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Authors
Livingston, M.S.
McMillan, Edwin M.

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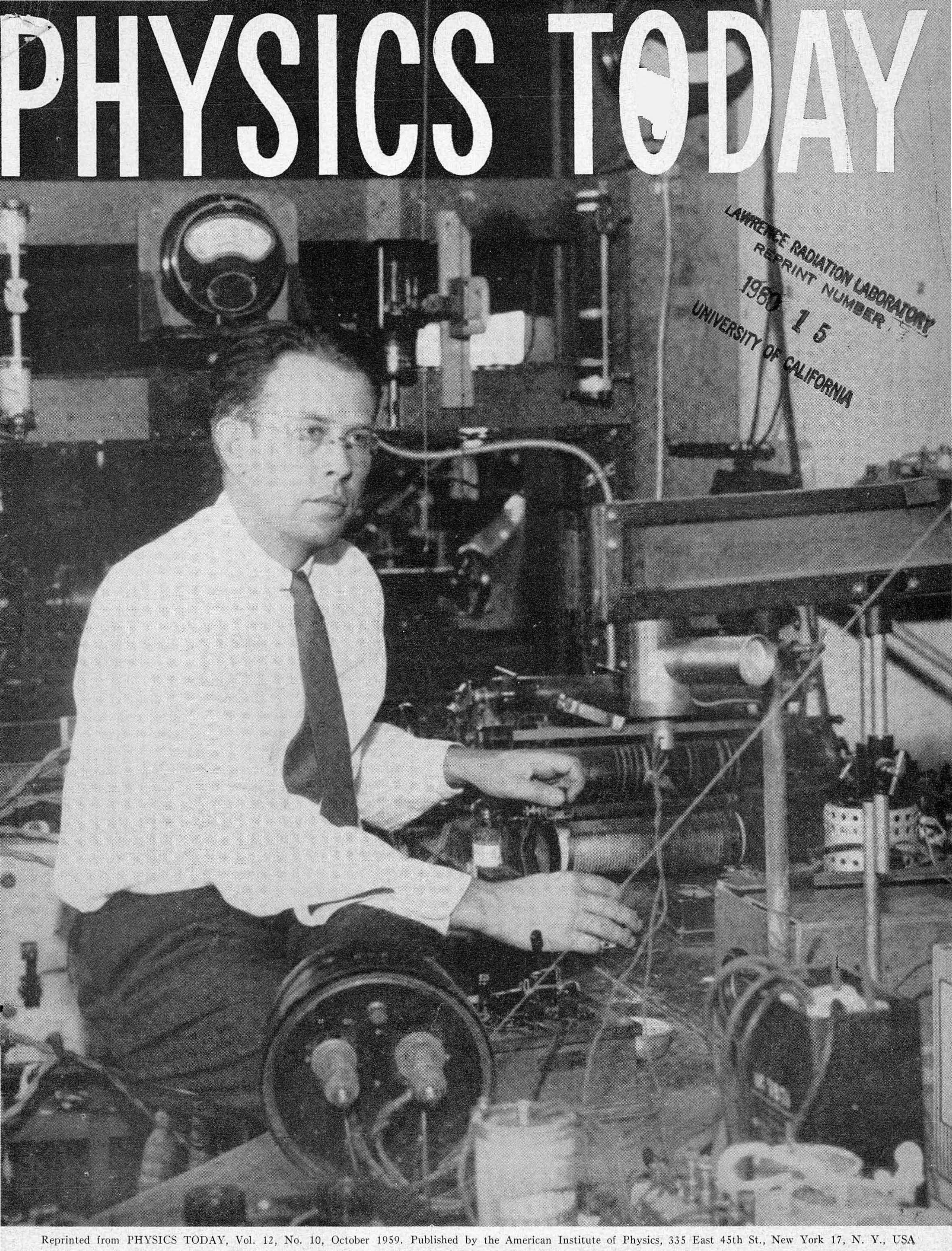

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This month's cover: A quarter-century-old photograph of E. O. Lawrence at the controls of the 27-inch cyclotron at the University of California Radiation Laboratory in Berkeley. The story of Lawrence and the evolution of the cyclotron is told in two articles beginning on pages 18 and 24 of this issue.

PART I

History of the CYCLOTRON

On May 1, 1959, in memory of the late Ernest Orlando Lawrence, two invited lectures on the history of the cyclotron were presented as part of the American Physical Society's annual spring meeting in Washington, D. C. The present article is based on Prof. Livingston's talk on that occasion. The second speaker was E. M. McMillan, whose illustrated account also appears in this issue beginning on p. 24.

By ***M. Stanley Livingston***

THE principle of the magnetic resonance accelerator, now known as the cyclotron, was proposed by Professor Ernest O. Lawrence of the University of California in 1930, in a short article in *Science* by Lawrence and N. E. Edlefsen.[1] It was suggested by the experiment of Wideröe [2] in 1928, in which ions of Na and K were accelerated to twice the applied voltage while traversing two tubular electrodes in line between which an oscillatory electric field was applied—an elementary linear accelerator. In 1953 Professor Lawrence described to the writer the origin of the idea, as he then remembered it.

The conception of the idea occurred in the library of the University of California in the early summer of 1929, when Lawrence was browsing through the current journals and read Wideröe's paper in the *Archiv für Elektrotechnik*. Lawrence speculated on possible variations of this resonance principle, including the use of a magnetic field to deflect particles in circular paths so they would return to the first electrode, and thus reuse the electric field in the gap. He discovered that the equations of motion predicted a constant period of revolution, so that particles could be accelerated indefinitely in resonance with an oscillatory electric field —the "cyclotron resonance" principle.

Lawrence seems to have discussed the idea with others during this early formative period. For example, Thomas H. Johnson has told the writer that Lawrence discussed it with himself and Jesse W. Beams during a conference at the Bartol Institute in Philadelphia during that summer, and that further details grew out of the discussion.

The first opportunity to test the idea came during the spring of 1930, when Lawrence asked Edlefsen, then a graduate student at Berkeley who had completed his thesis and was awaiting the June degree date, to set up an experimental system. Edlefsen used an existing small magnet in the laboratory and built a glass vacuum chamber with two hollow internal electrodes to which radiofrequency voltage could be applied, with an unshielded probe electrode at the periphery. The current to the probe varied with magnetic field, and a broad resonance peak was observed which was interpreted as due to the resonant acceleration of hydrogen ions.

However, Lawrence and Edlefsen had not in fact observed true cyclotron resonance; this came a little later. Nevertheless, this first paper was the initial announcement of a principle of acceleration which was soon found to be valid and which became the basis for all future cyclotron development.

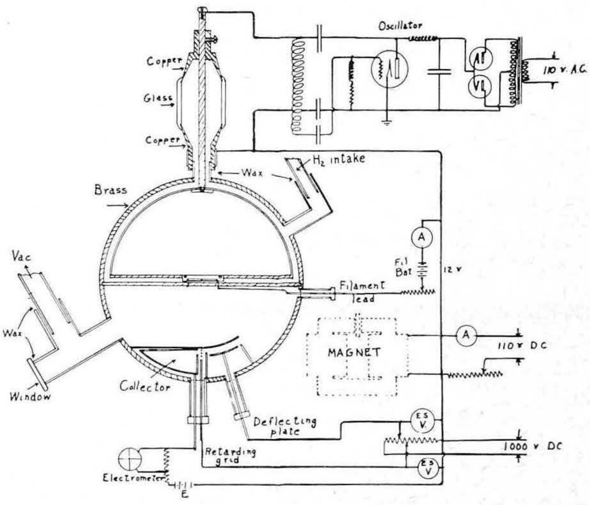

Fig. 1. Vacuum chamber of the first cyclotron. (PhD Thesis, M. S. Livingston, University of California, April 14, 1931)

M. Stanley Livingston, professor of physics at the Massachusetts Institute of Technology, is director of the Cambridge Electron Accelerator project at Harvard University, a program conducted under the joint auspices of Harvard and MIT.

Doctoral Thesis

IN the summer of 1930 Professor Lawrence suggested the problem of resonance acceleration to the author, then a graduate student at Berkeley, as an experimental research investigation. In my early efforts to confirm Edlefsen's results I found that the broad peak observed by him was probably due to single acceleration of N and O ions from the residual gas, which curved in the magnetic field and struck the unshielded electrode at the edge of the chamber.

It was my opportunity and responsibility to continue the study and to demonstrate true cyclotron resonance. A Doctoral Thesis [3] by the author dated April 14, 1931, reported the results of the study. It was not published but is on file at the University of California library. The electromagnet available was of 4-inch pole diameter. Fig. 1 is an illustration from this thesis, showing the arrangement of components which is still a basic feature of all cyclotrons. The vacuum chamber was made of brass and copper. Only one "D" was used, on this and several subsequent models; the need for a more efficient electrical circuit for the radiofrequency electrodes came later with the effort to increase energy. A vacuum tube oscillator provided up to 1000 volts on the electrode, at a frequency which could be varied by adjusting the number of turns in a resonant inductance. Hydrogen ions (H_2^+ and later H^+) were produced through ionization of hydrogen gas in the chamber, by electrons emitted from a tungsten-wire cathode at the center. Resonant ions which reached the edge of the chamber were observed in a shielded collector cup and had to traverse a deflecting electric field. Sharp peaks were observed in the collected current at the magnetic field for resonance with H_2^+ ions as shown in Fig. 2, a typical resonance curve taken from the thesis. Also present were 3/2 and 5/2 resonance peaks at proportionately lower magnetic fields, due to harmonic resonances of H_2^+ ions. By varying the frequency of the applied electric field, resonance was observed over a wide range of frequency and magnetic field, as shown in Fig. 3, proving conclusively the validity of the resonance principle.

The small magnet used in these resonance studies had a maximum field of 5200 gauss, for which resonance with H_2^+ ions occurred at 76 meters wavelength or 4.0 megacycles frequency. In this small chamber the final ion energy was 13 000 electron volts, obtained with the application of a minimum of 160 volts peak on the D. This corresponds to about 40 turns or 80 accelerations. A stronger magnet was borrowed for a short time, capable of producing 13 000 gauss, with which it was possible to extend the resonance curve and to produce hydrogen ions of 80 000 ev energy. This goal was reached on January 2, 1931.

