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High-Current Accelerators

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It is hardly necessary to point out that the remarkable development of particle accelerators, like all far-reaching scientific and technologic advances, is the work of many people in many laboratories over the world. It was, for example, Cockcroft and Walton in England who first achieved the disintegration of lithium by accelerated protons, and it was Veksler of the Soviet Union who, in a classic paper on the theory of accelerators, was the first to describe the synchrotron, thereby pointing the way to much higher energies.

The bevatron at the University of California, which for the moment is the largest proton synchrotron, is shown in Fig. 1. The magnet is arranged in four quadrants and in the foreground may be seen the cavity-type linear accelerator, which serves to inject pulses of 10-Mev protons into the synchrotron. The radiofrequency accelerating electrode and its associated equipment are in the straight section on the right, while the target area is in the straight section opposite the injector area and hence is hardly visible in the figure.

Figure 2 is a limited view of the injector quadrant of the bevatron. On the right is shown the housing of the 500-kilovolt Cockcroft-Walton accelerator, the foreground shows the 10-Mev linear accelerator, and on the left can be seen the strong-focusing quadrupole magnetic lens, which focuses the beam appropriately into the bevatron.

Figure 3 shows the power supply of the bevatron, which provides 100,000-kilowatt pulses that are switched by the array of ignitrons shown in the foreground.

I shall not undertake a more detailed description of the bevatron. For some time now it has been in operation at full energy, 6.2 Bev.

I should like to note that this great machine is being utilized by scientists of many laboratories in America and abroad —indeed, about one-quarter of the operating time has been devoted to furthering work outside the United States. The many visiting scientists, especially from overseas, have been a real source of pleasure to all of us in Berkeley. Their presence has contributed greatly to the work in progress, and we appreciate even more the fact that their collaboration is increasing enormously the flow of new knowledge that the bevatron makes possible.

Of course, the finest flowering of this kind of international collaboration is embodied in the CERN Laboratory now being developed so auspiciously in Geneva by the European Organization for Nuclear Research.

It is perhaps an understatement to say that the richness of the domain of the nucleus opened up for investigation by accelerator developments has exceeded all expectations. Those of us who have had the good fortune to participate in these developments during the past quarter-century have, indeed, a vivid impression that each new door to a hitherto inaccessible region of nature that is opened by the development of an accelerator of new capabilities always leads to unexpected advances in knowledge of both scientific and technologic importance. It is, of course, for this reason that accelerator developments over the world are proceeding at an ever-increasing pace.

In his retiring address as president of the American Physical Society in 1954, Enrico Fermi humorously presented a logarithmic plot of the progress in accelerator developments toward ever higher voltages. He extrapolated the exponential progress of recent years to show that in a few more decades our accelerators would circle the earth and compete with very energetic cosmic rays!

In the same spirit, one may extrapolate the currents that will be produced (Fig. 4). Taking a milliampere for cyclotrons in 1940, a microampere for synchrocyclotrons in 1943, and a millimicroampere for the cosmotrons and bevatrons of 1956, we obtain a current of 5×10^{-4} particles per second or 2 protons per hour when our energy should reach 10^{16} electron volts!

In a more serious vein, it is clear that the duty-cycle limitation on beam currents imposed on all pulsed accelerators is a matter of concern. For it goes without saying that increasing beam intensities manyfold opens up new possibilities for research just as ever higher energy opens new domains of investigation. If, for example, 15 years ago cyclotron currents had been small fractions of microamperes, rather than many microamperes, the discovery of neptunium, plutonium, and other transuranium elements and their remarkable properties would surely have been delayed. Indeed, perhaps the United Nations International Conference on the Peaceful Uses of Atomic Energy in Geneva would not have been held! The problem of producing high currents of high-energy particles is unquestionably an important one.

Many people have given thought to this problem, and the story of their work is interwoven with that leading to higher energies. However, it is less well known to most physicists. It begins, at least for circular accelerators, with a paper published by L. H. Thomas in 1938 in which he showed that the energy limitations of an ordinary cyclotron (because of relativity mass increase with energy) can be overcome by inserting periodic azimuthal variations in the magnetic field so that the particle orbits depart from circular form, the departure being larger for the higher-energy orbits of larger radius. This work of Thomas received but little attention for a period of more than 10 years. This may be ascribed partly to the fact that the cyclotron people had all they could do to develop and exploit the simpler and more straightforward conventional cyclotron until they all became occupied with assisting in the defense of their various countries. After the war, it seemed simpler to raise cyclotron energies by using the principle of phase stability of Veksler and McMillan as embodied in the synchrocyclotron.

A few years after the war, however, at-

The author is director of the Radiation Laboratory, University of California, Berkeley. This article is based on a lecture that was given on the evening of 11 August at Geneva, Switzerland, during the United Nations International Conference on the Peaceful Uses of Atomic Energy.

