadfast and more careful experimentalist than all the others, especially in the magnet design. His first apparatus brought 2.3 MeV for the electrons. He called the apparatus at first Rheotron, later Betatron. In a paper with Serber (Ke 41) he gave in 1941 the full theory of its operation.

This success of Kerst, published in the last issue of the *Physical Review* to come to Germany during the war, strongly influenced my personal life. At that time I was an assistant to H. Kopfermann, who worked for years on the isotope shifts in atomic spectra, in order to get information about the charge distribution in nuclei. Immediately he realized that scattering experiments with high-energy electrons would be a superior method. He stimulated me to give up spectroscopy and to convert to the new technique of electron accelerators.

K. Gund had started also at Siemens a new attempt in constructing for medical purposes an "Elektronenschleuder" (centrifuge), as he called the Betatron in those days. In 1943 6 MeV was reached, and Gund succeeded in 1947 in extracting an electron beam out of the vacuum tube for the first time (Gu 47). At the same time, Wideroe with R. Kollath and B. Touschek, built in Hamburg a 15-MeV "ray transformer," which successfully came into operation in 1944. Fifteen years later Touschek made important contributions to the development of electron storage rings.

It is characteristic for the time before the war that the physicists involved in such developments worked completely

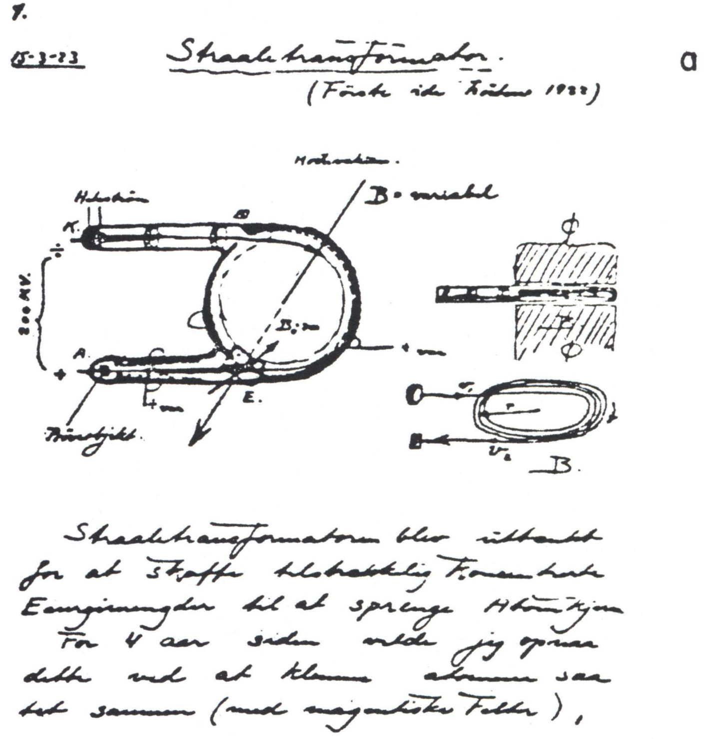
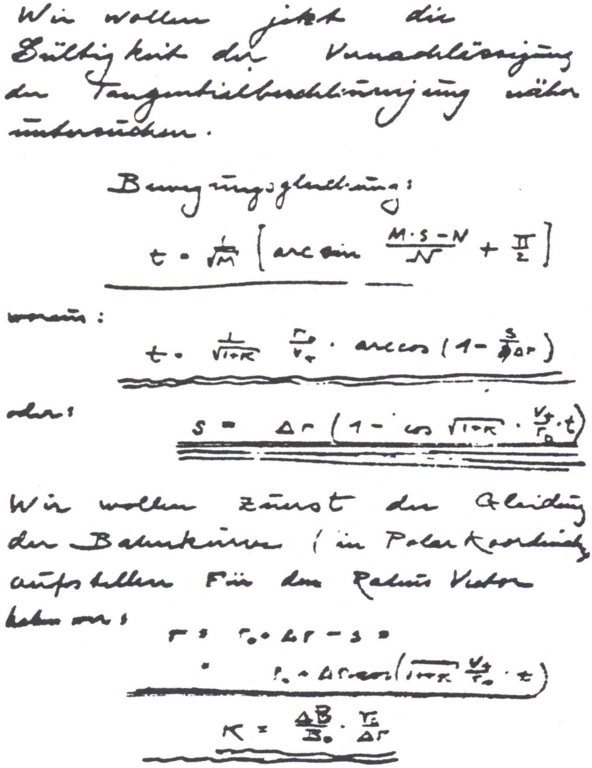


Abb. 2 und 3 *Auszüge meiner ersten Notizen (in norwegisch)*

Fig. 12. Pages of the notebook of R. Wideroe concerning acceleration by induction. (a) "Strahlentransformator"; (b) Derivation of the focusing condition, Aachen 1925.

b



Wir wollen jetzt die Gültigkeit der Vernachlässigung der Tangentialbeschleunigung näher untersuchen.

Bewegungsgleichung:

$$t = \frac{1}{\sqrt{M}}\left[\arcsin\frac{M\cdot s - N}{N} + \frac{\pi}{2}\right]$$

woraus:

$$t = \frac{1}{\sqrt{1+K}}\,\frac{r_0}{v_0}\cdot\arccos\left(1-\frac{s}{\Delta r}\right)$$

oder:

$$s = \Delta r\left(1-\cos\sqrt{1+K}\cdot\frac{v_0}{r_0}\cdot t\right)$$

Wir wollen zuerst die Gleichung der Bahnkurve (in Polarkoordinaten) aufstellen. Für den Radius Vektor haben wir:

$$r = r_0 + \Delta r - s =$$
$$= r_0 + \Delta r \cos\left(\sqrt{1+K}\,\frac{v_0}{r_0}\cdot t\right)$$

$$K = \frac{\Delta B}{B_0}\cdot\frac{r_0}{\Delta r}$$

Abb. 4 *Foto einer Seite meines Notizbuches aus Aachen (Sommer 1925)*

Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

Mitgeteilt am 12. März 1924 durch C. W. OSEEN und M. SIEGBAHN.

