ORIGINAL ARTICLE

Rolf Wideröe and the Development of Particle Accelerators

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The development of particle accelerators is traced from the simple but ingenious table-top devices conceived during the late 1920s to the present day's large, complex machines which extend over tens of kilometers. The emphasis is on Rolf Wideröe and his seminal contributions to the field. Not only did Wideröe construct the first accelerator which accelerated charged particles to an energy higher than the maximum voltage difference is the accelerator proper, he also invented particle colliders, today's work horse in experimental particle physics.

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It is a great privilege to be given the opportunity to pay tribute to the seminal contribution made by Professor Rolf Wideröe to the field of particle accelerators.

The development of particle accelerators at the energy frontier has been driven by the urge to understand the structure of matter at short distances. Indeed, the urge to explain the apparent complexity and infinite variety of the visible world in terms of a few basic constituents existing at distance scales well beneath our everyday experience dates back to antiquity. We have now explored the structure of matter down to a distance scale of 10^{-18} m or distances which are a hundred million times smaller than the size of an atom. On this scale, nature is beautiful and simple—everything you see, living or dead, is made up of three basic building blocks; i.e. the u- and d-quarks which make up the neutron, the proton and the electron. These buildings blocks and the neutrino—a massless particle which appears in radioactive decay—belongs to the first family of elementary particles, as shown in Fig. 1. Two further families of elementary particles exist, but these particles are not stable and were present in the Universe only a fleeting moment after the presumed Big Bang. These constituents can be created in the laboratory by colliding high-energy particles.

How do we know that this is true—how can we explore the structure of matter at such incredibly short distances?

As we all remember from our school days, if you want to examine an object you must view it with light whose wavelength is shorter than the extent of the structure you wish to explore. Viewing an object with visible light, we can explore structures of size down to, say, 400 nm. Structures down to a size of an atom or roughly 0.1 nm can be investigated by illuminating the object with electromagnetic waves of short wavelengths (x-rays).

To explore the structure of matter at subatomic scales we make use of the duality between particles and waves. In 1926 Louis de Broglie postulated that a particle of energy E travelling in free space, corresponds to a wave with a wavelength $\lambda = h/p$, where h is the Planck constant and p the momentum of the particle. For particle energies well above the rest energy m_0c^2, this formula can be written as

$$\lambda = \frac{hc}{E} = \frac{1.3 \cdot 10^{-6}}{E(eV)}\, m$$

where the particle energy is measured in electron Volt.

Thus to penetrate deeper and deeper into matter, we need accelerators of ever increasing energies.

The development of particle accelerators is forever linked with the name Rolf Wideröe (1) and in this tribute I trace and explain his seminal contributions to the field of accelerators and show how his ideas have grown from sketches in notebooks, to table-top devices, to large, complex machines extending over tens of kilometers.

Particle accelerators (2), however, are not only used to study the fundamental structure of matter—they are also important tools in solid-state physics, chemistry, material science, molecular biology and more, including medicine. The practical application of accelerators—in particular the use of ionizing radiation—for radiation therapy was also pioneered by Wideröe. This is a fascinating topic, but for the present I will focus on the high-energy frontier.

It is probably fair to say that the modern journey towards shorter distances started in 1911 with the discovery by Lord Rutherford that an atom is not just an amorphous cloud of electricity, but has a structure with the positive electricity concentrated in a point at the center of the atom surrounded by a negatively charged cloud of electrons.

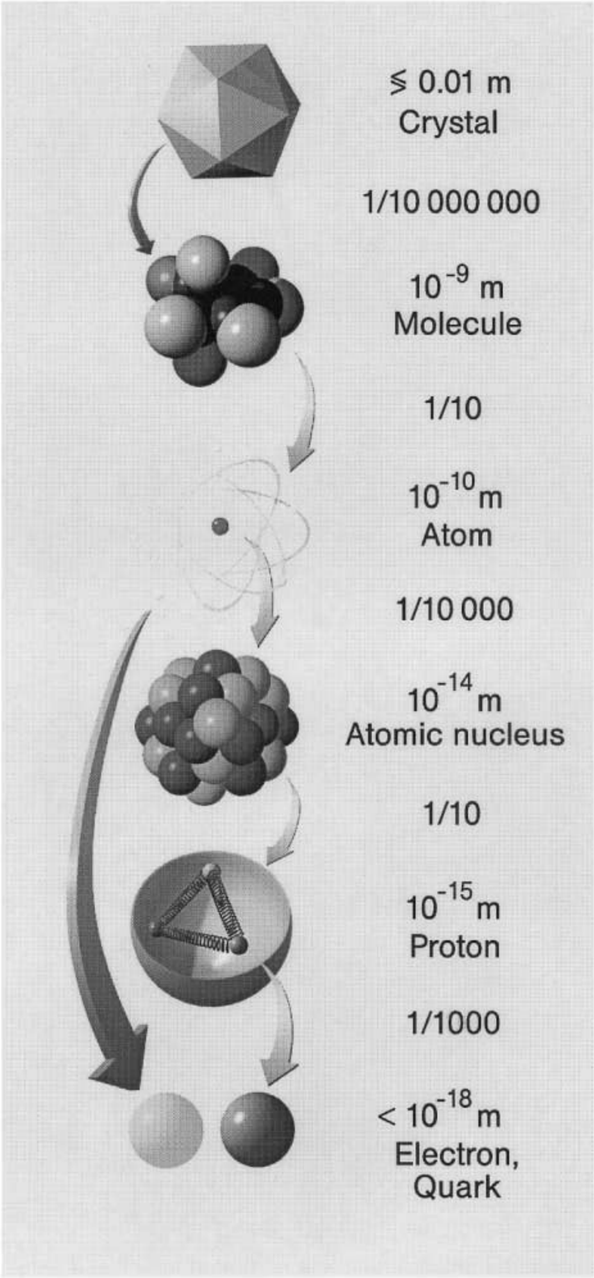
In the period from 1912 to 1917 Rutherford succeeded in disintegrating nitrogen by bombarding the air with α-particles from a radioactive source. This was both exciting and important, and when Rutherford was reprimanded by the Admirality for not attending a meeting, he is reputed to have answered, 'Dear Sirs, I have reason to believe that we can split the atom and that is more important than the war'. The response of the Admirality is unknown.