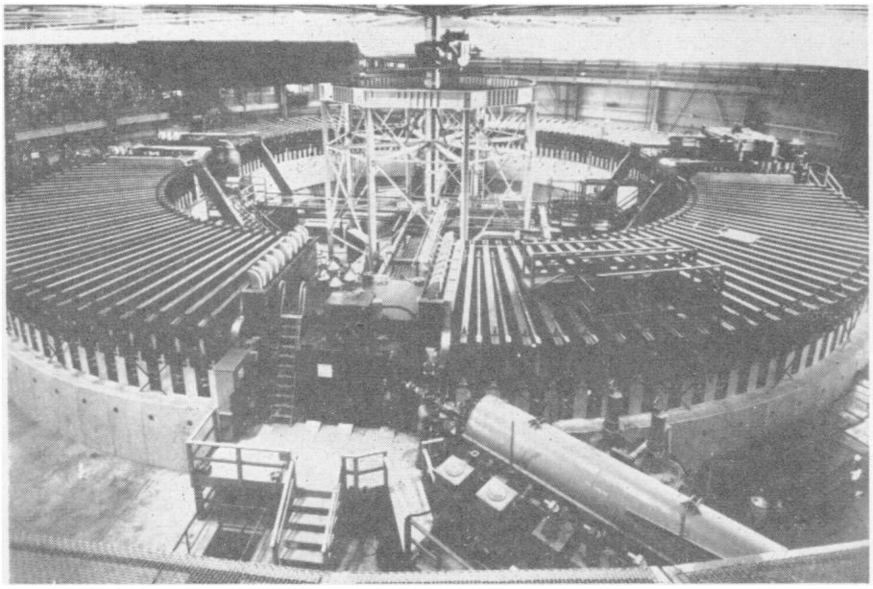


Fig. 1. General view of the bevatron.

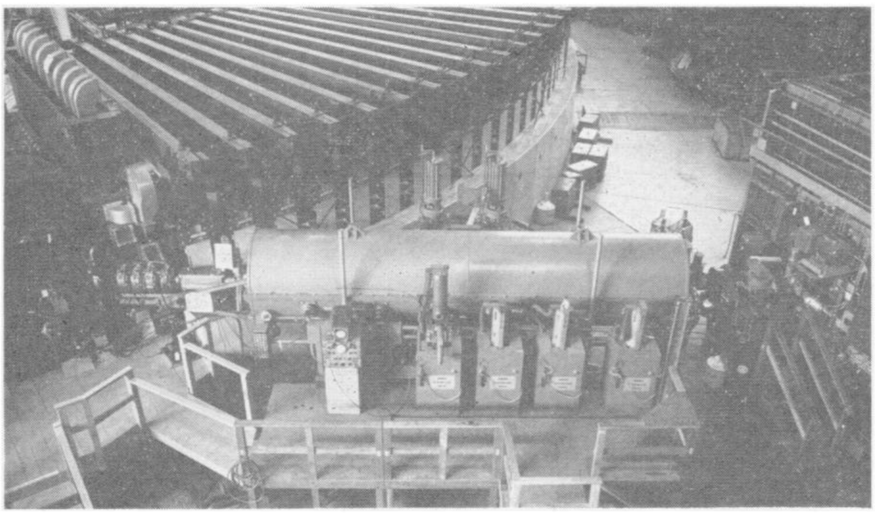


Fig. 2. Bevatron injector.

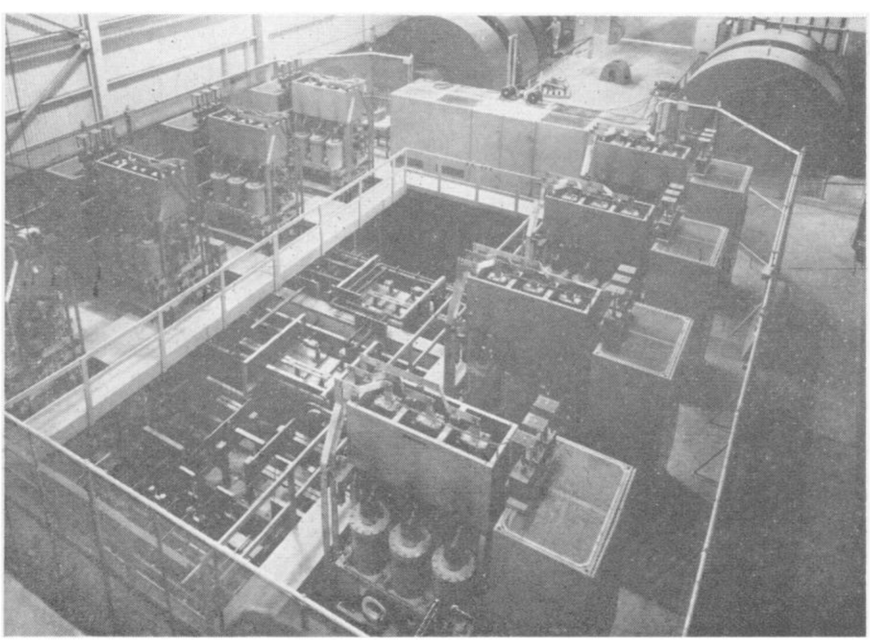


Fig. 3. Bevatron magnet power supply.

tention in our laboratory was drawn to the problem of producing high currents of particles accelerated to energies in the range reached by the synchrocyclotron, and in that connection my colleague McMillan came forward with an independent approach to the problem of a magnetic field that would be suitable for a high-energy cyclotron.

There is not space here to discuss the relationship of McMillan's solution to that of Thomas, although they were basically similar in providing an azimuthal variation in the magnetic field to achieve focusing. Nor is it possible to describe Judd's and later Richardson's contributions to the design of suitable fields, which made possible cyclotrons capable of continuous (in contrast to pulsed) operation with deuterons in the energy range above 700 Mev.