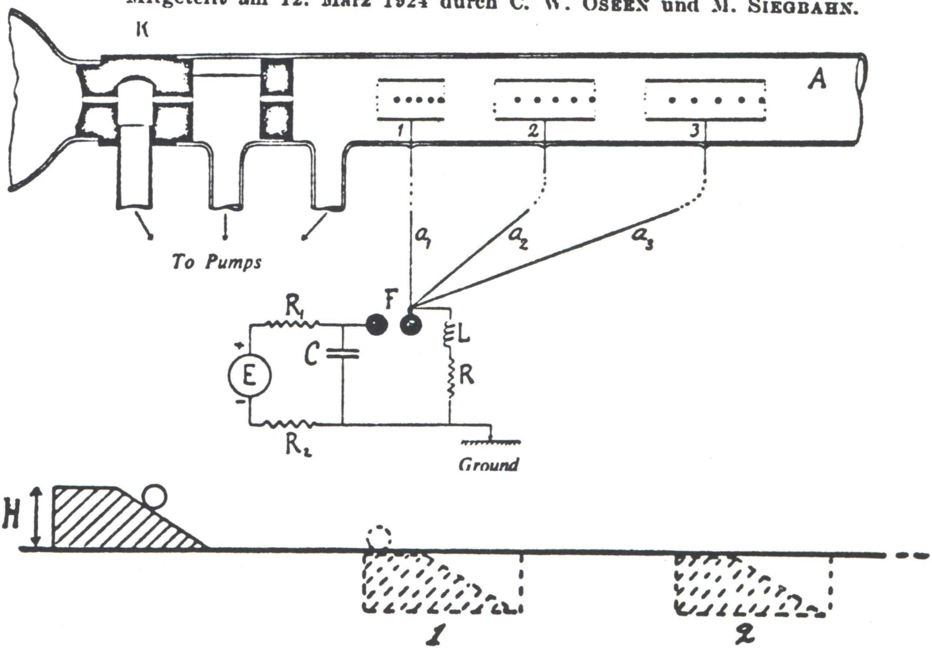


Fig. 13. Linear accelerator proposed by G. Ising 1924.

independently without knowing each other. There was no exchange of ideas or experiences; symposia or special conferences which we feel today to be indispensable were almost never held. Nuclear tourism did not yet exist.

III. Resonance Accelerators

When Wideroe failed in accelerating electrons according to the Betatron principle, he turned in order to save his doctoral thesis in Aachen, to another method proposed by the Swede, G. Ising in 1924. In a paper *Principle of a Method for the Production of Canal Rays of High Voltage*, Ising (Is 24) described the possibility of accelerating ions in the front of a radio-frequency wave traveling along a tube as is shown in Fig. 13. The wave front arrives at the accelerating electrodes at the same time as the ions. But Ising performed no experiment. Wideroe modified the method a little bit using drift tubes alternately connected to ground and an rf voltage generator. The travel time inside the field-free drift tubes is kept half the oscillation time of the rf voltage U_o by increasing their length proportional to the ion velocity. In that way the ions see in all gaps an accelerating field. The total energy is then given by the voltage U_o multiplied by the number of gaps. This time Wideroe was successful in a pilot experiment with only two gaps using Na- and K-ions (Wi 28). He showed that the method worked according to his theoretical prediction of resonance acceleration (Fig. 14). As an example he gave the parameters for a heavy-ion (Cesium) accelerator for 2 MeV. With an rf voltage of 170 KV and a frequency of 1.7 MHz the length of the apparatus would be only 1.20 m.

With this experiment based on Ising's idea, the method of resonance acceleration was born, followed by many variants and improvements leading to the powerful cyclotrons, synchrotrons, and linacs of today. One story reported by Wideroe (Wi 64) is worth mentioning. In a discussion at Aachen in 1928 he was asked by Flegler, a professor of electrical engineering, if it is possible to bend the ion beam in a circle in a magnetic field and to use the same accelerating gap repeatedly. Wideroe answered that it would be possible in principle, but the beam would not be stable. He had calculated the stabilization by a proper magnetic field but the space-charge effects would compensate the focusing forces already at a current of 10 mA. And in another note that Wideroe sent to me, he says that for him as an electrical engineer accustomed to many amps, milliamps were negligible. At that early time he did not know that physicists were already happy with microamps. However, Wideroe missed the invention of the cyclotron in which Ernest Lawrence succeeded two years later.

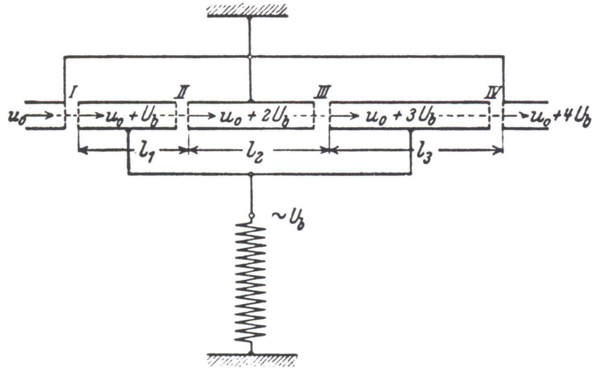
The *History of the Cyclotron* was extensively reported by M. S. Livingston and E. M. McMillan in memorial lectures to E. O. Lawrence in 1959 and published in *Physics Today* (Liv 59). Lawrence, in his Nobel Prize Lecture (1951), tells us about the background of his great invention: When he became a physics professor at Berkeley in 1928 he planned to join the new exciting field of nuclear physics and he was taking into consideration all types of high-voltage generators for an accelerator in Berkeley. One evening in early 1929 he was glancing over current periodicals in the library and came across the article by Wideroe on multiple acceleration. He could not read German well, but from the formulas and figures he was aware that this method was just what he needed to compete in the race for higher energies. Thinking big he realized that for millions of electron volts it would be advantageous to bend the linear beam of Wideroe to a circle in a magnetic field. He realized soon that the rotation frequency of the particles is independent of the velocity as the orbit radius increases. Therefore a fixed frequency on the electrodes can be used depending on (e/m)B. For realization he gave the problem at first to the student N. E. Edlefsen. In spite of the fact that the experiment did not work so well, the method was published (La 30).

