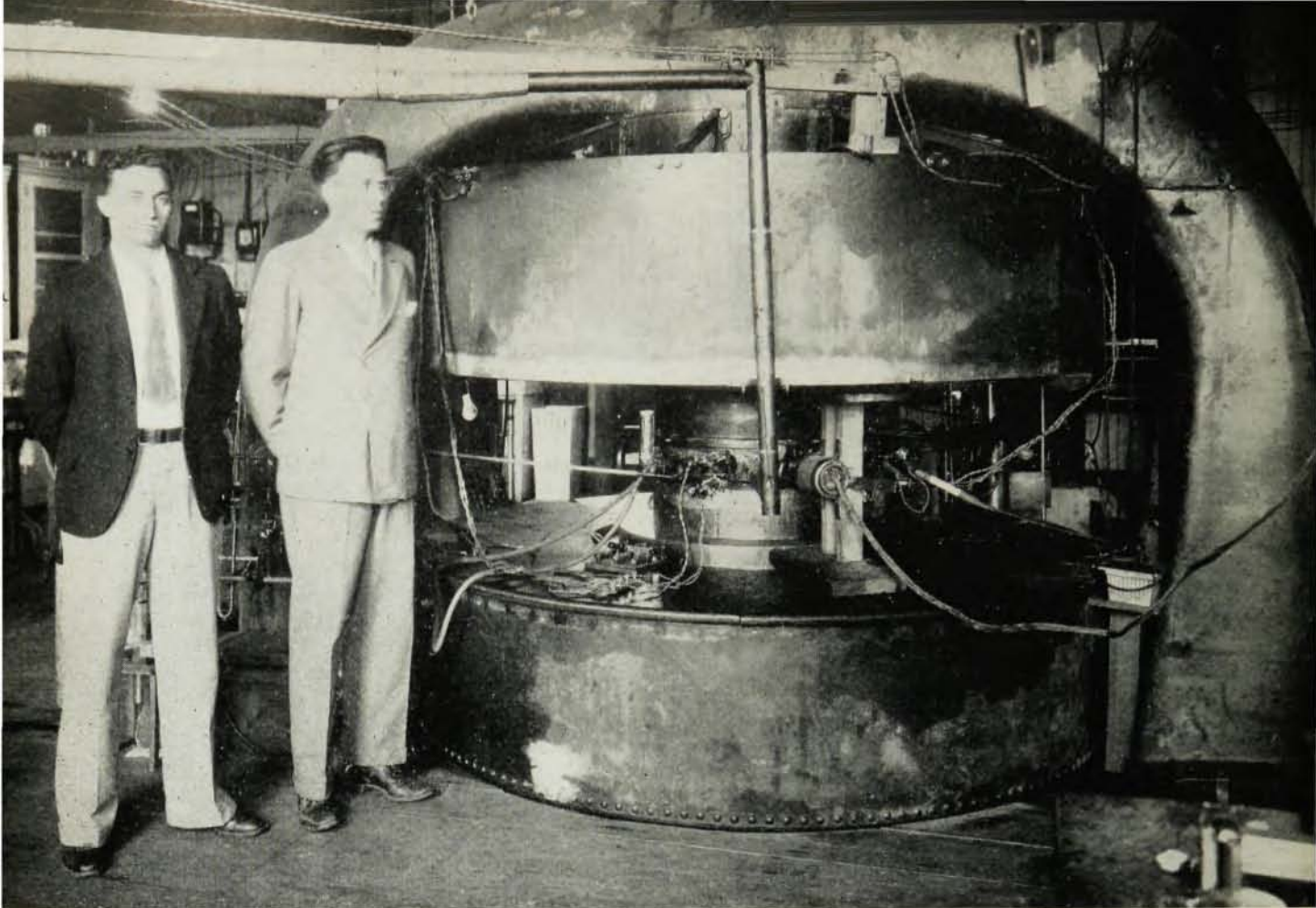




PART II

History of the CYCLOTRON

By Edwin M. McMillan

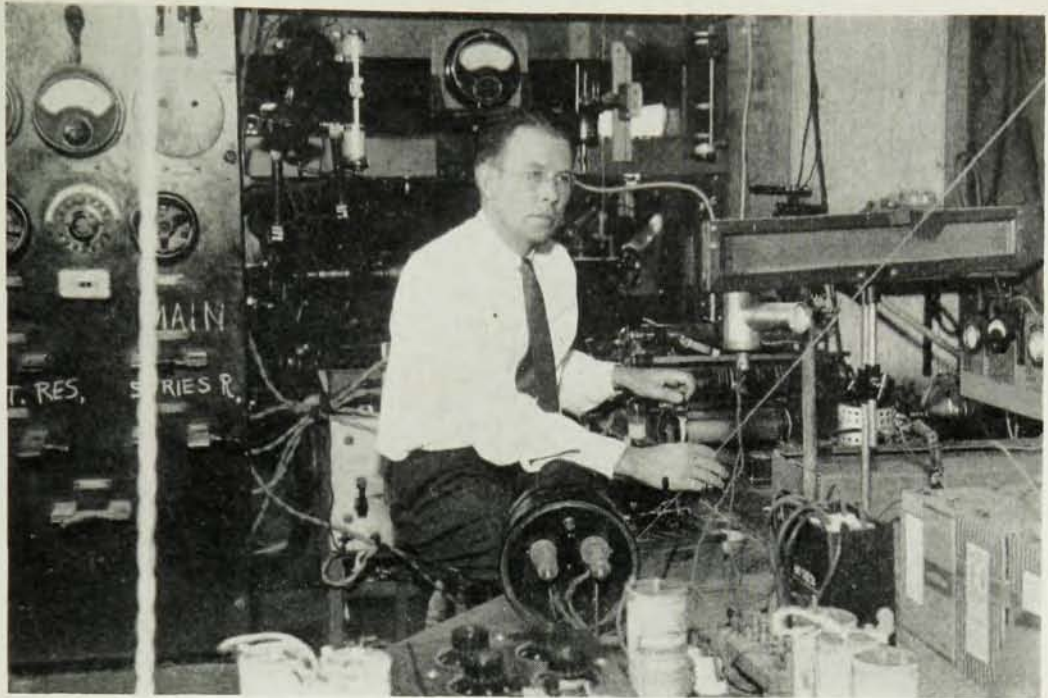
AS Dr. Livingston has told you, our activities overlapped by a few months, so that between us we can give a continuous story of cyclotron development as carried out at Berkeley under the guidance of Professor Lawrence. My start in his laboratory was in April of 1934, but I was around Berkeley before 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.



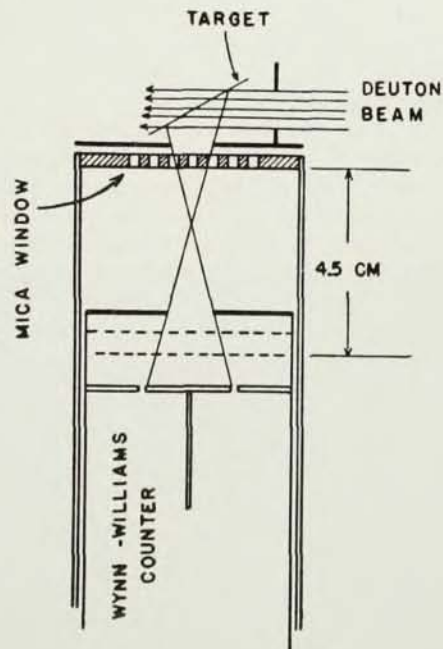
Slide 2

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.