Figure 5 shows schematically the orbit of a particle in such a magnetic field which is a function of both azimuth and radius. Here n varies around the orbit as does the radius, so that the focusing action is partly due to the variation in radius, which produces focusing like that of a wedge-shaped magnet, while the variable n gives the effect of alternating-gradient focusing of Christofolis and of Courant, Livingston, and Snyder.

Now I should like to describe the experiments that have been carried out in our laboratory with an electron model of a cloverleaf cyclotron (so called because of the shape of the magnet pole pieces), which have so beautifully substantiated the theoretical expectations.

One of the pole faces of the magnet of the electron model is shown in Fig. 6. Here the magnet diameter is 40 inches, and the magnetic field chosen has a threefold symmetry.

Figure 7 shows a general view of the interior of the electron model. The variable magnetic gap is in view as well as one of the three accelerating electrodes that occupy the three wide-gap regions between the poles.

Now, in this electron model, where the electrons reach final velocities equal to that of 300-Mev deuterons ($\beta = 0.5$), the magnetic fields are small—only about 20 gauss—and inhomogeneities of the iron make it difficult to produce the desired magnetic field. The mechanical problem of shaping the pole pieces accurately is also quite severe, and consequently field-correcting coils are mounted on the pole pieces as shown in Fig. 8. As is seen, there are a considerable number of concentric coils to vary the average radial value of the field, while a number of coils in the valleys of the gap provide for azimuthal and radial variations.

With these orbit-correcting coils, it was possible to produce the desired field with the desired precision to tenths of 1 percent everywhere.

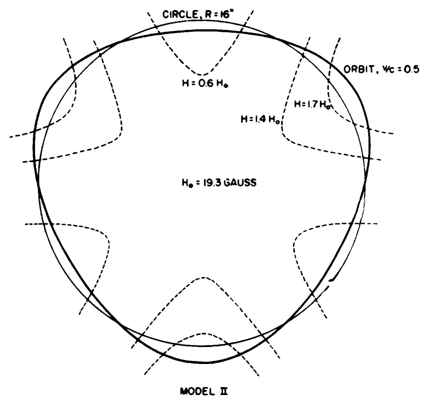
With a suitable electron gun at the

center, the model operated quite in accord with theoretical expectations. The measured threshold voltage to accelerate electrons was only 23 or 24 volts, which corresponded to the energy gain required for electrons to miss striking the electron gun. It is estimated that the electrons required 2000 or 3000 revolutions to reach their final energy of 70,000 volts. This corresponds in an actual accelerator to an electrode potential of about 100 kilovolts to accelerate deuterons to 300 Mev. Thus, it is clear that the Thomas-type field does indeed provide the necessary axial and radial stability and that, within the limits expected on theoretical grounds, the particles can stay in phase with the constant-frequency accelerating voltage.

It was observed that essentially the entire electron beam escaped from the machine in three divergent beams from each of the three hills, and by weakening the field on one of the hills, it was found possible to produce a beam containing 90 percent of the total circulating energy from the hill in question. By use of an external focusing magnet, the external beam could be converged, and all together it appeared that this type of cyclotron, which we called a cloverleaf cyclotron, had the admirable property of easy beam extraction along with high currents at high energy with very low voltages on the accelerating electrodes.

At this stage, I should like to draw attention to yet another approach to the problem of high-current high-energy cyclotrons, which is a by-product of the new and interesting set of proposals now under investigation by the accelerator design group of the Midwestern Universities Research Association (MURA), under the leadership of Kerst, whose interest lies primarily in the attainment of high energies in proton synchrotrons. Their work is so new that it has not yet been put to practical test, although they are now engaged in constructing an electron model accelerator that will explore some aspects of their proposals. It is based on the observations of Keith Symon that a proton synchrocyclotron can be built with a magnet of small radial extent like that of a synchrotron, provided that particles are injected with reasonable energy. This can be done by exploiting the alternating-gradient focusing with its well-known property of "momentum compaction" by which orbits of widely differing energies may be made to be very near each other in space. It certainly will be interesting to see whether such a scheme appears to be as attractive in practice as the alternating-gradient modulated magnets being employed by the Brookhaven and CERN groups for machines in the 20- to 30-Bev range.

The MURA group has introduced the idea of spiraling the hills and valleys of the magnetic field so that particle orbits cross them at a rather steep angle instead of perpendicularly. Applying these ideas to betatrons, they predict that using a greater flux change than necessary to attain the desired energy may free a betatron from its duty-cycle limitation and its current may be increased 10,000-fold! Moreover, with the spirally rigid poles, it is possible to arrange matters so that orbits of all energies are geometrically similar, with the frequencies of radial



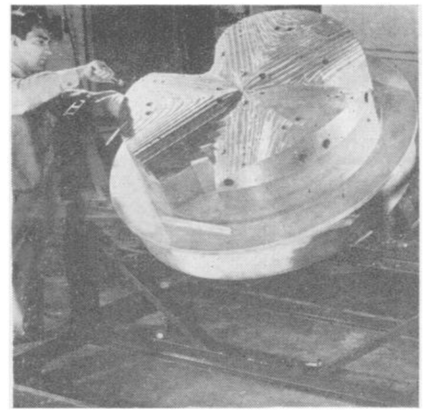


Fig. 5. Left, particle orbit in Thomas-type cyclotron field. Fig. 6. Right, electron model cyclotron pole face.

