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HIGH ENERGY ACCELERATORS AT THE UNIVERSITY OF CALIFORNIA RADIATION LABORATORY

Geoffrey F. Chew and Burton J. Moyer

September 9, 1949

Berkeley, California

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HIGH ENERGY ACCELERATORS AT THE UNIVERSITY OF CALIFORNIA RADIATION LABORATORY

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Introduction

This is the first of a series of four articles describing recent research in high energy nuclear physics at the University of California Radiation Laboratory in Berkeley. The term "high energy" is used here to distinguish the energy region above about 20 Mev from that below, the latter having sometimes been called the region of "classical nuclear physics." This dividing line has a manifold theoretical significance which will be made clear in the subsequent articles. Experimentally, 20 Mev is also about the energy at which relativistic effects begin to be noticeable in problems of acceleration. The adjectives "high-energy" and "relativistic," in reference to nuclear particles, will be used interchangeably in these articles.

It seems appropriate, in an account of the high energy physics research at the Radiation Laboratory, to begin with a description of the three new accelerators which are the basic tools. These are the proton linear accelerator, the 184-inch synchrocyclotron, and the synchrotron. All three have been in operation for less than three years. The other operating research accelerators at the Radiation Laboratory are non-relativistic cyclotrons of a design which has been widely publicized. They will not be described again here.

All practical accelerators depend upon the possession of an electric charge by the particle which is to be accelerated. The force, $\vec{F}$, on a particle with charge, e, in an electromagnetic field is given by the Lorentz equation,

$$\vec{F} = e\left[\vec{E} - \left(\frac{\vec{v}}{c} \times \vec{H}\right)\right] \tag{1}$$

where $\vec{E}$ and $\vec{H}$ are the electric and magnetic fields in c.g.s. units, $\vec{v}$ is the velocity of the particle, and c is the velocity of light. An electric field is, therefore, required to increase the energy of a particle, but a magnetic field can be used to curve the orbit in a particularly convenient way. The electric field may in some cases, as for instance in the betatron, be produced by a changing magnetic field.

In using equation (1), the relativistic mass of the particle must be employed if the velocity v is not small compared with c. Thus, if we wish to write $\vec{F} = \frac{d}{dt}(m\,\vec{v})$, the mass must be understood as

$$m = \frac{m_o}{\sqrt{1 - v^2/c^2}} \tag{2}$$

where m_o is the rest mass. The relativistic mass increase is not very important for the proton linear accelerator but it dominates the operation of the other two machines.

For each accelerator there will be three main topics of interest: (1) The geometrical configuration which allows a particle to fall through a "potential difference," $\int \vec{E} \cdot d\vec{s}$, producing its final energy. (2) The focussing and stability characteristics of the beam. (3) The performance of the machine; that is, its capabilities as a research tool. The second point is usually passed over in qualitative discussions, although it is of crucial practical importance. Focussing and stability will receive a considerable share of our attention.

The Berkeley Proton Linear Accelerator[1]

The name "proton linear accelerator" is descriptive and accurate. This

[1]This section is largely abstracted from a complete report by L. W. Alvarez, H. Bradner, H. Gordon, W. K. H. Panofsky, C. Richman, and J. R. Woodyard, to be published in the Reviews of Scientific Instruments.

machine accelerates protons in a straight line, producing a collimated mono-energetic external beam. The general principles upon which the Berkeley linear accelerator is based have been understood for twenty years. Wideröe[2] in 1929 published a description of a two gap linear accelerator, and Sloan and Lawrence[3] built a multi-gap machine in 1931 which successfully employed a radiofrequency electric field to accelerate mercury ions. Nevertheless, there was a general feeling before World War II that radiofrequency linear accelerators would never be appropriate for nuclear research. To accelerate nuclear particles in this way to energies in the million volt region required far higher power than was then available at short wavelengths. The great success of the cyclotron made the prospect of a competitive linear accelerator seem small indeed.

During the war, the main technical bars to the construction of linear accelerators were removed. Radar research led to the development of vacuum tubes capable of producing megawatts of pulsed radiofrequency power down to the microwave range. It seemed, too, as if an upper limit at around 100 Mev to the energy attainable by cyclotrons would soon be reached. We shall see later that this difficulty was circumvented, but at the time it led to a reawakening of interest in linear accelerators, which possessed no such limitation. At Berkeley, L. W. Alvarez was the chief supporter of the "linac," and he supervised the construction of the present 40 foot machine. The Berkeley accelerator was actually originally designed as a pilot model for a machine which might eventually reach the billion volt energy region! An extension to the 200-300 Mev range may still be made, but at present, the original plans have been dropped in favor of the "bevatron" or proton synchrotron. The 40 foot accelerator is being used now as a research tool.

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[2]Wideröe, Arsch. f. Electrotechnik 21, 387 (1929)

[3]Sloan and Lawrence, Phys. Rev. 38, 2021 (1931)

General Description of the "Linac"

A direct quotation from reference (1) will serve as a basis for describing the machine. "The accelerator consists of a cavity 40 feet long and 39 inches in diameter, excited at resonance in a longitudinal electric mode with a radio frequency power of about 2.5 megawatts peak at 202.5 megacycles. Acceleration is made possible by the introduction of 46 axial drift tubes into the cavity, which is designed such that the particles traverse the distance between the centers of successive tubes in one cycle of the r.f. power."

If the drift tubes are temporarily ignored, one has, therefore, a large cylindrical cavity with copper conducting walls in which a standing electromagnetic wave is set up. In the particular mode chosen, the electric field is parallel to the axis of the cylinder, its magnitude being a maximum at the center of the tank and falling to zero at the radial walls. The electric field, in this simplified situation does not vary along the axis of the cylinder.

At any instant, the lines of electric force would look as in Fig. 1, with an amplitude varying sinusoidally in time. (The instantaneous power flow, however, is radial not longitudinal.) The period is easily calculated, since the situation is exactly like that of a circular membrane, where

$$\omega/c = 2.4/\text{radius}$$

Here c is the velocity of light, so we find

$$T = \frac{2\pi}{\omega} = 2.62 \frac{\text{radius}}{c} = 4.3 \times 10^{-9} \text{ sec}$$

or a frequency of about 230 megacycles. The actual resonance frequency, quoted above, is lower because of the presence of the drift tubes.

There is, of course, at all times in this mode a magnetic field perpendicular to the electric. The magnetic lines of force are circumferential, as shown in the cross section of the cavity, Fig. 2. The magnetic intensity on the axis is zero although it does not vanish on the radial walls. It plays no direct role

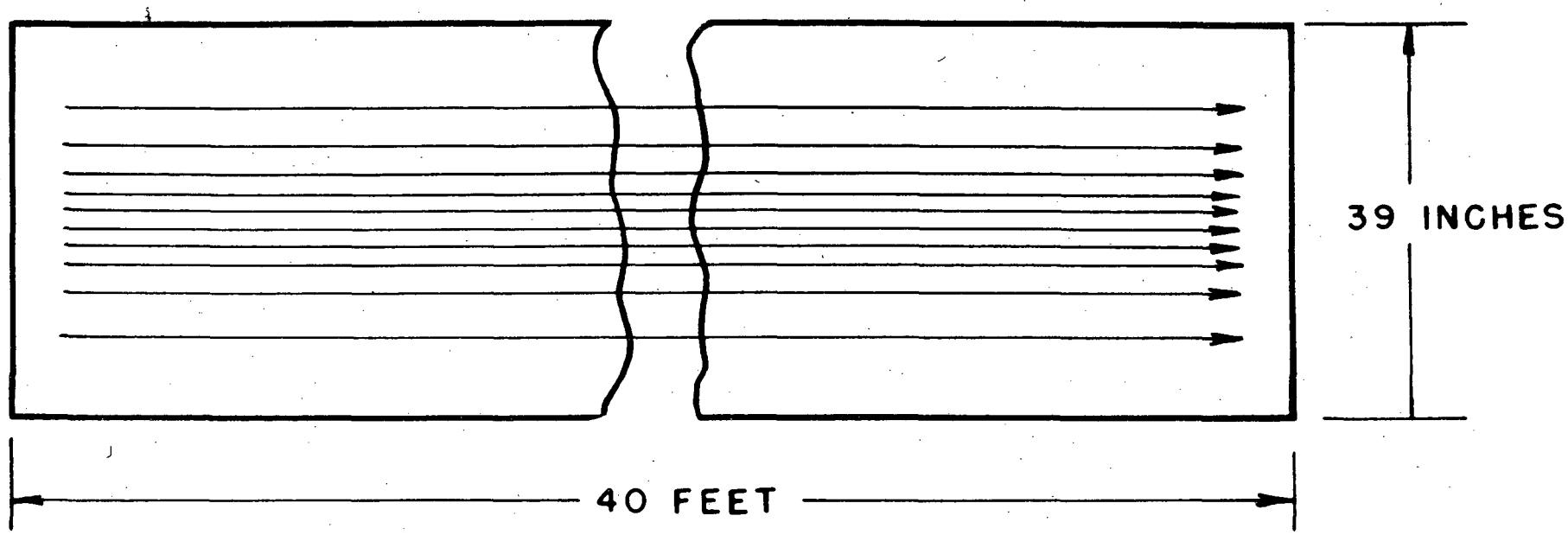

Fig. 1

Electric lines of force; side view of tank.

