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The investigations carried out by means of charged particle accelerators, based on the phase stability principle discovered by **V.I.Veksler** and **E.M.McMillan**, have resulted in radical changes in our picture of the microcosm: new laws of nature and physical principles have been discovered.

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THE PRINCIPLE OF PHASE STABILITY AND THE ACCELERATOR PROGRAM AT BERKELEY, 1945 - 1954

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ABSTRACT

The discovery of the Principle of Phase Stability by Vladimir Veksler and Edwin McMillan and the end of the war released a surge of accelerator activity at the Lawrence Berkeley Laboratory (then The University of California Radiation Laboratory). Six accelerators incorporating the Principle of Phase Stability were built in the period 1945-1954.

First I remind you of the state of accelerator development at Berkeley in 1939-40 just before the Radiation Laboratory, as it was then known, converted completely to war-related research. The highest energy accelerator at Berkeley, indeed in the world, was the just completed 60-inch cyclotron, which produced a beam of 16 MeV deuterons. Lawrence, who was at the height of his powers, began, even before the 60-inch produced its first beam in the spring of 1939, to think of the next step in the sequence of higher and higher energy accelerators. One hundred MeV became his goal. That there was an eventual limitation to cyclotron energy imposed by the relativistic mass increase of the ions was known, but the practical limit was not understood. The limit might be pushed up by higher dee voltage, by grids or other details of geometry at the dee edges, or some new idea might come along. There was a lively exchange of letters between Hans Bethe and Ed McMillan on this subject. The belief in Berkeley was that with 1 million volts on the dees an energy of 100 MeV could be reached. L. H. Thomas' publication in 1938 of the possibility of circumventing the relativistic limit of energy by the introduction of an azimuthal variation in the magnetic field was so far in advance of the general understanding of cyclotron theory and practice that it was overlooked. [1].

Accelerator development went into decline at Berkeley in 1940-41 as some of the leading personalities, including Edwin McMillan and Luis Alvarez, left the Laboratory for urgent work on radar, sonar, and other war related research. The Laboratory itself was converted to war time- work. The 184-inch Cyclotron magnet was completed with high priority in early 1942 and it became the center piece for the development of the electromagnetic method of separation of uranium isotopes, called the Calutron.

In the Summer of 1945 as the war drew to a spectacular close, the minds of many scientists reverted to pre-war problems, stimulated by the added experience and technology gained during the period of war research. Alvarez saw in the thousands of surplus 1.5 meter wave length radar sets the means of building a 500 MeV electron linear Accelerator. Mc Millan first thought of building a very large

air-core Betatron. But, realizing that it would be a brute of a machine, he continued to think about resonance acceleration.

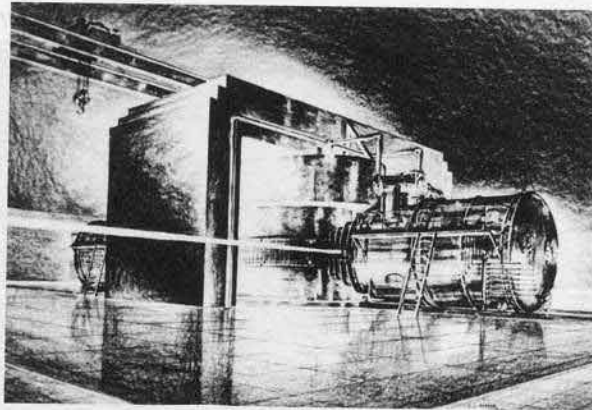


Fig. 1. Conceptual drawing of a 100 MeV cyclotron, 1940.

In total ignorance of the publications of Vladimir Veksler, he had the same insight that Veksler had and he quickly formulated the Principle of Phase Stability [2]. He decided on a 300 MeV electron Synchrotron as a first application. Alvarez thought that this was such a superior means for reaching high energies with electrons that his thinking changed from electron to proton linear accelerators. All this was at Los Alamos during the first days of July, just before the bomb test at Alamogordo on July 16, 1945.