In 1919, the 17-year old Wideröe learned from articles in newspapers and magazines that nitrogen had been transformed into carbon. Wideröe was fascinated by this discovery and he realized that particles of higher energies and higher intensities that could be provided by an electrostatic generator were needed. Perhaps the solution to the problem was hidden somewhere in Maxwell's equations? This discovery confirmed his decision to study electrical engineering and in 1920 Wideröe enrolled in the Polytechnical University of Karlsruhe. In 1928, only 8 years later, a seminal paper by Wideröe entitled 'Über ein neues Prinzip zur Herstellung hoher Spannungen', appeared in the 21st Volume of *Archiv für Elektrotechnik*.

In this paper Wideröe presented the design of the first functioning linear accelerator and showed the experimental results. In the second part of this paper Wideröe described a novel device which he called a 'Strahlentransformator'—an accelerator now generally known as a betatron.

Before discussing the history behind Wideröe's first paper, let me first give a résumé of the principles of a circular accelerator. One of the very first accelerators is depicted in Fig. 2a. The centrifugal force mv^2/r acting on the circling stone is balanced by the string tension and the longitudinal force component acting tangentially to its orbit increases the velocity of the stone, turn by turn.

In the modern version of a circular accelerator (as depicted in Fig. 2b) the string is replaced by a magnetic field produced by a set of magnets, and the longitudinal force component is provided by an rf cavity located along the particle orbit. The magnetic field has a dual function—a dipole field B provides a force evB which acts on the charged particle travelling with a velocity v. This Lorenz force balances the centrifugal force mv^2/r



$$\begin{pmatrix} \nu_e & u \\ e & d \end{pmatrix} \quad \begin{pmatrix} \nu_\mu & c \\ \mu & s \end{pmatrix} \quad \begin{pmatrix} \nu_\tau & t \\ \tau & b \end{pmatrix}$$

Fig. 1. The structure of matter and the elementary constituents. The mass of the constituents ranges from the neutrinos, which perhaps are massless, to the t-quark, which weighs as much as a gold atom.

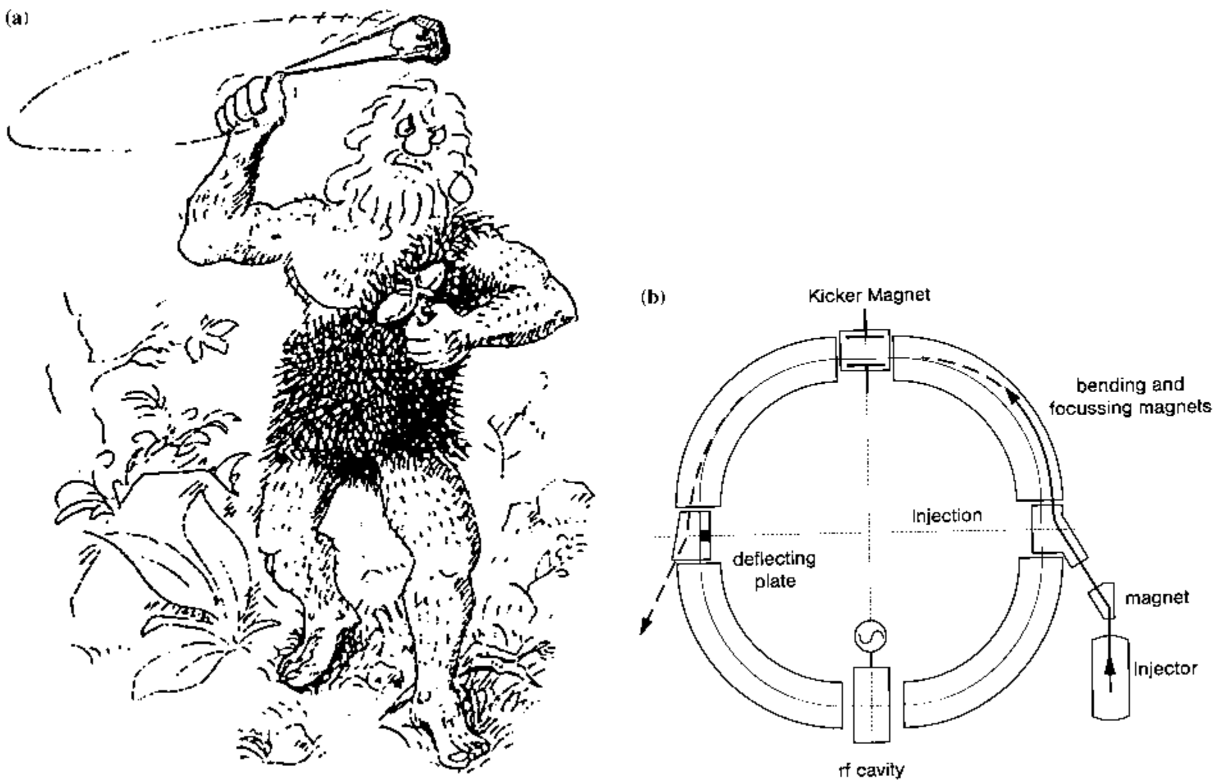


Fig. 2. (a) An early model of a particle accelerator. (b) A modern version of a particle accelerator—a synchrotron. The particles are travelling on an orbit of constant radius by increasing the magnetic field structure with energy.

leading to a circular particle orbit with a radius r given by the following equation:

$$r = \frac{mv}{eB}$$

The magnetic field also contains a quadrupole component which provides a transverse focusing force. Under the influence of this restoring force the circulating particles execute transverse oscillations around the ideal orbit. The number of these transverse oscillations per turn is called the Q-value. Stable oscillations only occur for certain values of Q_x and Q_y.

The rf cavity is excited by an external power source and provides an electromagnetic wave travelling along the structure with the velocity of the particles. By matching the rotational frequency of the particle and the frequency of the rf system, the particle will gain energy each time it traverses the cavity.

After this brief excursion into accelerator theory, let us return to Wideröe. After enrolling in Karlsruhe, Wideröe continued to ponder how to accelerate charged particles to high energies and in 1923 he developed his first ideas about the 'Strahlentransformator', as shown in the sketch from his notebook and reproduced in Fig. 3.

