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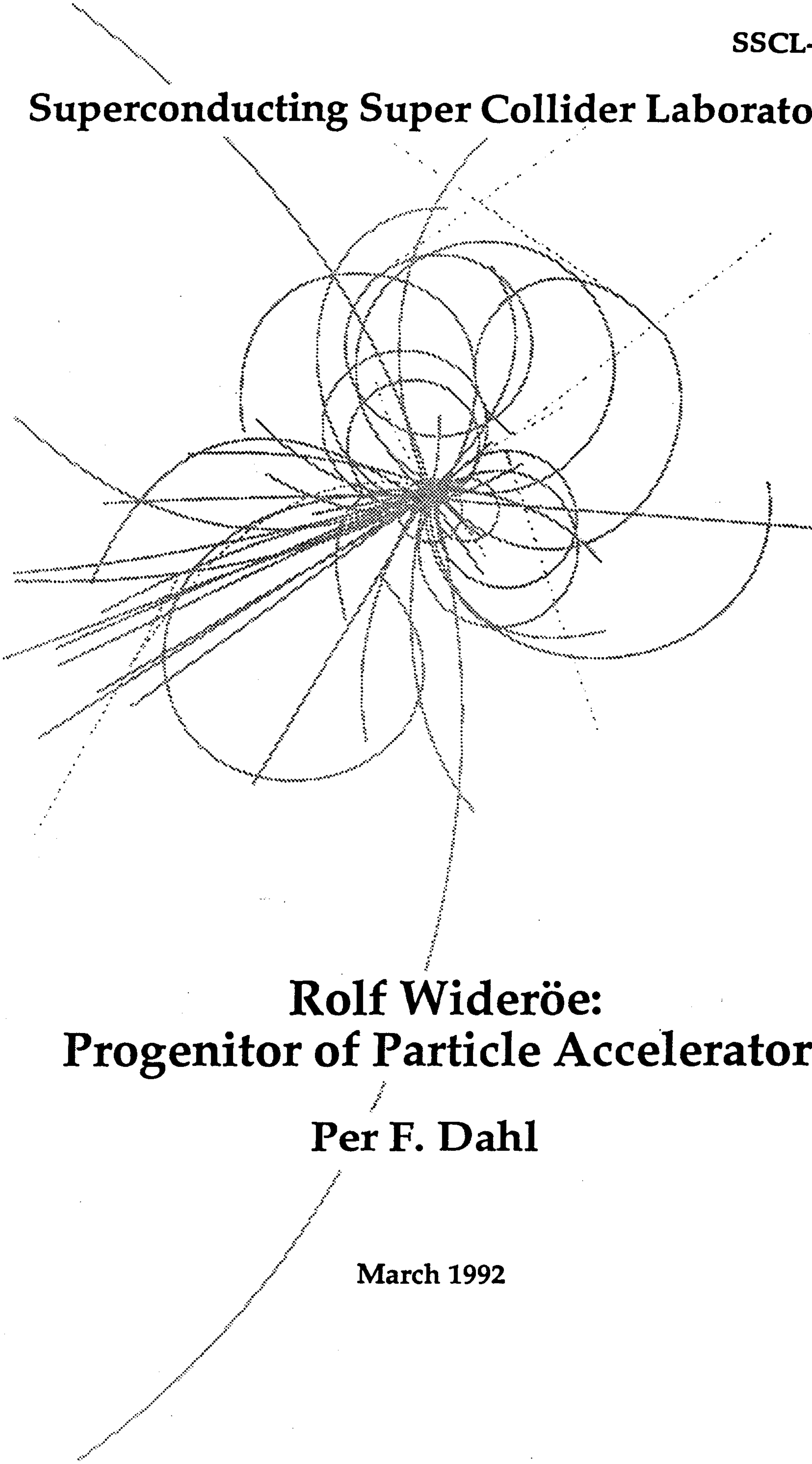

Rolf Wideröe: Progenitor of Particle Accelerators

Per F. Dahl

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1.0 INTRODUCTION

This year, 1992, marks the 65th anniversary of the publication of Rolf Wideröe's doctoral dissertation. In it, he described not only the operating principles of the betatron, but also a working model of the first linear accelerator, constructed according to his own design. The latter, a resonance accelerator, gave Ernest Lawrence the idea for his cyclotron. Since Wideröe and his accelerator initiatives may not be very familiar to today's accelerator physicists, the following is a brief recapitulation of the man and his work.

