Szilard as Inventor: Accelerators and More

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Physics Today **53** (10), 25–28 (2000);
https://doi.org/10.1063/1.1325189

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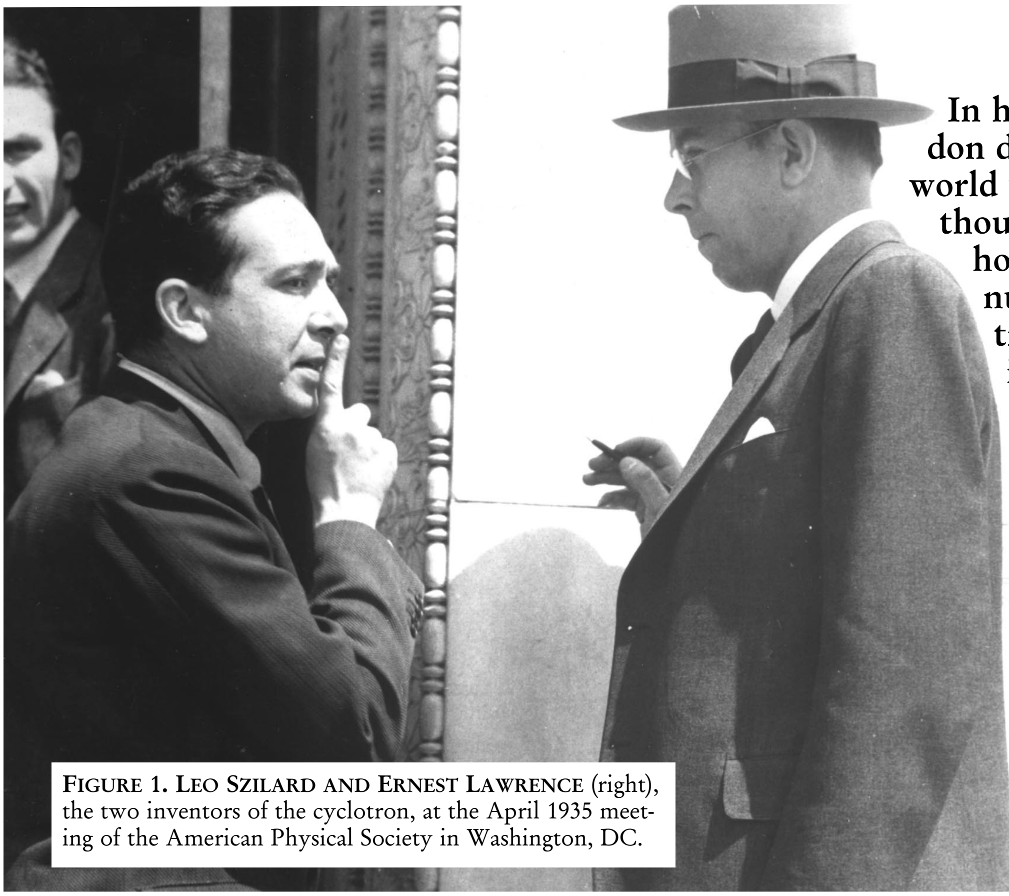

Figure 1. Leo Szilard and Ernest Lawrence (right), the two inventors of the cyclotron, at the April 1935 meeting of the American Physical Society in Washington, DC.

It is little appreciated, even in William Lanouette's excellent biography,[1] that Leo Szilard worked as a professional inventor during most of his scientific career, constantly filing patent applications that covered an astonishingly large range of novel ideas.

Born in Budapest in 1898, Szilard came to Berlin to study engineering after World War I and the upheavals in Hungary that followed in its wake. During his Berlin period (1920–1933) Szilard was granted 31 patents and abandoned 5 other patent applications. Contrast this with his published output as a physicist during the same period: two theoretical papers and two experimental articles.

Hardly any of his inventions seem to have been realized in practice, and there is no evidence that he reaped any financial rewards from his German patents or their foreign equivalents. One exception is a patent on a "Discharge Tube to Be Used as an Electron Source," which he assigned to the Siemens–Schuckert Company in Berlin. One may speculate that he acted as a paid consultant to that firm.

The most famous of Szilard's patents is, of course, his 1934 patent for the idea of a nuclear chain reaction. He was, by then, an unemployed refugee in London. Though the patent did mention uranium and thorium in passing, Szilard had his eye primarily on beryllium. The following year, to keep this patent secret, he assigned it to the British Admiralty.