The First 1-Mev Cyclotron

LAWRENCE moved promptly to exploit this breakthrough. In the spring of 1931 he applied for and was awarded a grant by the National Research Council (about $1000) for a machine which could give useful energies for nuclear research. The writer was appointed as an instructor at the University of California on completion of the doctorate in order to continue the research. During the summer and fall of 1931, the writer, under the supervision of Lawrence, designed and built a 9-inch diameter magnet and brought it into operation, first with H_2^+ ions of 0.5-Mev energy. Then the poles were enlarged to 11 inches and protons were accelerated to 1.2 Mev. This was the first time in scientific history that artificially accelerated ions of this energy had been produced. The beam intensity available at a target was about 0.01 microampere. The progress and results were reported in a series of three

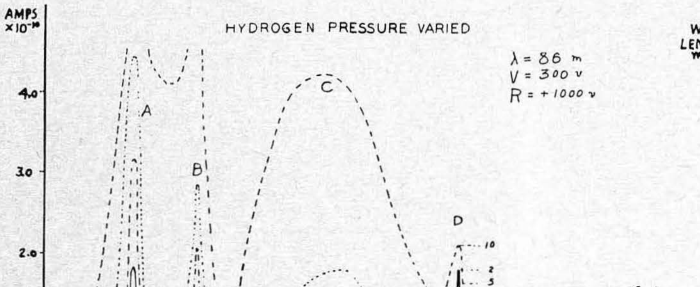

Fig. 2. Typical curves of current at the collector vs. magnetic field, showing resonant H_2^+ ions of 13 000 ev energy (peak D) and the variation of intensity with hydrogen gas pressure. (Thesis—Livingston)

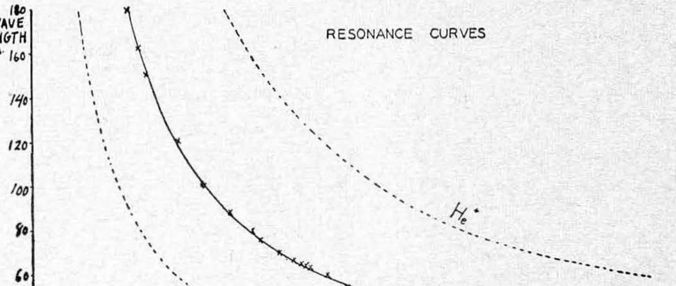

Fig. 3. Experimental values of cyclotron resonance for H_2^+ ions. (Thesis—Livingston)

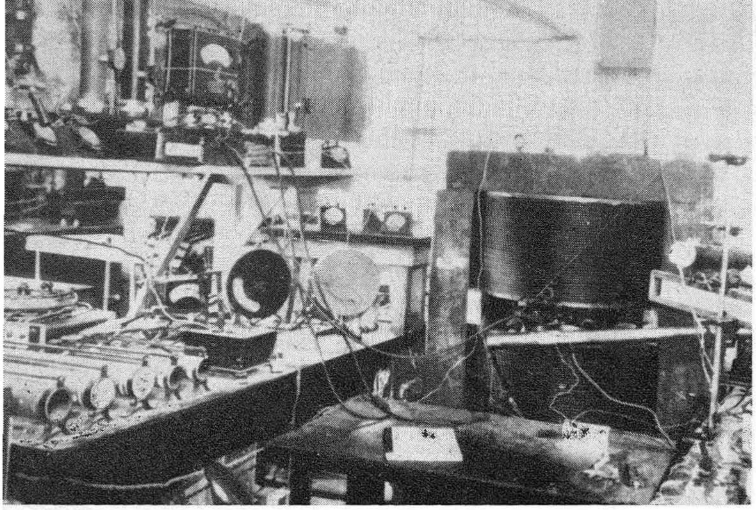

Fig. 4. 1.2 Mev H⁺ cyclotron at the University of California.[4]

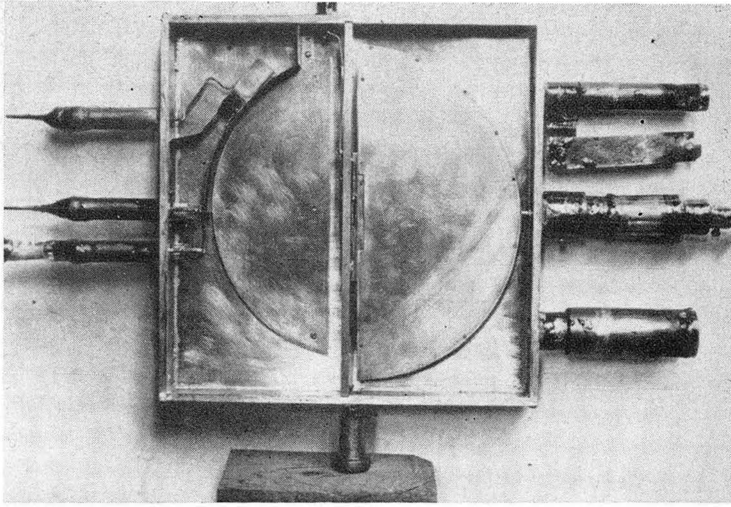

Fig. 5. Vacuum chamber for 1.2 Mev cyclotron with 11-inch pole faces.[4]

abstracts and papers by Lawrence and Livingston in *The Physical Review*.[4] Figs. 4 and 5 show the size and general arrangements of this first practical cyclotron.

Of course, Lawrence had other interests and other students in the laboratory. Milton White continued research with the first cyclotron. David Sloan developed a series of linear accelerators for heavy ions, limited by the radio power tubes and techniques available at that time, for Hg ions and later for Li ions. With Wesley Coates, Robert Thornton, and Bernard Kinsey, Sloan also invented and developed a resonance transformer using a radiofrequency coil in a vacuum chamber which developed 1 million volts. With Jack Livingood and Frank Exner he tried for a time to make this into an electron accelerator. I must again thank Dave Sloan for the many times that he assisted me in solving problems of the cyclotron oscillator.

The Race for High Voltage

TO understand the meaning of this achievement we must look at it from the perspective of the status of science throughout the world. When Rutherford demonstrated in 1919 that the nitrogen nucleus could be disintegrated by the naturally occurring alpha particles from radium and thorium, a new era was opened in physics. For the first time man was able to modify the structure of the atomic nucleus, but in submicroscopic quantities and only by borrowing the enormous energies (5 to 8 Mev) of radioactive matter. During the 1920's x-ray techniques were developed so machines could be built for 100 to 200 kilovolts. Development to still higher voltages was limited by corona discharge and insulation breakdown, and the multimillion volt range seemed out of reach.

Physicists recognized the potential value of artificial sources of accelerated particles. In a speech before the Royal Society in 1927 Rutherford expressed his hope that accelerators of sufficient energy to disintegrate nuclei could be built. Then in 1928 Gamow and also Condon and Gurney showed how the new wave mechanics, which was to be so successful in atomic science, could be used to describe the penetration of nuclear potential barriers by charged particles. Their theories made it seem probable that energies of 500 kilovolts or less would be sufficient to cause the disintegration of light nuclei. This more modest goal seemed feasible. Experimentation started around 1929 in several laboratories to develop the necessary accelerating devices.

This race for high voltage started on several fronts. Cockcroft and Walton in the Cavendish Laboratory of Cambridge University, urged on by Rutherford, chose to extend the known engineering techniques of the voltage-multiplier, which had already been successful in some x-ray installations. Van de Graaff chose the long-known phenomena of electrostatics and developed a new type of belt-charged static generator to obtain high voltages. Others explored the Tesla coil transformer with an oil-insulated high-voltage coil, or the "surge-generator" in which capacitors are charged in parallel and discharged in series, and still others used transformers stacked in cascade on insulated platforms.

The first to succeed were Cockcroft and Walton.[5] They reported the disintegration of lithium by protons of about 400 kilovolts energy, in 1932. I like to consider this as the first significant date in accelerator history and the practical start of experimental nuclear physics.

All the schemes and techniques described above have the same basic limitation in energy; the breakdown of dielectrics or gases sets a practical limit to the voltages which can be successfully used. This limit has been raised by improved technology, especially in the pressure-insulated electrostatic generator, but it still remains as a technological limit. The cyclotron avoids this voltage-breakdown limitation by the principle of resonance acceleration. It provides a method of obtaining high particle energies without the use of high voltage.

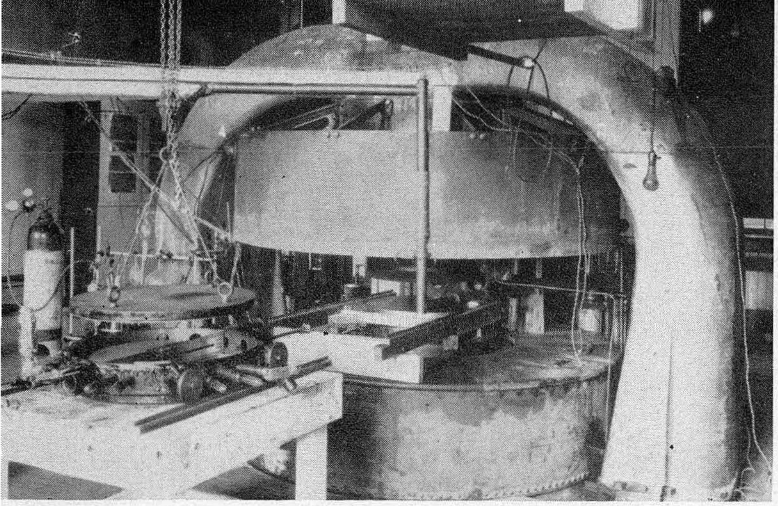

Fig. 6. The "27-inch" cyclotron which produced 5 Mev D^+ ions, with chamber rolled out.[7, 8]

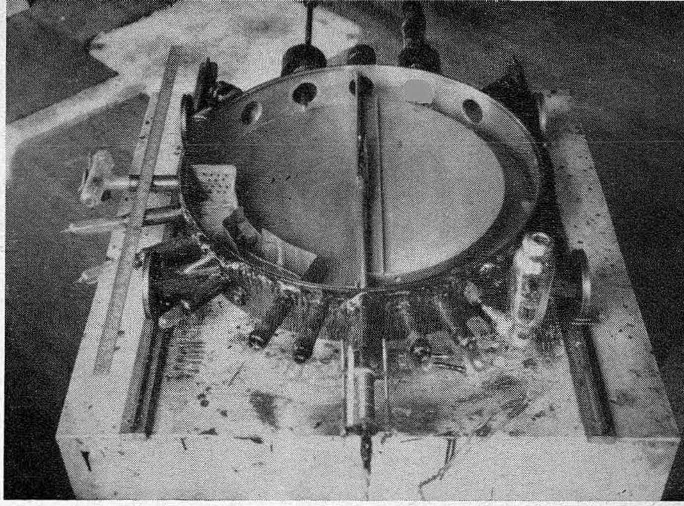

Fig. 7. Vacuum chamber for the "27-inch" cyclotron.[7, 8]

The Cyclotron Splits its First Atoms

THE above digression into the story of the state of the art shows why the 1.2-Mev protons from the 11-inch Berkeley cyclotron were so important. This small and relatively inexpensive machine could split atoms! This was Lawrence's goal. This was why Lawrence literally danced with glee when, watching over my shoulder as I tuned the magnet through resonance, the galvanometer spot swung across the scale indicating that 1 000 000-volt ions were reaching the collector. The story quickly spread around the laboratory and we were busy all that day demonstrating million-volt protons to eager viewers.