Rolf Wideröe was born in Norway in 1902, two years earlier than his brother Viggo, who became a well-known aviator and founder of the aviation company which bears the family name. (Viggo Wideröe's daughter Turi became Norway's first female airline pilot.) Rolf was educated in Oslo, then Christiania, and he graduated from Halling Gymnasium in 1920. While still a student he read in the local newspapers about the disintegration of nitrogen nuclei with alpha particles from RaC by Ernest Rutherford in 1919.[1] Having speculated on the possibility of "splitting the atom" at an even younger age, Wideröe saw that the limited flux and energy of naturally occurring alpha particles provided an impractical approach; particles electrically accelerated with high voltage technology appeared much more promising.[2] With this in mind, and with his parents' concurrence, he decided to take up electrical engineering at the Technische Hochschule in Karlsruhe, in diffidence to Norway's own Tekniske Höyskole in Trondheim.

2.0 THE BETATRON: ALMOST

At Karlsruhe Wideröe conceived of the specific idea of accelerating electrons, maintained in a circular orbit by a transverse magnetic field, by the electric ("vortex") field induced by the changing magnetic flux linking the orbit—the principle of the betatron, which is simply a transformer. He anticipated that the voltage gained per turn would be small, perhaps 30 volts, but during the acceleration period the electrons would perform many revolutions and should attain millions of volts. In 1927, with diploma studies under his belt, he broached the concept to Wolfgang Gaede, professor of physics at Karlsruhe and inventor of the diffusion high-vacuum pump. To his dismay, Gaede gave him a "cold shower."

> On the long way the electrons will have to travel before they reach high energy [Gaede retorted] they will be absorbed by the remaining gas molecules. Your idea will not work; forget it.[3]

Not to be put off, Wideröe nevertheless convinced himself by virtue of earlier measured cross-section values in air for cathode rays by Philipp Lenard, and with 10^{-6} Torr obtainable with Gaede's pump, that the absorption would be less than 10% for energies up to 10^7 eV. The only trouble was, an experiment at Karlsruhe was out of the question.

Next, he wrote Walter Rogowski, an expert on cathode ray tubes and oscillographs at the Technische Hochschule in Aachen. As a result, he outlined his ideas to Rogowski on a train between Karlsruhe and Mannheim. Rogowski was much more receptive, and without delay took him on as a doctoral candidate. Consequently, Wideröe undertook to construct at Aachen a "ray transformer" or "beam transformer," as he variously called his device, as his thesis project.

His transformer is depicted schematically in Figure 1.[4] The primary winding W_1 induces a changing magnetic flux in the laminated iron core of the transformer. The electrons circulating in the evacuated glass doughnut-shaped tube R serve as the secondary winding. They are emitted by the cathode K and are guided into the vacuum tube, where they orbit. Acceleration takes place during the quarter-cycle while the flux is rising and while the magnetic field B_s at the orbit has the correct value to guide the electrons in a circular path. The two fields F_1 and F_2 guide the electrons into and out of the circular orbit.

Wideröe had shown the essential condition for a successful transformer to be as follows: the magnetic flux through the orbit must be twice what it would be if the field were uniform and equal to the field at the orbit, or $\varnothing(t) = 2\pi r^2 B_s(t)$. This would become the famous 2:1 rule for the betatron—a condition, he argued, that is automatically satisfied if the guide field B_s at the orbit is half as strong as the inducing field. The latter condition is achieved if the pole pieces of the magnet are suitably tapered. The value of the guide field is determined by equating the centrifugal and electromagnetic forces, or $mv^2/r = B_s ev$.

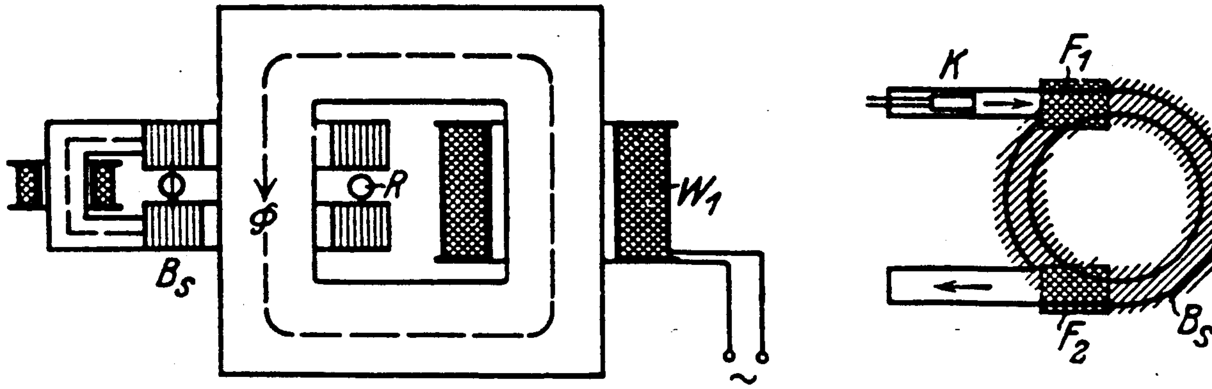

Figure 1. Principle of Operation of the Beam Transformer.