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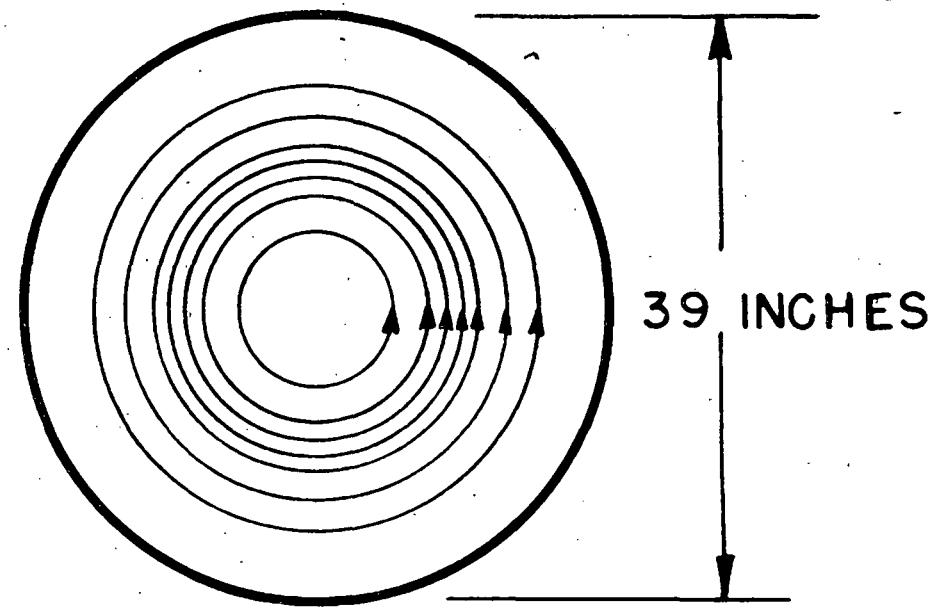

Fig. 2

Magnetic lines of force; end view of tank.

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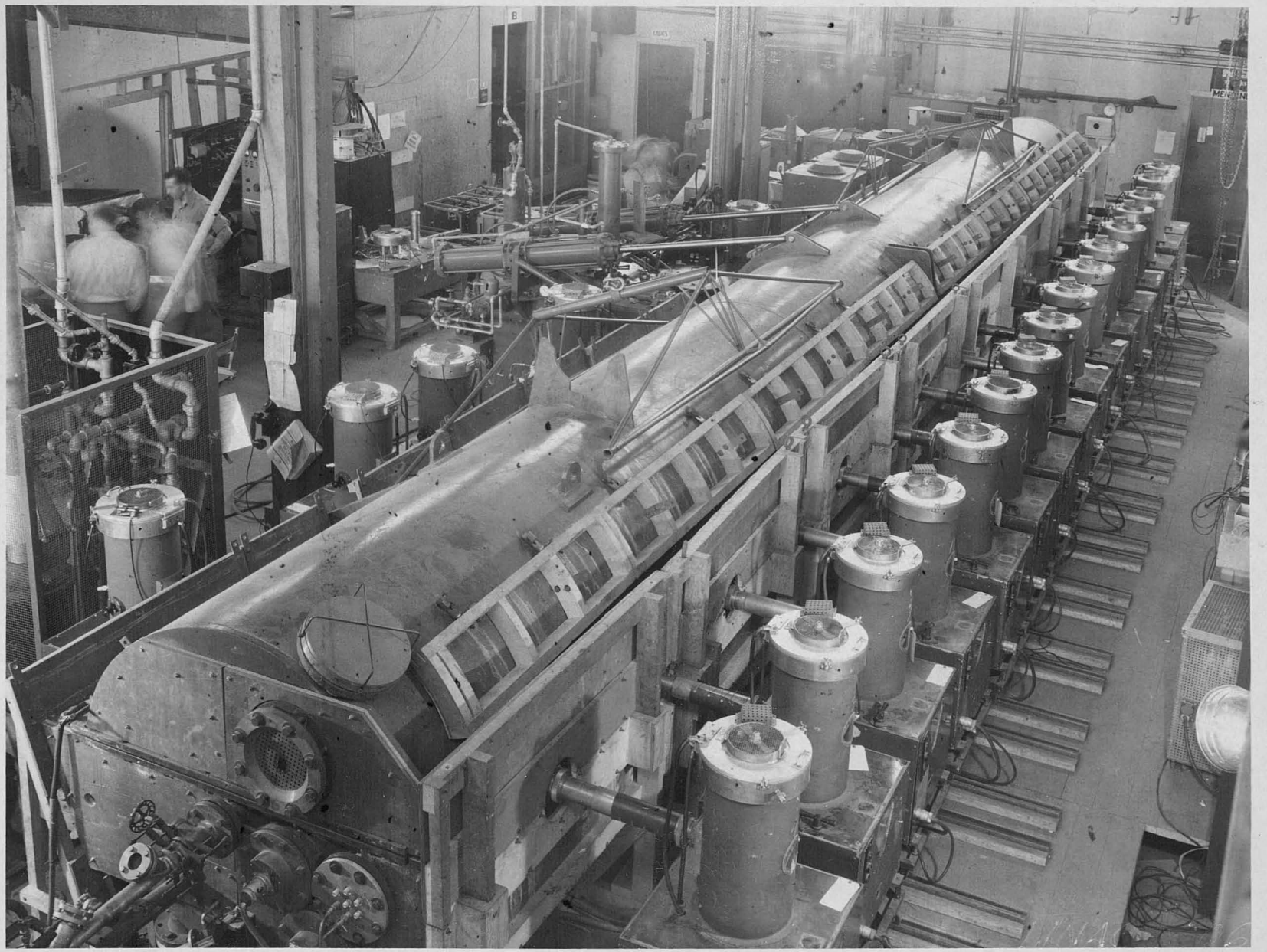
either in the acceleration or focussing of the protons since they must travel near the axis and never acquire extreme relativistic velocities. The cavity is excited however via the magnetic field, whose time variation is then responsible for the electric field.

The scheme of acceleration is now clear. Protons are introduced into one end of the tank on the axis. When the electric field is in the correct direction, the protons are accelerated along the axis. If the protons could traverse the entire length of the cavity in half a period, i.e., before the electric field could change sign, there would be no need of further complications. It turns out, however, that about 46 periods are required to make the trip, so 46 "drift tubes" are introduced along the axis to shield the protons from the adverse half cycles of the electric field. A photograph of these drift tubes is shown in Fig. 3b. They are simply cylindrical sections of a heavy copper tube, cut in appropriate lengths. Their presence in the cavity modifies the electromagnetic field so that the crude considerations given above do not suffice for the actual problem of design. For more detail, readers are referred to the complete report.[1]

The question naturally arises as to what limits the amplitude of the electric field along the axis when there is a supply of power to the cavity. The answer is that the copper cavity walls are not perfect conductors and that there is a flow of energy into the walls which is dissipated as heat. When this power loss equals the power input, the electric field has reached its maximum amplitude. Putting it the other way around, the value of the desired electric field amplitude determines the power input required. In practice, power is supplied in pulses, not continuously, and it turns out that for a fixed electric field amplitude the energy required per pulse is inversely proportional to the square of the resonance frequency. Since the cost of important portions of the equipment is proportional to the energy per pulse, the advantage of a high frequency is obvious. High frequencies, of course, mean small cavity radii, and the limit



EXTERNAL VIEW OF LINEAR ACCELERATOR. INPUT IS AT NEAR END, THE VAN DE GRAAFF BEING TO THE LEFT JUST OUTSIDE THE PICTURE.