The Government, mindful of the major role of Lawrence, McMillan, Alvarez, and indeed the Radiation Laboratory as an institution in wartime research, was very interested in reconstituting the Laboratory as a peacetime research center to exploit all the fields connected with atomic energy and accelerators. Prompt approval was given to a program to fund the completion of the 184-inch cyclotron, and to build both a 300 MeV electron synchrotron and a proton linear accelerator. Before the war all Laboratory funding had been from private foundations and individuals, and was on a much smaller scale.

The prewar plans for the 184-inch as a conventional cyclotron were revived and a few large components were fabricated. As the difficult problems of a conventional cyclotron at very high energy were faced, McMillan's suggestion to redesign it as frequency modulated phase stable accelerator - a Synchrocyclotron - became very attractive. However, there were thought to be some very difficult problems. How do you modulate the radio frequency power? Would the small turn-to-turn spacing make injection and beam extraction difficult? Would the relatively slow acceleration result in excessive gas scattering losses? Altogether, it was thought that the application of Phase Stability to the acceleration of protons was more difficult than to electrons. In the event, the opposite proved to be true by a wide margin. Accordingly, it was decided early in 1946 to build a working

model of a Synchrocyclotron to prove the Principle and to find solutions to the expected problems.

The 37-inch Cyclotron had been dismantled in November 1941 and its magnet used in the preliminary development of the Calutron. It was again to be converted to a new purpose. The pole tips were enlarged to 41 inches (although we continued to call it the 37-cyclotron) and they were tapered to cause the magnetic field to decrease by 13% from the center to a radius of 18 inches. This would produce the same decrease of the rotational frequency as the acceleration of deuterons to 200 MeV in the 184-inch cyclotron, with 10.7 % of the falloff of the magnetic field corresponding to the relativistic mass increase and an additional 2.3% to provide for axial focusing. Frequency modulation of the r.f. power at 2000 Hz was accomplished with a mechanical rotating condenser. With a dee voltage of only 3 kv a circulating beam of 3 micro-amperes of 7.5 MeV deuterons was quickly achieved. The beam was extracted with a conventional deflector with an efficiency of 10% [3]. My notes tell me that the first beam was achieved early in March 1946 just three months after the design was started. To my knowledge this was the first accelerator to incorporate the Principle of Phase Stability in its design. Subsequently the radio frequency system was modified to provide for the acceleration of protons to 15 MeV and the beam was used in p-p scattering and other experiments. After two years service at Berkeley it was moved to the University of California at Los Angeles, where it became the center piece of a nuclear research and graduate student training program for ten years. The rapid construction and the excellent performance of the 37-inch Synchrocyclotron left no doubt that the original design of the 184-inch Cyclotron should be scrapped and that it should be completed as a Synchrocyclotron. Redesign and construction began immediately.

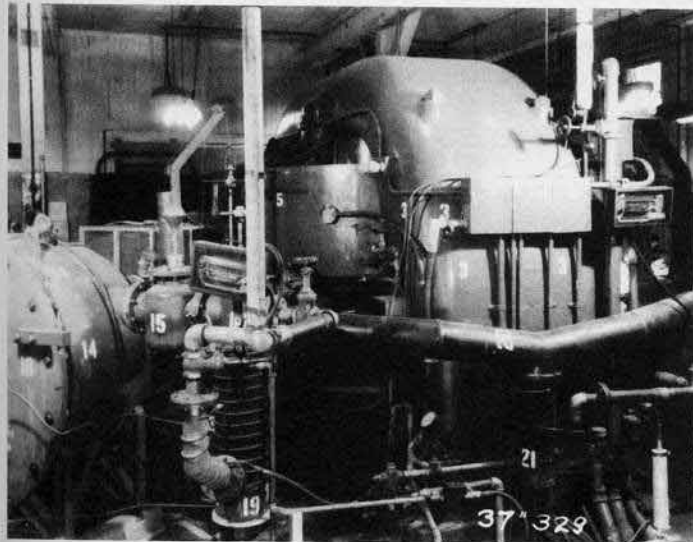


Fig. 2. The 37-inch synchrocyclotron. The cylindrical tank at the left houses the rotating condenser.