Wideröe's actual arrangement is shown in Figure 2. It consisted of three components: the hot-cathode electron tube (similar to one developed by Rogowski), the transformer itself, and the energizing circuit. Electrons emitted from a heated tungsten wire passed through the electrical field between cathode and anode, and were directed into the ring-shaped vacuum tube *R*. The earth's field and the fringing field of the transformer were compensated by the pair of crossed coils S_1 and S_2, and the particles were focused by the coil *KS*. The entrance to the circular transformer tube was closed by means of a flap attached to a lubricated ground joint *V*. For better visual observation, the glass walls of the whole tube were dusted with a thin layer of zinc sulfide. The magnetic poles were laminated from transformer steel sheets; the two air gaps *d* and *d'* served to adjust the flux densities B_i (inducing) and B_s relative to each other.

The transformer produced a maximum flux density B_i of 14 000 G. With a mean orbital radius of 7.25 cm, this would correspond to a maximum increase in voltage of 6 MV. Since, however, Wideröe's intention was simply to demonstrate an acceleration of the electrons, the primary winding was connected to a dc-voltage source, thus producing a single transformation. In operation, the cathode rays were focused on the front of the zinc sulfide-coated shutter screen guarding the entrance to the toroidal vacuum tube. When a well-focused, stable spot of maximum intensity had been obtained, the shutter was opened and the initial magnetic field was adjusted to the value for the orbit radius appropriate for the 2:1 rule.

> [In the event] it proved to be very difficult to keep the electrons in the correct orbit. Only by using the coil S_3 (in Figure 2) and a suitable shape of tube could the electrons be made to complete about 1.5 revolutions. It was not possible to keep the electrons in orbit permanently. Shortly after one revolution the beam usually struck the wall. For these reasons it was quite apparent why no acceleration could be demonstrated. The transformer was excited several times but no high-voltage electrons were observed.[5]

The reason for the failure, Wideröe decided, was his failure to create an optimal arrangement of magnetic fields and electrodes for confining the electrons to the central orbit of the tube, that would have had "a stabilizing effect on the trajectories."[6] In fact, he was not alone in his failed attempt. The very same year, Merle Tuve, Gregory Breit, and Odd Dahl tried a similar experiment with only slightly more success at the Carnegie Institution in Washington, D.C. Their apparatus used a spark discharge of a large capacitor through a coil to produce the magnetic field, and a much more energetic electron gun as injector; however, they too were bedeviled by an inadequately-shaped field unable to stabilize the electron beam. Though claiming an acceleration to "one- and one-half or two million volts," they admitted that "the radiations obtained so far... are very weak and intermittent."[7] In hindsight, Wideröe regrets that he dropped the transformer at Aachen so quickly; retrospective study of his model convinced him that "the guiding field of my magnetic structure really was right and the calculations in my notebook from that time show the same results and criteria as Kerst and Serber published 15 years later.... My mistake at the time was that I regarded the calculated stabilizing forces as too small and not of any importance—probably the prejudice of an electrical engineer."[8]