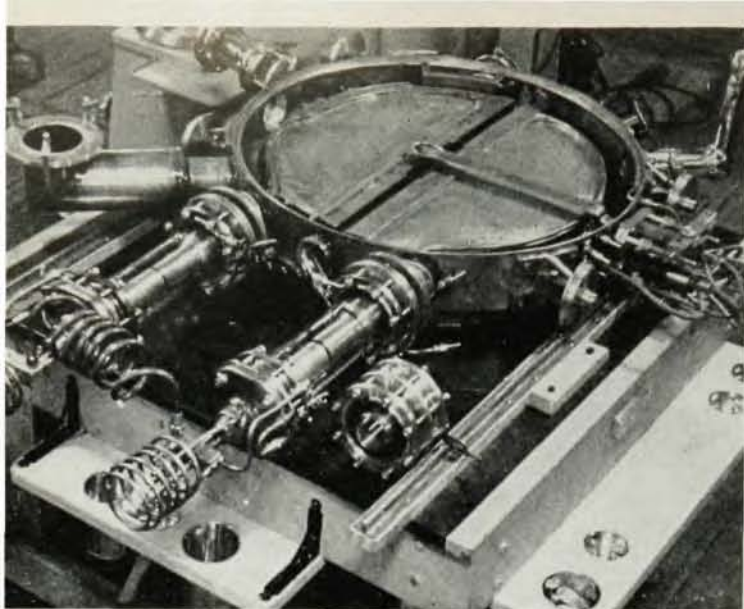
As an illustration of the kind of experimental equipment one used, I have this drawing which was taken from a publication of about that period, early in 1935. (Slide 3.) This was an experiment to disintegrate aluminum with deuterons. You'll notice that in those days they were called deuterons. The story was told that Ernest Rutherford objected to the name deuteron; 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 deuterons 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,

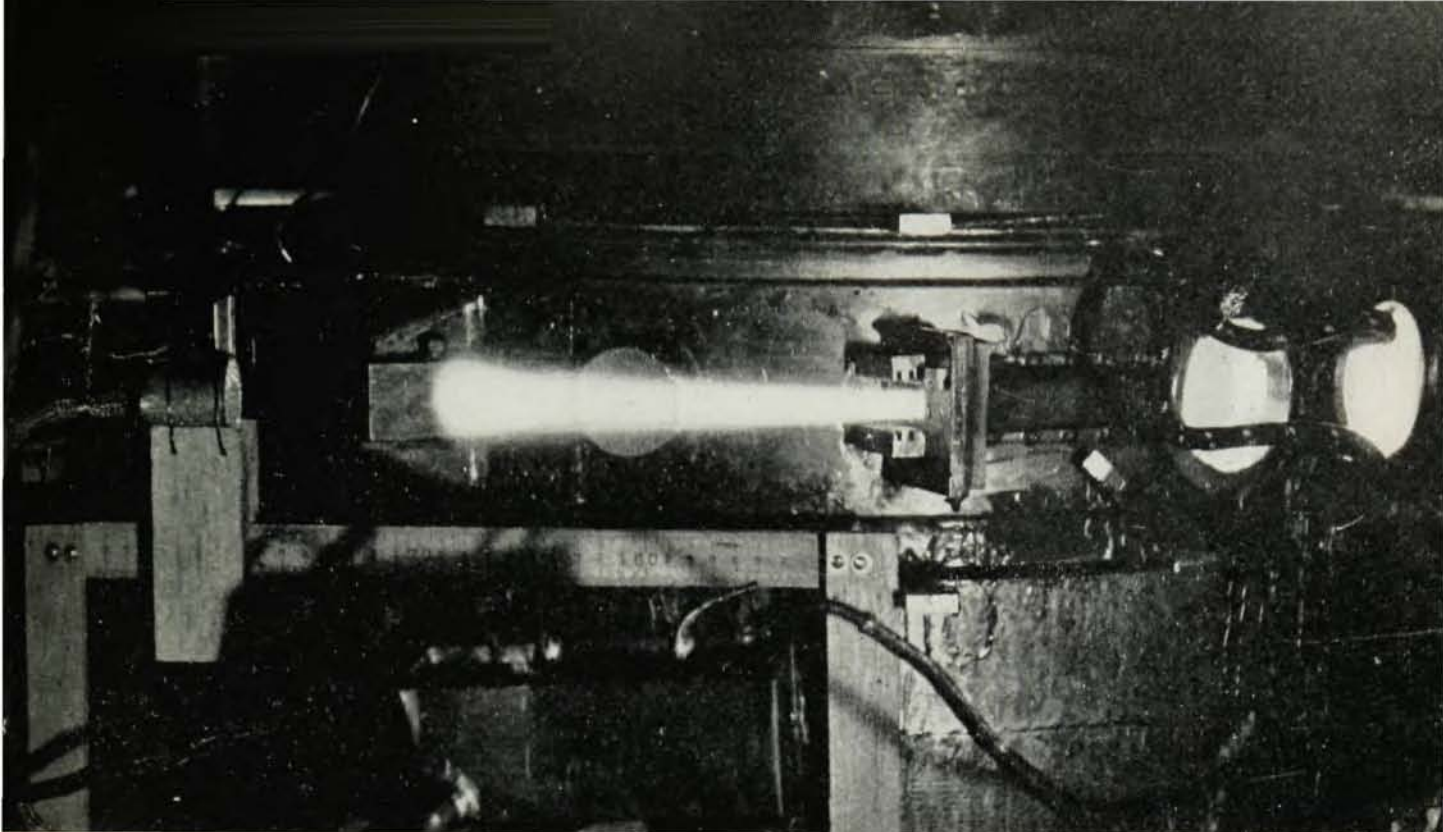
people have always been careful with radiation even though it was soon discovered that somebody had forgotten to turn on the air supply which was supposed to provide ventilation for this mouse so that he died of anoxia. Anyhow, it was a very dramatic thing at the time.