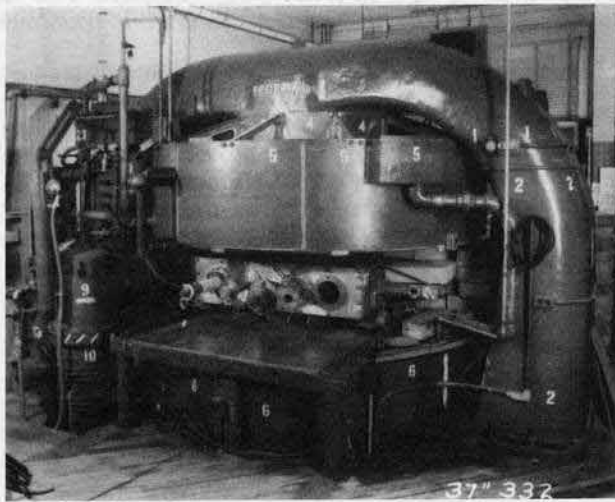


Fig. 3. The 37-inch synchrocyclotron, vacuum pumps at the left, beam exit port at the right.

The work was completed and first operation of the 184-inch Synchrocyclotron was achieved on November 1, 1946.

It produced a beam of deuterons at 195 MeV with very little trouble, twice the energy that had seemed so difficult to attain when the machine was first proposed [4]. Lawrence was indeed correct in his belief that if there were problems, a new idea would come along. Later modifications provided for protons at 350 MeV and other ions up to 750 MeV. The early years of the experimental program were very fruitful and included the first accelerator production of pions. Later the machine provided beams for pioneering medical programs and in the last years of operation its program was entirely medical. In 1987 operation of the 184-inch Synchrocyclotron was discontinued to conserve funds and effort for the Bevalac medical program.

The building now houses a synchrotron light source, and the yoke of the venerable 184-inch magnet stands as a monument in the center of the ring.

Although McMillan had a very important guiding influence on the first synchrocyclotrons, his 'own' project was the 300 MeV Synchrotron. Design and construction of it started in September, 1945. The orbit radius was to be 1 meter, the magnet to be of laminated silicon steel, and it was to be powered by a large bank of surplus capacitors obtained from another wartime project. The vacuum tank with all its ports and fittings was made of plastic. This proved to be too porous and was replaced by a fused quartz torus. The efforts to bring the machine into operation were stalemated for a long time by irregularities in the low magnetic field at injection due to remanence in the laminations. First operation was not achieved until November 1948. [5]. Similar difficulties were experienced by other groups who were then trying to bring high energy synchrotrons into operation, although low energy synchrotrons at other laboratories were brought into operation as early as 1946.

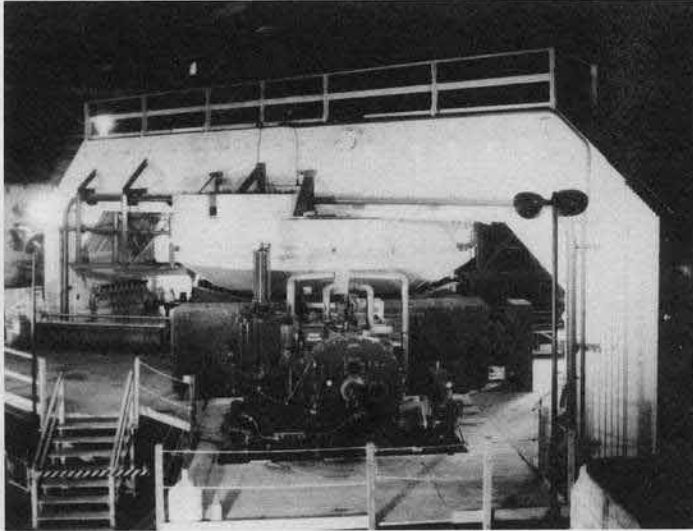


Fig. 4. The 184-inch Synchrotron as completed in 1946.

