

Early Milestones in the Evolution of Accelerators

E. D. Courant

*Brookhaven National Laboratory,
Upton, NY 11973, USA
ecourant@msn.com*

About 80 years ago Rutherford [1] expressed the hope that particles could be accelerated to energies exceeding those occurring in radioactivity, enabling the study of nuclei and their constituents. Physicists and engineers have more than met this challenge, and today the LHC (Large Hadron Collider) at CERN, Geneva is about to accelerate protons to 7 trillion (7×10^{12}) eV. Here we describe some of the crucial steps that have gotten us there.

Keywords: Accelerator; cyclotron; betatron; phase stability; synchrotron; strong focusing.

1. Resonance Acceleration — The Cyclotron

In 1927, in Aachen, Germany, Norwegian engineering student Rolf Wideröe accelerated sodium ions in a sequence of drift tubes to 50 kV using a radio frequency voltage of only 25 kV, i.e. using the same voltage twice. He published an account of this achievement as his doctoral dissertation [2]; it was clear that with more drift tube electrodes the acceleration could be repeated many times, though Wideröe's first accelerator went only to a factor of 2. A few years later Ernest Lawrence came across Wideröe's paper in the Berkeley library. Not being proficient in German he skipped the text, but the diagrams and the equations were enough to give him the idea that if the particle beam was bent in a circle by a magnetic field, the same accelerating electrode could be used many times rather than requiring a long sequence of many electrodes as implied by Wideröe. He noted the crucial and fortunate fact that the angular frequency of revolution of a particle of mass M and charge e traveling in a circle in a magnetic field B is

$$\omega = \frac{eB}{Mc}, \quad (1)$$

independent of energy. Therefore, with two hollow semicircular D-shaped electrodes excited at this frequency, the beam gets accelerated every time it crosses the gap between the two dees, and thus in

n revolutions it picks up a total energy of $2neV$ (V is the voltage between the dees). The maximum energy is determined by the size of the circular magnetic poles.

Lawrence had his student M. S. Livingston build a model demonstrating this principle. Using a magnet with pole faces 10 cm in diameter, and a maximum rf voltage of 2000 V on the dees, Lawrence and Livingston [3] succeeded in accelerating hydrogen molecular ions to an energy of 80 kV. And early in 1932 a larger machine, with 11-inch magnet poles and 4000 V on the dees, accelerated protons to 1.22 MeV [4], the first time in the world that particles were accelerated to over a million volts.

In the following years Lawrence and others built ever-bigger cyclotrons, culminating with a 60-inch machine in 1939, which accelerated deuterons to 20 MeV, and alphas to 40 MeV. Cyclotrons were also built in other US universities and in France and Japan (the Japanese cyclotrons were wantonly destroyed by the US occupying forces in 1945).

It became clear that there was a limit to the energy that could be achieved: the mass M in Eq. (1) is the relativistic mass, and therefore the frequency ω in a uniform magnetic field decreases with increasing particle energy rather than being exactly constant. Furthermore, it had already been found [4] that, to maintain vertical focusing, the magnetic field, rather than being exactly uniform, had to decrease

with increasing radius and energy, thus exacerbating the decrease of frequency with energy. Therefore the rf phase at which particles cross the accelerating gap changes until it reaches a decelerating phase, limiting the number of turns on which the particles gain energy. Bethe and Rose [5] estimated that, with magnetic fields as high as 18 kG and rf voltages around 50 kV, the maximum attainable energy would be around 17 MeV for deuterons; higher dee voltages would only increase the attainable energy with the square root of the dee voltage.

Lawrence was not discouraged by this. He built a magnet with poles of 184-inch diameter, intending to reach 100 MeV with dee voltages of around a million volts. But by the time the magnet was finished the wartime Manhattan Project was underway and the giant magnet was diverted to use for electromagnetic isotope separation (the “Calutron”), and cyclotron development was suspended.