We had barely confirmed our results and I was busy with revisions to increase beam intensity when we received the issue of the *Proceedings of the Royal Society* describing the results of Cockcroft and Walton in disintegrating lithium with protons of only 400 000 electron volts. We were unprepared at that time to observe disintegrations with adequate instruments. Lawrence sent an emergency call to his friend and former colleague, Donald Cooksey at Yale, who came out to Berkeley for the summer with Franz Kurie; they helped develop the necessary counters and instruments for disintegration measurements. Within a few months after hearing the news from Cambridge we were ready to try for ourselves. Targets of various elements were mounted on removable stems which could be swung into the beam of ions. The counters clicked, and we were observing disintegrations! These first early results were published on October 1, 1932, as confirmation of the work of Cockcroft and Walton, by Lawrence, Livingston, and White.[6]

The "27-inch" Cyclotron

LONG before I had completed the 11-inch machine as a working accelerator, Lawrence was planning the next step. His aims were ambitious, but supporting funds were small and slow in arriving. He was forced to use many economies and substitutes to reach his goals. He located a magnet core from an obsolete Poulsen arc magnet with a 45-inch core, which was donated by the Federal Telegraph Company. Two pole cores were used and machined to form the symmetrical, flat pole faces for a cyclotron. In the initial arrangement the pole faces were tapered to a 27½-inch diameter pole face; in later years this was expanded to 34 inches and still higher energies were obtained. The windings were layer-wound of strip copper and immersed in oil tanks for cooling. (The oil tanks leaked! We all wore paper hats when working between coils to keep oil out of our hair.) The magnet was installed in the "old radiation lab" in December 1931; this was an old frame warehouse building near the University of California Physics Building which was for years the center of cyclotron and other accelerator activities. Fig. 6 is a photograph of this magnet with the vacuum chamber rolled out for modifications.

Other dodges were necessary to meet the mounting bills for materials and parts. The Physics Department shops were kept filled with orders for machining. Willing graduate students worked with the mechanics installing the components. My appointment as instructor terminated, and for the following year Lawrence arranged for me an appointment as research assistant in which I not only continued development on the cyclotron but also supervised the design and installation of a 1-Mev resonance transformer x-ray installation of the Sloan design in the University Hospital in San Francisco.

The vacuum chamber for the 27-inch machine was a brass ring with many radial spouts, fitted with "lids" of iron plate on top and bottom which were extensions of the pole faces. This chamber is shown in Fig. 7. Sealing wax and a special soft mixture of beeswax and rosin were first used for vacuum seals, but were ultimately replaced by gasket seals. In the initial model only one insulated D-shaped electrode was used, facing a slotted bar at ground potential which was called a "dummy D". In the space behind the bar the collector could be mounted at any chosen radius. The beam was first observed at a small radius, and the magnet was "shimmed" and other adjustments made to give maximum beam intensity. Then the chamber was opened, the collector moved to a larger radius, and the tuning and shimming extended. Thus we learned, the hard way, of the necessity of a radially decreasing magnetic field for focusing. If our optimism persuaded us to install the collector at too large a radius, we made a "strategic retreat" to a smaller radius and recovered the beam. Eventually we reached a practical maximum radius of 10 inches and installed two symmetrical D's with which higher energies could be attained. Technical improvements and new gadgets were added day by day as we gained experience. The progress during this period of development from 1-Mev protons to 5-Mev deuterons was reported in *The Physical Review* by Livingston [7] in 1932 and by Lawrence and Livingston [8] in 1934.

I am indebted to Edwin M. McMillan for a brief chronological account of these early developments on the 27-inch cyclotron. (It seems that earlier laboratory notebooks were lost.) These records show, for example:

June 13, 1932. 16-cm radius, 28-meter wavelength, beam of 1.24-Mev H_2^+ ions.

August 20, 1932. 18-cm radius, 29 meters, 1.58-Mev H_2^+ ions.

August 24, 1932. Sylphon bellows put on filament for adjustment.

September 28, 1932. 25.4-cm radius, 25.8 meters, 2.6-Mev H_2^+ ions.

October 20, 1932. Installed two D's in tank, radius fixed at 10 in.

November 16, 1932. 4.8-Mev H_2^+ ions, ion current 10^{-9} amps.

December 2–5, 1932. Installed target chamber for studies of disintegrations with Geiger counter. Start of long series of experiments.

March 20, 1933. 5 Mev of H_2^+; 1.5 Mev of He^+; 2 Mev of $(HD)^+$. Deuterium ions acelerated for first time.

September 27, 1933. Observed neutrons from targets bombarded by D^+.

December 3, 1933. Automatic magnet current control circuit installed.

February 24, 1934. Observed induced radioactivity in C by deuteron bombardment. 3-Mev D^+ ions, beam current 0.1 microampere.

March 16, 1934. 1.6-Mev H^+ ions, beam current 0.8 microampere.

April–May, 1934. 5.0-Mev D^+ ions, beam current 0.3 microampere.

Those were busy and exciting times. Other young scientists joined the group, some to assist in the continuing development of the cyclotron and others to develop the instruments for research instrumentation. Malcolm Henderson came in 1933 and developed counting instruments and magnet control circuits, and also spent long hours repairing leaks and helping with the development of the cyclotron. Franz Kurie joined the team, and Jack Livingood and Dave Sloan continued with their linear accelerators and resonance transformers, but were always available to help with problems on the cyclotron. Edwin McMillan was a major thinker in the planning and design of research experiments. And we all had a fond regard for Commander Telesio Lucci, retired from the Italian Navy, who became our self-appointed laboratory assistant. As the experiments began to show results we depended heavily on Robert Oppenheimer for discussions and theoretical interpretation.

One of the exciting periods was our first use of deuterons in the cyclotron. Professor G. N. Lewis of the Chemistry Department had succeeded in concentrating "heavy water" with about 20% deuterium from battery acid residues, and we electrolyzed it to obtain gas for our ion source. Soon after we tuned in the first beam we observed alpha particles from a Li target with longer range and higher energy than any previously found in natural radioactivities—14.5-cm range, coming from the Li^6 (d,p) reaction. These results were reported in 1933 by Lewis, Livingston, and Lawrence,[9] and led to an extensive program of research in deuteron reactions. Neutrons were also observed, in much higher intensities when deuterons were used as bombarding particles, and were put to use in a variety of ways.

We had frustrations—repairing vacuum leaks in the wax seals of the chamber or "tank" was a continuing problem. The ion source filament was another weak point, and required continuous development. And sometimes Lawrence could be *very* enthusiastic. I recall working till midnight one night to replace a filament and to reseal the tank. The next morning I cautiously warmed up and tuned the cyclotron to a new beam intensity record. Lawrence was so pleased and excited when he came into the laboratory that morning that he jubilantly ran the filament current higher and higher, exclaiming each time at the new high beam intensity, until he pushed too high and burned out the filament!

We made mistakes too, due to inexperience in research and the general feeling of urgency in the laboratory. The neutron had been identified by Chadwick in 1932. By 1933 we were producing and observing neutrons from every target bombarded by deuterons.[10] They showed a striking similarity in energy, independent of the target, and each target also gave a proton group of constant energy. This led to the now forgotten mistake in which the neutron mass was calculated on the assumption that the deuteron was breaking up into a proton and a neutron in the nuclear field. The neutron mass was computed from the energy of the common proton group,[11] and was much lower than the value determined by Chadwick. Shortly afterward, Tuve, Hafstad, and Dahl in Washington, D. C., using the first electrostatic generator to be completed and used for research, showed that these protons and neutrons came from the $D(d,p)$ and $D(d,n)$ reactions,

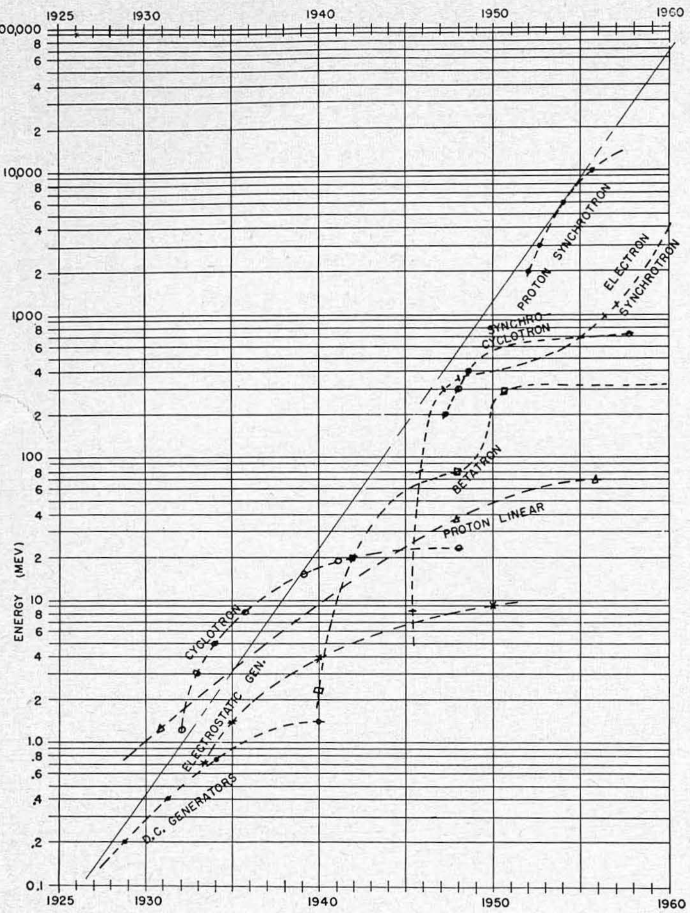

Fig. 8. Energies attained with accelerators as a function of time.

in which the target was deuterium gas deposited in all targets by the beam. We were chagrined, and vowed to be more careful in the future.

We also had many successful and exciting moments. I recall the day early in 1934 (February 24) when Lawrence came racing into the lab waving a copy of the *Comptes Rendus* and excitedly told us of the discovery of induced radioactivity by Curie and Joliot in Paris, using natural alpha particles on boron and other light elements. They predicted that the same activities could be produced by deuterons on other targets, such as carbon. Now it just so happened that we had a wheel of targets inside the cyclotron which could be turned into the beam by a greased joint, and a thin mica window on a re-entrant seal through which we had been observing the long-range alpha particles from deuteron bombardment. We also had a Geiger point counter and counting circuits at hand. We had been making 1-minute runs on alpha particles, with the counter switch connected to one terminal of a double-pole knife-switch used to turn the oscillator on and off. We quickly disconnected this counter switch, turned the target wheel to carbon, adjusted the counter circuits, and then bombarded the target for 5 minutes. When the oscillator switch was opened this time, the counter was turned on, and click-click--click---click----click. We were observing induced radioactivity within less than a half-hour after hearing of the Curie-Joliot results. This result was first reported by Henderson, Livingston, and Lawrence[12] in March, 1934.

I left the laboratory in July, 1934, to go to Cornell (and later to MIT) as the first missionary from the Lawrence cyclotron group. Edwin McMillan overlapped my term of apprenticeship by a few months, and stayed on to win the Nobel Prize and ultimately to succeed Professor Lawrence as director of the laboratory which he founded. McMillan can tell the rest of the story.