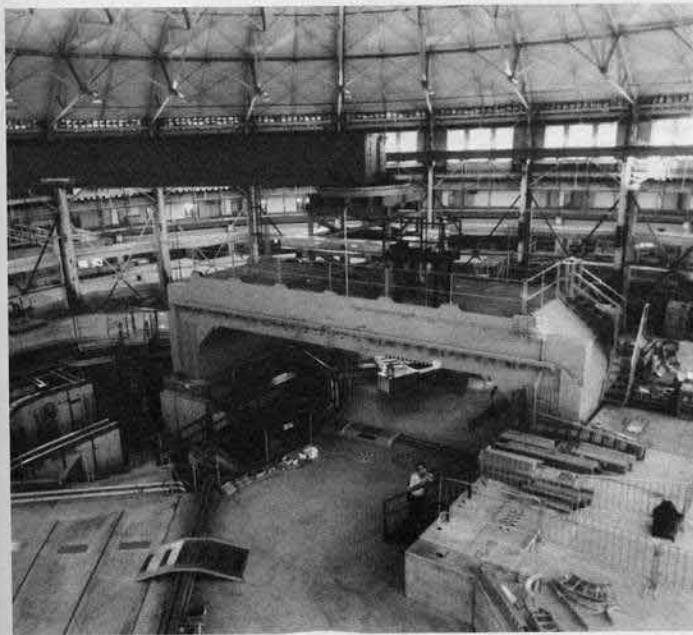


Fig. 5. The Advanced Light Source, with the yoke of the 184-inch cyclotron magnet in the center. 1994.

The most notable achievement with the 300 MeV Synchrotron was the discovery in April, 1950 of the neutral pion.

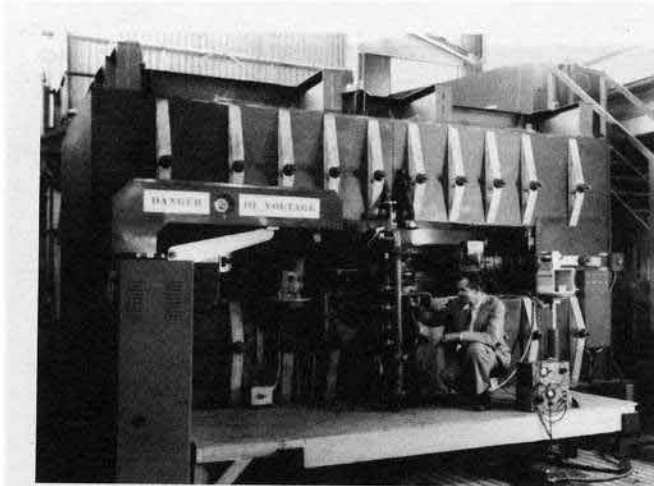


Fig. 6. Edwin McMillan and the 300 MeV Synchrotron.