FIG. 3A

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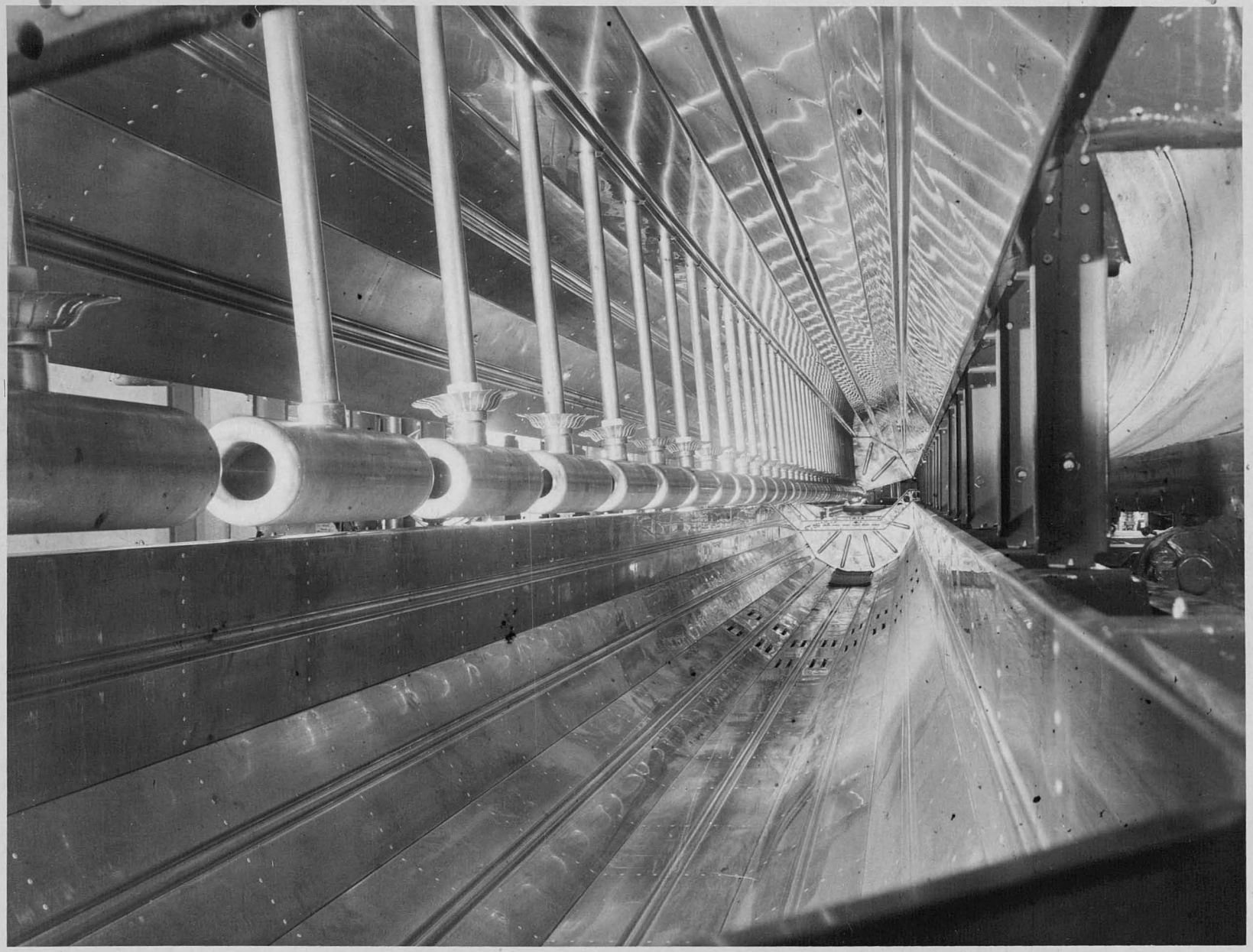

INTERIOR OF LINAC TANK SHOWING DRIFT TUBES.

FIG. 3B

OZ 655

is set by the question of geometrical aperture as well as by availability of equipment.

Stability of the Linac Beam

The very important question of beam stability has two quite different aspects, which will be called "phase focussing" and "radial focussing," respectively. Phase focussing refers to those restoring forces which act in the longitudinal direction and tend to keep the protons arriving at the successive gaps at the proper time or "phase" with respect to the oscillations of the electric field. Radial focussing has to do with the radially acting forces which keep the protons on or near the axis of the cavity.

It is clear that the centers of two successive gaps between drift tubes must be separated by just the distance which a proton will traverse in one period of the electric field oscillation.

Thus, if the average velocity of the proton in the nth drift tube is v_n,

$$x_n = v_n T,$$

where x_n is defined in Fig. 4 and T is the oscillation period. The drift tubes at the exit end of the cavity are, therefore, longer than those at the input end in the ratio of exit to input proton velocity. Even with this condition satisfied, a negligible number of protons could stay in correct phase for the whole 46 cycles if there were no phase focussing. It will be recalled that the electric field is not constant in time as the proton crosses a gap. Suppose that a proton passing C_n (Fig. 4) at the correct time is going slightly faster than the velocity for which the tube length and separation were designed. The proton will arrive at the next gap too soon and will consequently encounter an electric field which is either stronger or weaker than had been intended, depending on whether the field is decreasing or increasing. If the field is stronger, the proton's velocity is thrown even farther out of line, and it eventually falls completely out of phase. If the field is weaker, however, the proton receives a smaller

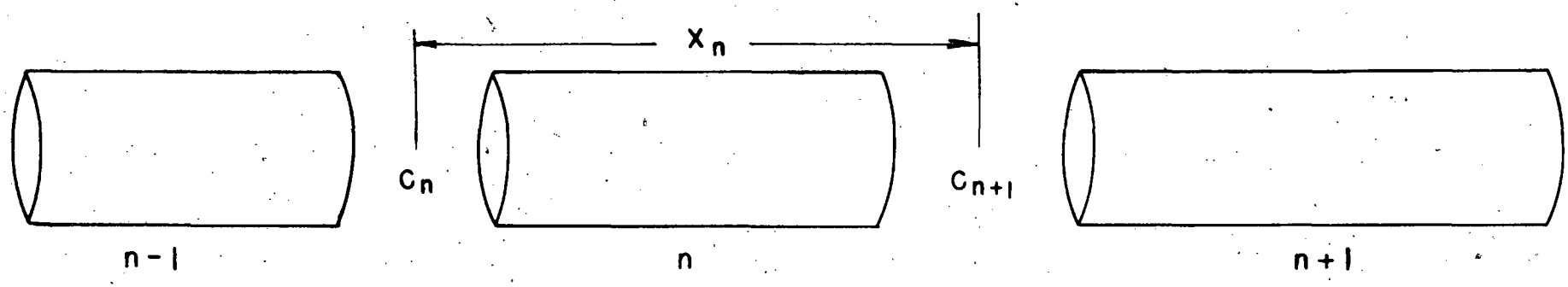

Fig. 4

Drift tube configuration, showing the distance a proton must travel in one period of the electric field oscillation.

kick than normal so that its velocity after crossing the gap is closer to the selected value than before. An analogous situation exists if the proton starts out too slow, with all statements just reversed. Again it is the increasing field which "bunches" and the decreasing field which "debunches" the protons; so that of the half cycle during which the electric field is in the correct direction for acceleration, only the increasing portion can be used.

We can define the proton's phase at the nth gap, $\phi(n)$, as the difference between its actual arrival time at C_n and the selected time for this arrival, expressed in radians. From the arguments of the above paragraph we see that the selected time must be during the quarter cycle which has a positive and increasing field. If the proton is injected into the first gap with a velocity not too far from the proper value and with only a small phase, $\phi(1)$, then during the passage through the cavity its phase will oscillate about zero due to the continuous restoring influence described above. In the 40 feet of acceleration there will be about two such phase oscillations. The largest permissible initial phase amplitude depends on the selected time. It is about 30° in actual operation, when the selected phase is 20° before the maximum. (See Fig. 5.)

The second stability problem concerns radial oscillations. What forces are there to keep the protons in a narrow beam along the axis of the cavity? It has already been pointed out that the magnetic field has negligible influence. If there were no radial components in the electric field, one might hope to inject a well focussed beam and get it back again at the output end. The field between drift tubes necessarily has a radial component for any point off the axis, however, just because the longitudinal component has to vary along the axis. In other words, the condition, div E = 0, requires $\frac{\partial E_r}{\partial r}$ to be non-zero if $\frac{\partial E_z}{\partial z}$ fails to vanish. We know that E_z, the longitudinal component, is zero inside the drift tube and non-zero in the gap. Consequently if the radial

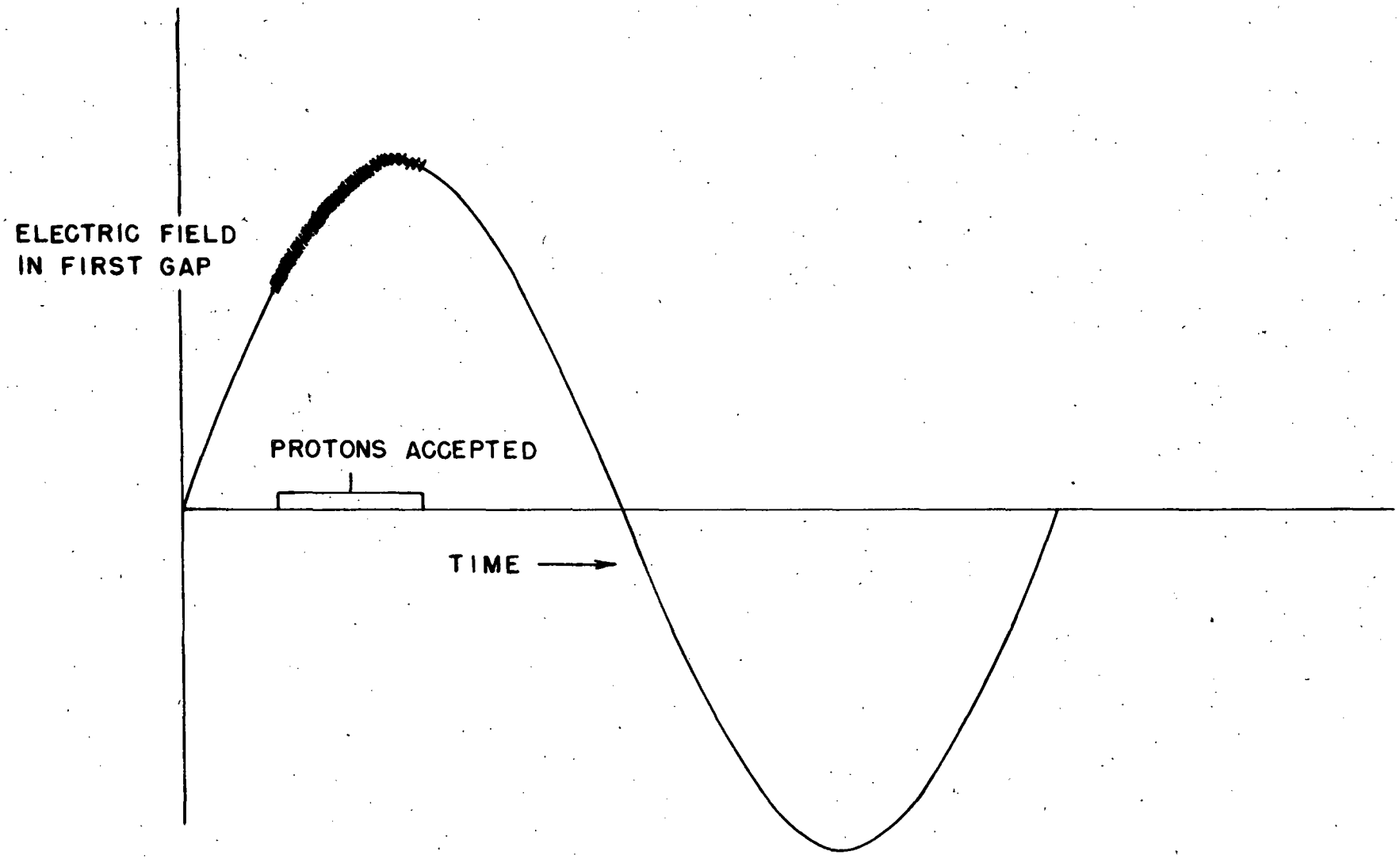

Fig. 5

Time variation of the electric field, showing the interval during which protons can be accepted for stable acceleration.