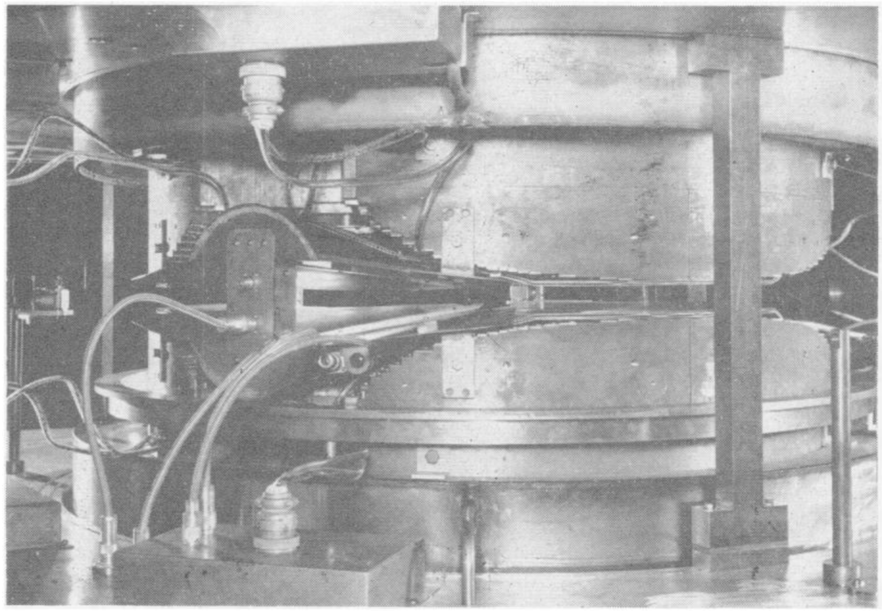


Fig. 7. Interior of electron model cyclotron.

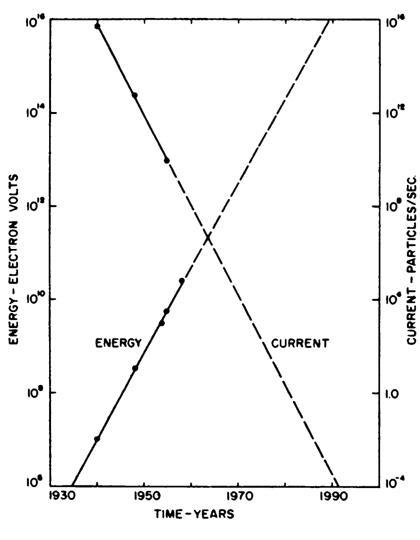


Fig. 4. Extrapolation of accelerator energy and current output.

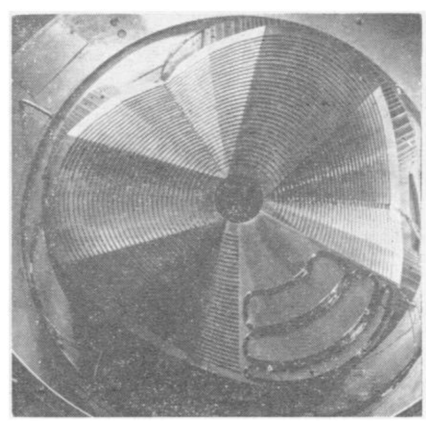


Fig. 8. Electron model cyclotron pole face with field-correcting coils.

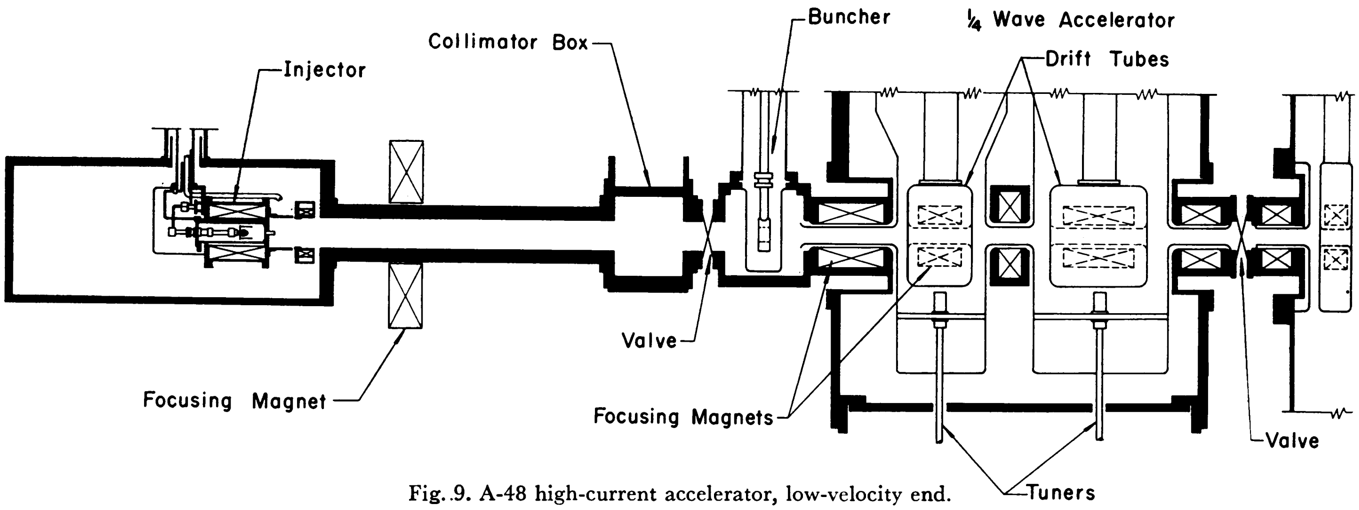


Fig. 9. A-48 high-current accelerator, low-velocity end.