2. Electron Acceleration — The Betatron; Orbit Theory

Clearly, the cyclotron principle is not suitable for electrons, which are relativistic at all energies in the MeV range. A different approach is needed. One possibility, already thought of by several people in the 1920's, was to accelerate electrons with the electric field associated with a time-varying magnetic field. Wideröe conceived of a “ray transformer” (*Strahlentransformator*): in a radially symmetric magnetic field $B(r)$, electrons of momentum p can travel in a circular orbit of radius R with

$$RB(R) = \frac{pc}{e}. \quad (2)$$

If the magnetic flux $\Phi = 2\pi \int_0^R rB(r)dr$ enclosed by this orbit is increased, a tangential electric field $E_\phi = \dot{\Phi}/2\pi Rc$ is produced on the orbit, accelerating the electrons. Wideröe saw that if the field $B(R)$ on the orbit and the flux Φ increase proportionately, *and the flux is just twice what it would be if the field throughout the inside of the circle were equal to the field on the circle*, the electrons will be accelerated just enough to stay on the same circle as they gain energy. So he built a device satisfying this condition, hoping to accelerate electrons to 6 MeV. But he did not succeed in accelerating the electrons. Therefore he then turned to the linear drift tube accelerator described in the previous section; his dissertation

paper [2] describes the ray transformer as well as the linear accelerator.

Others also attempted, unsuccessfully, to use this induction method of acceleration. Finally, in 1940, Kerst succeeded [6, 7], obtaining acceleration to 2.3 MeV. The secret of his success, at least in part, was theoretical analysis of orbit stability. The paper of Kerst and Serber [8] shows that around a circular orbit in a radially symmetric magnetic field the particles undergo radial and vertical oscillations of angular frequency

$$\omega_r = \Omega\sqrt{1-n}, \quad \omega_v = \Omega\sqrt{n}, \quad (3)$$

where Ω is the angular velocity, and the field in the vicinity of the orbit radius R varies as $(R/r)^n$, defining the field index n . Thus, for stability, we require that

$$0 < n < 1. \quad (4)$$

Equations (3) and (4) and Ref. 8 constitute the pioneering foundation of accelerator orbit theory.

Following this success Kerst proceeded to build a series of ever-larger induction accelerators. They were named “betatrons,” because high energy electrons have been called “beta radiation” ever since radioactivity was discovered.

Following Kerst's publication [6–8], Wideröe succeeded in building a 15 MeV betatron in Germany (described by Kaiser [9]).

A 100 MeV betatron at General Electric in Schenectady (designed largely by Kerst) was the world's highest energy accelerator by 1945, eclipsing cyclotrons.

3. Phase Stability — Synchrotron and Synchrocyclotron

As the Manhattan Project approached success toward the end of the war, the thoughts of people at Berkeley returned to the matter of cyclotrons. McMillan [10] saw a way to get around the limitation of the cyclotron. He noted that (1) can be rewritten in the form

$$E = Mc^2 = \frac{eBc}{\omega} \quad (5)$$

and saw that if we have a field B , an rf system with frequency ω , and a particle with energy E satisfying (5), and that we then slowly change ω and/or B , the energy E will automatically adjust itself so as

to maintain the synchronism condition (1) or (5), as long as the speed at which the field or frequency changes is not too fast, and the rf field has enough voltage to keep up with the rate at which the energy has to change in order to keep (5) satisfied. The mechanism is this, as described by McMillan [10]:

“Consider a particle whose energy is just (5), which we call the equilibrium energy for field B and frequency ω . Suppose that the particle crosses the accelerating gaps just as the electric field passes through zero, changing in such a sense that an earlier arrival of the particle would result in an acceleration. This orbit is obviously stationary. Now suppose that a displacement in phase is made such that the particle arrives at the gap too early. It is then accelerated; the increase in energy causes a decrease in angular velocity, which makes the time of arrival tend to become later. A similar argument shows that a change of energy from the equilibrium value tends to correct itself. These displaced orbits will continue to oscillate, with both phase and energy varying about their equilibrium values.”

“In order to accelerate the particles it is now necessary to change the value of the equilibrium energy, which can be done by varying either the magnetic field or the frequency (or both). While the equilibrium energy is changing, the phase of the motion will shift ahead just enough to provide the necessary accelerating force; the similarity of this behavior to that of a synchronous motor suggested the name “synchrotron” of the device.”

In fact, the same principle of phase stability and its application to accelerators had already been discovered earlier by V. I. Veksler [11] in Moscow. When McMillan became aware of this work he lost no time in acknowledging Veksler’s priority [12].