component, E_r, is zero on the axis, it is not zero a finite distance away from the axis and may be such as to either focus or defocus the beam radially. It can be proved that unless a grid or foil is introduced across the entrance end of the drift tubes, the radial field defocuses when the conditions are correct for stable phase oscillations. Qualitatively, this point can be understood as follows: The electric lines of force between drift tubes look roughly as in Fig. 6, in the absence of foils or grids.

The first half of the gap is a focussing region and the second half defocussing. The electric field intensity must be increasing with time, however, to achieve phase stability, and this means that the second half of the gap outweighs the first. The net effect is defocussing. This simple argument is only true if the fractional increase in proton velocity per gap is small so that the time spent in each half of the gap is about the same.

The only way to avoid this defocussing is to introduce charge into the beam, allowing the electric lines of force to end abruptly without swinging out again. This can be done by means of a grid or foil across the entrance of each drift tube. In the new situation the lines of force may look as in Fig. 7, so that the net effect now is one of focussing.

At the time the linear accelerator was planned, it was thought that foils were more desirable than grids, since the latter give an exponential attenuation with increasing number. Consequently, an injection energy of 4 Mev was used, in order to bypass the problem at low energies, where multiple scattering in the foils would attenuate the beam seriously. (Multiple scattering increases rapidly with decreasing energy.) The 4 Mev injection beam was obtained from a pressure Van de Graaff generator of conventional design. Actual tests showed later that foils were destroyed by sparking in the tank, and grids replaced them with apparently just as good focussing properties. The present grids are extremely

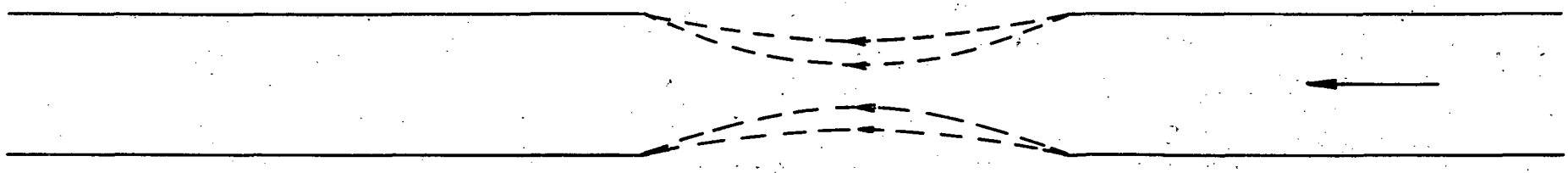

Fig. 6

The electric field between drift tubes, without grids or foils.

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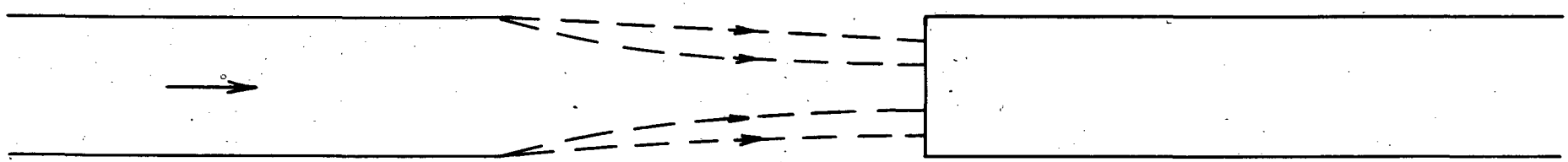

Fig. 7

The electric field between drift tubes when a conducting grid or foil is placed across the tube entrance.

OZ 649

transparent, the whole set of 46 removing only about half the beam. Since the multiple scattering problem does not exist with grids, it would now be possible to inject at a much lower energy. (The grid attenuation in a long machine could be eliminated by changing over to foils at high energy, where the scattering loss is small.) However, the Van de Graaff generator is working so well that the status quo will be maintained.

Linac Performance

In June, 1949, the performance of the Berkeley proton linear accelerator was as follows: Power was supplied to the cavity in pulses 30 times per second, each pulse lasting 600 microseconds, of which 525 microseconds were useful, i.e., at maximum field amplitude. A fraction, 1/30, of the 1.0 milliampere injection current from the Van de Graaff was accepted for acceleration, and of this, about one-half was removed by the grids. What remained amounted to an average current of 0.25 microamperes, or a peak current of 16 microamps during the pulses. The average energy of the emerging protons is between 31.5 and 32 Mev, with a spread of less than 100 kev (0.3 percent). The beam is very well collimated, about 85 percent passing through a circular hole 1/8 inch in diameter. The angular divergence is 10^{-3} radians.

As far as reliability of operation is concerned, there were only three openings of the tank for repairs involving leaks, etc., during the first year of operation. Time lost in repairing the power supply units was negligible. Originally the main source of trouble was the Van de Graaff generator, but this is now very reliable. The machine is operated 16 hours a day, 6 days a week, with beam available 85-90 percent of the time. At present a modification is under way which, it is hoped, will raise the average current by a factor of more than 10. The fraction of the injected beam which arrives in an acceptable phase will be increased by an appropriate bunching of the protons before they

enter the cavity, in the manner employed in klystrons. Two large oscillators will eventually replace the 27 now used. This will involve only four vacuum tubes instead of 108.

The performance of the linear accelerator, for proper evaluation, must be compared with that of the synchrocyclotron, to be described next. The external beam will be seen to be 5000 times more intense in pulses 40,000 times as long, although at a much lower energy. The proposed extensions of the linear accelerator should be able to overcome the energy discrepancy while still maintaining the advantage in intensity and pulse length.

The 184-inch Synchrocyclotron

Before the last war, work had begun at Berkeley under the encouragement of E. O. Lawrence on what was thought of then as a giant accelerator. The object was to push to the limiting energy permitted by the cyclotron principle. The basis of conventional cyclotron operation is the fact that the orbital period of an ion circulating in a uniform magnetic field is independent of the velocity so long as the latter is small compared with c. The period is given by

$$T = \frac{2\pi mc}{eH} \qquad (3)$$

which can be derived from equation (1). Thus, an electric field across a diametral gap, which oscillates with just this frequency, will always find the ion in the correct phase to be accelerated if it started in this phase. One would expect the maximum energy attainable for a fixed magnetic field to be set only by the outer radius of the cyclotron (the orbital radius expands in proportion to the ion momentum), and to be independent of the amplitude of the applied electric field. However, in equation (3) the mass appears, which means that as the velocity of the particle increases the corresponding mass increase will cause the period to lengthen. If too many cicrulations in the cyclotron are required and too high a velocity acquired, the ion will eventually fall out of

phase with the electric field and no longer be accelerated. To reach a high energy, therefore, the applied electric field must be so strong that not many circulations are necessary. The original plans for the 184-inch Berkeley cyclotron envisaged a dee voltage of one to two millions volts! This necessitated a very large magnetic gap and gave promise of extraordinary difficulties. Even so, the maximum energy for deuterons was to be only 70 Mev. To go higher seemed impossible.

After the war work on the big machine was resumed under the supervision of R. L. Thornton, but before completion, E. M. McMillan[4] at Berkeley and V. Veksler[5] in Russia independently proposed a scheme to remove the upper limit on the energies attainable and eliminate the need for large dee voltages. Oliphant, in England during the war, had also thought of the scheme which is based on the existence of phase stable orbits. Since not only the synchrocyclotron but also the electron synchrotron and the proposed bevatron or proton synchrotron depend on this principle, it is worthwhile to devote a separate section to it.