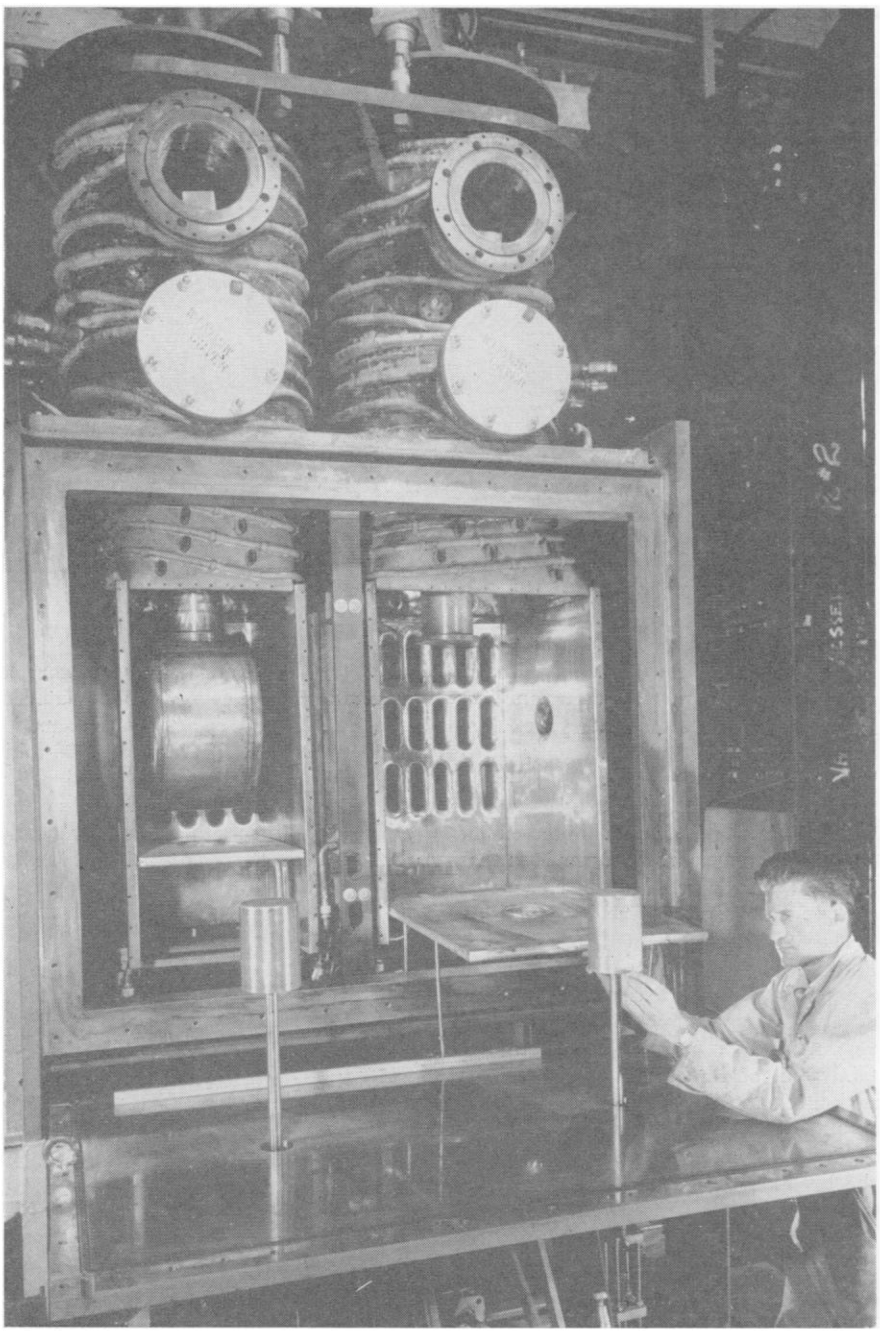


Fig. 10. Quarter-wave accelerator with one drift tube in place.

and axial oscillations remaining constant throughout the acceleration process. Therefore, in principle, troubles with resonance effects can be avoided. This MURA work, therefore, seems to constitute another improvement in the development of fixed-frequency cyclotrons.

All of this work has shown that the original energy limitations of the ordinary cyclotron can be surmounted in a variety of ways. This information can be applied directly to improve the performance or to lower the dee-voltage requirement on existing cyclotrons by simply reshaping the poles. This procedure has already been carried out under the direction of Keith Boyer on the Los Alamos cyclotron and has resulted in very satisfactory operation with a greatly reduced loss of particles during acceleration. The present reasonable energy limit for high-current cyclotrons producing currents of many milliamperes is not easy to establish, but it seems certain that it will increase with the development of accelerator technology that is certain to continue as long as physicists are interested in looking for new problems to solve.