The betatron, made from a single magnet (as depicted in Fig. 4a) is one of the most elegant accelerators ever produced. The magnetic guide field and the accelerating voltage are both provided by a single sinusoidal time-varying magnetic field, as shown in Fig. 4b. Electrons are injected into the accelerator during the cycle of increasing field strength shortly after the zero crossing of the field.

The electrons travel on a circular orbit of constant radius r in a magnetic field of strength $B_f(t)$. The value of the magnetic field averaged over the area enclosed by the beam is denoted by B_j. The change in magnetic flux $\pi r^2 \bar{B}_j$ in the area enclosed by the beam during the acceleration cycle produces a longitudinal electric field E_φ pointing along the particle orbit. The longitudinal force seen by the electron is given by:

$$e \cdot E_\varphi = \frac{e}{2\pi r} \cdot \frac{d(\pi r^2 B_j)}{dt} = \frac{er}{2} \frac{dB_j}{dt}$$

Since the radius of the orbit should be constant during acceleration, the guide field B_f must meet the condition:

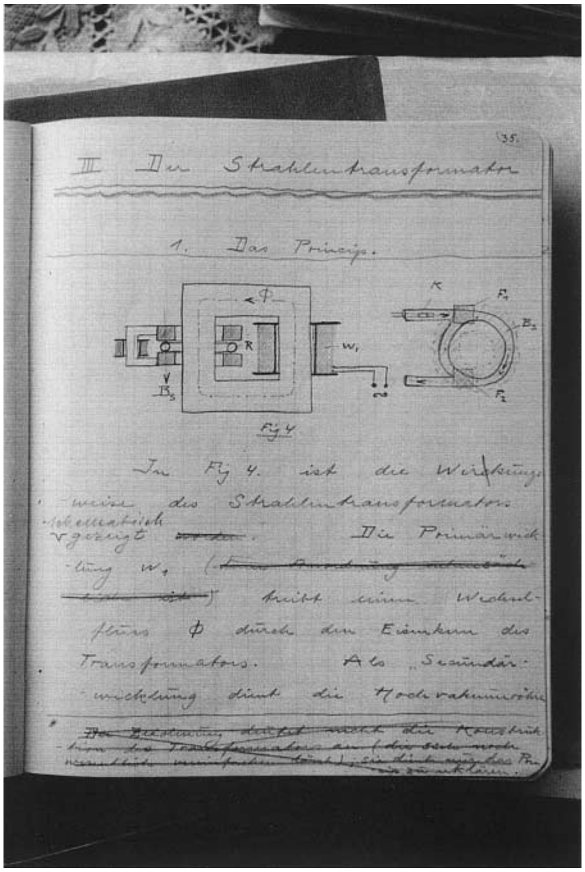
$$\frac{d(mv)}{dt} = er \cdot \frac{dB_f}{dt}$$

As both equations must be valid at the same time, we obtain

$$\frac{dB_j}{dt} = 2\frac{dB_f}{dt} \quad \text{or} \quad B_j = 2B_f$$

Thus the longitudinal motion is stable if the strength of the average field in the yoke gap is twice the strength of the guide field. This is the basic equation guiding the operation of a betatron and was first derived by Wideröe when he was a third-year student.

After the completion of his Master's thesis in Karlsruhe and his military service in Norway, Wideröe returned to Karlsruhe, eager to get on with his PhD thesis. As a thesis topic Wideröe proposed to construct a betatron. Although the Department of Electrical Engineering supported his proposal, the Physics Department was less enthusiastic. Indeed W. Gaede, a well-known professor of physics at the University and one of the world's leading experts in vacuum technology, was convinced that the betatron as proposed by Wideröe would not work. With the best vacuum pumps available, a pressure of the order of 10^{-6} mbar could be reached. At this pressure the interaction between the remaining gas molecules and the circulating electron beam would prevent the electrons from reaching high energy. However, in Heidelberg a few years earlier, Ph. Lenard had shown that the strength of the electron–gas interaction drops rapidly with energy and thus the bulk of the electrons would indeed survive to the end of the acceleration cycle. Wideröe left Karlsruhe for Aachen where his new thesis adviser, W. Rogowski, accepted his proposal to construct a 6 MeV betatron and Wideröe set to work. However, despite valiant efforts, the device did not deliver electrons of 6 MeV. Today we know why: Wideröe's test accelerator with its homogeneous magnetic field did not provide transverse focusing, and electrons would be lost during the acceleration cycle.



35.

III Der Strahlentransformator

1. Das Prinzip.

Fig 4

In Fig 4. ist die Wirkungsweise des Strahlentransformators schematisch gezeigt ~~wurde~~. Die Primärwicklung W₁ (~~[illegible]~~) treibt einen Wechselfluss Φ durch den Eisenkern des Transformators. Als „Sekundärwicklung" dient die Hochvakuumröhre

~~[illegible]~~

Fig. 3. The first sketch in Rolf Wideröe's notebook of the Strahlentransformator.

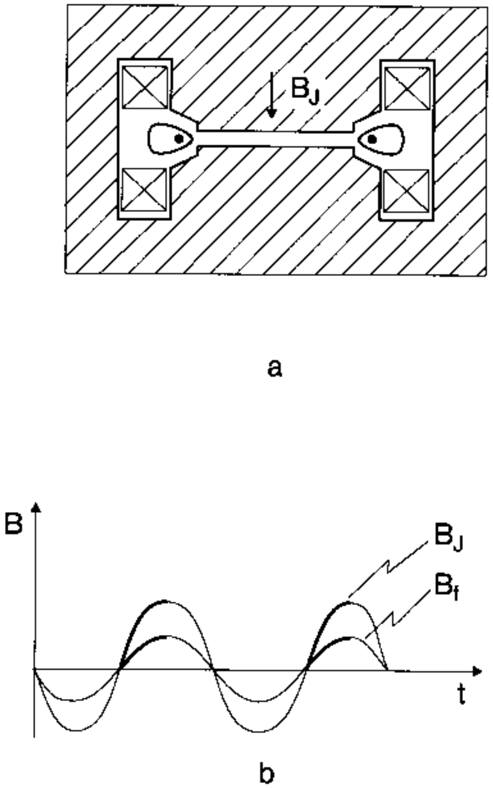


Fig. 4. (a) The schematic layout of a betatron. (b) Single sinusoidal time-varying magnetic field.