The Principle of Phase Stability

The increase of orbit period with velocity, which was an undesirable feature in the conventional cyclotron, actually makes the phase stable orbits possible. In direct contrast to the linear accelerator, the faster a particle goes in a cyclotron, the longer it takes to make the trip between successive gaps. This is because the radius of curvature increases and the longer path more than compensates the increased velocity. Therefore, the same type of argument that was applied to the "linac" will in this case show that if the ion arrives at the gap when the electric field is decreasing, phase stability can result. This means that for a fixed magnetic field H and a fixed frequency ω of the electric

[4] E. M. McMillan, Phys. Rev. 68, 143 (1945)

[5] V. Veksler, J. Phys. U.S.S.R. 9, 153 (1945)

field, an ion of mass near

$$m = \frac{eH}{\omega c}$$

or total energy near

$$E = mc^2 = \frac{Hec}{\omega} \qquad (4)$$

can revolve indefinitely in a cyclotron orbit with the appropriate radius. If its energy is momentarily larger than the resonance value above, it arrives at the gap later, relative to the phase of the gap voltage, on each successive turn and eventually finds a retarding field to slow it down. If the energy is smaller than the resonance value, the reverse is true. The "synchronous phase" in this case, about which the phase of the ion will oscillate, corresponds to that time at which the electric field is zero, going from positive to negative. (See Fig. 8.)

Clearly the ion, on the average, gains no energy from the electric field and the amplitude of the latter can be very small. If now H is increased and/or ω decreased by a small fractional amount, the resonance energy increases by a correspondingly small amount. The ion is able to readjust itself and will oscillate about the new energy. In the process it has gained some energy from the electric field; and if the small changes in H or ω continue, the energy of the ion can be increased indefinitely. It is necessary, of course, to have a very good vacuum in the cyclotron tank so that in the course of this long trajectory the ions are not scattered.

Bohm and Foldy[6] have given a complete discussion of the phase oscillations in which they point out the analogy to a pendulum which is acted upon by a constant torque. A given rate of change of the magnetic field or the frequency corresponds to a certain rate of increase of energy which must be supplied by the electric field. This is the external "torque" and it displaces the synchronous phase

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[6] D. Bohm and L. Foldy, Phys. Rev. 70, 249 (1946)

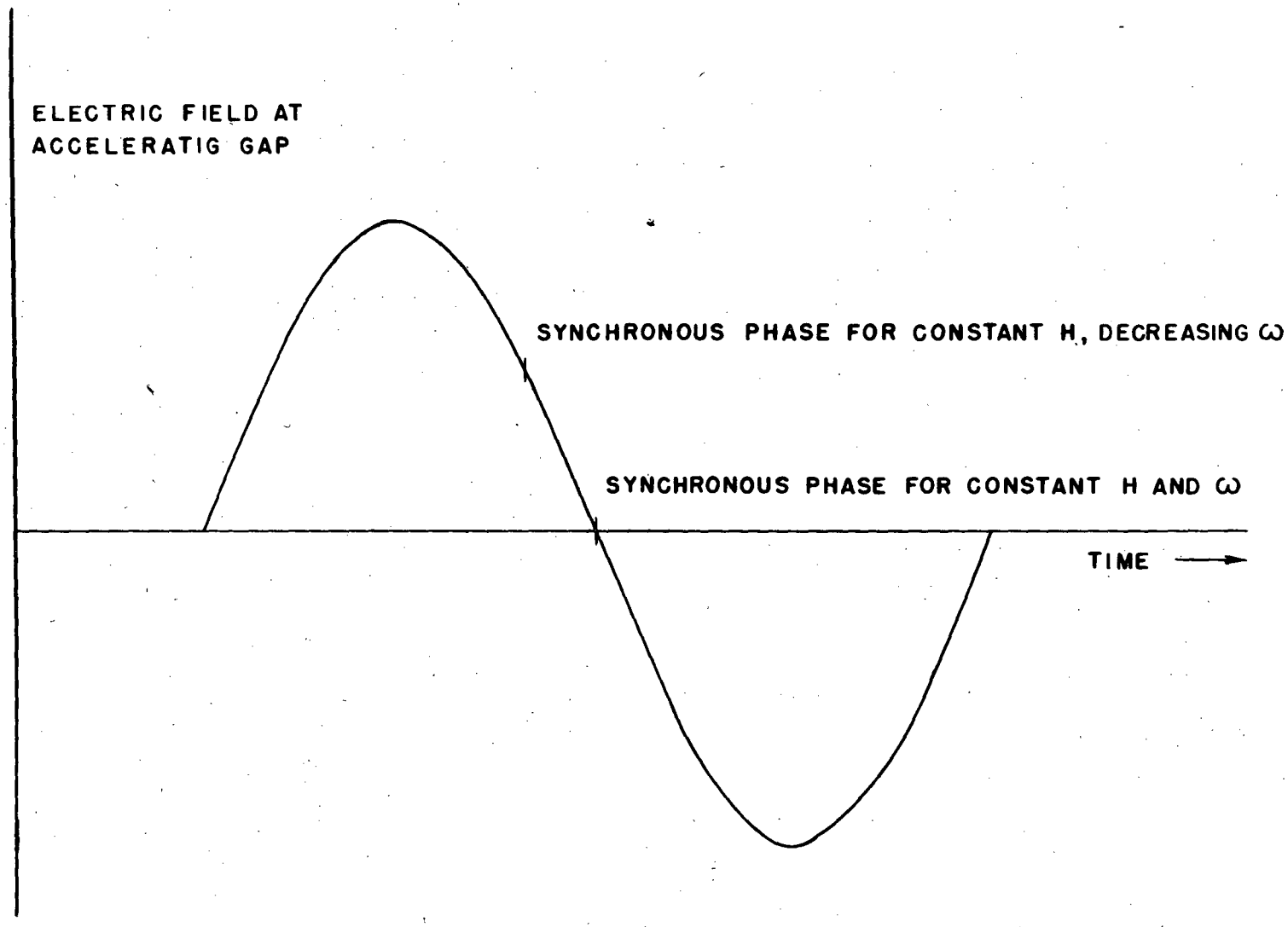

Fig. 8

Time variation of the electric field at the accelerating gap, showing two possible positions of the synchronous phase.

(or rest point of the pendulum) as shown in Fig. 8. If the initial displacement of the ion phase from this rest point is not too great, it will execute oscillations with an amplitude which decreases with increasing energy. An ion once trapped in a stable orbit will stay trapped. The only problem is to get it properly started.

That the phase stable orbits could actually be used to accelerate an appreciable number of ions was proved in 1946 by experiments on the old 37-inch Berkeley cyclotron.[7] Although the maximum energy was only 7 Mev, this was achieved with a peak potential across the gap of 3 kev! The time average current was 0.2 microamperes. This is adequate for many purposes, even though several hundred times less than can be achieved by conventional continuous operation. The relativistic mass increase expected at higher energies was simulated by causing the magnetic field intensity to fall off radially. This was then compensated by decreasing the frequency of electric field oscillation during the acceleration. As expected, there was no appreciable change in the number of ions in a pulse during the 5000 revolutions required. The limitation on the current lay in the ability of the ion source to deliver at the right place and in the right phase at the start.

General Description of the Synchrocyclotron

When it became evident that a dee voltage of only a few tens of kilovolts would be adequate, it was possible to modify the design of the 184-inch cyclotron so as to reach more than twice the energy originally hoped for. The magnetic gap could be reduced to 19 inches, allowing a field of 15,000 gauss at the center. To achieve the synchronous operation, it was necessary to modulate the frequency and not the magnetic field, since the magnet (already built) was not constructed of laminated iron. The required frequency variation was obtained from a rotating

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[7] J. R. Richardson, K. R. MacKenzie, E. J. Lofgren, and B. T. Wright, Phys. Rev. 69, 669 (1946)