Then the task was passed to Stan Livingston. He was just the right man for it and in his Ph.D. thesis he reported on the first cyclotron resonance with a quickly built small model for 80 KeV protons with D-shaped electrodes with an applied potential of only 1000 volts (Fig. 15a,b). In December 1932 with a larger device 1.2 MeV were achieved and the first nuclear disintegration was observed. A new chapter in nuclear experimental technique was opened. Figure 16 shows the next stage, the 27-inch cyclotron with the proud-looking Lawrence and Livingston in front of it.

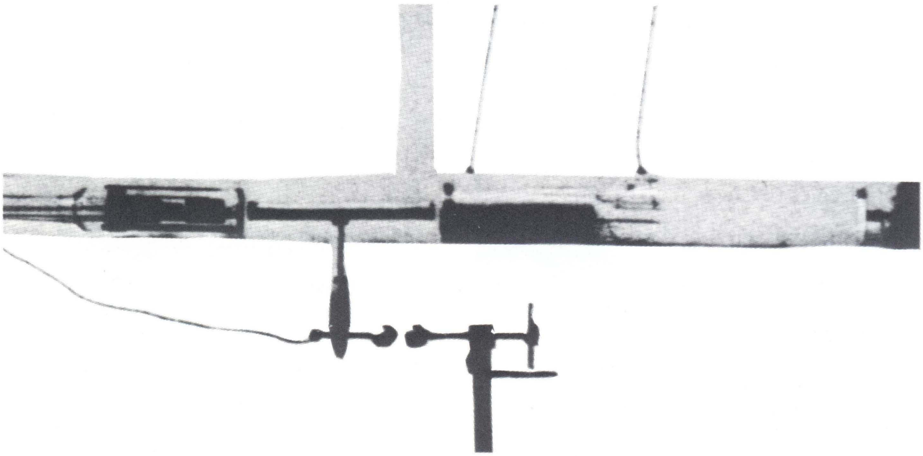
Lawrence was quite lucky that his experiment fulfilled the two conditions necessary for a successful operation of a cyclotron: beam focusing and isochronism. The magnet with its wide gap automatically gave a field which decreases with the radius necessary for radial focusing and the gap between the dee's provided an electric field suited for axial stabilization. Qualitatively this behavior was understood by the authors but the full theoretical treatment and understanding of these problems came after the experiment. R. R. Wilson, also in Berkeley, published the relevant paper on *"Magnetic and Electrostatic Focusing in the Cyclotron"* (Wil 38). Only seven days earlier M. E. Rose (Ro 38) submitted his paper dealing with the focusing problem and with the maximum available energy in the cyclotron. H. A. Bethe (Be 37) had just remarked that due to the relativistic mass increase the particles may fall out of isochronism during the acceleration process.

Lawrence not only developed the cyclotron with Livingston, but also followed at the same time the other way opened by Wideroe, the linear accelerator. In this field D. Sloan was his co-worker.

In 1931 Lawrence reported in the *Proceedings of the National Academy of Sciences* (La 31) that they had succeeded in



Principle of voltage transformation by means of potential fields.



The experimental tube.

Fig. 14. Wideroe's first linear accelerator.