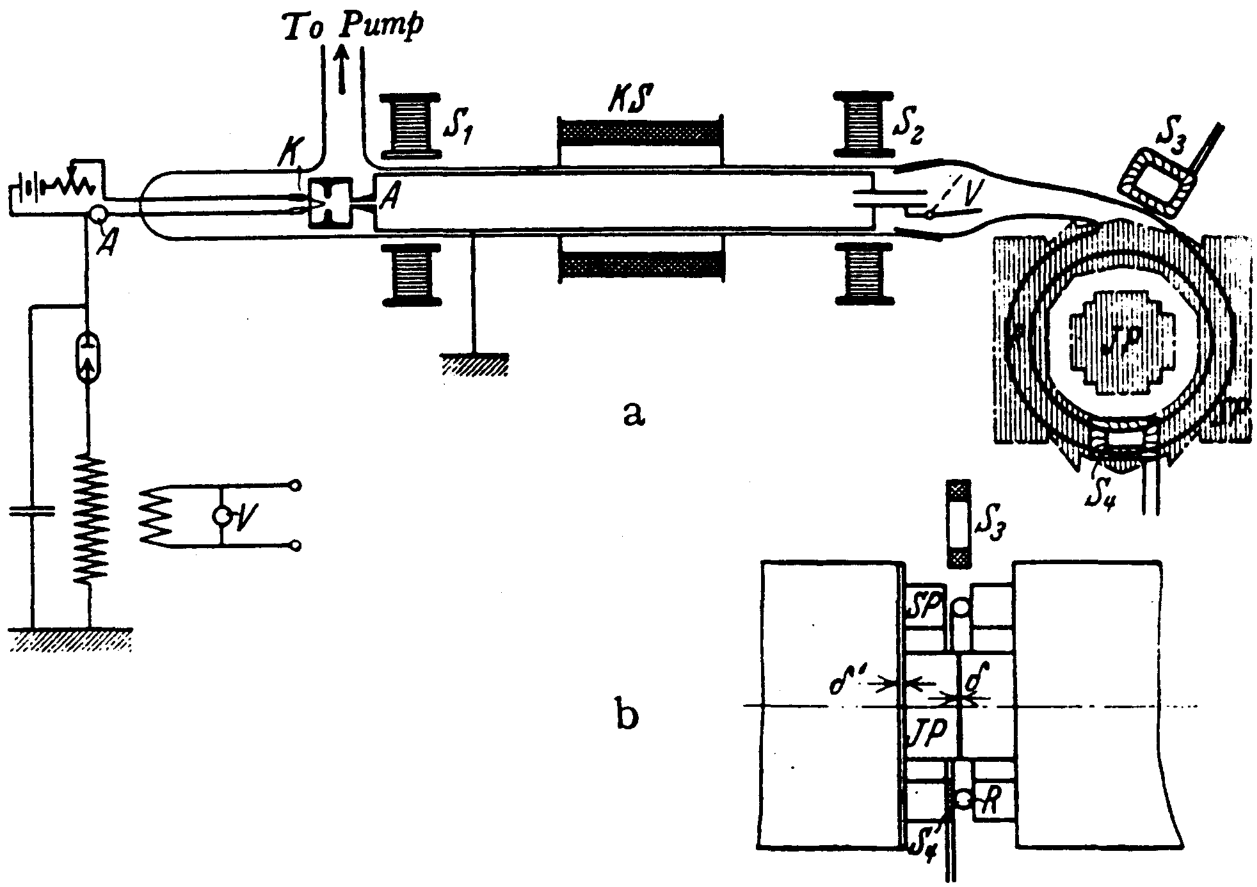

Figure 2. The Hot-cathode Electron Tube (a) and the Transformer Poles (b).

3.0 THE LINAC: CLOSER TO THE MARK

In any case, a non-working device would not do as a dissertation project, but Wideröe did not give up. Instead, he resurrected a scheme proposed by Gustaf Ising of Stockholm in 1924 for the acceleration of heavy ions (canal rays) in what amounted to a traveling-wave linear accelerator. It consisted of a linear array of cylindrical electrodes connected to transmission lines of increasing length.[9] A potential pulse generated by a spark gap in an oscillatory circuit was conducted along the wires, arriving sequentially at the electrodes and creating accelerating fields in the gaps between successive electrodes. Inside the electrodes, the beam was shielded and was not accelerated. The gap spacing increased in unison with the increasing ion velocity, ensuring acceleration at each gap.

Ising apparently did not follow up his expressed intention of conducting practical experiments, but Wideröe did.[10] With the goal of simply demonstrating the principle of resonance acceleration (not a feature of the betatron, which does not depend on an rf field for acceleration), he chose the simplest arrangement of two accelerating gaps (Figure 3), replacing the spark vibrator with a vacuum tube oscillator. Sodium and potassium ions from a "Kunsmann" source were accelerated through a potential of

20 kV across the first gap I; thence the ions drifted through an electrostatically shielding tube *BR* and arrived at the second gap II. Since the distance traveled by the ions after the first acceleration in one-half cycle of the rf field was equal to the spacing between gaps, the ions were again accelerated in transversing the second gap, with their energy doubled to 40 kV. Following the second acceleration, the ions drifted through a second shielded section, were masked by the slot *S* to a 0.1 mm-wide strip, and were electrostatically deflected in the capacitor *K*; they finally struck a photographic plate *P*, where the voltage of the ions could, in principle, be calculated from the deflection *a*, which was independent of the ion mass and dependent only on the total accelerating voltage. In practice, a precision measurement of the voltage was "hardly possible with the simple apparatus used," although "experiments with accelerating voltages indicated at once that the ions did gain a doubled kinetic voltage, as expected."[11]

Though the principles at stake were confirmed to Rogowski's satisfaction, earning Wideröe his Aachen doctorate in the fall of 1927, to Wideröe the obtainable currents seemed disappointingly low for practical engineering applications.