But it would be unfair to the spirit of Professor Lawrence if I failed to indicate some gleam of great things to come, some vision of the future. Recently I prepared a graph of the growth of particle energies obtained with accelerators with time, shown in Fig. 8. To keep this rapidly rising curve on the plot, the energies are plotted on a logarithmic scale. The curves show the growth of accelerator energy for each type of accelerator plotted at the dates when new voltage records were achieved. The cyclotron was the first resonance accelerator to be successful, and it led to the much more sophisticated synchronous accelerators which are still in the process of growth. The over-all envelope to the curve of log E vs time is almost linear, which means an exponential rise in energy, with a 10-fold increase occurring every 6 years and with a total increase in particle energy of over 10 000 since the days of the first practical accelerators. The end is not yet in sight. If you are tempted to extrapolate this curve to 1960, or even to 1970, then you are truly sensing the exponentially rising spirit of the Berkeley Radiation Laboratory in those early days, stimulated by our unique leader, Professor Lawrence.

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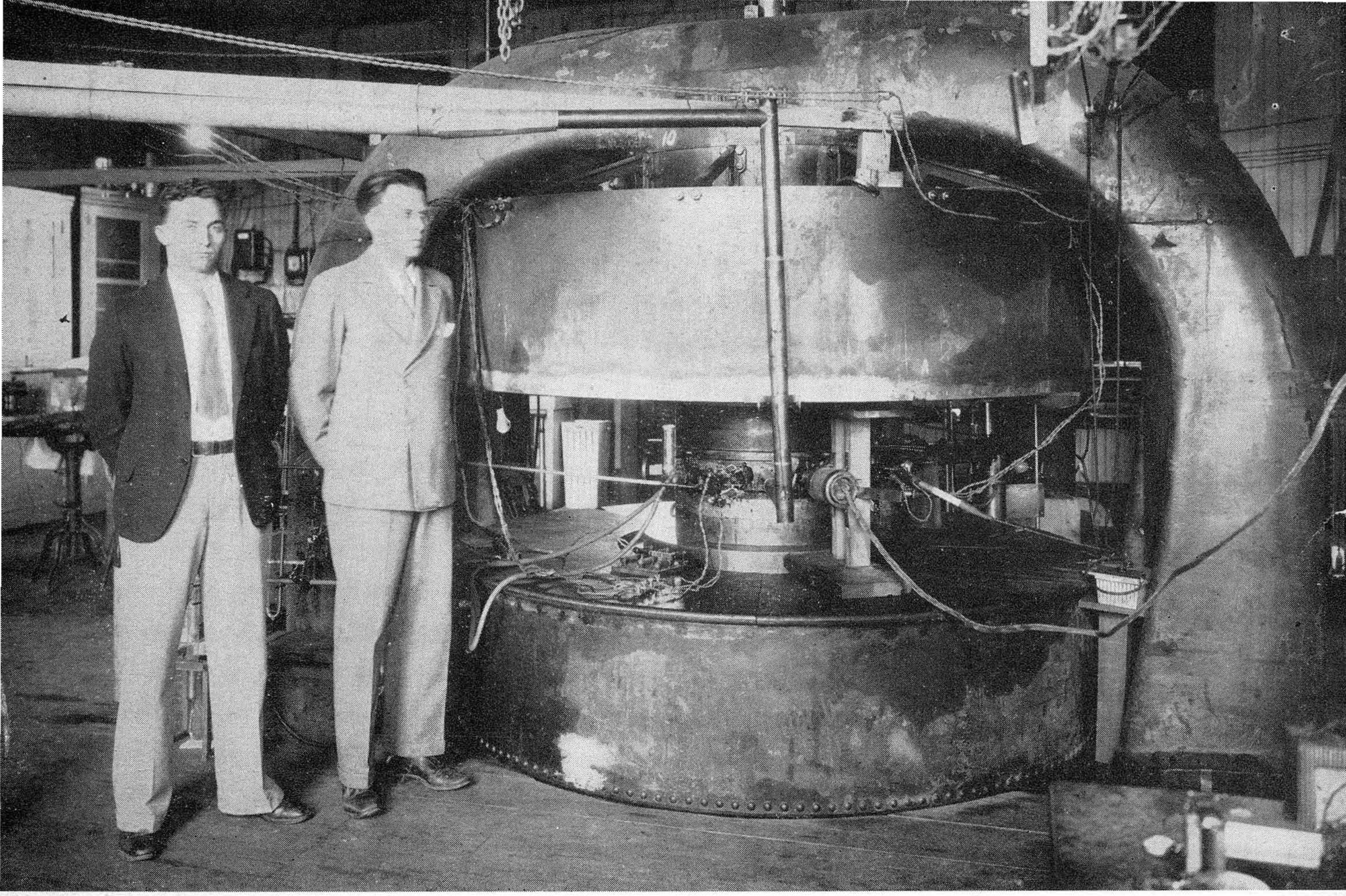

PART II

(UCRL 8837)

History of the CYCLOTRON

By Edwin M. McMillan

As Dr. Livingston has told you, our activities overlapped by a few months, so that between us we can give a continuous story of cyclotron development as carried out at Berkeley under the guidance of Professor Lawrence. My start in his laboratory was in April of 1934, but I was around Berkeley before that working in Le Conte Hall on a molecular beam problem. Therefore, I have two kinds of early memories of the Radiation Laboratory at that time. One is as a place that I visited occasionally before I was working there; the other is as a place where I came to work, which I remember better, although it still seems like a very long time ago. The whole way of working was rather different from what it is in most laboratories today. We did practically everything ourselves. We had no professional engineers, so we had to design our own apparatus; we made sketches for the shop, and did much of our own machine work; we took all of our own data, did all our own calculations, and wrote all our own papers. Things are now quite different from that, because everybody does just his share and the operations have become much larger and more professional. While the modern method produces more results, perhaps this older way may have been more fun.

What I have done in preparing a paper to give here is to let it be based mainly on a set of lantern slides, because I think pictures are more interesting than words. I would like to run through these pictures and try to recall what they illustrate and the various incidents, some amusing, some otherwise, that go along with them.

I'm going to start with another picture of the 27″ cyclotron. This shows the machine as it looked in 1934

Nobel Laureate Edwin M. McMillan is director of the Lawrence Radiation Laboratory at the University of California at Berkeley, having succeeded to that post following the death of the Laboratory's original director, E. O. Lawrence, in 1958. The article is based on the second of two talks presented before the American Physical Society last May in memory of Prof. Lawrence.

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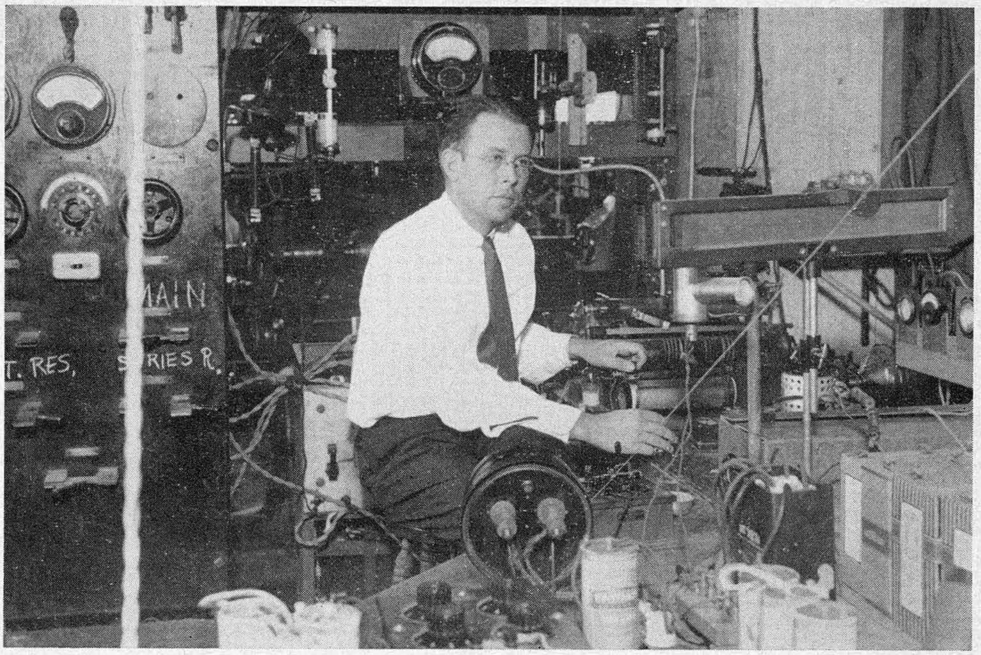
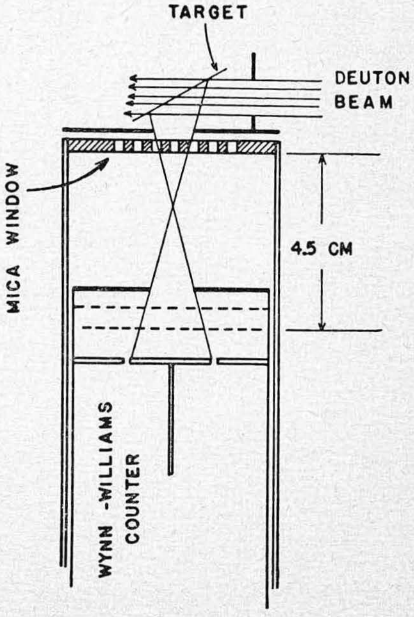


Slide 2

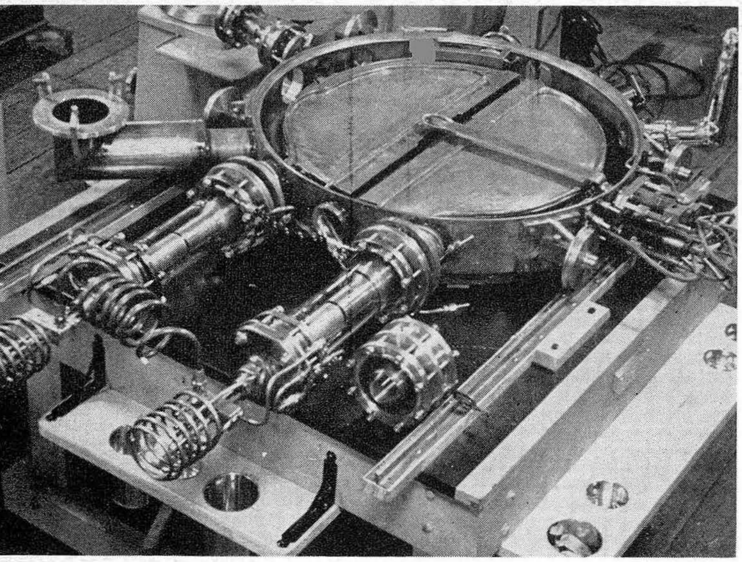
when Stan and I were both there. (Slide 1.) Dr. Livingston is in the picture, and Professor Lawrence. The machine is the same as in the views shown by Stan, but here it is all assembled with the 27″ chamber in place. I have another view here of Professor Lawrence sitting at the control table, showing how one operated the machine. (Slide 2.) This was the major tool of nuclear research of that day and this was the control station. The switchboard in back had to do with magnet control, and the beam current was observed on the galvanometer scale.