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

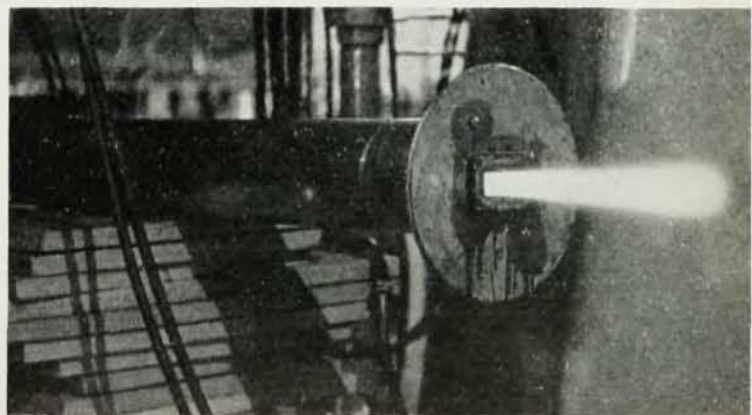


Slide 6

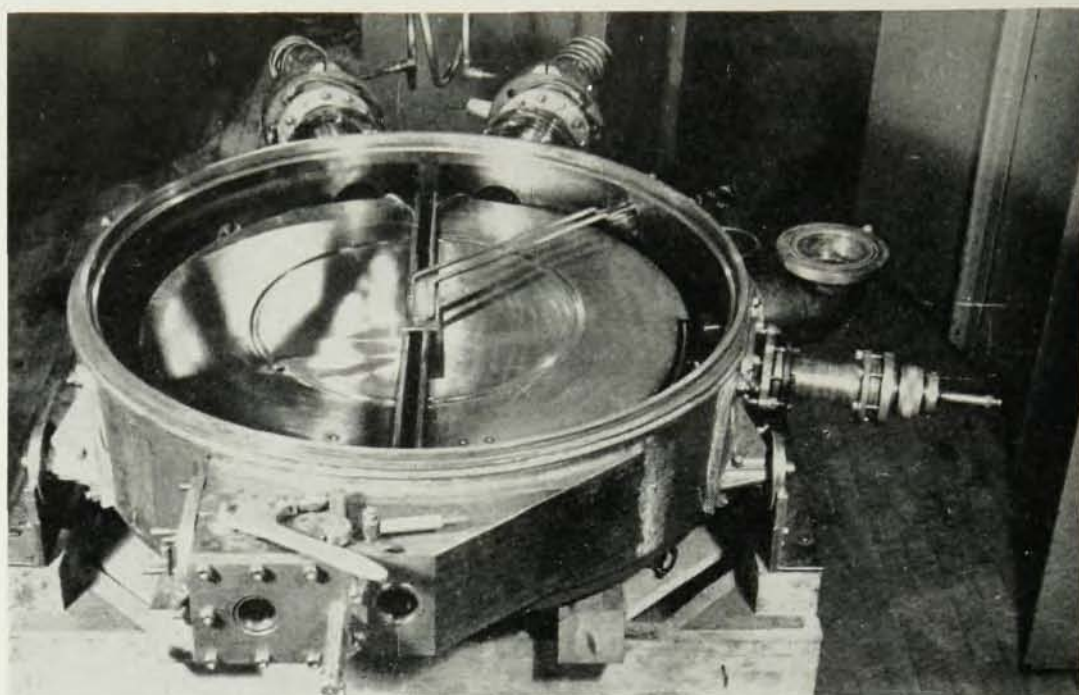
then, but that is what it would now be called). This, I think, was a fairly classical experiment because there were then some people who didn't quite believe that the artificial radioactive materials were on the same status as the naturally occurring ones. Jack Livingood put some bismuth in the deuteron 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. Be-