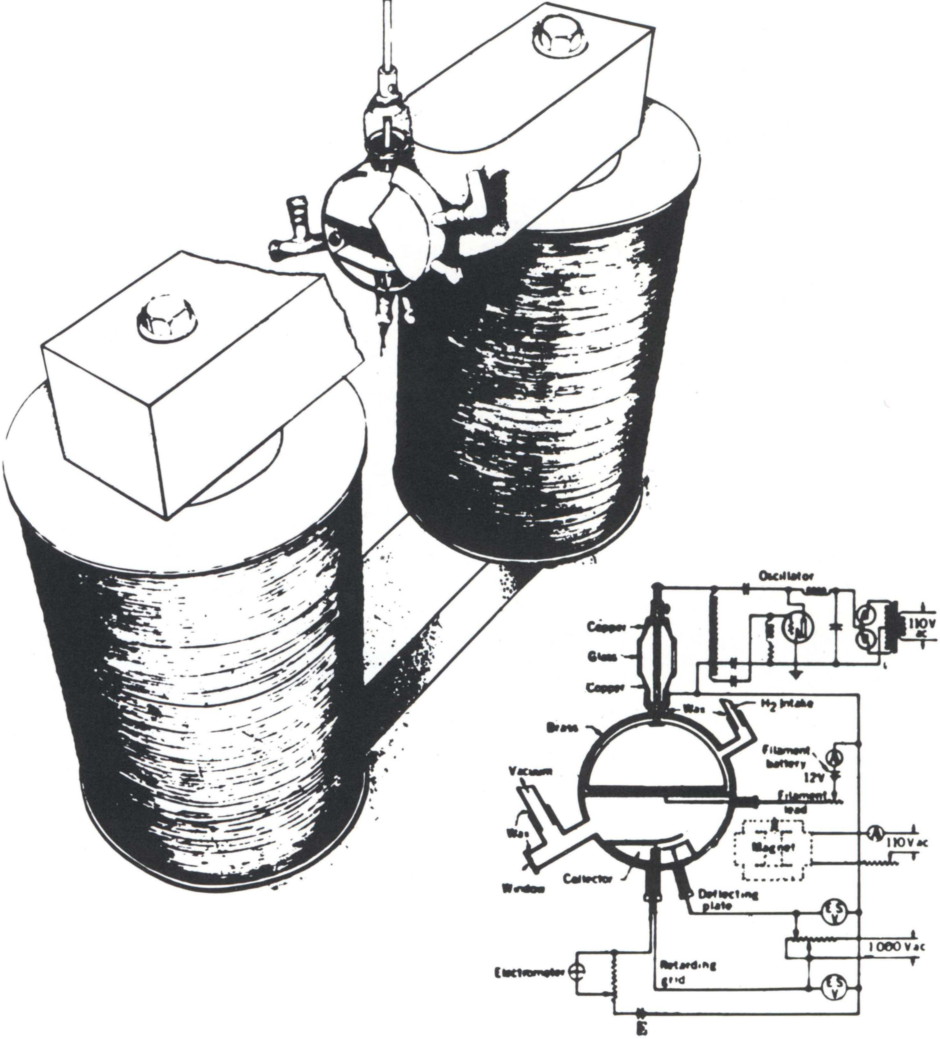


Fig. 15a. First cyclotron by E. O. Lawrence and M. S. Livingston.

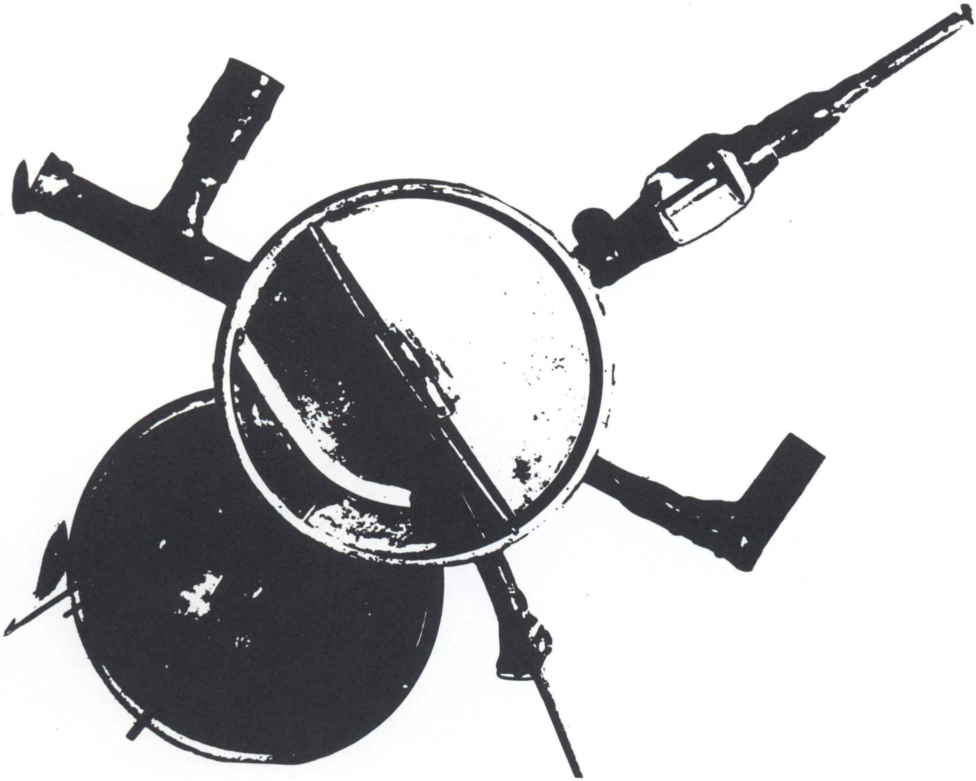


Fig. 15b. The vacuum chamber with the D.