As an illustration of the kind of experimental equipment one used, I have this drawing which was taken from a publication of about that period, early in 1935. (Slide 3.) This was an experiment to disintegrate aluminum with deuterons. You'll notice that in those days they were called deutons. The story was told that Ernest Rutherford objected to the name deuton; he didn't like the sound of it, but agreed that it would be all right if we put in his initials, E.R. (I don't think this story is really true, but at least the fact that it was told is true.) Well, these deutons came along inside the cyclotron vacuum chamber. This box is a cylinder soldered into the side of the brass wall of the cyclotron chamber. The beam that's inside passes through a thin target of aluminum foil. The secondary particles studied in this case were protons, making this an example of a *(d,p)* reaction. We didn't have that notation then, but that is what it would be called now. The secondary protons came out through a mica window, real old-fashioned mica, and into an ionization chamber counter and were counted. We measured the energy of these protons by simply sliding this counter back and forth inside of the tube, varying the range. We were measuring the range in air and plotting range curves in the way that one did in those days. This was considered a piece of research in physics; this was published, but nowadays, of course, nobody would think of doing a thing quite that way.

Now, let us go on to the development of the cyclotron itself. The two principal parameters of the cyclotron, as far as its use is concerned, are the energy of the particles and the intensity. With that older vacuum tank that we saw, the one that was in place



Slide 3: Arrangement of target, screens, and counter for bombarding in vacuum.



Slide 4

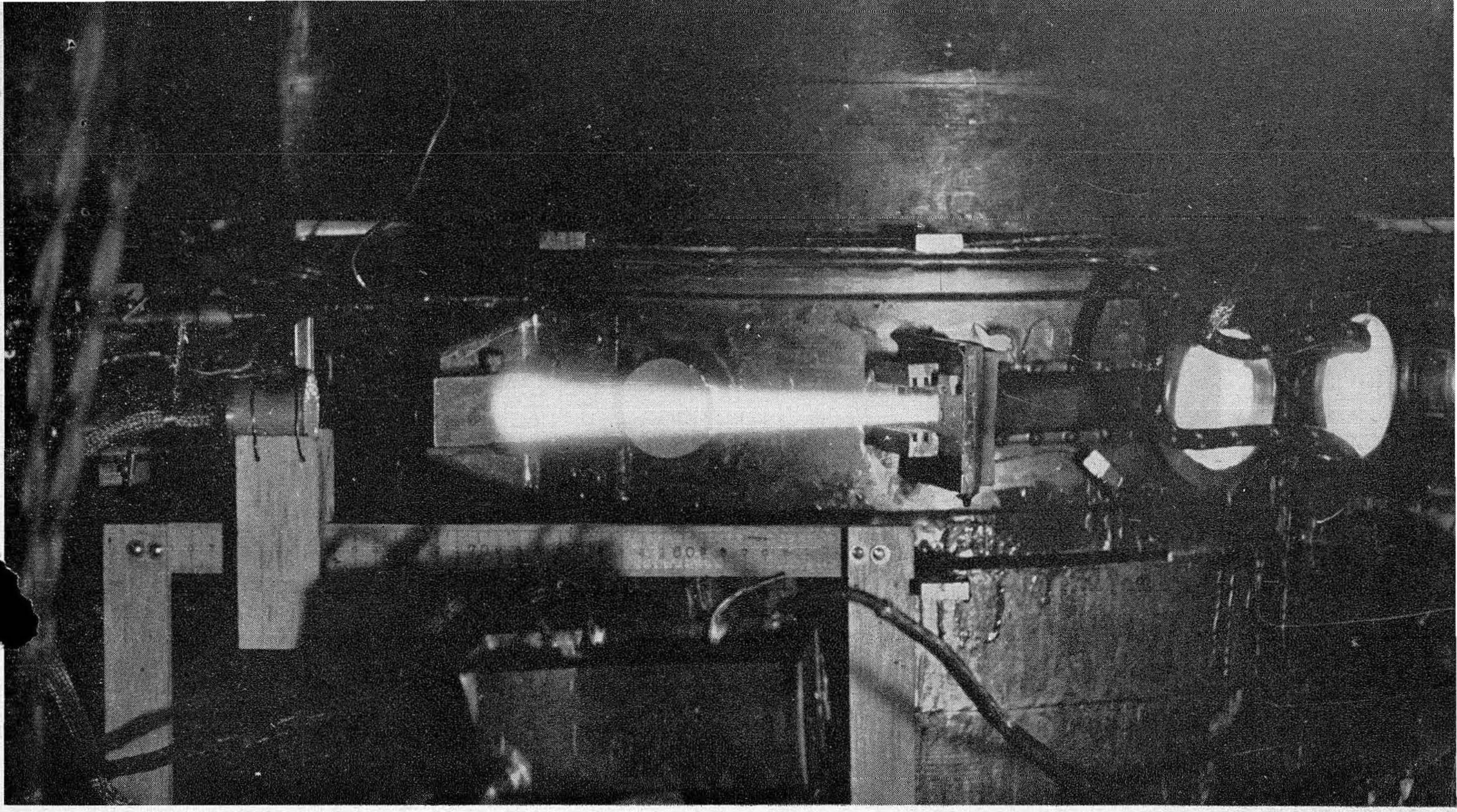
in Slide 1, the energy was up to about 3 Mev (this is the energy for deuterons). In 1936 a new chamber was built which is shown in the next slide. (Slide 4.) Comparing it with the chamber that Livingston showed, you'll see that there are many changes. For instance, the insulators for the two dees are made of Pyrex, with flanged ends which are clamped and bolted together rather than being waxed together, as the older ones were. The whole structure is more rugged, but there are still old-fashioned touches. You'll notice, coming into the center, a filament-type ion source that was still used then. Over in one corner you can see a glass liquid air trap, which was a very fragile and troublesome thing. People were always bumping into it and, of course, when it was bumped into, we'd have to pull the tank out, clean out the broken glass, and put the tank together all over again. With this new tank in place giving higher energies, up to 6 Mev for deuterons, and also larger currents, new types of experiments could be tried.

It was at about this time that an interest in biological work started in the laboratory, which has continued to the present. This was really started by John Lawrence, Ernest Lawrence's brother, who came out to the laboratory in 1935 to see what we were doing, and to see if there were any interest in the medical side. At this time biological experiments were started. I can recall the first time that a mouse was irradiated with neutrons. We put the mouse in a little cage and stuck him up on the side of the cyclotron tank and left him there for a while. Of course, nothing happened because there was not enough intensity. Then a serious attempt was made to see what neutrons did to mice. The first time this was done, it was done with an arrangement designed by Paul Aebersold in which the mouse could be put into the re-entrant tube shown in Slide 3, which was built into the cyclotron tank wall. In this way he could be close enough to the target to get some intensity. This mouse came out dead. This created a great impression at the time and I think perhaps was one reason why, in the Lawrence Radiation Laboratory, people have always been careful with radiation even though it was soon discovered that somebody had forgotten to turn on the air supply which was supposed to provide ventilation for this mouse so that he died of anoxia. Anyhow, it was a very dramatic thing at the time.

Also at about this same time the first radioactive tracer experiments on human beings were tried. The first one that I recall, and I think the first use anywhere of an artificially produced radioisotope in human beings, was an early experiment of Joseph Hamilton in which he measured the circulation time of the blood by a very primitive method. The experimental subject takes some radioactive sodium dissolved in water in the form of sodium chloride, drinks it, and then has a Geiger counter which he holds in his hand, so that when the radioactive sodium reaches the hand, it starts to register. His hand is in a lead box so that the stuff that's just in his body doesn't affect the counter by gamma rays. I brought along a picture of this setup. (Slide 5.) This drawing, I believe, was made by Dr. Hamilton's wife, who is an artist. It shows the hand in the box, you see this cutaway lead box, holding a Geiger counter; the beaker with the radio sodium isn't shown but you might have shown him in the act of drinking it. After he does this, within just a few seconds, you begin to get some registration. After a few minutes, you begin to get equilibrium, and from these observations you get the circulation time of the blood. This, of course, is a very simple beginning, just like the simple beginning in physics that I showed with the primitive experiment of a (d,p) reaction. There were also simple beginnings of therapeutic use, coming a little bit later, in which neutron radiation was used, for instance, in the treatment of cancer. These things have gone on and built up so that there's now a whole field of radio medicine which had its beginning back in that time.

Another highlight from 1936 was the first time that anyone tried to make artificially a naturally occurring radionuclide (of course, we didn't have the word nuclide

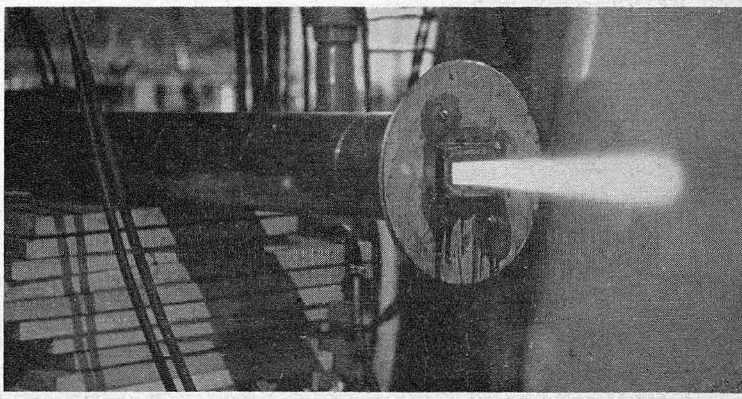
Slide 5



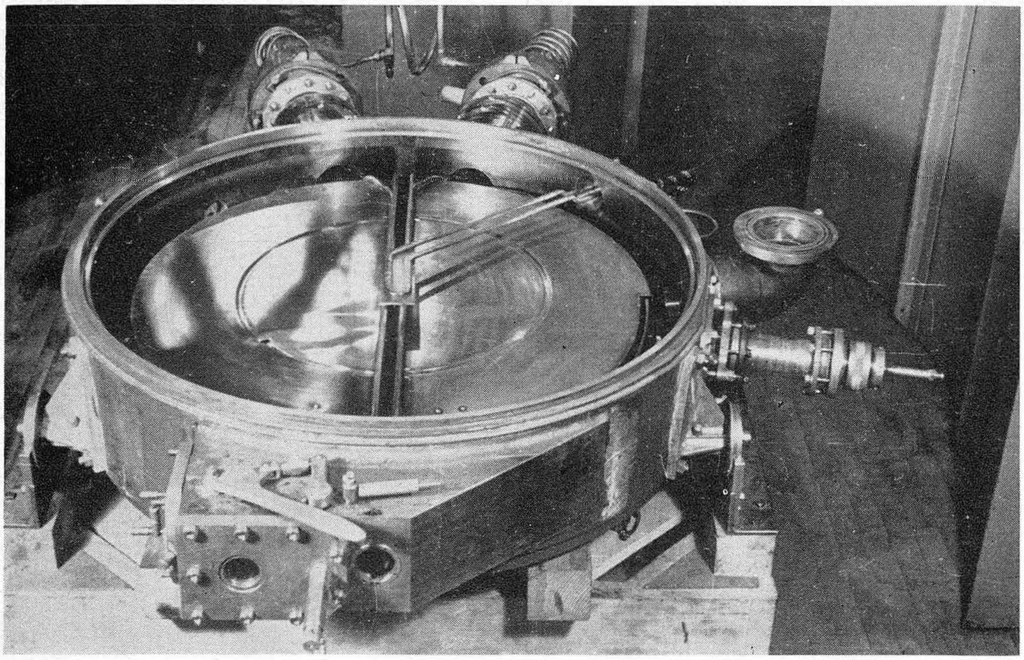
Slide 6

then, but that is what it would now be called). This, I think, was a fairly classical experiment because there were then some people who didn't quite believe that the artificial radioactive materials were on the same status as the naturally occurring ones. Jack Livingood put some bismuth in the deuteron beam of the cyclotron, with an energy of about 6 Mev. This is high enough that one does get an appreciable yield of the (d,p) reaction forming radium E, a bismuth isotope, which then decays into polonium. The periods and energies were identical to those of natural radium E and polonium, so everybody was happy. This was the first time that one had gotten up that far in the periodic table with a charged-particle disintegration experiment.