This principle of phase stability overcame the limitation on the cyclotron: simply modulate the frequency ω downward in a cyclotron magnetic field, and the particle will accelerate. The 184-inch magnet (see Sec. 2) that had been built with the hope of reaching 100 MeV in a cyclotron was now equipped with a pair of dees of moderate voltage and a frequency-modulated rf system, and reached 190 MeV with deuterons (380 MeV with alphas).

In principle the frequency-modulated cyclotron or *synchrocyclotron* can go as high in energy as one wishes if one makes the radius of the machine big enough. The radius for a given energy is determined by the equation

$$pc = eBR, \quad R = \frac{pc}{eB}, \quad (6)$$

where p is the particle momentum. But the whole area encircled by the top energy orbit has to be filled with magnetic field; this can get expensive if the size gets too big. In practice, synchrocyclotrons working this way have been built for energies up to about 600 MeV.

For electron acceleration we keep the orbit radius constant, and change the field — and the frequency — with time so as to keep (3) and (4) satisfied. Now magnetic field is needed only in a small annular region surrounding the orbit, in contrast with betatrons, where one needs a field inside the orbit averaging twice the orbit field.

In the immediate postwar years, the late 1940’s, synchrocyclotrons and electron synchrotrons in the 300 MeV range proliferated, because there was exciting new physics to be done: the pion had been discovered in cosmic rays, and these machines led to a thorough exploration of pion physics.

Protons can also be accelerated with constant orbit radius and changing field and frequency. Proton synchrotrons were proposed and built at Birmingham (1 GeV), Brookhaven (3 GeV), Berkeley (6 GeV), and Dubna, USSR (10 GeV).

4. Strong Focusing

Once the 3 GeV proton synchrotron at Brookhaven (named the Cosmotron) was completed in the summer of 1952, a study group was formed to explore possible improvements of the design. In the Cosmotron the magnet was constructed of 288 identical sectors, all with a C shape. The aperture faced the outside, with the back leg on the inside of the orbit. The magnets all had a field index n [see Eq. (3)] equal to 0.6, so as to satisfy the stability condition (4). The magnets of the Cosmotron all faced outward; therefore negative secondary beams were easily obtained, but positive secondaries would tend to hit the inside wall of the machine. In addition, magnet saturation effects tended to reduce the usable “good field” region at the fields corresponding to top

energy. Therefore it was proposed to alternate the magnet sectors, with some having the back legs on the inside and others on the outside.

This might lead to a problem: the focusing gradients might easily be different in the inward and outward sectors, especially in the fringing fields. Would this lead to instability of the orbits?

Almost at once analysis [13] showed that the alternating gradients could enhance stability rather than weaken it! With the right parameters the stability could be made much stronger than in the conventional case. The strength of the focusing is in effect determined by the ratio of the horizontal and vertical oscillation frequencies to the angular velocity. In the conventional case these ratios (known as the “tunes”) are $\sqrt{1-n}$ and \sqrt{n} , necessarily less than 1; with the new scheme the tunes can be much larger, and this corresponds to small oscillation amplitudes. This makes it possible to make the magnet aperture really small. That, in turn, makes the magnets — and other components — much cheaper, and so one can go to higher energies than without “strong” focusing. Reference 13 also proposes quadrupole magnets for focusing in straight sections without bending.

Again, it turned out that the discovery of the alternating gradient principle had been anticipated — by N. C. Christofilos, an engineer working in Greece [14]. Our Brookhaven group acknowledged his priority [15].

Alternating gradient (AG) proton synchrotrons were started almost immediately at Brookhaven and at CERN, Geneva. And practically all large accelerators in the world built since 1952, up to and including the LHC, use AG focusing.

In the process of planning and constructing these synchrotrons, it became evident immediately that detailed theoretical analysis (and of course a great deal of engineering innovation) was indicated. The study of the behavior of particle beams in AG focusing accelerators and storage rings has grown into an active discipline and numerous papers and books have been published on the topic; we list a few [16–20].

It soon became apparent that the reduction in oscillation amplitude promised in the initial paper [13] was somewhat exaggerated. Adams, Hine and Lawson [21] pointed out that when the ratios of oscillation frequencies to the frequency of revolution (soon named the “tunes,” ν_x and ν_y) are integral, any

small field errors will lead to large orbit excursions, and when the tunes are half-integral the oscillations will be exponentially unstable. Both these effects constitute *resonances* between the oscillations and Fourier components of field errors. The cure is to construct the magnets to very precise tolerances, and to design the fields and focusing gradients so as to ensure that the tunes are well away from resonant (i.e. integral or half-integral) values.