During Szilard's Berlin period, however, a more mundane topic had been at the center of his technical interests: refrigerators, presumably for household use. The commercially available refrigerators at the time were noisy and generally unreliable. Szilard tried to propose devices without moving parts. These were covered by 16 patents, of which 5 were filed jointly with Albert Einstein.

Szilard's collaboration with this illustrious former patent clerk was not confined to refrigerators. It extended to the fairly well-known Einstein–Szilard pump for liquid

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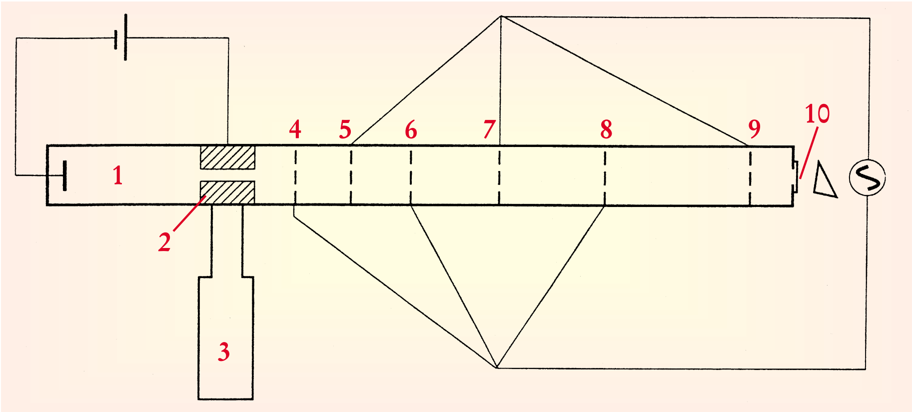

FIGURE 2. SZILARD'S SKETCH of the AC linac proposed in his 1928 patent application. (Labeling numbers have been added.) The components are: (1) the channel ray tube, (2) its cathode, (3) a vacuum pump, (4–9) grids connected to the AC voltage source, defining a widening sequence of accelerating gaps, and (10) the beam exit window.

metals, for which they filed a British patent in 1927. The proposed pump also had no moving parts. The key idea of the invention was to use a varying magnetic field to induce a ponderomotive force on a closed current loop in the fluid conductor. Nowadays pumps of this kind are used to circulate liquid sodium coolant in nuclear reactors.

Accelerators

Of Szilard's many inventions, the least recognized are those concerning devices for accelerating particles. That's not really suprising: The contents of all these patent applications (two in Germany and one in Britain) never became public knowledge because he eventually abandoned all three applications. It is not clear why. Either Szilard lost interest in pursuing them or the patent examiners may have raised questions of novelty on the basis of some "prior art."

Except for electrostatic machines like the Van de Graaffs, all modern accelerators are based on combinations of the following ideas: multiple acceleration, focusing, frequency modulation, and phase stability.

▷Multiple acceleration circumvents the high-voltage breakdown limit on a single accelerating gap by having a particle traverse the same gap many times (as in a cyclotron) or pass through a sequence of gaps (as in a linear accelerator, or "linac").

▷One needs to focus a particle beam during acceleration by carefully shaping the machine's magnetic field. In a circular accelerator, for example, the homogeneous magnetic field that bends the charged-particle trajectories into the desired circle does not, by itself, provide any restoring ("focusing") force to keep the circles from wandering out of the plane.

▷If a radio-frequency (RF) alternating voltage is used for acceleration, its frequency must match the particle's motion. In a nonrelativistic cyclotron, the particle's orbital frequency is a constant, independent of the particle's energy. It depends only on the homogeneous magnetic field strength and the particle's mass. But if the bending field is not constant over the plane or particles reach relativistically high energies, the frequency of the accelerating voltage must be varied ("modulated") during the acceleration cycle.

▷RF acceleration requires phase stability. That is to say, the particle must enter the accelerating gap in step ("in phase") with the varying voltage. The voltage across the gap must be near its peak and, of course, in the right direction.

Between 1928 and 1934 Szilard came up with all of these ideas, either first or independently of others. The only concept he missed, one that I purposely left out of the list, is the idea of alternating-gradient (or "strong") focusing, which came along in the early 1950s. But strong focusing required the advent of the synchrotron, which in turn is based on phase stability.