fore, 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

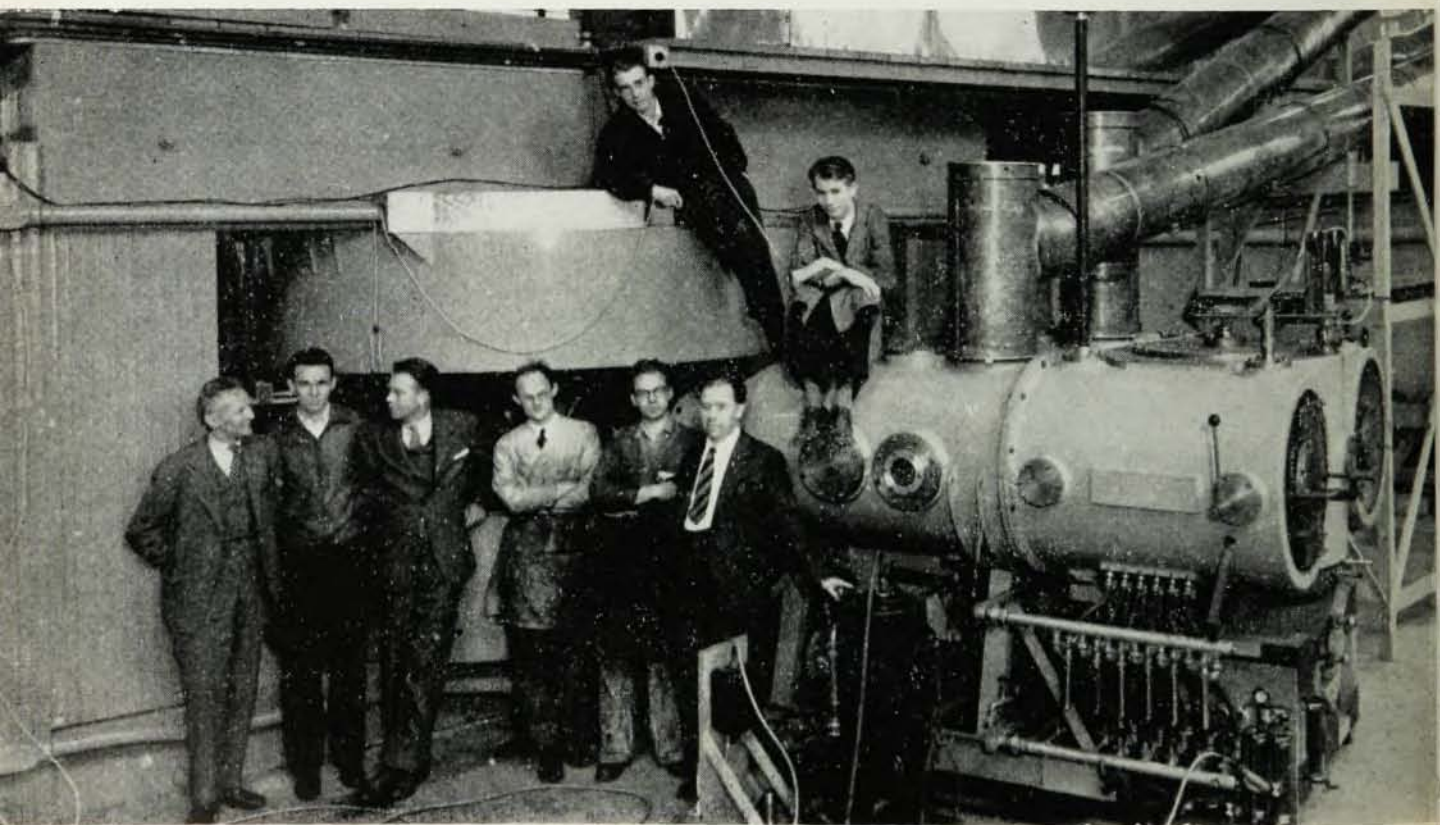


Slide 9



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.