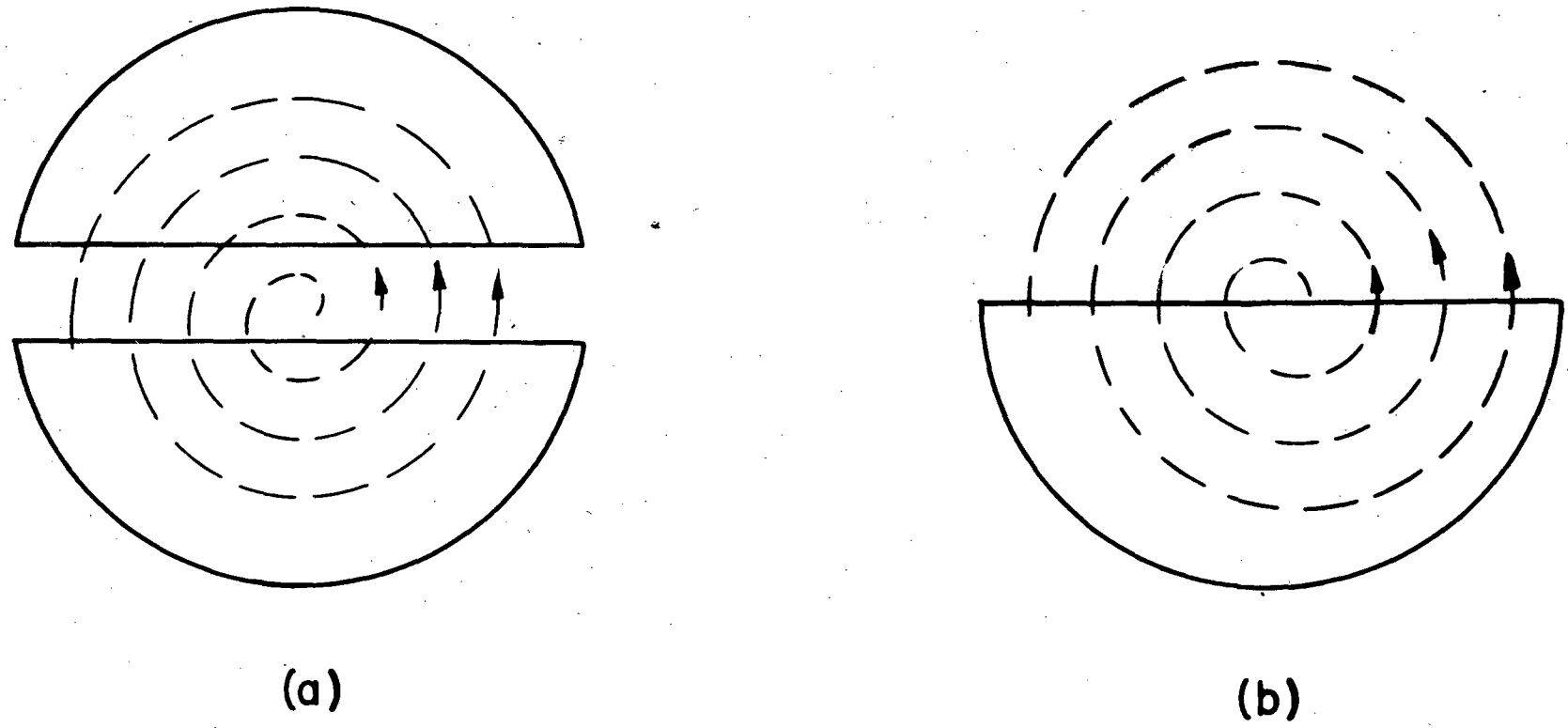


Fig. 9

(a) Dee configuration in conventional cyclotron.

(b) Dee configuration in Berkeley synchrocyclotron.

condenser which modulated the capacitance of the oscillator circuit.

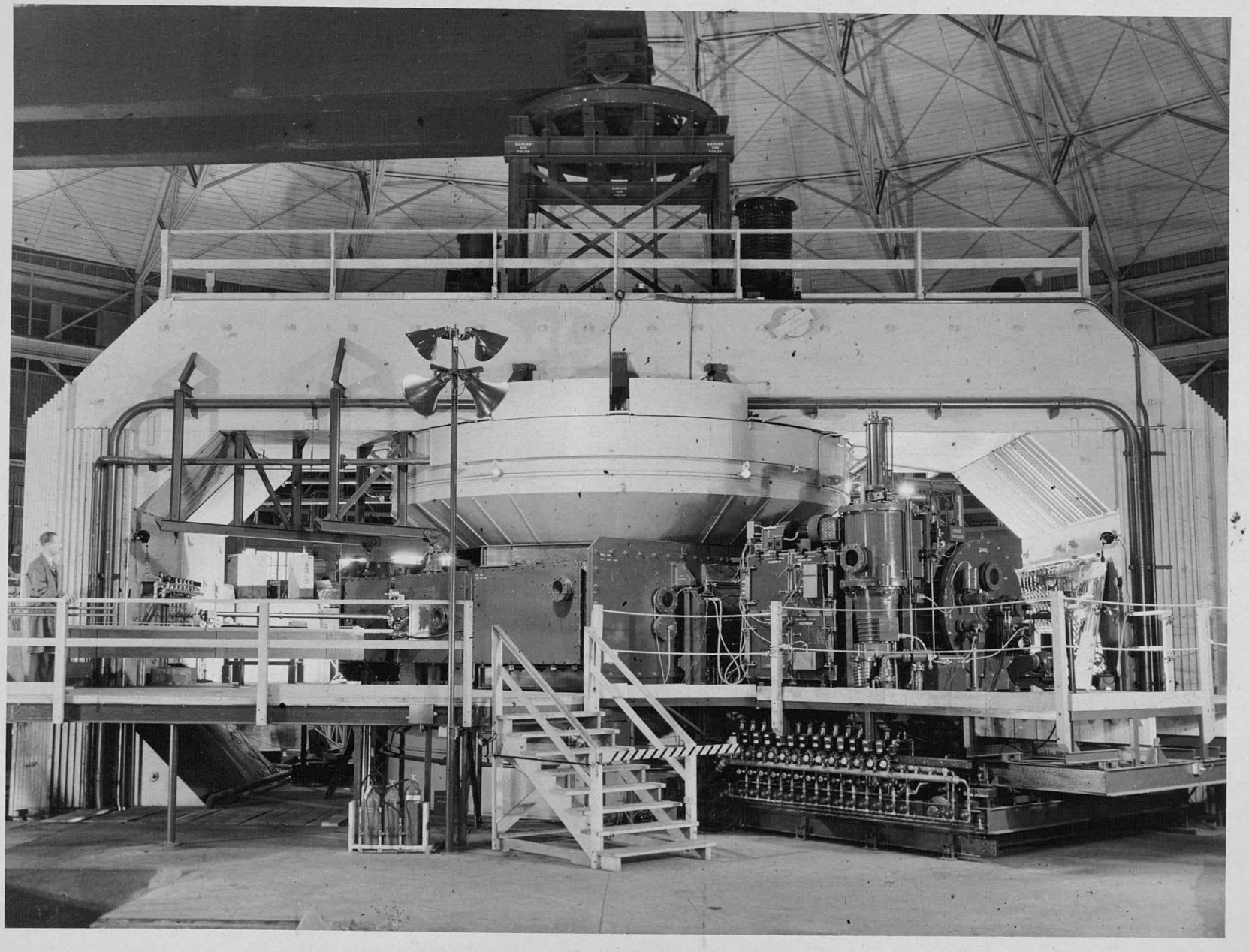
With the stronger magnetic field and the possibility of utilizing almost the full radius, the following maximum particle energies have been achieved: 190 Mev for deuterons, 380 Mev for alpha particles, and 350 Mev for protons. The dee voltage usually employed is 20 kev but this figure is not at all critical. Each ion makes about 10^4 revolutions, picking up 7 or 8 Mev each time around and taking about a millisecond to complete its total trajectory. The cycle is repeated 120 times a second, the ion source at the center being pulsed to coincide with the start of each cycle.

Because electric focussing is so inconsequential in the 184-inch machine (see next section), it was possible to have only a single dee rather than the double dee arrangement of a conventional cyclotron (see Fig. 9). This is a welcome simplification and facilitates access to the tank. The height within the dee available to the beam is five inches.

The deflection scheme which can be used to get part of the circulating ions outside the tank is quite interesting. When a group of ions has reached its maximum radius (about 81 inches, see next section), it can be given a radial kick by an auxiliary electric field. This displaces the center of the orbit, as in Fig. 11. The next time around the ions come much closer to the outer edge of the pole faces and encounter a region where the magnetic field has been intentionally weakened. They can then escape down a specially constructed channel through the shielding. The resulting pulse has a duration of $\sim 10^{-8}$ sec. This elaborate scheme is necessary because of the close spacing of successive turns, precluding the possibility of "peeling off" an outer orbit as in a conventional cyclotron deflector.

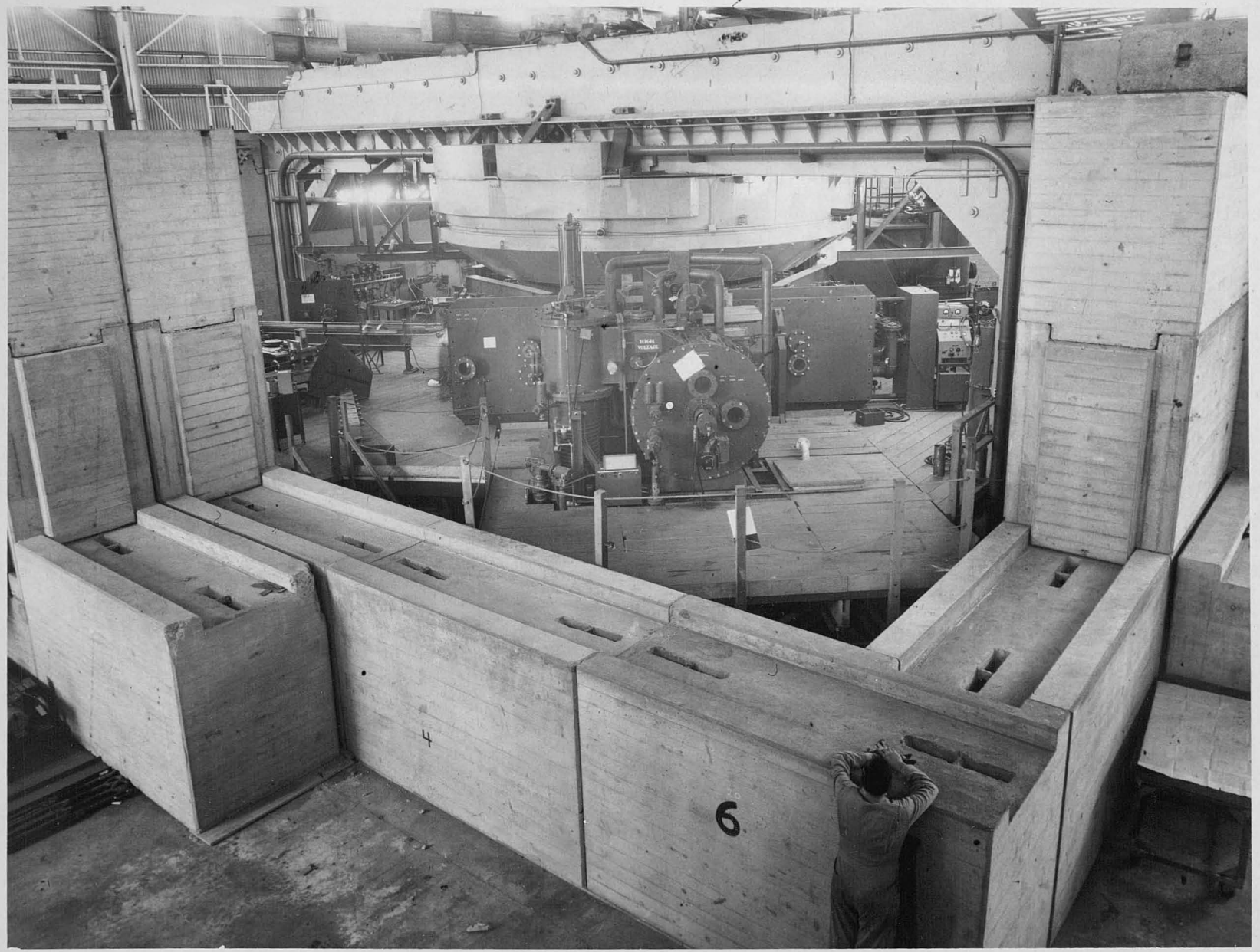
Injection and Stability of the Synchrocyclotron Beam