The art and science of devising layouts (“lattices”) of the magnets in AG synchrotrons has continued to advance over the years, starting with the simple alternation of horizontally and vertically focusing magnets in the first AG synchrotrons. Among the first innovations was the introduction by Collins [22] of structures incorporating long straight sections, which make it possible to incorporate all sorts of features in accelerators. And Milton White (unpublished) and Danby *et al.* [23] proposed that it might be useful to separate the bending and focusing functions, i.e. having pure bending magnets (with uniform fields) interspersed with quadrupole focusing magnets, rather than the “combined function” bending magnets with focusing gradients proposed in Ref. 13 and employed in the first AG synchrotrons at Brookhaven and CERN. Almost all AG accelerators built since the first ones employ this “separated function” configuration.

Many developments in the subsequent evolution of accelerators are described in the following articles in this issue.

References

- [1] E. Rutherford, *Proc. R. Soc. A* **117**, 300 (1927).
- [2] R. Wideröe, *Arch. F. Elektrot.* **21**, 387 (1928).
- [3] E. O. Lawrence and M. S. Livingston, *Phys. Rev.* **37**, 1707 (1931).
- [4] E. O. Lawrence and M. S. Livingston, *Phys. Rev.* **40**, 19 (1932).
- [5] H. A. Bethe and M. E. Rose, *Phys. Rev.* **52**, 1254 (1937).
- [6] D. W. Kerst, *Phys. Rev.* **58**, 841 (1940).
- [7] D. W. Kerst, *Phys. Rev.* **60**, 47 (1941).
- [8] D. W. Kerst and R. Serber, *Phys. Rev.* **60**, 53 (1941).
- [9] H. F. Kaiser, *J. App. Phys.* **18**, 1 (1947).
- [10] E. M. McMillan, *Phys. Rev.* **68**, 143 (1945).
- [11] V. I. Veksler, *J. Phys. (USSR)* **9**, 153 (1945).
- [12] E. M. McMillan, *Phys. Rev.* **69**, 534 (1946).
- [13] E. D. Courant, M. S. Livingston and H. S. Snyder, *Phys. Rev.* **88**, 1190 (1952).

- [14] N. C. Christofilos, Focussing system for ions and electrons. US Patent No. 2736299 (application 1950, patent issued 1956).
- [15] E. D. Courant, M. S. Livingston, H. S. Snyder and J. P. Blewett, *Phys. Rev.* **91**, 202 (1953).
- [16] E. D. Courant and H. S. Snyder, *Ann. Phys.* **3**, 1 (1958).
- [17] H. Bruck, *Accélérateurs Circulaires de Particules* (Institut National des Sciences et Techniques Nucléaires, Paris, 1966).
- [18] M. Conte and W. W. MacKay, *An Introduction to the Physics of Particle Accelerators* (World Scientific, Singapore, 1991).
- [19] D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators* (John Wiley, New York, 1993).
- [20] S. Y. Lee, *Accelerator Physics* (World Scientific, Singapore, 1999), 2nd edn. (2004).
- [21] J. B. Adams, M. G. N. Hine and J. D. Lawson, *Nature* **171**, 926 (1953).
- [22] T. L. Collins, Cambridge Accelerator Report CEA-86 (July 1961).
- [23] G. T. Danby, J. E. Allinger and J. W. Jackson, *IEEE Trans. Nucl. Sci.* **NS-14**(3), 431 (1967).

Ernest D. Courant is a physicist at Brookhaven National Laboratory since 1948, working primarily on particle dynamics in accelerators. Together with M.S. Livingston and H. Snyder, he originated alternating-gradient dynamics (“strong focusing”). He has taught at Princeton, Yale and Stony Brook. He was elected to the National Academy of Sciences 1976, received the Fermi Award 1986, and the Wilson Prize (American Physical Society) 1987. Retired as Distinguished Physicist Emeritus, 1990, he continues to participate in the RHIC project — primarily concerning polarized beams in accelerators.