> With the methods known today it seems hardly possible for ion currents higher than 1-10 mA to be obtained. Under these circumstances, the method is almost out of the question as a technical generator for high direct voltages,... But high-voltage ion beams are of great interest in physics and, therefore, the developed method should not be without value.[12]

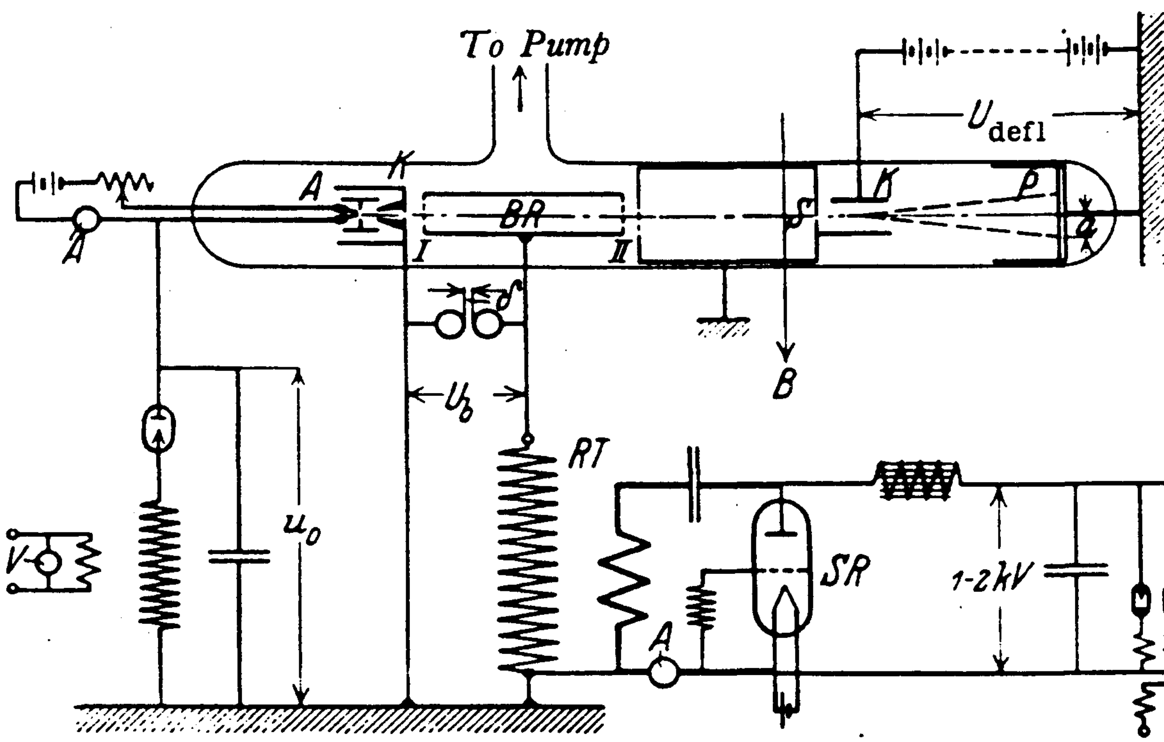

Figure 3. The Linear Accelerator and Its Energizing Circuit.

4.0 ENTER ERNEST LAWRENCE

In fact, Wideröe's development proved to be of great value indeed. His paper covering both the resonance accelerator and the beam transformer was published in the *Archiv für Electrotechnik* (under the editorship of Rogowski) in December 1928. At the University of California at Berkeley, Ernest O. Lawrence came across Wideröe's paper early the following year—perhaps not altogether by happenstance.[13]

Of Norwegian descent like his friend from boyhood years in North Dakota, Merle A. Tuve,[14] Lawrence studied for his master's degree under the colorful William F. G. Swann at the University of Minnesota in the company of Tuve. Swann, an English cosmic-ray physicist with a flair for foundations, patrons, and extroverted behavior, would leave his mark on Lawrence. In 1923 Lawrence followed Swann to Chicago, and thence to Yale with Swann as a National Research Fellow. There he finished his dissertation on the photoeffect in 1925. After a brief faculty stint at Yale, enlivened by attractive offers and counter offers from both Berkeley and Yale, Lawrence accepted a professorship at the University of California; he arrived in Berkeley in the summer of 1928.