It has already been pointed out that the beam is phase stable and that the



SYNCHROCYCLOTRON WITHOUT SHIELDING.

FIG. 10 A



VIEW OF SYNCHROCYCLOTRON WITH SHIELDING PARTIALLY IN PLACE. EACH BLOCK IS FIVE FEET THICK.

FIG. 10B

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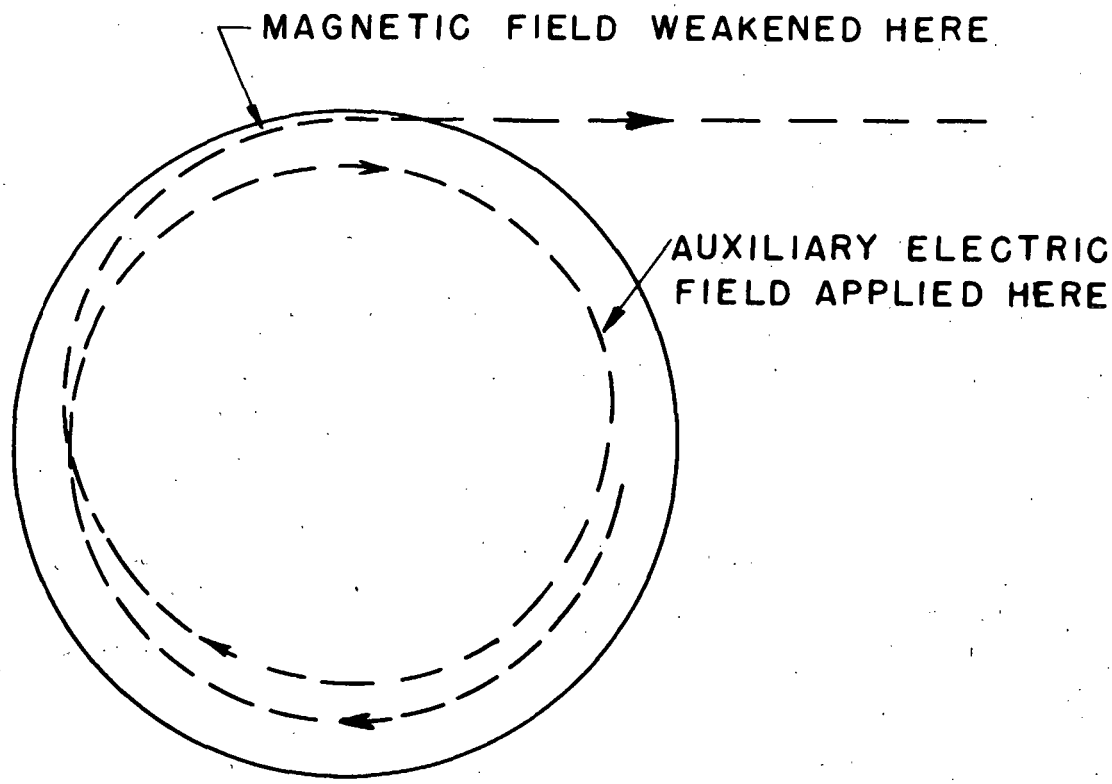

Fig. 11

Schematic drawing of deflection scheme to obtain external beam.

main problem is the injection. Bohm and Foldy[8] have made a detailed theoretical study of the injection difficulties in order to determine the synchronous or equilibrium phase which maximizes the efficiency of capture into the portion of the rf cycle giving phase stability. If the equilibrium phase is too great, measured from the time when the field goes through zero, the capture efficiency is limited by the narrow range of phase stability. (See Figs. 8 and 9.) If the equilibrium phase is too small, the orbital radius expands so slowly that the ions may return to the center in their first radial oscillation (see below) and be lost. The optimum phase, both theoretically and experimentally, turns out to be near 30°. This corresponds to a capture efficiency of the order of 1 percent.

The radial and vertical "free oscillations" in the synchrocyclotron are stable by virtue of the magnetic field design. The adjective "free" is used to distinguish these motions from the slow radial oscillations which are due to small variations in the energy of the particle. The free oscillations have a frequency which is comparable to the frequency of rotation, while the phase oscillations have a period long compared to that of rotation. Therefore, the two can be considered independently. The condition for the stability of free oscillations is the same as in the betatron or synchrotron or in any machine in which the electric focussing is negligible: The vertical magnetic field intensity must fall off radially. From the Maxwell equation, curl $\vec{H} = 0$, one can easily prove that this implies a radial component which quenches any attempt by the ion to leave the median plane. In the 184-inch synchrocyclotron, the magnetic field intensity decreases linearly to a radius of 80 inches, where its value is 95 percent that at the center. From that point on it decreases much more rapidly, so that the beam actually "gets lost" at 81 inches, due to a coupling between radial and

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[8] D. Bohm and L. Foldy, Phys. Rev. 72, 649 (1947)

vertical oscillations. The latter will invariably occur if the field intensity decreases too fast. The shaping of the magnetic field is accomplished by the appropriate placing of shims inside the vacuum chamber.

Performance of the Synchrocyclotron

The time average internal current is about 0.9 microamperes for protons and deuterons, and somewhat less for alpha particles. If it is necessary to bring the beam out, a factor of ten thousand is lost. Operation can be changed from one type of ion to another in only a few minutes. Because of the moderate dee voltage, problems of sparking and electrical breakdown in the tank are greatly reduced. Also the natural stability of the synchronous operation makes it unnecessary to maintain a critical relation between the frequency and magnetic field. For such reasons the internal beam operation is remarkably steady, often showing many minutes of operation without sparking or beam variation of more than a few percent. Access to the internal beam for experiments is obtained through vacuum locks so as to avoid loss of the tank vacuum condition.

The percent of time in which the cyclotron is available for operation has consistently averaged over 90 percent and for one months period was 97 percent. The percentage of time during which the beam was actually operated has averaged about 60 percent, the difference being accounted for by experimental set-up times, target changes, etc.

The Synchrotron, An Electron Accelerator

The acceleration of electrons to energies of the order of Mev and higher poses quite a different problem than does the acceleration of nuclear particles. The mass of an electron is almost 2000 times smaller than that of a proton, and relativistic effects become important at a proportionately lower energy. This is why the conventional cyclotron is useless for electrons.

The first successful high energy accelerator for electrons was the betatron,

built in 1941 by Kerst[10] at the University of Illinois. The betatron substitutes a continuous circumferential electric field for the cyclotron arrangement of a periodic electric field applied across a gap. This obviously avoids any difficulty of the ion's falling out of phase. The continuous circumferential field is achieved by the well known principle of induction. The magnetic flux through the electron orbit varies with time, inducing the electric field along the orbit. Using the induction equation, $\int E ds = -\frac{1}{c}\frac{\partial \phi}{\partial t}$, where ϕ is the total flux through the orbit, it is easy to show that if the electron is to be held at a constant radius, r, during the acceleration, then the following relation between ϕ and the magnetic field, H, at the orbit must be satisfied:

$$\phi = 2\pi r^2 H \qquad (5)$$

Thus, a large flux path must be provided if the electron is to reach a high energy. The total iron required is twice that for a synchrocyclotron, and it must be laminated to avoid eddy currents.

High energy betatrons are expensive, therefore, because of their iron requirment. There is also an upper limit to the energy which they can achieve, due to an effect which is completely negligible for nuclear particles. This is the radiation emitted by an accelerating charge. In a circular orbit, this is proportional to the fourth power of the ratio of the total energy of a particle to its rest energy. It is estimated that the radiation loss will prevent the betatron from ever going above about 400 Mev.

With the discovery of the principle of phase stability, it became possible to apply to electrons as well as nucleons the cyclotron technique of an external periodic electric field. This allows the radiation loss to be compensated up to a considerably higher energy than in the betatron. The limit is set in this case

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[10] D. W. Kerst, Phys. Rev. 60, 47 (1941)

by the maximum gap voltage which can be achieved. The limit is not really known, but electron energies of one or two Bev are conceivable.