Another thing that we were trying to do then was to bring the beam out of the tank. It seemed that there might some day be a use for a beam extractor. And so these experiments, which were spoken of as snouting experiments—getting the beam out of a snout—were done. Of course, in that re-entrant tube I showed you in Slide 3 you could get the beam in air by putting a little window on one side and letting the beam travel about two inches across the diameter of that brass tube. It was in air but it wasn't really outside the tank, because it plunged back into the wall of the tube. To get the beam the rest of the way out, we had to increase the strength of the deflecting field and move the deflector plate out some, so as to get enough radial displacement that the beam would come out to the edge of the magnetic field. The next slide I'm going to show is the first time that a beam was brought outside the tank in this sense. I remember this occasion very well because when we first tried, the beam didn't quite clear the edge of the tank; it was coming almost tangentially and the thickness of the tank wall stopped it, so I spent about half a day with a file, curled up alongside the cyclotron, filing a groove in the thickness of the tank wall so that the beam could come out. This beam is shown in the next picture. (Slide 6.) There's a copper fitting, which is truly a snout, since it is a nose-shaped affair, which is fastened to the side of the tank, and the beam comes out through it, with the meter stick indicating the range. A little later, about two months after this, the beam was carried farther around—about a quarter of the way around the magnet. (Slide 7.) This shows where it came out of the window, way outside the cyclotron field. This, one might say, is the ancestor of modern beam extraction which has become a very sophisticated art in comparison to what it was in those days.



Slide 7



Slide 8

Everything up to now has been about the so-called 27-inch cyclotron. By the way, one thing I should apologize for at some point is my concentration on work at Berkeley. This is supposed to be the history of the cyclotron. But, in the first place, for some time this was the only place where there was a cyclotron, so that's where cyclotron history was being made. Secondly, this talk is in honor of Professor Lawrence, and that's where he was doing his work. Nevertheless, when we get to about 1936 or 1937, there did begin to be feedback of cyclotron lore from other parts of the world. At the end of 1936 there were about twenty other cyclotrons in the world; so the art had spread and things were coming back—improved ion sources, improved arrangements of radiofrequency systems, magnet control circuits, and all kinds of things. And from then on, of course, development of the cyclotron really became an international matter. Nevertheless, I shall continue to show pictures taken at Berkeley.

This is the 37-inch cyclotron, which used the same magnet as the 27-inch. (Slide 8.) All one had to do was to take out the old pole pieces, which had a reduced diameter, and put in larger diameter poles and the new tank shown on this slide. This was in late 1937 and begins to show signs of professionalism. You'll notice a gasket groove around the top, you'll notice nicely machined surfaces and things welded together, bolted together, and gasketed together, showing improved standards of design and construction. Still, you see a few old-fashioned touches; I think that the tank coil on the top side looks a bit primitive. We were still using a simple resonant circuit and two dees, plus an inductance forming the resonant circuit, which was loosely coupled to an oscillator. With this larger diameter and better designed tank, the deuteron energy was now up to 8 Mev. The energy was climbing; currents were getting up to 100 microamperes which were tremendous currents at that time. Experiments were beginning to get sophisticated. It was in 1938 that Dr. Alvarez first introduced the method of time of flight for neutrons. By keying the cyclotron beam and then having a gated detector, one could use the time of flight to measure the velocity and to select out given energy ranges. That was the birth of that method.

Also in this period the first artificial element, technetium, was discovered by Segrè and Perrier, using a piece of the cyclotron. As you know, where the beam emerges from the dee there is a deflecting plate, and just next to the deflecting plate the boundary of the dee is made of a thin sheet of metal which has to decide whether a given turn of the beam is inside the dee or outside. Because the front edge of this metal sheet gets a lot of bombardment it is always made of a refractory metal. In this case it was made of molybdenum, and when the old tank was dismantled and thrown away and the new tank went in (the one I just showed you), Segrè said he wanted the old molybdenum strip, so we gave it to him. He was then in Italy and, with the help of Perrier, was able to get a definite proof that it contained the new element technetium made by deuteron bombardment of the molybdenum. If it hadn't been for the fact that this particular spot —this particular item—in the anatomy of the cyclotron gets a lot of bombardment, this new discovery would have been considerably delayed.

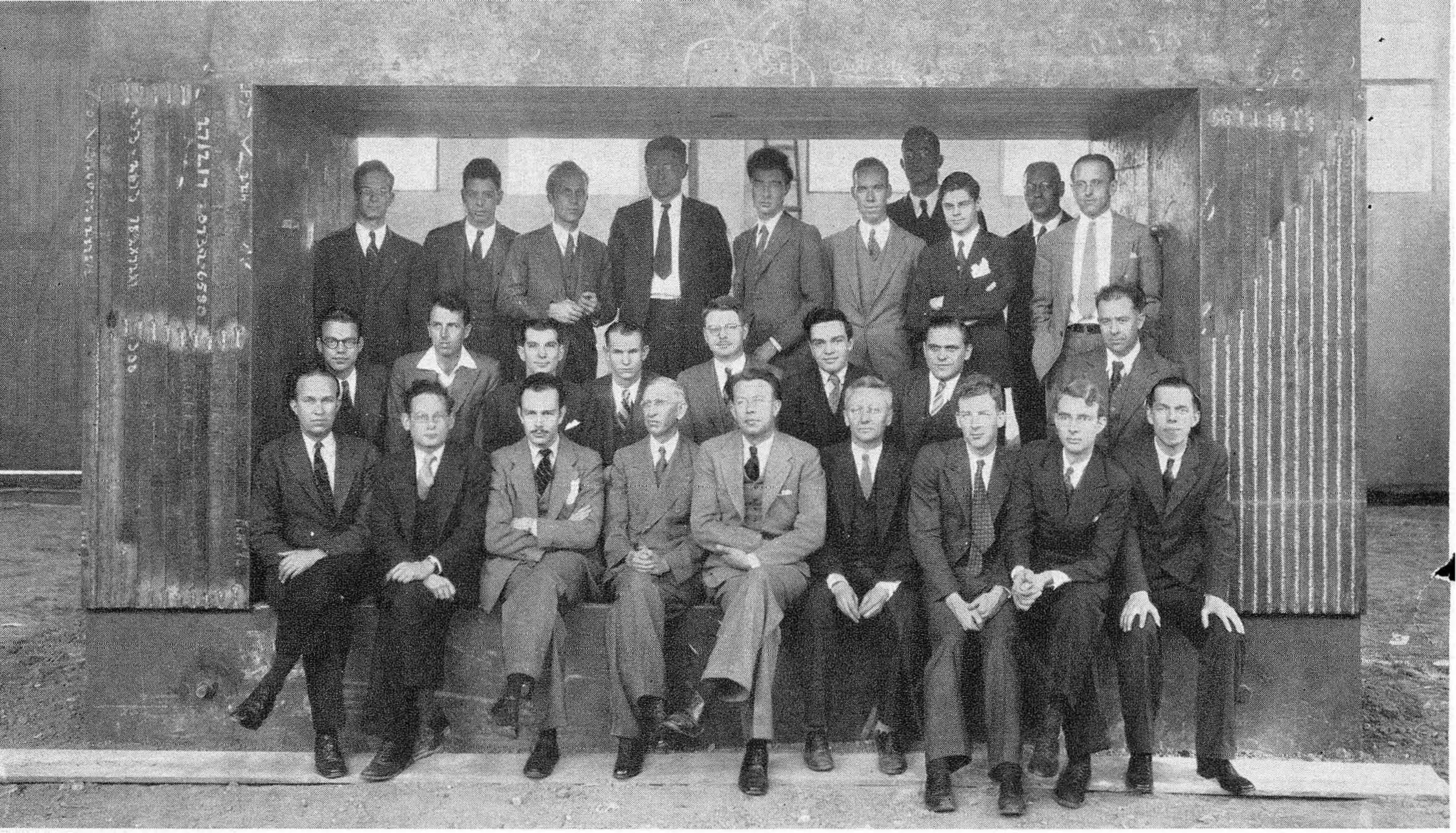
Another thing that started in this period is that the theorists were getting interested in the cyclotron. Before, you see, it was an experimental art, and the people that worked on the cyclotron sort of knew what they were doing, but they weren't very sophisticated about it. They didn't stop to think much about how and why it worked; they knew that it worked and that was enough. But it was at this time that Bethe and Rose first pointed out the relativistic limit on cyclotron energies and, a little after that, that L. H. Thomas devised an answer to the relativistic limit. This answer turned out to be a little hard for the experimenters to understand, so it lay fallow for many years. Now, of course, everybody wants to build Thomas-type cyclotrons or FFAG machines (which are, in a sense, extreme examples of Thomas cyclotrons), so it is now a great thing; but it lay dormant for quite a while because nobody took it very seriously at first. Also, at that time in 1937, cyclotron energies were limited by other factors such as sizes, budgets, and things like that, and not by the relativistic effect, which was thought of before it became a practical limit.

Shortly after, in my history, comes the 60-inch cyclotron, which was the first really professionally designed cyclotron that was built in Berkeley. There were some elsewhere in the world, but this was the first in Berkeley. Before I get to that, as a sort of transition, I want to show a picture, taken around 1938, that illustrates several things. (Slide 9.) Now, let's see, what does this illustrate? First, it illustrates that people had started worrying about shielding against radiation around the cyclotron. Those were 5-gallon cans that were filled with water and simply stacked around and above the cyclotron to give shielding. As a matter of fact, the cans in this picture were originally on top of the cyclotron. They developed leaks, and the people that worked underneath would get tired of having water drip on them, and then they would take the leaky ones down and kick big dents in them so that nobody would be tempted to put them back.

The second thing that this slide illustrates is the type of building this work was done in, the Old Radiation Laboratory. I might inject a slightly sad touch, in that as I left Berkeley to come to this meeting, the last boards of the Old Radiation Laboratory were being battered down by a great big clam shell. We managed to save a few pieces as historical relics; otherwise it is all gone now. The third thing illustrated is that the man pictured here is Bill Brobeck, who was our first professional engineer hired at the Laboratory, showing the coming in of the more professional approach to the design and building of accelerators.