Towards the end of the 1930s M. E. Rose and others showed that a dipole field whose strength decreases with radius will yield a focusing force in both the horizontal and the vertical plane. Based on this principle, D. Kerst in 1940 built a functioning 2.3 MeV betatron.

Wideröe returned to the betatron nearly 20 years later and in 1943/44 he built his first betatron in Hamburg. In the period 1946–1962, under his guidance, the BBC built more than 70 such accelerators ranging in energy from 31 MeV to 45 MeV. These accelerators were used mainly for cancer therapy in various hospitals around the world. An example of a medical betatron is shown in Fig. 5.

But back in 1927, Rogowsky could not accept a thesis based on a non-functioning device and Wideröe had to

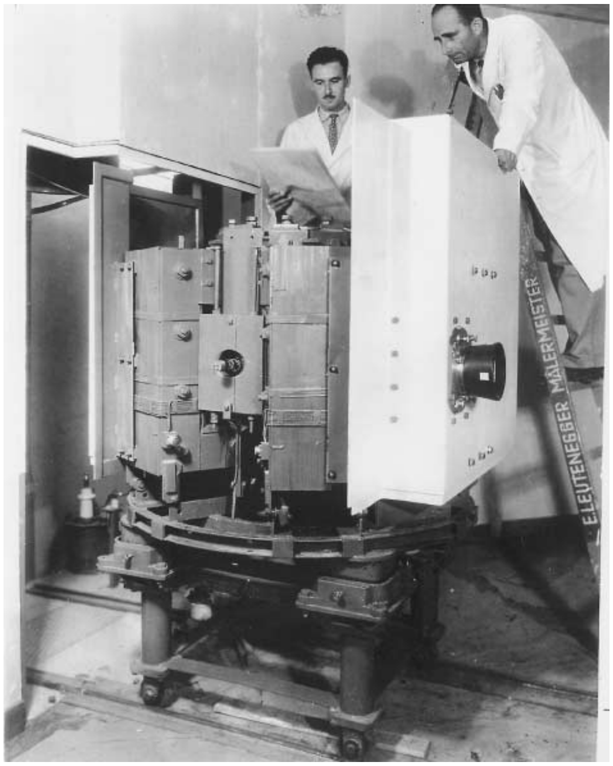


Fig. 5. A medical betatron built under the guidance of Wideröe.

find a new topic for his thesis. Luckily, he remembered an earlier idea by the Swedish physicist G. Ising who had proposed to construct a linear accelerator. Wideröe modified Ising's proposal and constructed the 80-cm-long linear accelerator depicted below. It is perhaps worth mentioning that the capital cost of the device was DM 500.

This accelerator (as depicted in Fig. 6) is constructed of a cathode A, a metal tube BR to shield the particles from the electric field and a plate capacitor K assembled within an evacuated glass tube. An oscillating electric field with a peak value $U_b = 25$ kV is produced in gaps I and II. Sodium ions, emitted from the cathode are accelerated in gap I and traverse a field-free region in the tube BR and arrive a certain time later at gap II. With the proper choice of particle velocity and electric field oscillation frequency the sodium ions are also being accelerated in gap II. Wideröe measured the energy of the ions emerging from gap II by observing their deflection in the electric field of a plate capacitor. The measurement yielded 50 keV or twice the gap voltage of 25 kV. This was the birth of the modern accelerator—for the first time, particles emerged from an accelerator with an energy higher than the maximum voltage difference in the accelerator proper.

The largest linear accelerator ever built is the Stanford Linear Accelerator (SLAC). An aerial view of this accelerator is shown in Fig. 7. This machine, which is based on disk-loaded cavity structures, is used to accelerate electrons and positrons to energies of order 50 GeV.

Experiments of the type $ep \rightarrow e'x$ performed at SLAC during the late 1960s gave the first clear evidence of the existence of pointlike constituents—the quarks—within the nuclei.

But let us return to 1927. The linear accelerator as developed by Wideröe was relatively complex and a series of cavities were needed to accelerate ions to high energies. To avoid this problem, E. O. Lawrence in Berkeley, after reading Wideröe's article, proposed to install a single cavity in a homogeneous magnetic field. Wideröe's resonance condition is automatically satisfied since the revolution frequency of a non-relativistic particle is independent of energy. The layout of a cyclotron is shown in Fig. 8.

The rf resonator is split into two 'D'-shaped electrodes which are imbedded in a homogeneous magnetic field, with its direction perpendicular to the plane of the resonator. A sinusoidal voltage U(t) is applied to the gap between the D's.

$$U(t) = U_0 \cdot \cos \omega_{rf} t$$

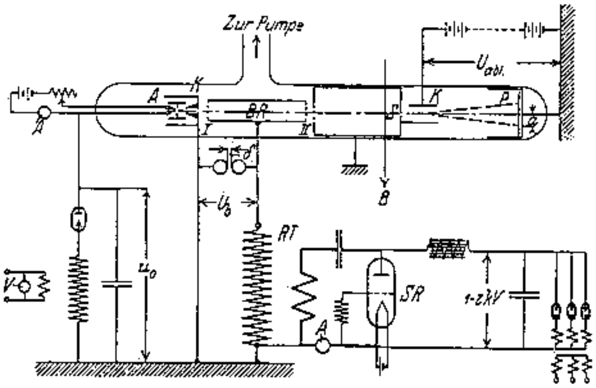


Fig. 6. The first linear accelerator constructed by Wideröe in 1927.

Fig. 7. An aerial view of the Stanford Linear Accelerator.

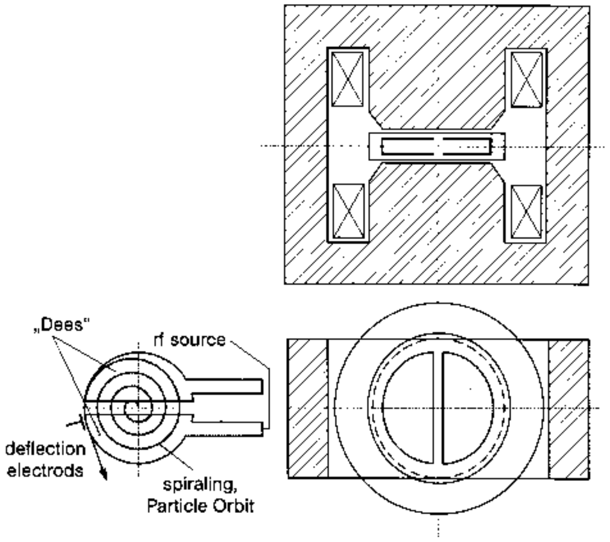


Fig. 8. The layout of a cyclotron.