Lawrence resolved to capitalize on what was rapidly becoming the hot topic of experimental physics: nuclear excitations and disintegrations by artificial means. Predicated on methods for producing beams of charged particles with energies in excess of 1 MeV, transformers and rectifiers in the style of Cockroft and Walton seemed excessively unwieldy and expensive to Lawrence. More promising, he felt[15], were alternative higher or lower-potential approaches to high energies—perhaps along the line of the surge generator of Brasch and Lange, perhaps the electrostatic generator pursued under Swann during Lawrence's stay at Minnesota and subsequently spearheaded on a large scale by Van de Graaff, or perhaps the Tesla coil approach of Tuve, Breit, Hafstad, and Dahl.

> One evening early in 1929 as I was glancing over current periodicals in the University library, I came across an article in a German electrical engineering journal by Wideröe on the multiple acceleration of positive ions. Not being able to read German easily, I merely looked at the diagrams and photographs of Wideröe's apparatus and from the various figures in the article was able to determine his general approach to the problem—*i.e.*, the multiple acceleration of the positive ions by appropriate application of radio frequency oscillating voltages to a series of cylindrical electrodes in line. This new idea immediately impressed me as the real answer which I had been looking for to the technical problem of accelerating positive ions, and without looking at the article further I then and there made estimates of the general features of a linear accelerator for protons in the energy range above one million volt electrons. Simple calculations showed that the accelerator tube would be some meters in length which at that time seemed rather awkwardly long for laboratory purposes. And accordingly, I asked myself the question, instead of using a large number of cylindrical electrodes in line, might it not be possible to use two electrodes over and over again by bending the positive ions back and forth through the electrodes by some sort of appropriate magnetic field arrangement. Again a little analysis of the problem showed that a uniform magnetic field had just the right properties—that the angular velocity of the ions circulating in the field would be independent of their energy so that they would circulate back and forth between suitable hollow electrodes in resonance with an oscillating electrical field of a certain frequency which now has come to be known as the cyclotron frequency.[16]

In other words, from

$$mv^2/r = Bev$$

(a relationship Wideröe had utilized in determining his beam transformer), we see that the angular velocity ω is independent of velocity or radius:

$$\omega = v/r = Be/m \, .$$

Fast ions describe long circular paths, and slow ions short paths, with the frequency of revolution $\omega/2\pi$ the same for all. Ergo, ions of mass m and charge e could be made to travel in phase with the rf field in a magnetic field B, repeatedly crossing a gap between electrodes, spiraling outward, and gaining energy each time around.

The rest is history, as they say. In the spring of 1930, Nels Edlefsen, a postgraduate student of Lawrence, constructed a crude model of the device which may or may not have worked after a fashion. In the fall of the same year another student, M. Stanley Livingston, constructed a 4-inch cyclotron (Lawrence's term), a model of which is on display at the Lawrence Hall of Science and which yielded 80 keV hydrogen molecular ions with relative ease. The saga of ever larger cyclotrons that sprouted at Berkeley has been often told—among others by Lawrence himself in his Nobel lecture.[17]

Wideröe and his colleagues at Aachen, in fact, narrowly missed inventing the cyclotron. He recalls a discussion of his resonance accelerator in which a fellow assistant, Flegler, asked whether perhaps the ions could be made to circulate, for instance on spiraling orbits in a magnetic field, and could be accelerated by high frequency-excited drift tubes. "My answer was that this was possible but that it would be difficult to stabilize the orbits and that the ions probably would be lost in collisions with the walls".[18]

It goes without saying that Wideröe's concept of a linear array of drift tubes was not lost on Lawrence as an alternative, if less elegant, route to resonance acceleration. However, with the vacuum tube oscillators then available, the upper limit of frequency was $\sim 10^7$ Hz, restricting the linear accelerator to heavy ions: since the lengths of the electrodes for accelerating ions of different masses are in inverse ratio to the square roots of the ion masses, the acceleration of protons—much more effective projectiles in penetrating the nuclear barrier—would require an impracticably long accelerator. Nevertheless, in 1931 David H. Sloan (yet another of Lawrence's students) designed and constructed a linac (to use a term coined much later) with 8 and then 21 accelerator sections in a tube 80 cm long, accelerating singly-charged mercury ions to 130 keV. Subsequently, a 30-section machine produced 1.26 MeV. Later yet, with a still longer array, Sloan and Wesley M. Coates obtained 2.8-MeV Hg^+ ions. But, as expected, heavy ions proved ineffective in causing nuclear disintegrations, and the linear accelerator program at Berkeley was dropped for the time being. The proton linac would have to await new developments in rf technology made during World War II.