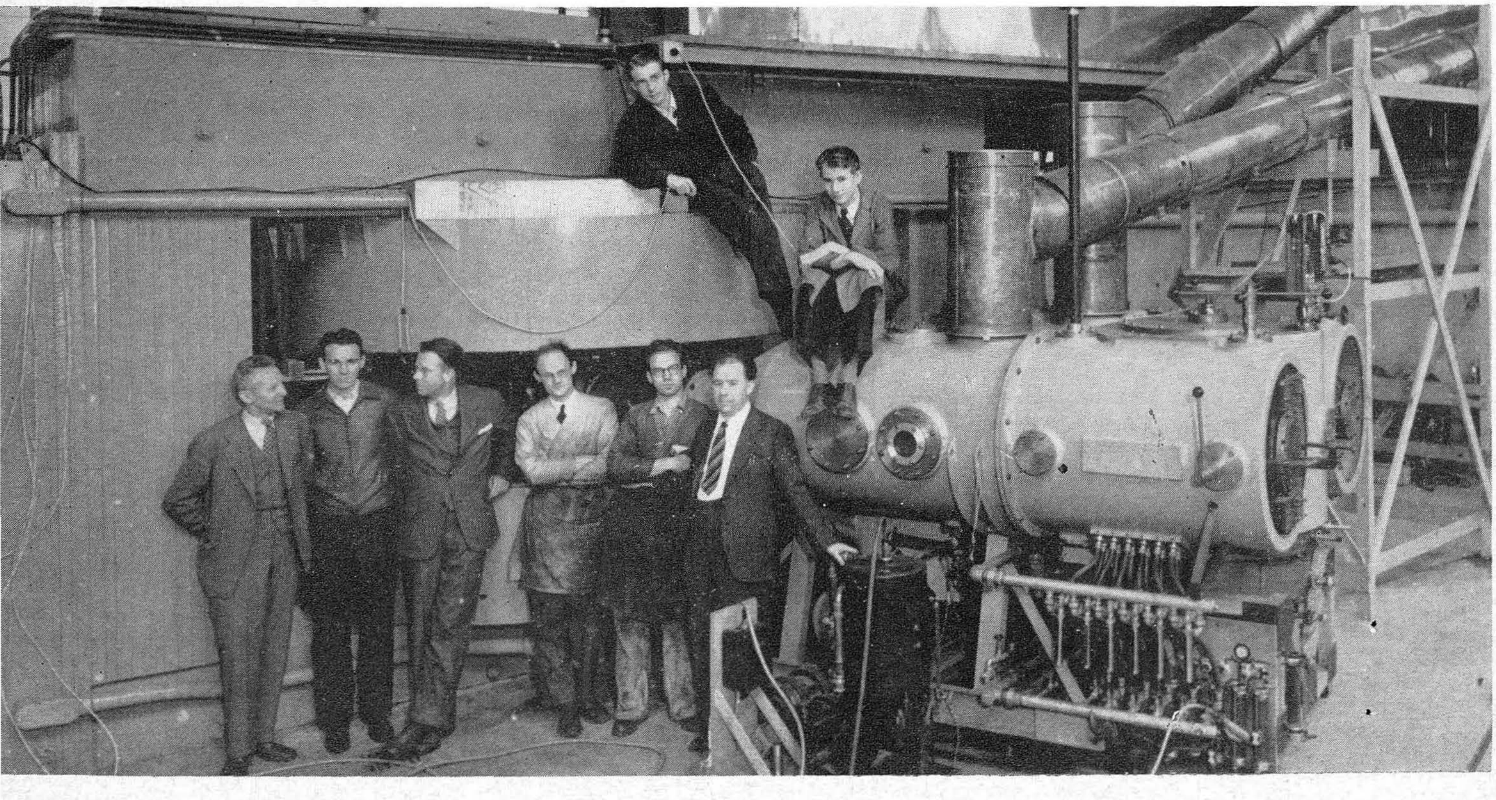
Now I will say a little about the 60-inch cyclotron, starting with a picture that was taken in 1938, showing

Slide 9



Slide 10 (Left to right and top to bottom): A. S. Langsdorf, S. J. Simmons, J. G. Hamilton, D. H. Sloan, J. R. Oppenheimer, W. M. Brobeck, R. Cornog, R. R. Wilson, E. Viez, J. J. Livingood, J. Backus, W. B. Mann, P. C. Aebersold, E. M. McMillan, E. M. Lyman, M. D. Kamen, D. C. Kalbfell, W. W. Salisbury, J. H. Lawrence, R. Serber, F. N. D. Kurie, R. T. Birge, E. O. Lawrence, D. Cooksey, A. H. Snell, L. W. Alvarez, P. H. Abelson.

Slide 11



the magnet, which had just been installed, and (approximately) the scientific staff of the Radiation Laboratory as of that time. (Slide 10.) You can see Professor Lawrence in the center, with Professor Birge, who was then chairman of the Physics Department, at his right, and Dr. Cooksey at his left. There are probably quite a few people here who can recognize themselves in that picture. It is always a little shocking to look at these old pictures and realize what time has done to us all!

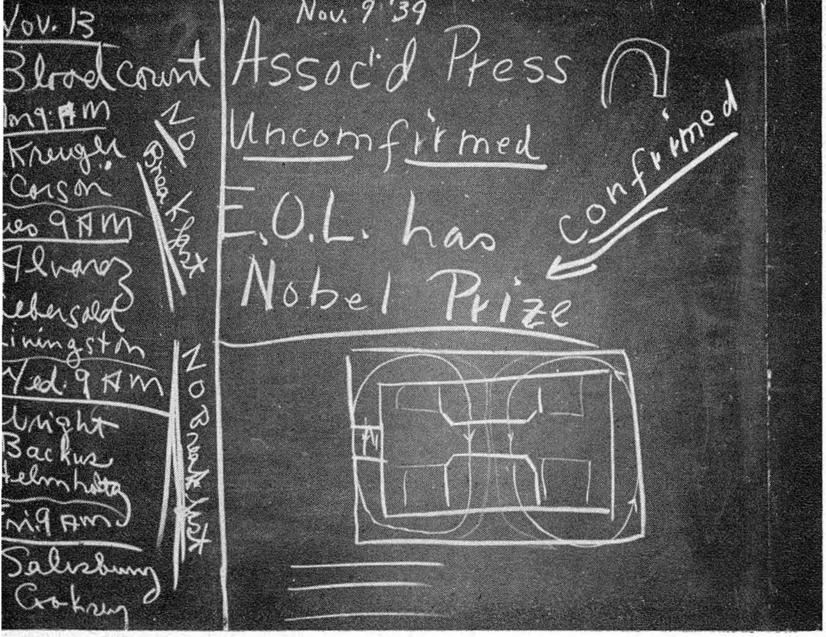
This is the 60-inch cyclotron shortly after it was put together. (Slide 11.) A good many modifications in design were embodied in this machine and one of the most important ones is one of the things that fed back from outside; that is, the idea of getting away from glass insulators altogether, and having the dees plus their stems form a resonant system which is entirely inside the vacuum. The two tanks at the right hold the dee stems. This system has no insulators except in the lead-in for radiofrequency power. The power lead-ins come down the slanting copper cylinders at the right. The round tank on top of the magnetic yoke contains the deflector voltage supply, a rectified voltage supply under oil. And I think you can recognize the people in there: Don Cooksey, Dale Corson, Ernest Lawrence, Robert Thornton, John Backus, Winfield Salisbury, Luis Alvarez on the magnet coil, and myself on a dee-stem tank.

Slide 12

Now, just to show that physicists are not always serious, I have made a slide of the following pose: Laslett, Thornton, and Backus posing in the dee-stem tank of the 60-inch cyclotron before it was assembled. (Slide 12.) The next slide shows the control station of the 60-inch; now we have a real control desk, designed and not thrown together. (Slide 13.) At the desk are Professor Lawrence and his brother, John Lawrence, who initiated the medical work and is still continuing it at the Lawrence Radiation Laboratory.

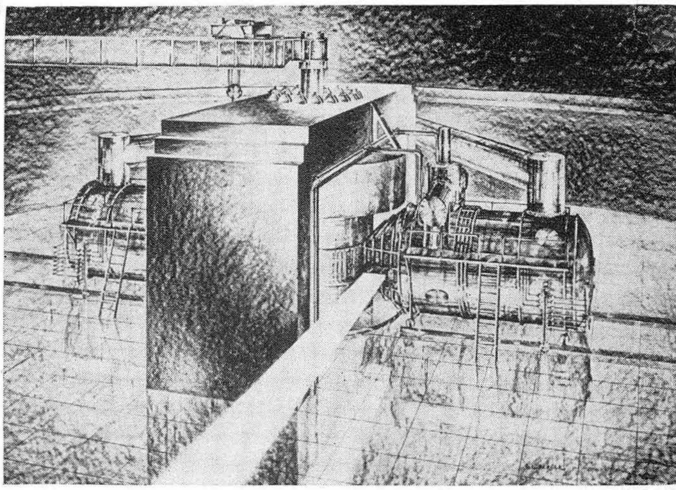
We are now up to 1939. Fission has been discovered. I should point out that the old 37-inch cyclotron was still running, since the 60-inch had a new magnet and a new building, the Crocker Laboratory. So some of these things I mention now were done on the old 37-inch, which ran, with some interruptions, right up to the time when it was used for the first model test on the principle of the synchrocyclotron in 1946. But when fission was discovered, everybody in the Laboratory immediately jumped on the band wagon the way people do, and tried to think of an experiment having to do with fission. They did things with cloud chambers and counters and and made recoil experiments and various things of that kind.