Electrons or ions

The first accelerator proposed by Szilard was a linac, covered in a German patent application entitled "Acceleration of Corpuscles" and filed on 17 December 1928. Figure 2 shows the proposed layout. Though Szilard writes of "canal rays" in the patent application, he also refers to "corpuscles, e.g. ions or electrons." Actually, with the low-frequency RF sources available in those days, an apparatus of modest length would have worked only for rather heavy ions.

The patent application contains a particularly perceptive remark:

> With our arrangement, the electric field can be conceived of as a combination of an electric field in accelerated motion from left to right and an electric field in decelerated motion from right to left. The device is operated in such a way that the velocity of the accelerated ion equals, at each point, the local velocity of the field moving from left to right.

That is exactly what modern accelerator designers mean when they speak of "traveling waves."[2]

This invention of Szilard's was anticipated by a young Norwegian engineer, Rolf Wideröe, then working in Aachen. Wideröe reported the acceleration of sodium and potassium ions through two successive tubular electrodes between which an oscillatory electric field was applied.[3] Wideröe's paper appeared in print in the summer of 1928, before Szilard submitted his patent application. By 1931, Ernest Lawrence and David Sloan at Berkeley were accelerating mercury ions to 1.25 MeV in a linac. Lawrence's awareness of Wideröe's work is, as we shall see, of great historical significance.

Though Wideröe's name may not be a household word among today's physicists, the name of the true inventor of the linac sounds much more familiar: Ising. But this Ising is not the German theorist of the eponymous model of ferromagnetism. Gustaf Ising was a Swedish experimentalist who published his pioneering linac paper[4] in 1925. Possibly the German patent examiner was aware of this "prior art" and used it to reject Szilard's application.

Cyclotrons

On 17 January 1929, just three weeks after proposing the linac, Szilard submitted a second application concerning accelerators, this one entitled "Corpuscular Ray Tube." In this short application (only 7 typed pages) Szilard proposed both the cyclotron and the betatron. For the cyclotron, he pointed out the resonance condition between the applied RF frequency and the orbital frequency, which is independent of the trajectory's radius as long as the particle's kinetic energy is much less than mc^2. Although Szilard' application speaks of electrons in connection with both devices, he must have realized that the cyclotron is not really suitable for them: Because the electron is so light ($mc^2 = 0.51$ MeV), its cyclotron resonance frequency is very high and, even if the requisite RF frequencies could be generated, the electron becomes relativistic at very modest energies. On the other hand, at the time of Szilard's proposal, high-energy electrons were much sought after as a source of hard x rays.

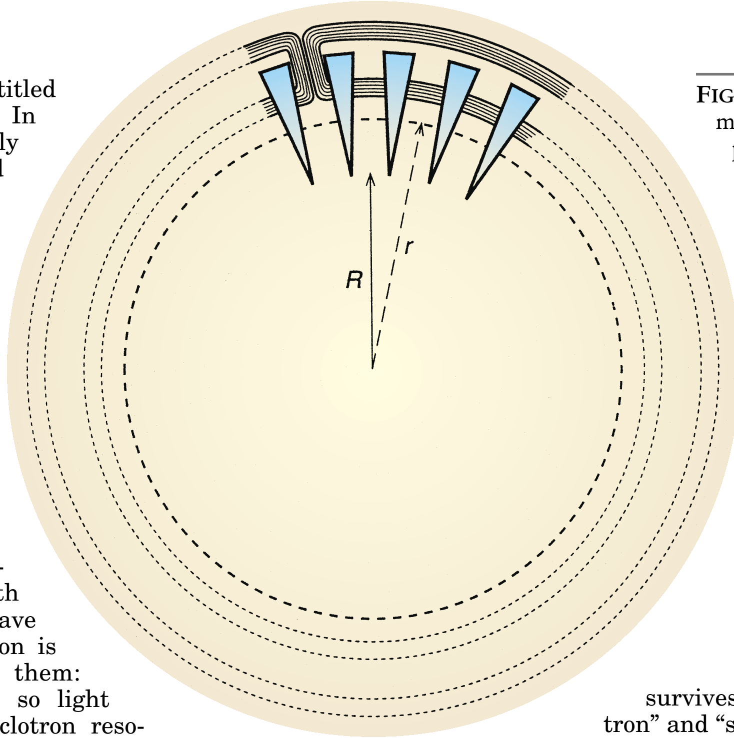

FIGURE 3. MAGNET arrangement in Szilard's 1934 proposed adaptation of cyclotrons for relativistic electrons. As the electrons gain energy, their orbital radii grow from the initial *R* and thus encounter the radially increasing average bending field provided by the wedge-shaped magnets arrayed all around the accelerator's circumference. The magnets are also designed to provide vertical focusing.