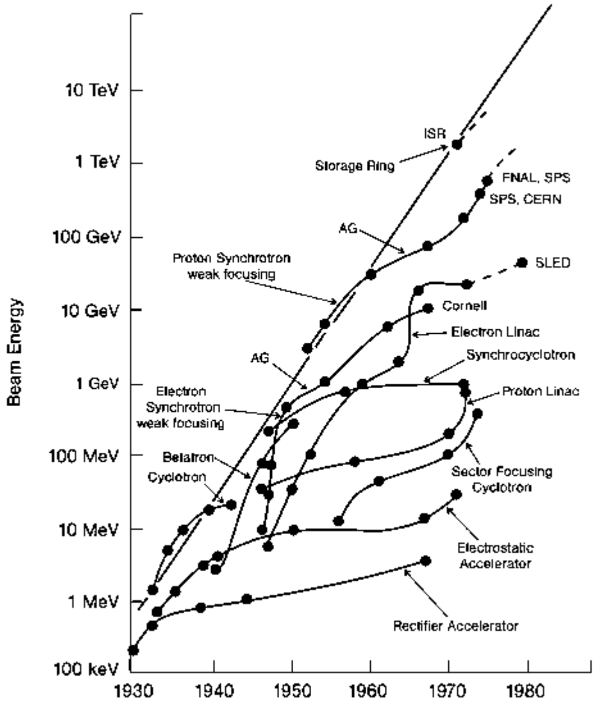


Fig. 9. The Livingstone plot. The maximum energy of different types of accelerators plotted versus the year in which they reached this energy. For the proton–proton collider ISR, the equivalent energy in the laboratory system is plotted.

To be in resonance, the frequency ω_{rf} must equal the particle revolution frequency ω_0, i.e.

$$\omega_{\mathrm{rf}} = \omega_0 = \frac{\mathrm{e} \cdot \mathrm{Z} \cdot \mathrm{B}}{\mathrm{M}}$$

Ions of mass M and charge eZ will then be in phase with the rf field and gain the same amount of energy each time they cross the gap between the D's.

Based on Wideröe's paper and fuelled by new ideas and progress in technology, particle accelerators have grown rapidly in both size and complexity. This rapid growth is shown clearly in the Livingstone plot, as depicted in Fig. 9.

In this graph the maximum energy reached by a certain type of accelerator is plotted versus the year in which this energy was reached.

Note the exponential growth in energy sustained during nearly five decades. At the same time the cost per MeV of particle energy has, inflation corrected, decreased almost as rapidly as the energy has increased. There are two reasons for this impressive development—first, novel ideas that have spawned new types of accelerators, and second the development and use of new technologies.

This can be illustrated by a comparison between the 7 GeV Synchrotron built at the Deutsches Elektronen-Synchrotron (DESY) and the DESY Electron-Proton Collider HERA which reaches an equivalent electron energy of 50000 GeV. The DESY synchrotron is housed in a tunnel with a circumference of some 300 m, the Electron-Proton rings of HERA are housed in a subterranean tunnel with a circumference of 6.5 km. With the synchrotron, center of mass energies of 3.5 GeV can be reached, with HERA 314 GeV. However, corrected for inflation the cost of the two accelerators differs only by a factor of 2.5. In this case the new idea was to store and collide particles of unequal mass, a favorable price-performance ratio was obtained by using superconducting magnets for the 820 GeV HERA proton ring. I will return to HERA later.

Let us return to the Livingstone plot and try briefly to trace the development of circular accelerators. Cyclotrons are limited to particle energies below 20 MeV because of the relativistic increase in mass which violates the resonance condition listed above. This problem can be overcome by modulating the rf frequency such that the resonance conditions,

$$\omega_{\mathrm{rf}} = \mathrm{n} \cdot \omega_0$$

where n is an integer, are always met. It is clear that this condition cannot be met for particles with a large spread in energies, which means that in a synchrocyclotron, particles of almost equal energy are accelerated in short bunches. However, the natural energy spread by the particles in a bunch leads to a spread in revolution frequences, and one might naively expect the particles to be uniformly spread around the ring circumference after a limited number of turns. This is prevented by the longitudinal focusing force created by the rf system. This phase focusing was discovered independently by V. Veksler and E. M. McMillan in 1944 and opened the road to higher energies.

The synchrocyclotron has one important drawback. The weight of the single magnet increases with roughly the third power of energy limiting the maximum particle energy to values of the order of 1000 MeV or 1 GeV.

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
21. AUGUST 1952

DEUTSCHES PATENTAMT

PATENTSCHRIFT

№ 847 318

KLASSE 21g GRUPPE 36

p 21107 VIIIc/21g D

Dr.-Ing. Rolf Wideröe, Ennetbaden (Schweiz)
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Beschleunigung von elektrisch geladenen Teilchen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 9. November 1948 an
Patentanmeldung bekanntgemacht am 9. August 1951
Patenterteilung bekanntgemacht am 26. Juni 1952
Die Priorität der Anmeldung in Norwegen vom 31. Januar 1946 ist in Anspruch genommen

Wenn Elektronen oder Ionen große Geschwindigkeiten erteilt werden sollen, kann dies durch Beschleunigung in Potentialfeldern geschehen, die durch eine hochfrequente Wechselspannung erzeugt werden. Dieser Vorgang ist in Fig. 1 der Zeichnung dargestellt. Eine Reihe von Zylindern ist abwechselnd an die zwei Pole für die hochfrequente Wechselspannung u angeschlossen, und die Elektronen bzw. die Ionen, die durch die Zylinder geleitet werden, werden im Raum zwischen zwei Zylindern von der Wechselspannung beschleunigt, wobei U_0 die Anfangsspannung der geladenen Teilchen ist. Durch die Wahl so langer Zylinder, daß ihre Polarität, während die Teilchen mit konstanter Geschwindigkeit durch sie hindurchgehen, wechselt, werden die Teilchen zwischen je zwei Zylindern beschleunigt und erreichen somit eine ständig höhere Geschwindigkeit, d. h. sukzessive die kinetischen Spannungen $U = U_0 + u$, $U_0 + 2u$, $U_0 + 3u$ usw.