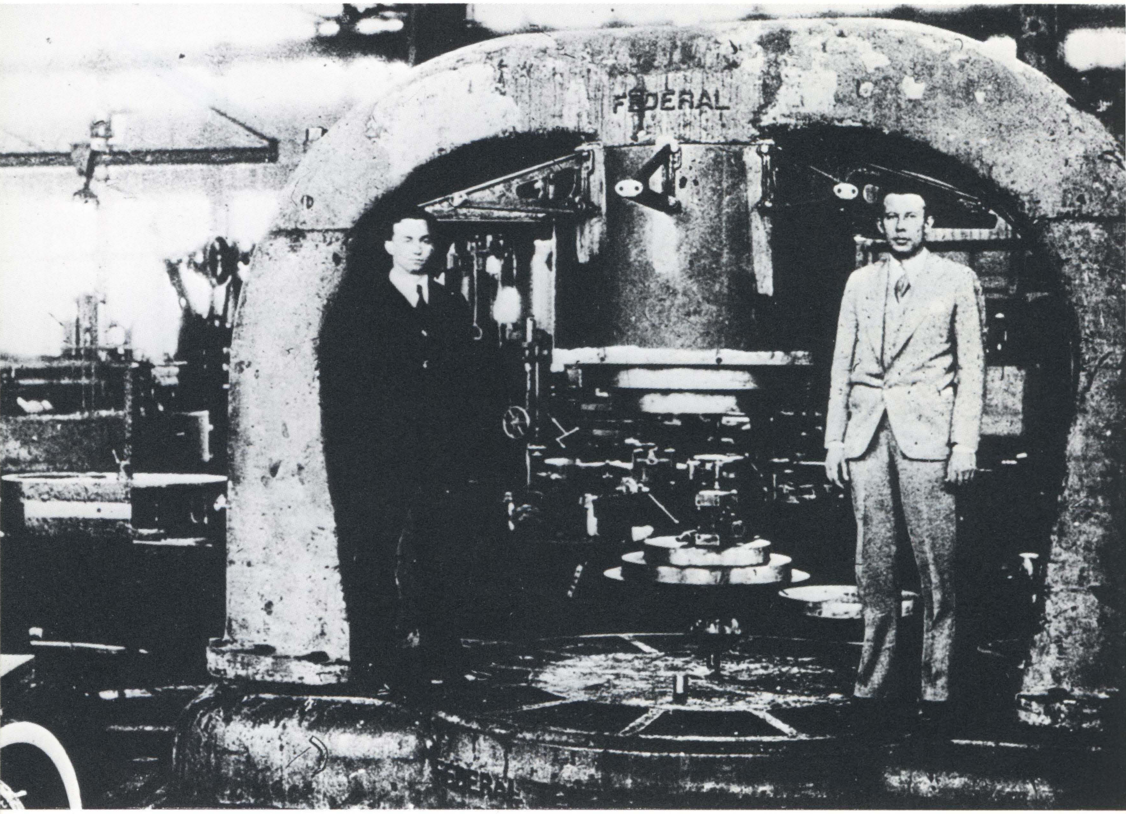


Fig. 16. The 27-inch cyclotron (Lawrence and Livingston posing in front of it).

accelerating mercury ions in a linac 1.07 m long with 20 stages up to 205 KeV with only 6.2 kV rf voltage of 4.5 mHz. The year after, with increased voltage they achieved 1.26 MeV at a current of 10^{-7} amps.

All these devices depend strongly on radio-frequency generators of high power and high frequencies. During the war such generators were developed for radar systems. High power magnetrons and klystrons became available, and the first proton linacs were successfully constructed by L. Alvarez (Al 46) at Berkeley and by the late John Williams in Minnesota. The largest linacs of this type are at present the proton meson factory at Los Alamos (800 MeV) and for heavy ions up to uranium the Unilac in Darmstadt combining the Wideroe and Alvarez acceleration structures.

Electron linear accelerators with their special problems of relativistically moving particles profited from the radar experiences in the so-called S-band. W. W. Hansen (Ha 48) is especially deserving of mention for his work in developing these traveling wave-guide accelerators, which Ising had proposed 20 years earlier in a primitive way. Another 20 years later the gigantic 2-mile long Stanford accelerator for 20 GeV came into operation.

IV. Synchronous Accelerators

As mentioned above, particles in a cyclotron fall out of resonance with the accelerating radio-frequency field due to the relativistic mass increase, and cease to gain energy. In a profound theoretical paper Thomas (Tho 38) treated all the connected problems in detail and showed quantitatively how one should overcome them experimentally. In order to achieve high energies he proposed that the magnetic field should not only vary with the radius but also with the azimuth. On his ideas the isochron - and the spiral-ridge cyclotron are based. But it took 20 years before these types of accelerators were realized. The strict mathematical treatment of the problem was not easily understood by the experimentalists.

In addition to the method proposed in Thomas's paper, there are two other ways to achieve high energies, the synchrocyclotron and the synchrotron. In both devices the parameters of the accelerator are changed adiabatically with increasing particle energy. In the *synchrocyclotron* one changes the frequency of the rf generator during the acceleration process according to the mass increase while the particle spirals out in the constant magnetic field.

In the *synchrotron* one keeps the orbit radius constant, therefore the magnetic field has to be increased according to the momentum. As long as the velocity of the particles is still increasing, the radio-frequency has to be changed too, but it can be kept constant when the particles approach the velocity of accelerating mercury ions in a linac 1.07 m long with 20 stages up to 205 KeV with only 6.2 kV rf voltage of 4.5 mHz. The year after, with increased voltage they achieved 1.26 MeV at a current of 10^{-7} amps.

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Fig. 17. The Fermilab 500-GeV synchrotron with the first superconducting magnets for the Energy Doubler.

light as is the case for electrons already at low energies. Due to the fixed-orbit radius only a ring magnet is required. But one has to pay a price for it. It is obvious that in these types of accelerators no continuous acceleration is possible anymore. They must operate in a pulsed mode, one acceleration process after the other.

Independently these principles were developed in 1945 by V. Veksler in Russia (Ve 45) and E. McMillan (Mil 45) in Berkeley and even Wideroe in 1946 took a patent on it (Wi 46). The authors showed that if the field or frequency variations in time proceed adiabatically, synchronism between revolution and radio frequency is automatically maintained. This result opened the door for the acceleration to ultra-high energies. At first the method was applied to electron acceleration and later to protons, culminating in the large 500-GeV accelerators at CERN and Fermilab, where one envisages in the near future 1000 GeV (Fig. 17). But these machines would not have been feasible either from the technical or from the economic point of view, if the method of strong focusing had not been invented.

Strong Focusing and the Use of Multipole Magnetic Lenses

The first synchrotron used the rules which were developed for the Betatron for focusing the particles on the orbit. The particles were guided by a magnetic field which was rotation symmetric and decreased with the radius according to a power law $B \sim r^{-n}$. In such a field the particles oscillate with a Betatron" frequency (number of oscillations per revolution) $Q_v = n^{1/2}$ in axial direction, whereas the radial frequency is given by $Q_v = (1-n)^{1/2}$ due to the fact that the centrifugal force is proportional to r^{-1}. Therefore one has to compromise in the choice of n between 1 and 0. This restricts the restoring force to a relatively low value which results in large amplitudes of the particles. Due to this weak focusing the guiding ring magnet must be relatively wide and becomes expensive.