Now I return to the accelerator development work in Berkeley during the last 4 or 5 years. Along with the development of the cloverleaf cyclotron, a greater effort was made in collaboration with the California Research and Development Company to develop the linear accelerator, of the cavity-resonator type devised by Alvarez, for high currents at high voltages. The over-all objective was what might be called a superpower particle accelerator capable of producing thousands of kilowatts of high-energy protons. The linear accelerator development appeared so promising that it was decided to abandon consideration of construction of a cloverleaf cyclotron, which would involve a very large capital expenditure, and to concentrate on the design and construction of a linear machine, the first sections of which would not entail too great a capital outlay and would

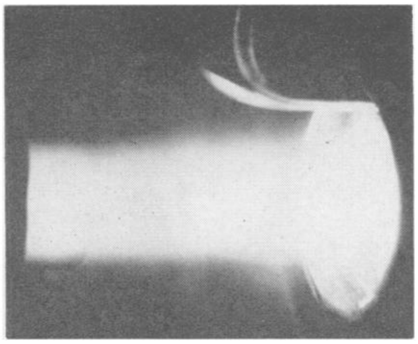


Fig. 11. Half-ampere, 100-kev proton beam entering input aperture of A-48 accelerator.

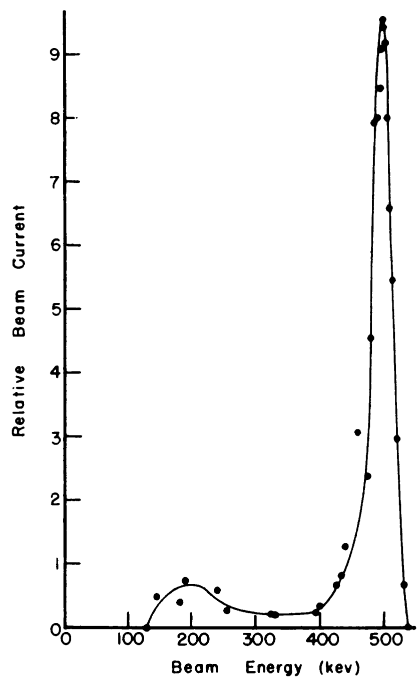


Fig. 12. Energy distribution of beam from quarter-wave accelerator.

allow extension almost indefinitely to higher voltage as desired in the future.

Of course, the first problem was a source of protons of many amperes from which could be withdrawn 100- to 200-kilovolt protons focused into a beam that would pass through an aperture of about 5 centimeters in diameter. After that there was the problem of accelerating the beam in a first stage to about half a million electron volts. Theoretical studies had shown that in a cavity-type accelerator operating at a frequency of 48 megacycles per second, where solenoid focusing was used in the drift tubes, there should be no great difficulty in accelerating such a 500-kilovolt beam on up to many hundreds of millions of volts with little loss and at comparatively high efficiency. In other words, the technical problem seemed essentially that of bringing a large current of ions up to about half a million volts or so, sharply focused and bunched for injection into the linear accelerator of the Alvarez type, which we call the A-48 accelerator.

The arrangement has worked out very well, as is shown in Fig. 9. At the left is the injector, consisting of an arc source in a solenoidal magnetic field mounted on insulators in a vacuum tank. The arc body is maintained at a positive potential up to 140 kilovolts and has produced up to ¾ ampere of focused ion beam. Ions produced in the arc are accelerated by a single gap through a 4-foot length of beam tube and are brought to a focus on a collimating aperture by a large solenoidal magnet, through which the beam tube passes. The diameter of the ion beam is controlled by varying the magnet current, and the centering of the ion beam is controlled by orienting the magnet, which is flexibly mounted.

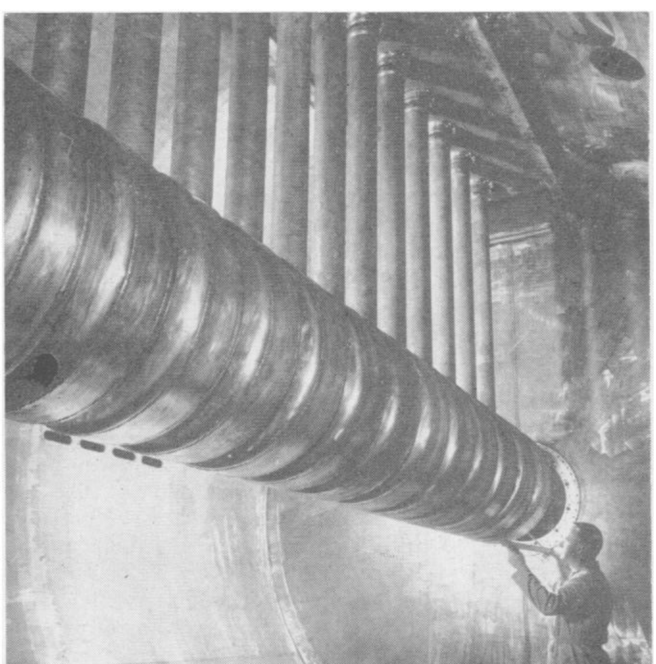
Just beyond the collimating aperture, the ion beam passes through the buncher, which applies a 24-megacycle ripple of 5 to 7 kev to the beam. As a result, a large fraction of the ions arriving at the first radiofrequency accelerating gap are bunched into a small phase angle of the 24-megacycle wave.