Diese bekannte Anordnung hat den Nachteil, daß die Zylinder zufolge der hohen Geschwindigkeiten der geladenen Partikel verhältnismäßig lang werden und die Frequenz der Wechselspannung sehr hoch sein muß, damit die obengenannte Resonanzbedingung erfüllt wird. Wenn man darum hohe kinetische Spannungen erreichen will, wird diese Anordnung sehr hohe Ladeströme (Blindleistung) erfordern und wegen der Verluste entsprechend große Hochfrequenzgeneratoren. Dies schränkt das Anwendungsgebiet auf verhältnismäßig schwere Ionen, z. B. Quecksilberionen, und die Spannungen auf einige wenige MV ein.

Vorliegende Erfindung bezweckt, diesem Nachteil abzuhelfen. Sie betrifft eine Anordnung zur Beschleunigung von elektrisch geladenen Teilchen mit

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Fig. 10. Wideröe's patent.

This problem, too, has been overcome. By increasing the magnetic guide field synchronous with the increase in particle momentum, the particles will travel on a constant radius orbit, as shown in Fig. 2b. In a modern synchrotron the magnets are arranged in a respective pattern of cells where each cell consists of bending magnets sandwiched between quadrupole magnets.

Wideröe worked out the theory of synchrotrons in 1946, and applied for a patent, which was granted in Norway in January 1946. The first synchrotron was constructed by F. K. Goward and D. E. Barnes in early 1946 without any knowledge of Wideröe's work.

The largest synchrotrons today, the TEVATRON constructed at Fermi National Accelerator Laboratory (FNAL) outside Chicago and HERA at DESY, reach energies approaching 1000 GeV or 1 TeV. With this type of accelerator it seems possible to reach particle energies in excess of 100 TeV.

However, it does not make much sense to make a very high-energy projectile particle of energy E collide with a target particle of mass m at rest. In this case, the energy E_{cm} in the center of mass system (cm) which is available in order to study the structure of the colliding particles or to create new particles is given by:

$$E_{cm} = \sqrt{2mE}$$

The center of mass energy increases only with the square root of the energy of the incident particle and the remainder of the energy is wasted to satisfy the conservation of energy and momentum. Clearly, if a large container ship collides with a small sailboat, only a small fraction of her energy is transferred to the sailboat. On the other hand, if two container ships travelling in opposite directions could be made to collide, a rather large cm energy would be liberated. Thus, if two particles, accelerated to high energies and travelling in opposite directions with energies E_1 and E_2 are made to collide, then the available cm energy is given by:

$$E_{cm} = \sqrt{4E_1 \cdot E_2}$$

In the case of identical particles of the same energy the center of mass energy is given by:

Fig. 11. Aerial view of the HERA site.

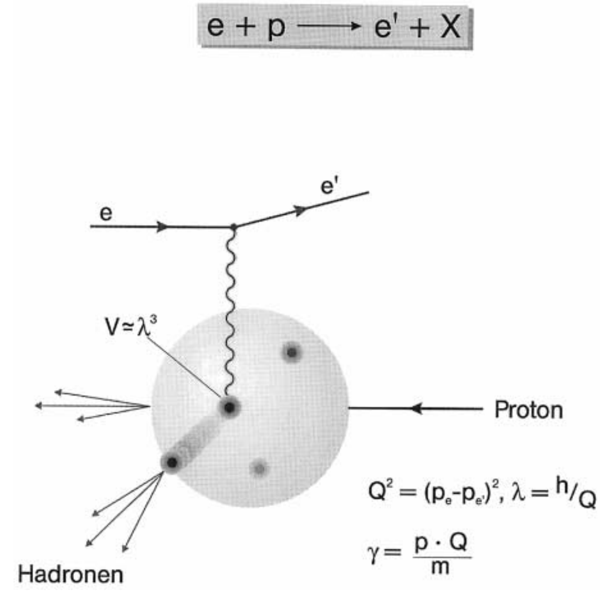

Fig. 12. The interaction between an electron and a proton. The final state topology is also indicated.

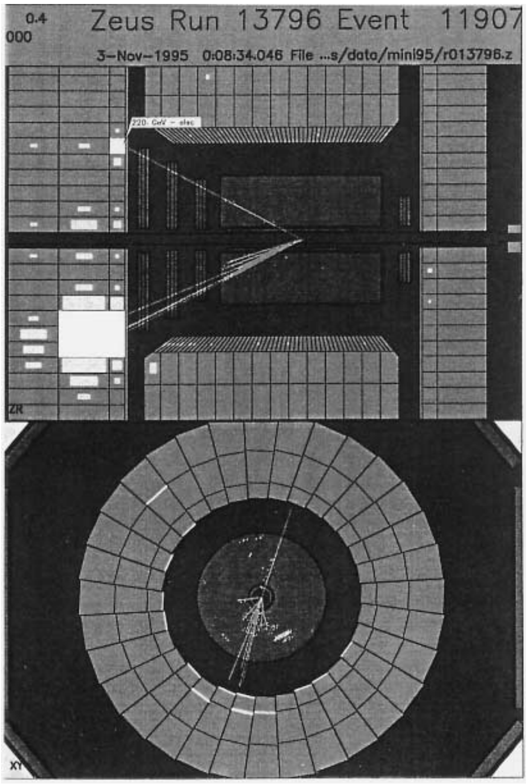

Fig. 13. Reconstruction of a deep-inelastic neutral current event, recorded by the ZEUS detector, viewed in projections transverse and parallel to the beam direction.

$$E_{cm} = 2E$$

i.e. the available center of mass energy increases linearly with the particle energy.

The idea of accelerating counter-rotating particles to high energies and causing them to collide was conceived by Wideröe in 1943 and patented the same year (see Fig. 10). Although his idea was conceptual in nature, it contained all the basic elements of a collider. Wideröe's idea was developed further by the American MURA group and the first realistic proposal on how to construct a collider was presented by G. K. O'Neill in 1956.