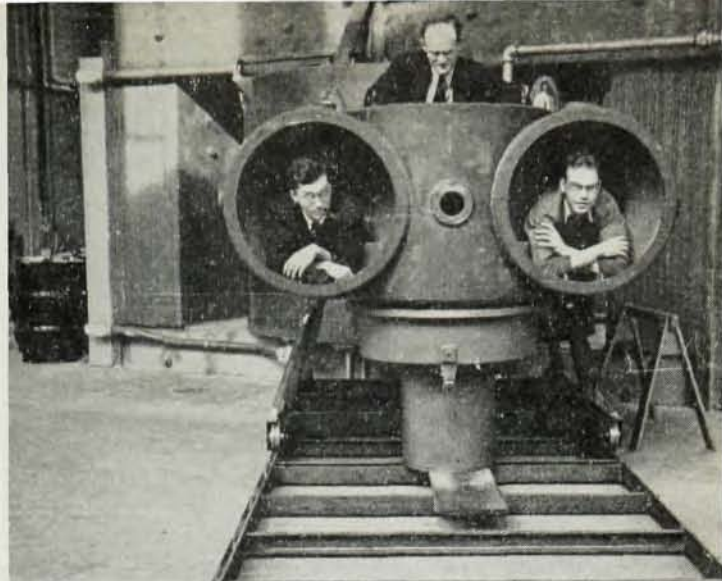
Slide 11



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.

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



Slide 12

Professor Lawrence and his brother, John Lawrence, who initiated the medical work and is still continuing it at the Lawrence Radiation Laboratory.

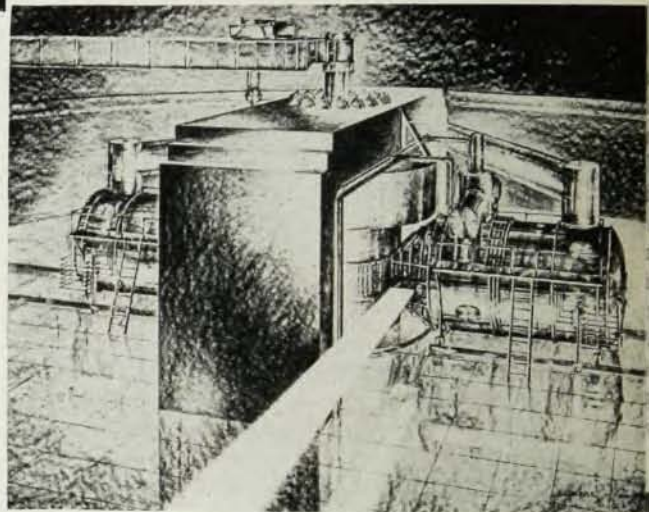
We are now up to 1939. Fission has been discovered. I should point out that the old 37-inch cyclotron was still running, since the 60-inch had a new magnet and a new building, the Crocker Laboratory. So some of these things I mention now were done on the old 37-inch, which ran, with some interruptions, 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