5.0 WORKING ACCELERATORS AND CONCEPTUAL STORAGE RINGS

With his doctorate in hand, Wideröe filled a position at the AEG Transformer Laboratory in Berlin during 1928–1931. Following that stint, he spent a decade with several electrical concerns in Norway, before returning to Germany. His first operational betatron was constructed during 1943–44 under what must have been difficult conditions at the Röntgenröhrenwerk of C.H. F. Müller at Pfuhlsbüttel near Hamburg. Wideröe does not say, but presumably he had access to Kerst's and Kerst and Serber's back-to-back papers on the betatron in the *Physical Review* for 1941. His principal collaborators were R. Kollath of the AEG Research Laboratory, G. Schumann, and the Austrian physicist Bruno Touschek, of whom we have more to say shortly. The 15-MeV betatron was operational as an x-ray therapy facility in late fall of 1944—the first working betatron outside the U.S.[19] At the end of the war it was disassembled by the British as war booty, transported to Woolwich Arsenal outside London, and used for nondestructive testing of materials.

If experimental conditions in wartime Hamburg were severely taxing, countless hours in bomb shelters gave ample opportunity for theoretical speculation. Thus, in 1943 Wideröe filed German patents for a number of accelerator principles and devices, including electrostatic and magnetic strong-focusing lenses.

In particular, he conceived of the use of storage rings and colliding beams for increasing the interaction energy of charged particles, based on electrostatic containment of counter-rotating particles of opposite polarity.

Wideröe has described the circumstances around his conception of what he termed a "Kernmühle" ("nuclear mill") while vacationing in Norway:

> On a nice summer day I was lying on the grass seeing the clouds drifting by and then I started speculating what happens when two cars collide. If we have a car moving with the velocity v colliding with a resting car of equal mass, the dissipated energy will be $1/4\, mv^2$ (inelastic collision), whereas two cars with the velocity v having a head-on collision would dissipate four times as much energy (mv^2) in spite of having only twice the energy before the collision. This clearly demonstrated that head-on collisions have to be avoided for cars, but might be very useful for protons.[20]

The same year Wideröe filed for a German patent on the device, and a patent was eventually awarded ten years later.

While of little direct influence on post-war developments in accelerator technology, Wideröe's conception played a role nevertheless. As noted, one of his collaborators on the betatron project was Bruno Touschek, whose principal contribution at the time was the use of the Hamiltonian formalism to study the orbits in circular accelerators.[21] Some years later Touschek left his own mark on accelerator technology when, at a seminar in 1960 at the Laboratori Nazionali de Frascati, he demonstrated rigorously that a single ring of magnets and rf cavities suffices for an electron-positron collider. It seems quite likely that Touschek derived his inspiration from his close association with Wideröe during the war years.[22] Touschek and colleagues subsequently constructed the first operational electron-positron storage ring, AdA (for Anello di Accumulazione e^+e^-), at Frascati.

Frustrated at not receiving adequate credit for such fundamental concepts in accelerator physics, Wideröe, in a discussion period at the 1956 conference on accelerators at CERN, gave an impromptu polemic on his storage ring scheme; in reply, Lawrence (who had never met Wideröe) countered with a scathing rebuff.[23]

One further incident involving Germany, Wideröe, and the betatron perhaps warrants mention. At the end of the war in Europe, the Alsos mission under Samuel A. Goudsmith came across indications of a German death-ray project involving gamma rays from a giant betatron. Subsequently, one of the mission members, the Norwegian astrophysicist Gunnar Randers, uncovered in a report to Field Marshal Milch what appeared to be an error in beam intensity exaggerating the effect by a factor of 10. This he soon confirmed in consultation with Wideröe himself, who happened to be in Norway when the war ended.[24]

In 1946 Wideröe joined the Brown-Boveri plant in Baden, Switzerland, where he would be ensconced as head of the BBC radiation laboratory until 1961. He immediately went to work on a second successful betatron for medical and industrial applications, the first of several Brown-Boveri betatrons. At the same time, his fertile imagination did not remain idle. Also in 1946, despite his temporary imprisonment by the Norwegian authorities at the end of the war for perceived wartime collaboration in Germany, he took out a Norwegian patent on the principle of the synchrotron, including "phase lock" adjustment of the acceleration frequency, use of half- or quarter-wavelength resonators, ferromagnetic tuning, and keeping the accelerating frequency an integral multiple of the rotational frequency. In the late 1950s he supervised a 100-MeV electron synchrotron for the University of Turin—an experience that left his team with the impression that "it sometimes is much more difficult to build a small machine than a bigger one."[25]