Besides the available cm energy, a collider is characterized by its luminosity. To recall the definition of luminosity, let us assume that we want to measure a reaction $ab \rightarrow cx$ with a cross-section σ $(ab \rightarrow cx)$. The number of events per second is then given by $N = L \cdot \sigma(ab \rightarrow cx)$, where L is the luminosity of the collider measured in $cm^{-2}s^{-1}$. (1 fb used below is equal to 10^{-36} cm^2.)

The luminosity of a collider is given by:

$$L = \frac{N^2}{4\pi\sigma_x^*\sigma_y^*} f_c$$

assuming a Gaussian distribution of the particles in transverse phase space. In this expression N is the number of particles per bunch, $\sigma_x^*\sigma_y^*$ is the beam cross-section at the

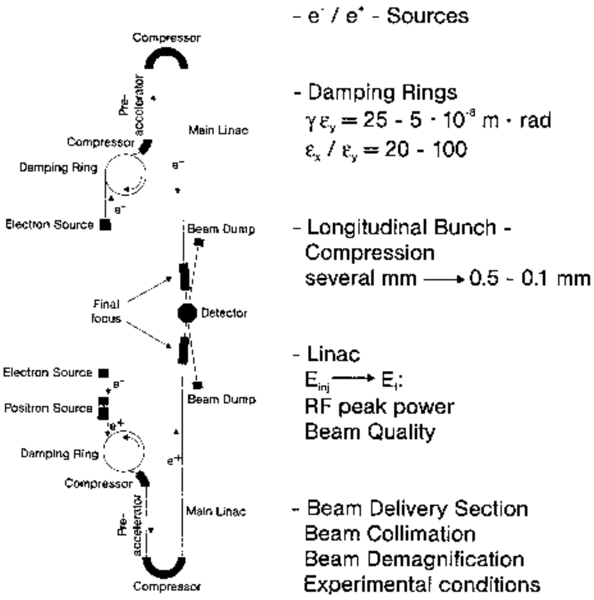

Fig. 14. The layout of a linear collider.

interaction point and f_c the collision frequency. Since the cross-section for a fundamental reaction generally lends to decrease with higher energies, the possibility of reaching high cm energies in a collider is of interest only if high luminosities are available.

K. Robinson and G. A. Voss invented a very clever arrangement of the magnets close to the interaction point, which made it possible to increase the luminosity by a factor of 100–1000 compared to the luminosity of the first colliders. This was the decisive breakthrough, and now all modern accelerators are constructed as colliders. With the electron and the proton we can construct three types of colliders: electron–positron (electron) colliders, proton–proton (antiproton) colliders or electron (positron)–proton colliders.

Electron–positron colliders were the first colliders ever constructed—high cm energies in the electron–positron system can only be reached using a collider. These devices have now grown from the AdA machine, which was a table-top device with a circumference of roughly 4 m into the Large Elektron–Positron Collider (LEP), an e^+e^- collider with a circumference of 27.4 km, constructed at the Organization Européenne pour la Recherche Nucléaire (CERN) outside Geneva.

The e^+e^- pair annihilates into a timelike electroweak current which couples directly to the basic constituents of matter. This process leads to a very clean final state with a well-defined topology and with little background from unwanted processes. It is thus possible to extract the physics information with a minimum of assumptions and the annihilation process is hence well suited for precision experiments and for the discovery of new and unexpected phenomena. However, the maximum energy of a circular e^+e^- collider is limited by the energy radiated by the circulating electrons. This energy loss by synchrotron radiation is proportional to E^4/ρ, where E is the electron energy and ρ is the bending radius. Thus the cost of an optimized e^+e^- collider is increasing as E^2 which limits the energy of this type of accelerator to roughly 200 GeV. Indeed LEP, which will reach a cm energy of 200 GeV, is probably the last accelerator of its kind. Higher energies can only be reached by linear colliders, as discussed below.

The Intersecting Storage Ring (ISR) constructed by CERN under the leadership of K. Johnsen is the first proton–proton collider ever constructed. This accelerator was followed by the construction of the proton–antiproton colliders at CERN and at FNAL. With the TEVATRON at FNAL center of mass energies of 1800 GeV can be reached in the proton–antiproton center of mass system. However, as the proton is made of quarks and gluons, this energy corresponds roughly to 300 GeV in cm system of the constituents.

The HERA electron–proton collider is designed to accelerate and store 820 GeV protons and 30 GeV electrons in two independent, strongly focusing synchrotrons. The outline of the 6.5 km circumference subterranean tunnel housing the two accelerators is shown in Fig. 11. To match the HERA cm energy of 314 GeV by colliding an electron with a proton at rest would require a linear accelerator some 3000 km long.

The two counter-rotating beams collide in the middle of the straight section North and South, whereas the beams are kept separate and used for fixed target experiments in straight section East and West.

The two collider experiments installed in straight section North and South are used to study the structure of the protons with a resolution of the order of 10^{-18} m or a thousand times smaller than the radius of the proton. How this is done is depicted in Fig. 12.

The electron interacts with the proton by the exchange of a 'heavy photon' of wavelength $\lambda = h/Q$, where Q is the momentum transfer between the electron and the proton.

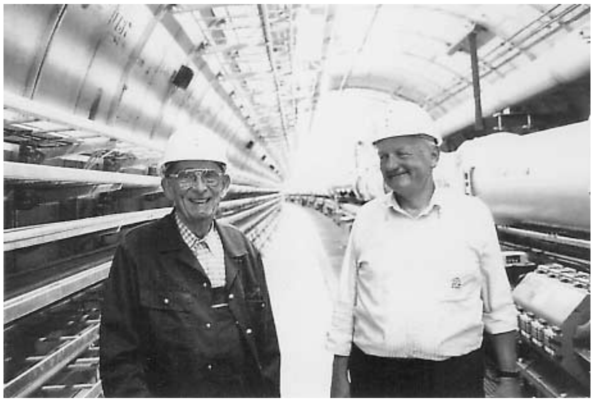

Fig. 15. R. Wideröe and G. A. Voss in the HERA tunnel.