The betatron

Once again, Wideröe's thinking paralleled Szilard's ideas, this time in connection with the betatron. The basic betatron idea is to accelerate circulating electrons by magnetic induction. The accelerating force is the electromotive force induced by a time-varying magnetic field linking the electron orbits. The orbits become, effectively, the secondary coils of a transformer.

Wideröe's discussion of the betatron concept appeared in the same paper as his report of the linear double acceleration of alkali ions.[3] But Wideröe did not consider the problem of focusing. Szilard did propose focusing by means of a radial decrease of the magnetic guide field. Joseph Slepian's even earlier proposal (1922) also suffered from the lack of focusing.

It is interesting that Wideröe missed the cyclotron, that is to say, the idea of using a magnetic field to curl up the particle trajectory of a linear accelerator into a spiral. That idea occurred to Lawrence in the summer of 1929, when he came across Wideröe's linac proposal while browsing in the library. The following year, Lawrence published the cyclotron principle in *Science*.[5]

Szilard's next (and probably his last) ideas on accelerators are contained in a British patent application filed on 21 February 1934, entitled "Asynchronous and Synchronous Transformers for Particles." The term *transformer* is, of course, inspired by the betatron concept. Szilard divided accelerators into synchronous and asynchronous, according to whether or not there is a correspondence between the orbital and applied frequencies. Thus the cyclotron belongs to the first class, and the betatron to the second. Nowadays we would speak of "resonant" and "nonresonant" accelerators. But Szilard's terminology survives in the terms "synchrotron" and "synchrocyclotron."

I won't say much about the part of the patent application devoted to betatrons, except to mention that it proposed four such machines connected in a closed circuit in order to exploit both half-cycles of the oscillating magnetic flux. In the second part of the application, Szilard proposed a variation on the cyclotron theme that is, in effect, a kind of electron synchrotron: Relativistic electrons are to be accelerated in an annular region where the *average* vertical bending field increases radially outward, so that the cyclotron frequency remains reasonably constant despite the lengthening trajectories. (See figure 3.) The wedges that are to produce this radially increasing bending field are also designed to provide focusing normal to the orbital plane. Furthermore, Szilard proposed both frequency modulation and phase stability—the former being impossible without the latter. Let me quote directly from Szilard's patent application:

> During the accelerating process, the time of revolution will increase as the momentum of the electron increases (again we assume that the initial energy is sufficiently high, otherwise the time of revolution would decrease in the beginning). Therefore the wave-length of the applied high frequency oscillation should not be constant but should increase during a time which is required for the acceleration of the electron within the magnet.

With the magnet design considered by Szilard, the orbit radius in the annular region where the acceleration occurs increases by 10% for a tenfold increase in momentum. (From the proposed dimensions, it seems that the accelerator was meant for a maximum electron momentum of 100 MeV/c.) Szilard continues:

> Accordingly the time of revolution will gradually increase by about 10% and therefore the wave-length should gradually increase by 10%. The change of wave-length is very small for a single revolution. It is important to note that the time required for the acceleration of the electron up to a certain momentum

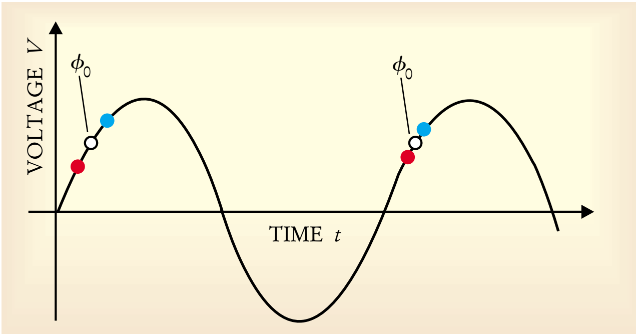

FIGURE 4. PHASE STABILITY in an accelerator driven by an oscillating voltage $V(t)$ can be arranged so that particles arriving at an accelerating gap too early (red dot) or too late (blue dot) to encounter the desired phase ϕ_0 automatically do better the next time around. The early ones are retarded by gaining too little energy and the late ones are correspondingly pushed ahead.