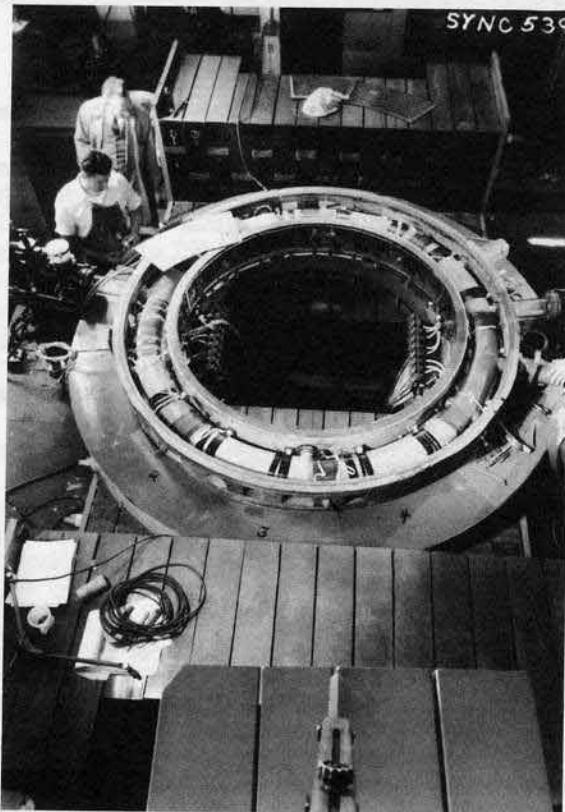


Fig. 7. The top magnet yoke and coils of the Synchrotron removed, showing the quartz vacuum tube.

Alvarez, who was convinced that the synchrotron idea preempted the field of electron acceleration, assembled a team and began the design of a proton linear accelerator as soon as he returned to Berkeley in the fall of 1945. This was intended to be the prototype of the first section of a high energy proton accelerator. The r.f. frequency was set at 200 MHz because radar research had developed technology and components at that frequency.

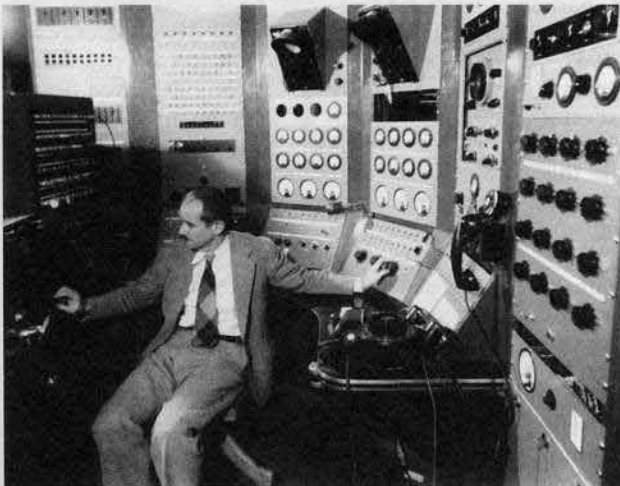


Fig. 8. With one hand on the injection timing control and the other on an oscilloscope, McMillan operates the Synchrotron.

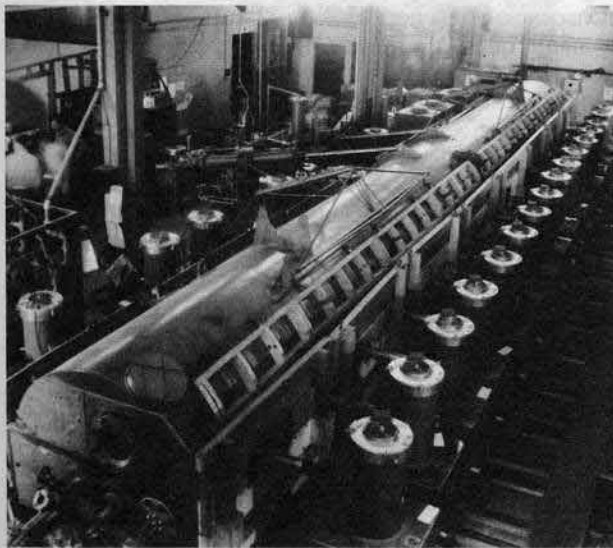


Fig. 9. The Alvarez linear Accelerator.

The size of the available building set the length of the accelerator, 40 feet, and hence the design energy at 32 MeV. Everything else had to be developed. Injection from a pressurized Van de Graaff at 4 MeV was 1 MeV higher than the beam energy from any existing Van de Graaff.