The next component shown is the 24-megacycle quarter-wave accelerator. This machine consists of two quarter-wave resonant stems, the ends of which are drift tubes for 24-megacycle acceleration. Each drift tube and stem is housed in a separate cavity to reduce to a minimum the coupling between them. The gap spacing for each drift tube is $(3/2)\ \beta\lambda$ and that between the two cavities is $1\ \beta\lambda$, so that ideally the two stems should operate 180 degrees out of phase. Actually, the two stems and the buncher are all separately driven and the phases between them are adjusted for optimum output.

In each drift tube and at positions before, between, and after the drift tubes, solenoidal magnets are located as shown to maintain beam focus throughout. Figure 10 is a view of the quarter-wave accelerator with one drift tube in place.

Deuterons are accelerated by the quarter-wave machine from 140 kev to about 1 Mev, for which energy the velocity is great enough that the frequency can be increased from 24 to 48 megacycles per second for subsequent acceleration.

Figure 11 shows the ion beam from the injector as it passes from the beam tube into the collimating aperture. When this photograph was made, a continuous beam of about ½ ampere of 100-kev protons was being injected through a 2.5-



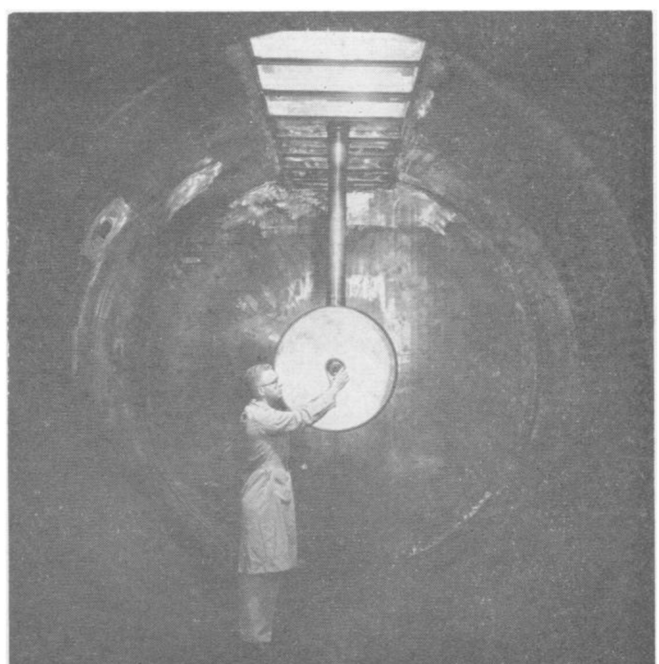


Fig. 13. Left, interior view through side porthole of A-48 cavity. Fig. 14. Right, interior view of A-48 cavity through the beam output port.

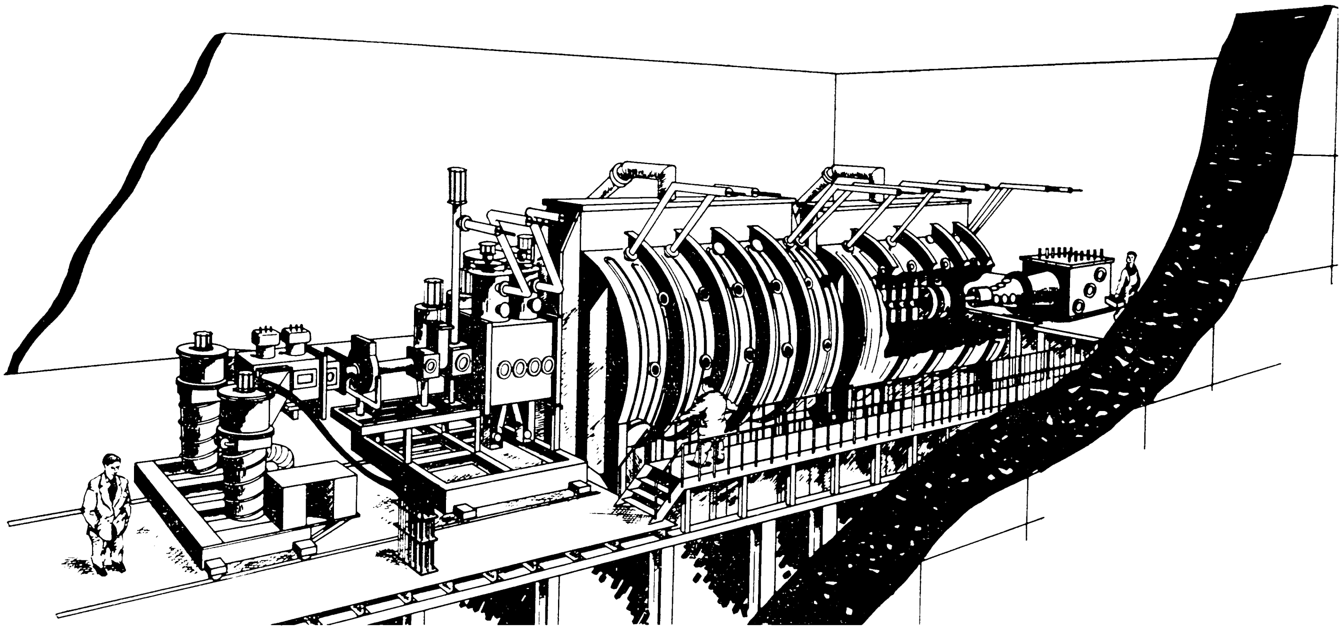


Fig. 15. Perspective drawing of A-48 accelerator.

inch-diameter collimating aperture into the accelerator.