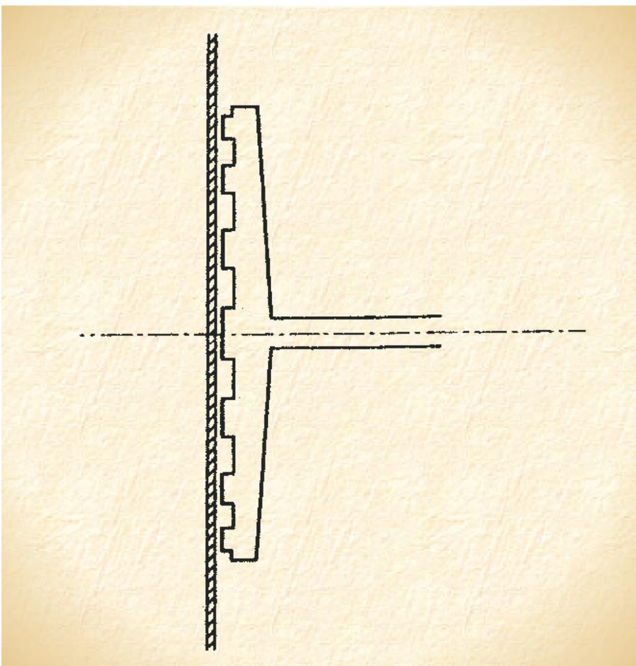

FIGURE 5. ROTARY CONDENSER PLATE proposed by Szilard in 1934 to provide the cyclic frequency modulation a relativistic electron cyclotron would need. Two such plates (only one is shown), studded with teeth that face each other across a thin quartz disk (shown shaded), are rapidly rotated in opposite directions about their common axis, thus providing the resonant circuit of the accelerator's radio-frequency source with rapidly oscillating capacitance.

> depends on the phase relation which characterizes the passage of the electron through the accelerating gaps. This leads to a considerable freedom in the rate at which the high-frequency oscillation may change its frequency within the limits within which it is effective in accelerating the electron. The oscillation having a changing frequency will stabilize the phase of the passage of the electron through the gaps.

Phase stability

Szilard next illustrates the notion of phase stability. But because his original diagram can be misleading, I prefer to offer my own explanation with the help of figure 4, which shows the oscillating voltage $V(t)$ across the accelerating gap. Assume that ϕ_0 represents the "desirable" phase for the passage of the particle through the gap. Consider first a particle (the red dot) that arrives at the gap too early in the voltage cycle. So it gains too little energy crossing the gap and arrives later in the cycle after the next revolution, and thus closer to ϕ_0. Similarly, a particle that arrives late (the blue dot) will gain too much energy and thus will also be closer to ϕ_0 the next time it crosses the gap. It only remains to be shown that the desirable phase is stable point.

At the end of the patent application, Szilard considered practical ways to implement frequency modulation. One of these is the rotary condenser shown in figure 5, which is, in fact, the kind of device eventually used in the synchrocylotrons of the late 1940s. It consists of two counter-rotating condenser plates with protrusions on their faces, so that one has a rapidly oscillating cycle of varying capacitance for the resonant circuit that produces the accelerating RF.

It is important to note that Szilard's 1934 patent application concentrated on the acceleration of electrons. He barely mentions protons. At the energies useful for the nuclear physics of the day, protons are essentially nonrelativistic and frequency modulation is of little interest. It was only in 1937 that the relativistic limitations on proton acceleration with a conventional cyclotron were investigated. Hans Bethe and Morris Rose at Cornell concluded that 15 MeV was about the maximum proton energy one could get without frequency modulation.[6]

On one occasion, Szilard was talking to a distinguished biologist who was going to explain some of his recent results. The biologist asked what knowledge he should assume on Leo's part. "Assume infinite intelligence and zero prior knowledge," was Szilard's reply. (On the printed page, deprived of its native Hungarian accent, such a remark might appear presumptuous.) This was the spirit in which Szilard approached the invention of novel accelerators.

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