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



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



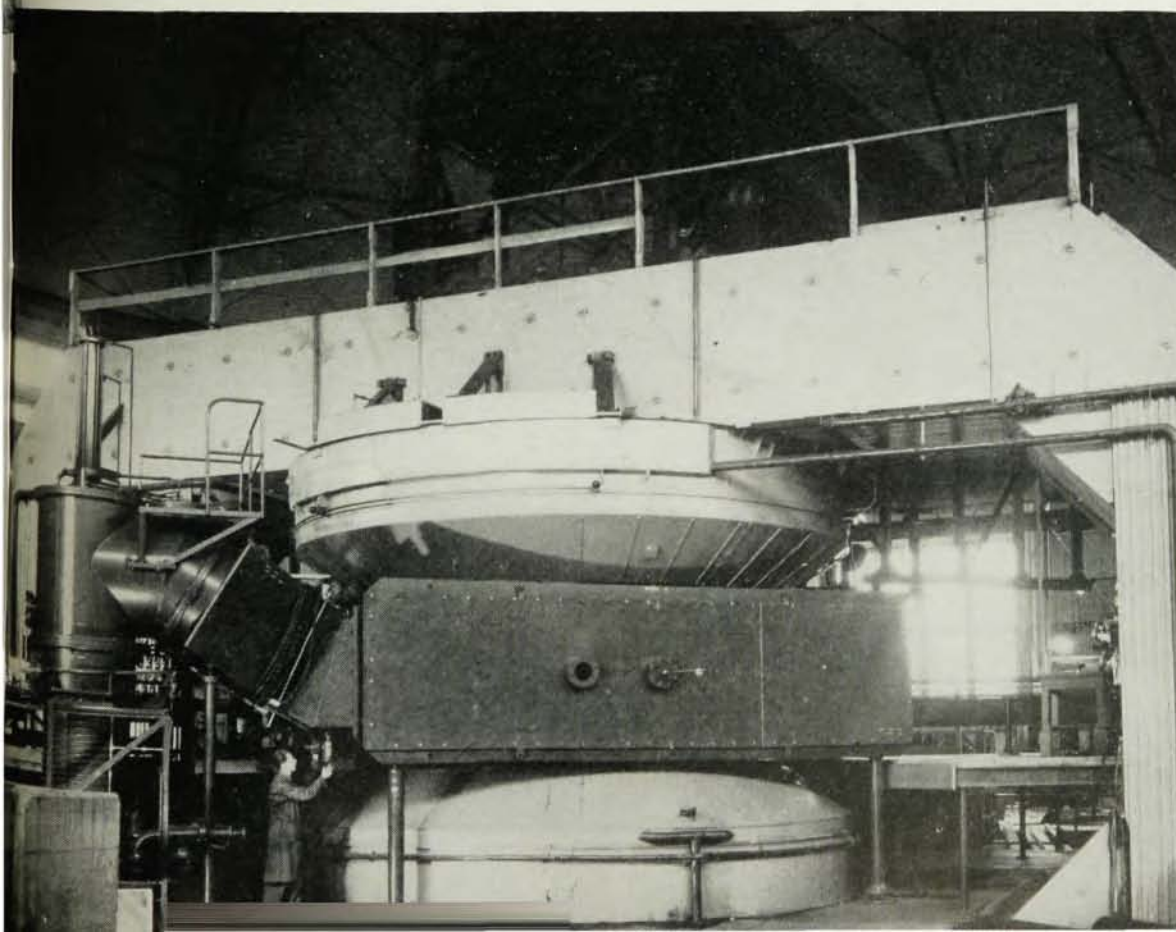
Slide 16

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?

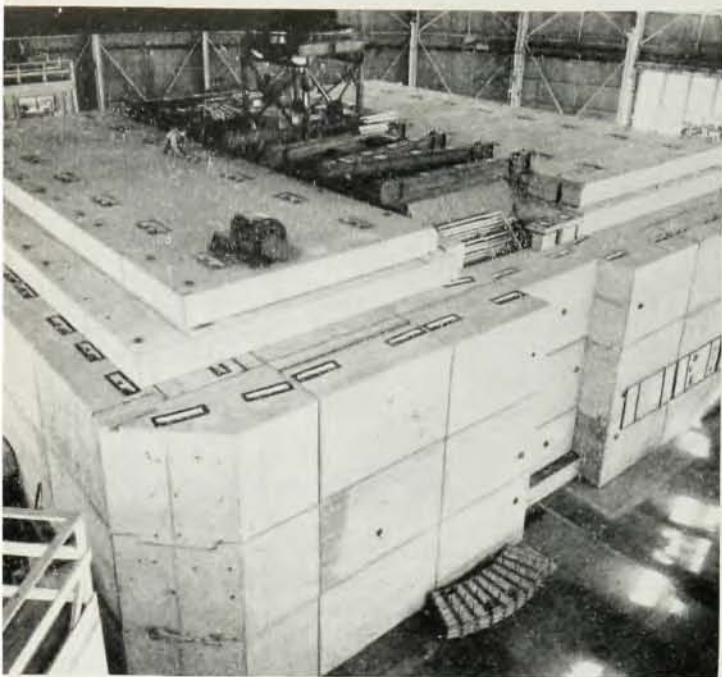
The next picture shows a conference in the Old Radiation Laboratory, the building that has just been torn down, between Ernest Lawrence, Arthur Compton, Vannevar Bush, James Conant, Karl Compton, and Alfred Loomis. (Slide 16.) They were discussing ways of getting support for the project, and were obviously 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



Slide 18

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 19