It is impossible to achieve both acceleration and focusing with open end drift tubes. The first solution, beryllium foils at the drift tube openings, was gone in a flash the first time the tank sparked.

The foils were replaced with tungsten grids, and a beam at design energy was achieved on October 16, 1947. [6]. This was the highest proton energy at any accelerator until, a few years later, the 184-inch Cyclotron was modified to accelerate protons. After several years as a research tool producing new isotopes and doing scattering experiments, the Alvarez linac was given to the University of Southern California. While this type of accelerator has never been extended to reach the highest proton energies, it has been used as the injector for every high energy proton synchrotron. It has also been very successfully adapted to the acceleration of heavy ions.

As early as 1946 William Brobeck began to think about the possibility of a proton synchrotron, and he produced schematic drawings and rough estimates of a 10 BeV (as GeV then were called) accelerator. [7]. This would require variation of both the magnetic field and the accelerating frequency. This concept received very little attention until early 1948 for the obvious reason that the Laboratory staff was fully occupied with all the other projects. There then were discussions with the Atomic Energy Commission (AEC) and with the staff of the recently established Brookhaven National Laboratory, the result of which was that in May, 1948 the AEC authorized work on a 3 BeV accelerator at Brookhaven and a 6 BeV accelerator at Berkeley. The latter became known as the Bevatron. Again, as in the case of the synchrocyclotron there was no doubt about the basic principle, but there were many questions. What injection energy would be required and how do you inject? What aperture would be required? Would straight sections introduce excessive beam orbit oscillations?

Also there were novel requirements in mechanical and electrical engineering. As with the synchrocyclotron in 1946 the answer was to build an operating model, and in July, 1948 the decision was made to build a proton synchrotron one quarter the size of the planned Bevatron.

The radius of the orbit would be 12.5 feet, the maximum aperture 9.5 by 36 inches, corresponding to 38 by 144 inches full size. The magnet yoke was also one quarter scale, but the magnet power supply would provide for a magnetic field of only 1000 gauss, giving a proton energy of 6.5 Mev. It was thought that most of the problems would be encountered at injection and early acceleration. Two injectors were built, a 500 keV Cockcroft-Walton and a 700 keV cyclotron.

This reflected the uncertainty as to what injector to use in the full scale machine. It should be remembered that the proton linear accelerator was just becoming operational and that Van de Graaff accelerators were very troublesome beyond about 4 MeV. In the event, only the cyclotron injector was used in the model, and the development of the proton linear accelerator proceeded so rapidly and successfully that a linear accelerator with a Cockcroft-Walton preaccelerator was used on the full scale Bevatron, as on all succeeding proton synchrotrons.

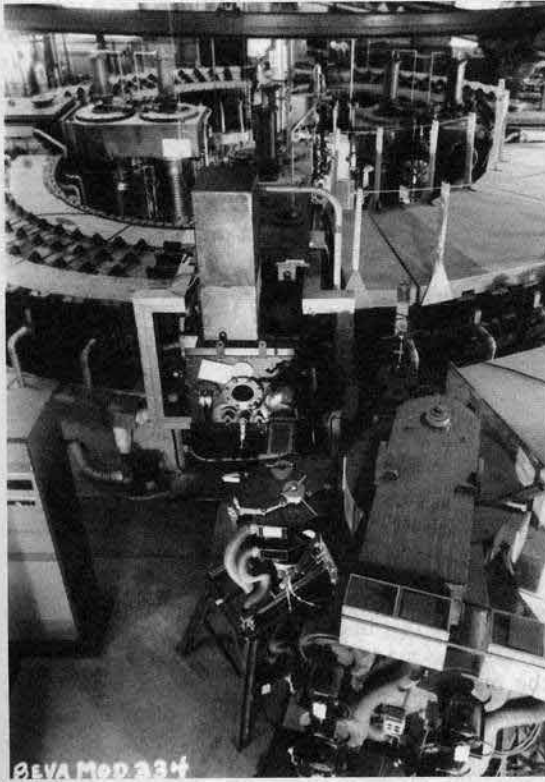


Fig. 10. The quarter-scale model Bevatron, the injector cyclotron in the right foreground.