In 1952 Courant, Livingston, and Snyder (Cou 52) from the Brookhaven Laboratory found a very sophisticated method of substantially improving these conditions in order to achieve a "strong-focusing" device. But soon they realized that a Greek engineer N. Christofilos (Chri 50), had already taken a patent on the same idea in 1949, despite the fact that he had no previous experience with accelerators (Fig. 18). They proposed to abandon the concept of a magnet ring with a field configuration constant in azimuth and instead to cut it into sections with a field-index alternating between high positive and negative values. In this case one gets alternating focusing and defocusing forces in both the radial and vertical directions. In such a field configuration the equation of motion is represented by the Hill equation which results in stable and unstable orbits. In the case of stability, which depends only on the field parameters, the oscillation amplitudes of the particles are substantially reduced compared with the previous weak-focusing method, in spite of the a

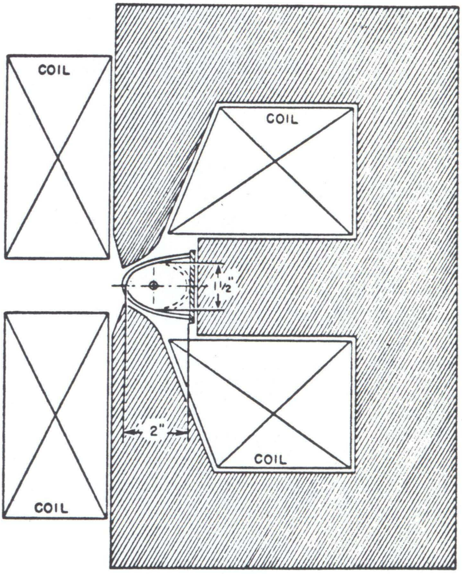


FIG. 5. Cross section of *E*-magnet with poles shaped to give $n=3600$ at an orbit radius of 300 ft. The vacuum chamber illustrated has an internal aperture of about 1×2 inches.

E. D. Courant, M. S. Livingston,† and H. S. Snyder

The Strong-Focusing Synchrotron—A New High Energy Accelerator*

Fig. 18. Strong-focusing magnets. (a) Courant et al., 1952; (b) Christofilos, 1950.

b

Nicholas Christofilos

Focussing System for Ions and Electrons

[U.S. Patent No. 2,736,799 (filed March 10, 1950, issued February 28, 1956).]

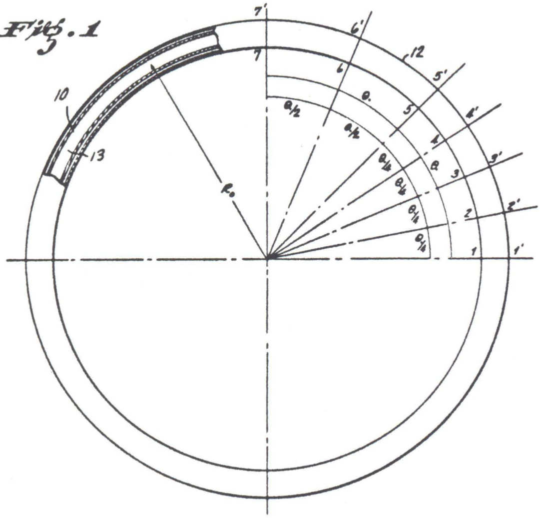


Fig. 1

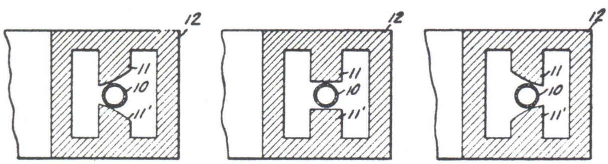


Fig. 2 Fig. 3 Fig. 4

fact that for half the time they see strong-defocusing forces. Figure 19 illustrates the size of the vacuum tube in weak- and strong-focusing accelerators and thus the width of the respective magnet gaps. The decisive progress is obvious.

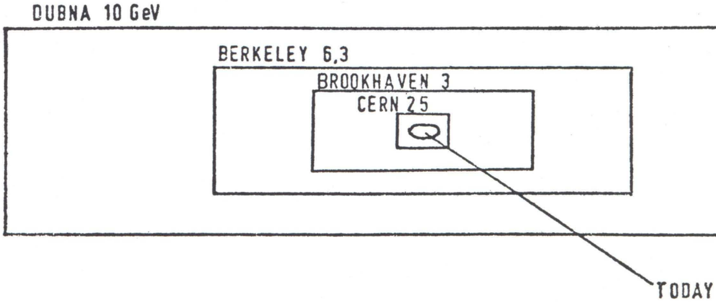


Fig. 19. The size of vacuum chambers. The synchrotron (Dubna) the Berkeley and Brookhaven accelerators are wesk-focusing synchrotrons, the others use the strong-focusing principle.

Immediately after the new principle worked out in Brookhaven became known, the newly founded European Laboratory for Nuclear Research (CERN) took up the idea. The already approved plans for a conventional weak-focusing proton synchrotron for 10 GeV were changed. A rough estimate showed that for the same cost a 25-GeV accelerator could be built. It came into operation in 1959, only a few months in advance of the Brookhaven machine. But it is worth mentioning that the first strong focusing synchrotrons to deliver beam to experiments in the USA and Europe, were the electron synchrotrons at Cornell University and the University of Bonn.

In the same paper, Courant et al., showed that quadrupole magnets are good cylinder lenses for particles and that a system of alternate polarity quadrupoles can serve as a beam-transport system over long distances. Only a few weeks later, Kitagaki from Tohoku University in Japan (Ki 53) proposed to separate in a synchrotron the task of focusing and bending the particles in a circle by using alternating quadrupole lenses in straight sections between dipole bending magnets. Already at that time, Kitagaki gave the parameters for a 100-GeV proton accelerator. Only in 1962 did this idea of a separate-function machine come up again and was first realized at the Fermilab 500-GeV synchrotron.

However, the conception of non-circular symmetric "magnetic or electrostatic lenses for charged particles" existed already in electron optics. In 1947, a paper by O. Scherzer (Sche 47) dealt with this problem and introduced lenses of even higher symmetry than quadrupoles for achromatic and non-linear corrections. Friedburg and Paul had also shown that such multipole configurations are good lenses even for neutral atoms and neutrons.