Indeed, big machines were then in the making in Europe, and Wideröe lent a hand almost from the start. In the early fall of 1951, Julien Leon Verhaege pointed out that Wideröe could provide valuable assistance to a small scientific committee (Amaldi, Auger, Dahl, Goward, Kowarski, Mussard, Perrin, Preiswerk, Regenstreif, and Bakker) organized to lay the foundation for an inter-European accelerator laboratory.[26] Two accelerators were proposed for parallel construction: a proton synchrotron envisioned as a scaled-up version of the Brookhaven Cosmotron, and a large synchrocyclotron. Odd Dahl took charge of the design of the proton synchrotron (PS), with Frank Goward (who built the world's first electron synchrotron in England) as his deputy, and Wideröe became a part-time consultant to the PS group from its foundation. In August 1952 he accompanied Dahl and Goward on their much-publicized trip to Brookhaven, when the concept of alternating-gradient focusing was presented to the visitors by Courant, Livingston, Snyder, and Blewett. The concept was adopted virtually at once for the CERN machine, a decision Wideröe undoubtedly played a role in.

During 1953–1972 Wideröe, in addition to his position at Brown-Boveri, was also Professor at Zürich's Eidgenossiche Technische Hochschule (ETH). In 1969 he received the Röntgen Prize for his contributions to accelerator applications in radiation therapy, a subject that increasingly occupied his interest in later years. Now retired in Switzerland, Wideröe has 180-odd scientific and technical papers to his credit and easily as many patent applications. If somewhat outside the mainstream community of accelerator scientists, he has been a prolific inventor of well-nigh every type of accelerator principle, and he has left his mark on laboratories from Lawrence's to CERN. As much as anybody, he can be said to be the father of the modern particle accelerator.

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3. Wideröe quoting Gaede, *Ibid.,* p. 9.
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5. Wideröe in Livingston (Reference 4), p. 113.
6. *Ibid.*
7. G.M. Breit, M.A. Tuve, and O. Dahl, "Magnetism and Atomic Physics," *Carnegie Institution of Washington Yearbook,* **27** (1927), pp. 208–209. Ernest Walton did no better at Cambridge in 1929, nor did Ernest Lawrence at Berkeley in 1931. Leo Szilard applied for a German patent for the betatron in 1929 without building one, as did Max Steenbeck in 1937 and Penney in 1941 without significant progress. The first operating betatron was constructed by Donald Kerst at the University of Illinois in 1939, utilizing Steenbeck's patent and the theoretical expertise of Robert Serber.
8. Wideröe, "Some Memories..." (Reference 2), on p. 9.
9. Gustaf Ising, "Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl," *Arkiv för Matematik, Astronomi och Fysik,* **18** (1924), pp. 1–4; translated by F.W. Brasse as "The Principle of a Method for the Production of Canal Rays of High Voltage," in *The Development...* (Reference 4), pp. 88–90.
10. Wideröe, "Über ein Neues Prinzip..." (Reference 4), pp. 92–107.
11. *Ibid.,* pp.104–105.
12. *Ibid.,* p. 106.
13. J.L. Heilbron and Robert W. Seidel, *Lawrence and His Laboratory: A History of the Lawrence Berkeley Laboratory,* Volume I (University of California Press, Berkeley, 1989), pp. 82–83. The authors suspect the library entered the journal subscription at Lawrence's behest, since its technical emphasis, albeit in German, was highly pertinent to his own experimental program.
14. It is uncanny how so many of the accelerator pioneers were Norwegians or of Norwegian extraction: Wideröe, Lawrence (original family name Larsen), Tuve, Hafstad, Dahl, and Kjell Johnsen.
15. E. O. Lawrence, "The Evolution of the Cyclotron," *Les Prix Nobel en 1951,* Imprimerie Royale (P.A. Norstedt & Söner, Stockholm, 1952), pp. 127–140; reprinted in *TheDevelopment...* (Reference 4), pp. 136–150.
16. *Ibid.* (The Development...), pp. 136–137.
17. *Ibid.,* pp. 136–149.
18. Wideröe, "Some Memories...," (Reference 2), p. 9.
19. Wideröe, "Some Memories...," (Reference 2), p. 10. Incidentally, a microfilm roll containing Kerst's papers was smuggled via London into Bergen, Norway, in the winter of 1945 and delivered to Odd Dahl by the head of the military resistance organization in Bergen—a gift from his former

colleagues Tuve and Hafstad. *Odd Dahl: Trollmann og Rundbrender*, Odd Dahl, as told to Jan H. Landro (Gyldendal, Oslo, 1981), p. 162.

20. John Blewett, "The First Proposal for Colliding Beams," *Particle Accelerators*, **3** (1972), pp. 127–128.
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23. Larry Jones, *Ibid.*, p. 199. Despite his harsh putdown, Lawrence embraced Wideröe on the steps to the lecture hall podium. Davis, Nuel Pharr, *Lawrence and Oppenheimer*, (Simon and Schuster, New York, 1968), p. 18.
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