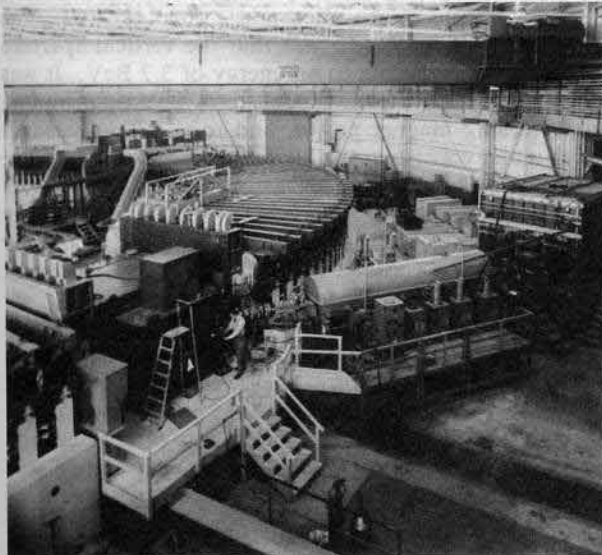


Fig. 11. The Bevatron as completed, without shielding, injector linac and Cockcroft-Walton pre-injector at the right.

Fig. 12. Edwin McMillan and Edward Lofgren at top Bevatron Shielding.



As I have noted before, we could move fast in those days, and we had a beam 9 months and 10 days after the decision was made to build the model [8]. The most important result of work with the model was that it began to give a basis for deciding on the aperture of the full scale Bevatron. In the original design, provision was made for a possible vertical aperture of four feet, corresponding to an energy of less than 2 BeV.

Pole tips reducing the aperture and giving a higher energy would be installed later. This would have been a very serious interruption and a great expense. The immediate conclusion from operation of the model was that the vertical aperture need not be greater than two feet, corresponding to an energy of 3.7 BeV. It was planned to increase the energy of the Bevatron Model to 1 BeV by installing pole tips in the magnet and increasing magnet power, and to use it in research while the full scale machine was under construction. However, that was not done. Work ceased on both the model and the full scale Bevatron in October, 1949 as the Laboratory undertook the development of a very high current high energy accelerator to produce neutrons, the MTA Project. However, that is another story. The Bevatron Model was given to Caltech where it was converted to a 1 BeV electron synchrotron and was used in research for several years.

After a two year interruption, work was resumed on the Bevatron. Reconsideration of results with the model together with work on the Cosmotron at Brookhaven, gave confidence that the aperture could be less than 2 feet. Panofsky and independently McMillan had calculated the threshold energy for the production of antiprotons, and they were insistent that the energy of the Bevatron should be above that threshold. Accordingly the aperture was set at one foot which corresponded to an energy of 6.2 BeV. First operation at the design energy

was on April 1, 1954. There were many technical and engineering troubles to overcome as the capability of the accelerator was steadily improved - far too long a story to go into at this time. Until the early 1960's it was one of the world's most productive high-energy accelerators then, as it became outclassed by the several higher energy proton accelerators in the world, one could see the end.

But it was not the end, the Bevatron was converted to a unique high-energy-heavy-ion accelerator, The Bevalac, by injecting ions from the existing heavy-ion linear accelerator (the Hilac). It was capable of accelerating ions of any element to an energy of 1 GeV per nucleon. It supported a number of programs in nuclear physics, space physics, biology and both research and clinical medicine.

Finally, after 38 years and 10 months of very fruitful operation, the Bevatron was shut down in February 1993, not for a lack of capability or good programs, but for lack of funds for operation.

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