The momentum transfer and hence the wavelength λ are determined by measuring the energy and direction of the scattered electron. The probability for this reaction to occur—i.e. its cross-section—is proportional to the square of the electroweak charge contained in the volume λ^3. As seen above, λ and hence this volume decrease with increasing values of the momentum transfer Q. Thus if the charge of the proton were to be smeared uniformly over its volume, one would naively expect the cross-section to drop rapidly with increasing value of Q^2. However, early experiments at SLAC showed that the observed electon–proton deep inelastic scattering cross-section was nearly constant, independent of Q^2. The natural conclusion is that the charge of the proton is not uniformly distributed but rather tied to pointlike constituents. This was the discovery that quarks—earlier postulated by M. Gell-Mann and G. Zweig to explain regularities observed among the hadrons—in fact existed as real entities, but unlike hadrons (π-meson, nucleons...), free quarks have never been observed. They exist only as quark–antiquark pairs (mesons), as triplets of quarks (baryons) or as triplets of antiquarks (antibaryons).

The virtual photon is absorbed by a single quark which then appears at a large angle with respect to the direction of the incident proton. Since free quarks do not seem to exist in nature, the quark materializes as a jet of hadrons with the sum of their transverse momenta balanced by the transverse momentum of the scattered electron. The remainder of the proton will materialize as a narrow jet of hadrons travelling along the direction of the incident proton. At the high energies available at HERA, this topology is visible to the naked eye (see Fig. 13).

Finally, what are the prospects for the future? The next generation of proton colliders will clearly be based on strongly focusing synchrotrons with the protons guided by superconducting magnets.

The Large Hadron Collider LHC now under construction at CERN will reach cm energies in the proton–proton system of 14 TeV or 1–1.5 TeV in the cm system of its constituents. The collider, to be installed in the LEP tunnel, will be based on superconducting magnets with their coils wound using a thin NbTi filament conductor imbedded in a Cu-matrix. The design field of the LHC dipole magnets is of the order of 8.5 Tesla, a value which is close to the practical limit for this type conductor. The principle of strong focusing makes it possible to construct proton–proton colliders reaching cm energies of 100 TeV or more. Groups in Europe and US are now studying this option.

In an e^+e^- circular collider, bunches of electrons and positrons are stored in a single ring and the two counter-rotating beams are made to collide at well-defined points around the ring. Electrons traversing a circular orbit radiate photons and the energy loss per turn increases with the fourth power of the energy. This energy loss must be replenished by a large and costly rf system and this causes the price of a cost-optimized e^+e^- ring to increase proportionately to the energy squared and thus to become prohibitively high for energies of the order of 1 TeV.

In 1964 M. Tigner at Cornell made the suggestion to accelerate bunches of electrons and positrons to high energies in two opposing linear accelerators and to bring them into collision. In a linear collider the electrons and positrons will not radiate since they travel in a straight line and hence the cost of a linear collider would increase in proportion to the energy.

The first—and so far only—linear collider was built by B. Richter and his colleagues at the Stanford Linear Accelerator Center and went into operation in 1988. The Stanford Linear Collider (SLC) makes use of the 3-km-long Stanford Linac to accelerate one bunch of electrons and one bunch of positrons to 50 GeV, and then to bring the bunches into head-on collision by two 180° bends.

There is agreement within the particle physics community that e^+e^- collisions beyond LEP energies can only be realized using linear colliders. This is a new and demanding technology and it would require an extreme extrapolation of the SLC performance to match the constituent cm energy of 1 to 1.5 TeV which will become available at the CERN LHC proton–proton collider. Since the challenge of constructing a linear collider increases rapidly with energy, it seems prudent first to construct a linear collider with an initial cm energy of 500 GeV. Based on experience, the energy can then be raised later to 1.5 or perhaps 2.0 TeV, making full use of the initial investments.

To exploit the physics potential of a 500 GeV cm, e^+e^- linear collider requires a peak luminosity of the order of $5 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, or three orders of magnitude above the LEP luminosity. This unprecedented, high luminosity can only be reached by pushing beam parameters and technology well beyond the present state of the art. In fact, to reach this high luminosity the beams at the collision point are focused to a height of about 10 nm and a width of about 500 nm. To obtain such a small beam spot requires a short bunch with extremely low vertical emittance. The layout of a linear collider is shown in Fig. 14.

A train of low-emittance electron or positron bunches is extracted from a source system, compressed longitudinally, and injected into two opposing linear accelerators. The bunches are carefully aligned along the machine axis as defined by the quadrupole magnets and the rf cavities, and accelerated to 250 GeV. After acceleration, the beam halo is removed by a set of precision collimators, and the bunches are transported and focused down to a few hundred nm in the horizontal direction and a few tens of nm in the vertical plane, and collided head-on. The spent beams are extracted from the interaction point and either used to produce the next batch of positrons and electrons or buried in a beam absorber.

The collider can also be used as the driver for the next generation of synchrotron radiation sources. Interleaved with the bunches for particle physics, bunches of electrons originating from a low emittance rf photocathode gun are longitudinally compressed and accelerated to energies between 10 GeV and 50 GeV. They are then extracted from the linac, transported to the surface and passed through long, high-precision undulators. The low-emittance electron bunches traversing the undulators will yield a very bright, very short burst of transversely coherent light with tunable wavelengths in the Ångström region. In fact the computed peak brightness is some ten orders of magnitude above the brightness reached in third-generation sources, whereas the length of the x-ray burst is nearly three orders of magnitude shorter.

Particle accelerators thus remain a vibrant and active field which impacts on many areas of science and technology. It is perhaps fitting to end this brief journey through the evolution of particle accelerators with a picture of the person who started it all (Fig. 15).

REFERENCES

These books also include references.

1. An account of the life and work of Rolf Wideröe can be found in an autobiography entitled 'The Infancy of Particle Accelerators', compiled and edited by Pedro Waloschek and published by Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, Braunschweig/Wiesbaden, 1994.
2. For the history of the development of particle accelerations, see M. S. Livingstone 'Particle Accelerators: A Brief History', Harvard University Press, Cambridge, MA, 1964; 'The Principles of Circular Accelerators and Storage Rings', P. J. Bryant & K. Johnsen, Cambridge University Press, 1993.