This part of the A-48 accelerator operates continuously and smoothly, delivering several hundred milliamperes of ½-million-volt protons or 1-million-volt deuterons, thus several hundred kilowatts of nicely focused ions reach a target about 1 meter from the last accelerator electrode.

The beam, of course, is bunched into short pulses (less than 10^{-8} second), and the instantaneous currents therefore are of the order of 1 ampere. The energy distribution in the beam when protons are accelerated is shown in Fig. 12. It is seen that most of the beam is close to the desired energy and indeed is very close to theoretical expectations.

We are now building two sections of the A-48 accelerator to produce ¼ ampere of 7.8-Mev deuterons. Figure 13 is a view of the interior of one of the 20-foot cavities looking in through a porthole in the side. The drift tubes are viewed from below and off to one side. The cavity tank is fabricated of copper-clad steed, the drift tube shells of copper sheet, and the supporting stems of heavy-wall steel tubing, copperplated on the exposed surfaces. Figure 14 is another view looking down the line of drift tubes, showing the aperture through which the beam passes. The drift-tube volume is much larger than the beam aperture because of space requirements for water cooling and solenoidal focusing magnets.

The general arrangement of the A-48 high-current accelerator is shown in a perspective drawing, Fig. 15. At the left are located the ion injector, the beam-focusing and steering magnet, the 24-megacycle buncher, and the quarter-wave accelerator as previously described.

The deuteron beam at 1 Mev from the quarter-wave accelerator then enters the first of two 48-megacycle resonant-cavity acccelerator sections, each 20 feet long. A portion of the side wall of the second cavity is cut away to show the drift tubes and supporting stems. As I have already mentioned, each drift tube contains a solenoidal magnet for maintaining beam focus throughout the machine. The gap spacings in both resonant cavities are 1 $\beta\lambda$; that is, the ions receive one accelerating impulse during each radiofrequency cycle.

Since the design deuteron current output at 7.5 Mev is 0.25 ampere, the target system is designed to dissipate 2 megawatts of beam power. To prevent excessive power concentration at the target, the ion beam passes through a rotating magnetic field at the exit aperture so that the beam is slightly deflected and processed over a target spot up to 3 feet in diameter. The target consists of a bank of overlapping tubes of aluminum, magnesium (Dow metal), or other metal with high-velocity water flow to insure good heat transfer.

The construction of this superpower accelerator is well along, and we expect that it will begin operation next year. A recent photograph of the present stage of construction is shown in Fig. 16. I cannot help but wonder what new knowledge will come from the availability in the laboratory of these very high currents of high-energy particles. Just as it is certain that new things of great interest will indeed turn up, so we may be confident that plans will go forward to build additional accelerating sections for this machine for ever higher voltages.

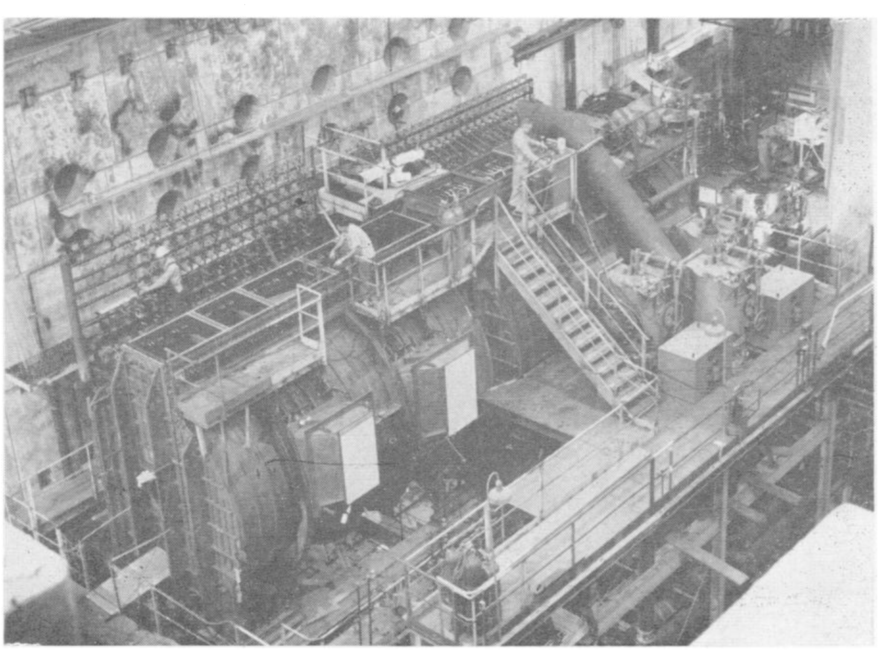


Fig. 16. View of A-48 accelerator during construction.