Slide 13



Slide 14

Slide 15

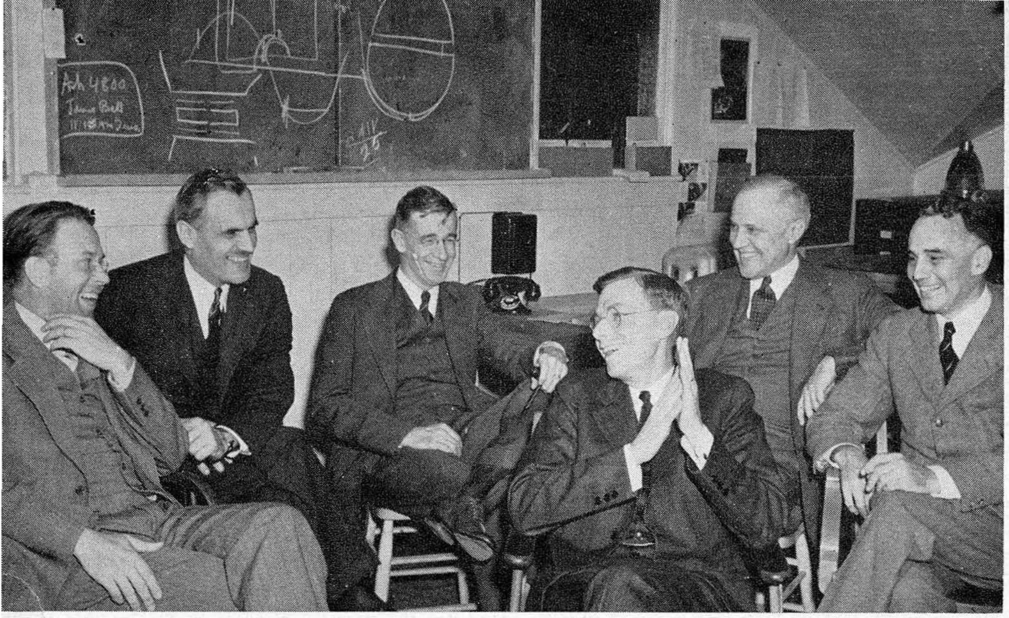


In 1940 came the first production of a transuranium element, which was done with the 60-inch cyclotron, although some of the experiments that led up to it had been done with the 37-inch. Carbon 14, which is perhaps the most important of all the tracer isotopes, came in this period. Kamen and Ruben finally pinned that down. Carbon 14 was something people had been trying to discover for a long time. I tried once myself but didn't quite get it. The mass 3 isotopes, hydrogen 3 and helium 3, were discovered then, helium 3 being found by an unusual use of a cyclotron. It was used as a mass spectrometer rather than as a cyclotron; that is, it was set for a resonance point for particles with charge 2 and mass 3, and when something came through at that resonance it had to be helium 3. This was done by Alvarez.

Perhaps the crowning event of that time was the award of the Nobel Prize to Professor Lawrence. Somebody, I think Cooksey, had the foresight to take a photograph of what appeared on the blackboard then. (Slide 14.) You see there is a two-stage announcement: first it says ASSOCIATED PRESS—UNCONFIRMED and then it says CONFIRMED with an arrow. The column down the left is a schedule of dates when people in the Laboratory received blood counts. I see Kruger, Corson, Alvarez, Aebersold, Livingston, Wright, Backus, Helmholz, Salisbury, and Cooksey. That's the other Livingston, Bob Livingston.

Now Ernest Lawrence was never a man who wanted to rest on achievement; he always wanted to go a step farther. I think it was this forward-looking spirit, and his ability to communicate it to others, that was his true greatness. So, even though the 60-inch cyclotron was a beautiful machine, was running fine, and was doing a great deal of important work, he had this dream of 100 million volts. I've looked at some of his old correspondence and it's always referred to as "100 million volts"; and he believed this could be achieved with the cyclotron. When he got the Nobel Prize, this helped things by focusing attention on this whole concept, and he set out on a campaign to see if he could raise the money to build a 100-million-volt cyclotron. Of course, in those days, money was essentially private money. There was no Manhattan District; there was no Atomic Energy Commission; and so he was trying to get this money by private funds.

In the course of this effort a good many things were written, plans and calculations were made, and one rather interesting picture was drawn which I will show you now. This was an artist's concept of a cyclotron for 100 million volts. (Slide 15.) This is what is now called the 184-inch cyclotron. You can see that this concept is rather different from the way the machine really looks. The magnet yoke is the same, but you see two tremendous tanks projecting on either side. Those were the dee-stem tanks; the beam was supposed to be deflected at one dee, make a complete turn inside, pass through a slit in one dee stem, and emerge as shown in the picture. But the important point this illustrates is that one was designing this as a conventional cyclotron, and one could easily estimate what dee voltages would be required to reach a given particle voltage, following the ideas of Rose and Bethe. We estimated that to reach 100 million electron volts for deuterons with this sort of design we would have wanted about

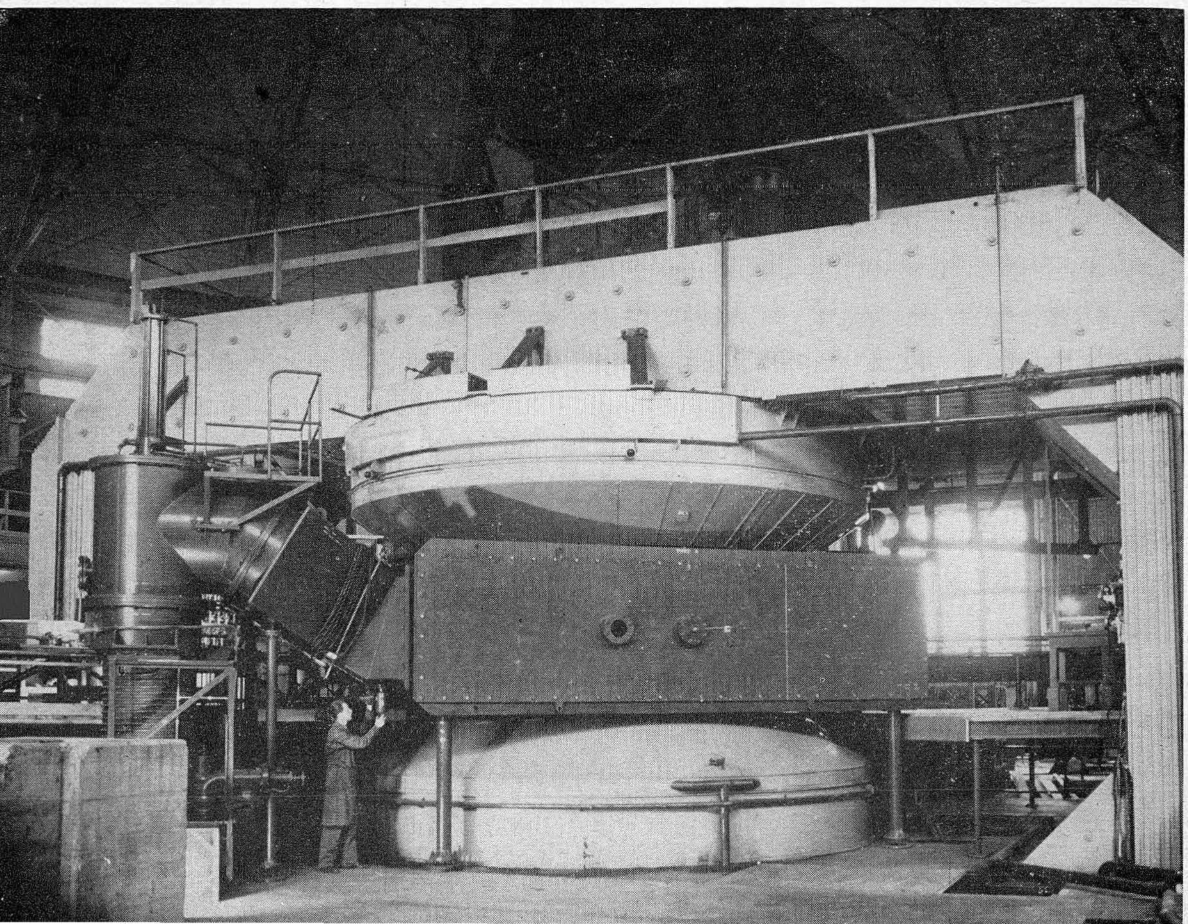


Slide 16

1.4 million volts between dees, or 700 000 volts to ground on each dee. We were planning to go ahead with floods of rf power to reach this voltage, and perhaps we would have, who knows?

The next picture shows a conference in the Old Radiation Laboratory, the building that has just been torn down, between Ernest Lawrence, Arthur Compton, Vannevar Bush, James Conant, Karl Compton, and Alfred Loomis. (Slide 16.) They were discussing ways of getting support for the project, and were obviously in a happy mood. Dr. Cooksey, who took the picture, tells me that someone had just told a joke, but the happiness may have had a deeper justification, for a few days later, on April 8, 1940, the Rockefeller Foundation decided to give 1.15 million dollars for the cyclotron. This grant, with help from the Regents of the University and others, made it possible for the project to go ahead.

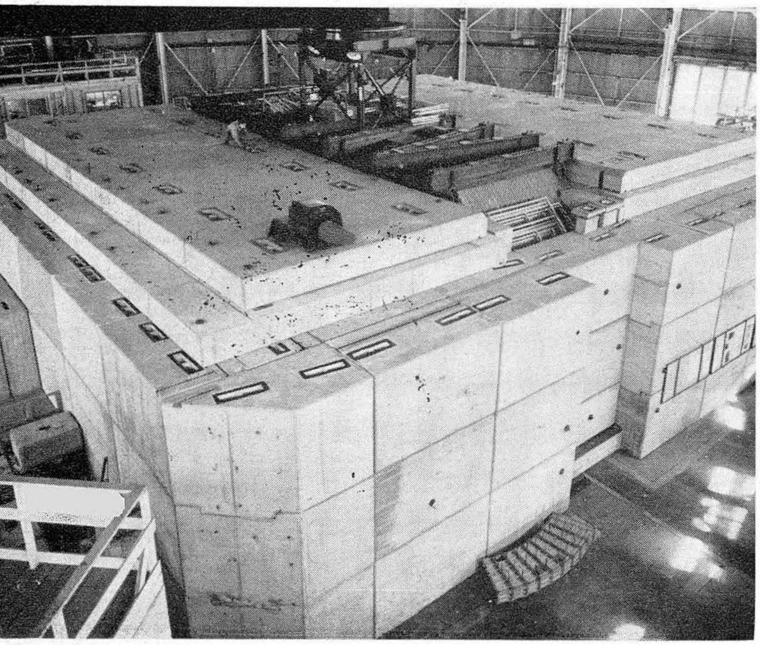
But then the war came along and the whole effort of the Laboratory was diverted to other things. The magnet for this cyclotron was used for research on the electromagnetic isotope separation process, and it wasn't until quite a while later that it came back to use as a cyclotron. By that time other ideas had come out—the idea of the use of phase stability and frequency modulation—and so when the machine finally was built as a cyclotron, it didn't look like that picture on Slide 15 but looked like this one. (Slide 17.) Here



Slide 17

is what the 184-inch cyclotron looked like when it was first assembled. You can get some idea of the size, since there's a man there for scale. Of course, by now this is a synchrocyclotron. When I think of the history of the cyclotron in the sense of this talk, I think of it as the history of the fixed frequency cyclotron, so I won't say much more about this machine except that it does work. I'll show you a picture of about the way it looks today, encased in concrete blocks for shielding, which is a better solution to the shielding problem than 5-gallon cans of water. (Slide 18.) If you look hard, you can see a man in this picture, too.

I shall close this talk with an aerial view of the present establishment in Berkeley of the Lawrence Radiation Laboratory. (Slide 19.) In the foreground, in the circular building, is the Bevatron, which is of course a descendant of the cyclotron since it does use the magnetic resonance principle. A little farther back is another circular building which houses the 184-inch cyclotron, the machine I just showed you. The other buildings house other accelerators, research laboratories, shops, and all the things which make up the laboratory which really, one can say in all truth, is the outgrowth of the ideas and the faith and the strength of Professor Lawrence, in whose memory we have spoken today.



Slide 18

Slide 19