In this first period of accelerator development, experimental physicists and a few engineers were pioneering with imagination but relatively low theoretical background. Building accelerators was an art; the principles were understood only in first approximation and the success in properly shimming the magnets or matching the primitive rf generators relied strongly on the skill or intuition of the experimentalist. In a next step, high-rank theoreticians joined the field, calculating the complicated motion of particles moving nearly relativistically in complex magnetic and electric fields and teaching the experimentalists the theoretical background for the proper design of better and better accelerators.

V. Storage Rings

The development of storage rings was started later, initiated in 1956 by D. Kerst (Ke 56) and his co-workers from the MURA group. Shortly thereafter O'Neil (On 56) submitted a proposal for an electron colliding-beam device. Touschek was the first to point out the importance of the physics with electron-positron colliding beams and proposed a technical solution for using only one magnet ring. In an early experiment, together with a Frascati group, he succeeded in storing electrons for a considerable time (Tou 60) (Fig. 20). Again, the principal idea was anticipated by R. Wideroe in a patent in 1943 (Wi 43), but his patent did not treat the stability problems in any detail. Stability problems are however of decisive importance in such devices with 10^{12} and even more revolutions of the particles such as one observes in the ISR at CERN, a thousand times more than the earth has circulated around the sun. A proton current of 40 amps at an energy of 30 GeV is circulating in this extraordinary device. The method of filling so many particles in the rings is based on the rf beam-stacking method worked out by the MURA group. All in all, it means that the physicists have to master particle optics to the utmost.

At present we are again in the early days of a new technique. The dream of experimentalists to observe antiproton-proton collision in the center-of-mass system at high energy now seems to be feasible. Antiprotons are produced in high-energy collisions but with a large phase space. For filling these particles in a storage ring one has not only to match their phase space to that of the ring but also to increase the phase-space density. In other words, one has to cool the antiprotons.

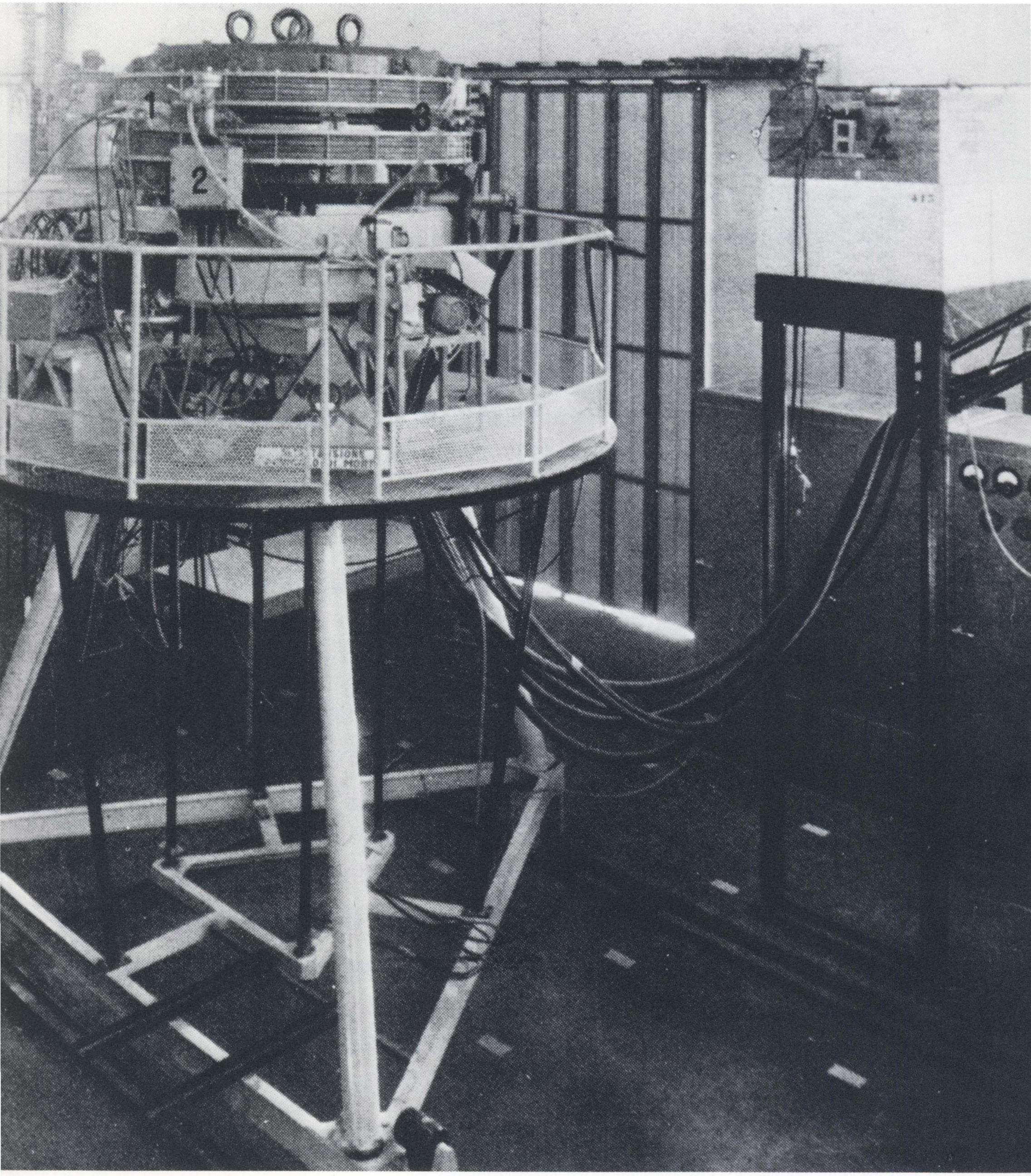
In 1966, Budker (Bu 66) in Novosibirsk had the first idea of how to do it. He used the method of a heat-exchanging device. Along the straight section of a storage ring for the protons a "cool" electron beam of nearly the same velocity as the protons is brought in close contact to them. Both particles exchange momentum which is taken away by the always new cool electrons.

Van der Meer at CERN (Me 72) invented a second method--the process of stochastic cooling. It makes use of a "Maxwellian demon" who measures the statistical fluctuations in the ensemble of "hot antiprotons." With this information, taken from a section of the circulating proton beam, one controls an rf field on the opposite side of the ring in order to minimize the fluctuations, or to decrease the entropy of the particles in the beam. As the protons are running on a circle and the correcting signal propagates along the diameter, the correcting signal can be applied in time.

As both cooling devices look very promising in many respects, accelerator physicists are faced again with a new task; they have to learn statistical mechanics!

All in all, accelerator physics is a fascinating field, covering many disciplines and always prepared to follow new theoretical ideas or to incorporate new experimental techniques.

Fig. 20. The electron storage ring "Ada" at the Frascati laboratory.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REFERENCES

Al 46 L. W. Alvarez, Phys. Rev. **70**, 799 (1946).

Ar 45 Armstrong, Mechanical Magazine 43/64, 1845.

Be 37 H. A. Bethe and M. E. Rose, Phys. Rev. **52**, 1254 (1937).

Bra 31 A. Brasch and F. Lange, Z. Physik **70**, 10 (1931).

Br 28 G. Breit and M. A. Tuve, Carnegie Inst. Yearbook **27**, 209 (1928).

Bu 93 R. Busch, Prakt. Phys. **6**, 143 (1893).

Bu 66 G. I. Budker, Proc. International Symposium on Electron and Photon Storage Rings, Saclay, II-1-1/1966.

Co 32 J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. (London) **A137**, 229 (1932).

Cou 52 E. D. Courant, M. S. Livingston, and H. S. Snyder, Phys. Rev. **88**, 1190 (1952).

Chri 50 N. Christofilos, U. S. Patent No. 2.736799, 1950.

De 32 A. J. Dempster, Phys. Rev. **42**, 901 (1932).

Fa 43 Faraday, Exper. Res. Ser. 18, 1843.

Ge 32 C. Gehrtsen, Naturwiss. **20**, 743 (1932).

Gr 21 H. Greinacher, Z. Physik **4**, 195 (1921).

Gr 31 R. J. Van de Graaff, Phys. Rev. **38**, 1919 (1931); Phys. Rev. **43**, 149 (1933).

Gu 47 K. Gund, Naturwiss. **34**, 343 (1947).

Ha 48 E. L. Ginzton, W. W. Hansen, and W. R. Kennedy, Rev. Sci. Instr. **19**, 89 (1948).

He 35 H. G. Herb, D. Parkinson, and D. Kerst, Rev. Sci. Instr. **6**, 261 (1935).

He 86 H. Hertz, Ann. Phys. **45**, 28 (1886).

He 85 Hempel, Wied Annalen, **25**, 487 (1885).

Is 24 G. Ising, Arkiv. Matematik och Fysik, **18**, 1 (1924).

Ka 33 H. Kallmann, Sitz. Ber. Preuss. Akad. d. Wiss. XII, 451 (1933).

Ke 40 D. Kerst, Phys. Rev. **58**, 841 (1940).

Ke 41 D. Kerst and R. Serber, Phys. Rev. **60**, 53 (1941).

Ke 56 D. Kerst et al., Phys. Rev. **102**, 590 (1956).

Ki 53 Kitagaki, Phys. Rev. **89**, 1162 (1953).

La 30 E. O. Lawrence and N. E. Edlefsen, Science **72**, 376 (1930).

La 51 E. O. Lawrence, Nobel Lecture 1951.

La 32 E. O. Lawrence and M. S. Livingston, Phys. Rev. **40**, 19 (1932).

La 31 E. O. Lawrence and D. Sloan, Proc. Nat. Acad. Sci. **17**, 64 (1931).

Liv 59 M. S. Livingston, Physics Today, 1959.

Mil 45 E. M. McMillan, Phys. Rev. **68**, 143 (1945).

Me 72 S. van der Meer, CERN ISR-PO/72-31.

On 56 O'Neill, Phys. Rev. **102**, 1418 (1956).

Pe 36 O. Peter, Ann. Phys. **27**, 299 (1936).

Ru 27 E. Rutherford, Nature **120**, 809 (1927).

Ro 38 M. E. Rose, Phys. Rev. **53**, 392 (1938).

Sche 47 C. Scherzer, Optik **2**, 114 (1947).

Tho 38 L. H. Thomas, Phys. Rev. **54**, 580 (1938).

Sle 22 S. Slepian, U.S. Patent 1645304, 1922.

Ste 35, 43 M. Steenbeck, Naturwiss. **31**, 234 (1943).

Toe 67 A. Toepler, Pogg, Ann. **130**, 518 (1867).

Tou 67 C. Bernardini, G. Corazza, B. Touschek, Nuovo. Cimento **18**, 1293 (1960).

Tu 35 M. Tuve, L. R. Hafstad, and O. Dahl, Phys. Rev. **48**, 315 (1935).

Ve 45 V. Veksler, J. Phys. USSR **9**, 153 (1945).

Vi 11 P. Villard and H. Abraham, Compt. Rend. **152**, 1813 (1911).

Wa 29 E. T. S. Walton, Proc. Cambridge. Phil. Soc. **25**, 469 (1925).

Wi 28 R. Wideroe, Arch. Electrotech. **21**, 387 (1928).

Wi 46 R. Wideroe, Norwegian Patent No. 84507, 1946.

Wi 43 R. Wideroe, D.R.P. **876**, 279 (1943).

Wi 64 R. Wideroe, Wiss. Zs. Univ. Jena, **13**, 432 (1964).

Wil 38 R. R. Wilson, Phys. Rev. **53**, 408 (1938).