Another advantage over the betatron is of more immediate importance. There is no need, with the external electric field, to have a tremendous flux through the center of the orbit. The consequent saving in iron probably cuts down the overall cost by a factor of three. This was the primary consideration which led in 1945 to the planning of a 300 Mev electron synchrotron at Berkeley. It was built under the supervision of E. M. McMillar, one of the three inventors, and first operated at full energy on January 17, 1949.

General Description of the Synchrotron

The only basic differences between the synchrotron and the synchrocyclotron are that the former accelerates electrons rather than nuclear particles and that modulation of the magnetic field rather than the frequency is employed. Because of its small rest mass, the total energy, E, of an electron is practically equal to its kinetic energy if the latter is more than a few Mev. This requires changing either H or ω by a factor of several hundred in reaching the hundred Mev range, (Eq. (5)), and the former task seemed easier. In addition, if ω is held constant, the radius of the electron orbit is also very nearly constant during the entire acceleration. This can be seen from the relation, $r = v/\omega$, connecting the angular and linear velocities. Except at the very beginning of the cycle, therefore, the orbital radius is close to the value c/ω since the electron velocity is almost that of light. The radius of the Berkeley machine was chosen to be one meter, corresponding to a frequency of 47.7 megacycles.

It is clearly necessary to restrict the orbit if the saving in iron mentioned above is to be achieved. How then is one to get past the starting region when the electron moves relatively slowly? Some supplementary means must be found to carry out the acceleration up to one or two Mev, at which point the synchrotron can take over. This is accomplished by operating the machine as a betatron in

the low energy region. A few flux bars (laminated iron bars which carry flux through the center of the orbit) can satisfy the betatron condition (5) until the magnetic field at the orbit reaches a value of ~80 gauss. The flux bars saturate at this point, when the electrons have energy of 2 Mev, and play no further role. The rf field is now turned on, catching half or more of the circulating electrons in stable orbits, and these are carried up to the peak magnetic field of 10,000 gauss by synchrotron operation.

In Fig. 12 the entire magnetic field cycle is shown, with the various stages of electron acceleration indicated. No attempt has been made to get an external electron beam; the rf is turned off just before the peak of the magnetic field is reached. The orbit then contracts and strikes a solid target projecting from the inner wall of the accelerating chamber. Bremsstrahlung results, giving a beam of photons whose energy ranges from 335 Mev down to zero. This x-ray beam penetrates the chamber walls almost unaffected and can be collimated with external absorbers. It might seem to be a less useful experimental tool than a beam of monochromatic 300 Mev electrons, but it can be shown that the properties of the two are almost identical.

The accelerating chamber is a hollow donut made of silica, with internal dimension 2-5/8 inches vertically by 5-3/8 inches horizontally. The vacuum must be very high, .02 microns of mercury. One segment of the donut, occupying one-eighth of the circumference, is copper plated except for a 3/8-inch transverse gap at one end. This segment forms a resonant cavity in which the accelerating rf electric field is produced. The maximum gap voltage is 2.5 kev, while the average gain per turn is about 0.7 kev.

The excitation of the magnet presents quite a different problem from that in a cyclotron, where the magnetic field is constant. Here the magnet is the inductance of a huge oscillating circuit. An 805 microfarad capacitance, which

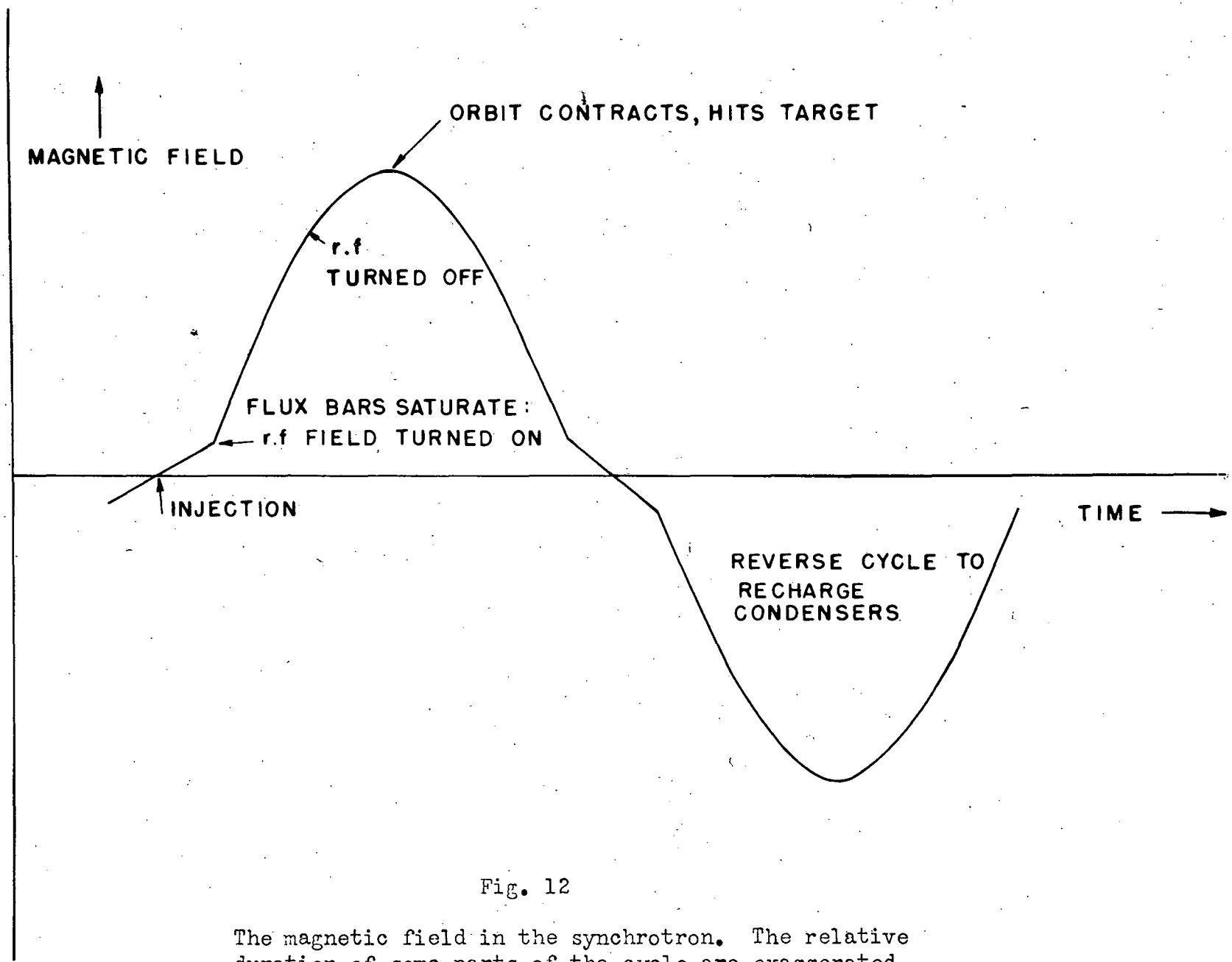


Fig. 12

The magnetic field in the synchrotron. The relative duration of some parts of the cycle are exaggerated so that they may be clearly visible.

requires a bank of 3328 individual condenser units, makes up the other half. The natural frequency of this circuit is 30 c.p.s. but it is triggered only six times a second by an electronic switch. In each pulse the switch is closed just long enough to allow one complete cycle.

Injection and Stability of the Synchrotron Beam

The original injection into the donut presents the same problem as in an ordinary betatron. It has never been well understood, the chief difficulty arising from ions striking the back of the injector on one of their first few turns. The capture efficiency of the Berkeley machine is still lower than one might hope for, and work is continuing on this point. It was expected theoretically[6] that after the original injection the electrons would be easily caught in phase stable orbits at 2 Mev. This is indeed the case, more than half the beam making the transition. The stability of free oscillations in both betatron and synchrotron orbits depends on the same requirement as in the synchrocyclotron. The magnetic field intensity must decrease in the radial direction. Accordingly, the pole faces above and below the donut are shaped so that $\frac{d \ln H}{d \ln r} = -2/3$, a choice which seems to work well.

Synchrotron Performance

The largest beams so far obtained have had 6×10^8 electrons per pulse, producing an x-ray intensity at one meter of 2300 roentgens per hour. In the first six months of operation for research, the machine was unavailable for a total of five weeks, due to breakdowns and continuing efforts to improve the beam. These interruptions should be progressively less frequent. Under normal conditions, the beam is available 90 percent of the time.

Shielding Problems at Berkeley

A considerable number of fast neutrons are necessarily produced in both the cyclotron and linear accelerator wherever the ion beams strike solid matter. For reasons of safety, concrete shielding has been set up to prevent these neutrons

from diffusing into areas where people must work. No such precautions need be taken with the synchrotron, which does not produce neutrons, although standing directly in the x-ray beam is to be avoided.

The cyclotron shielding consists of a concrete enclosure, with ten foot thick walls and a four foot thick roof, which surrounds the entire machine (see Fig. 10b). In the direction in which neutrons are deliberately produced by allowing the proton or deuteron beam to fall on a solid target, an additional large concrete block with collimating facilities is set up. Under normal operating conditions the energy delivered by fast neutrons outside the shielding is between 50 and 500 Mev per cm^2 per sec. Since the safe limit is supposed to be about 200 Mev and since a further increase in beam intensity is contemplated, another five feet of concrete is to be added to the side walls.

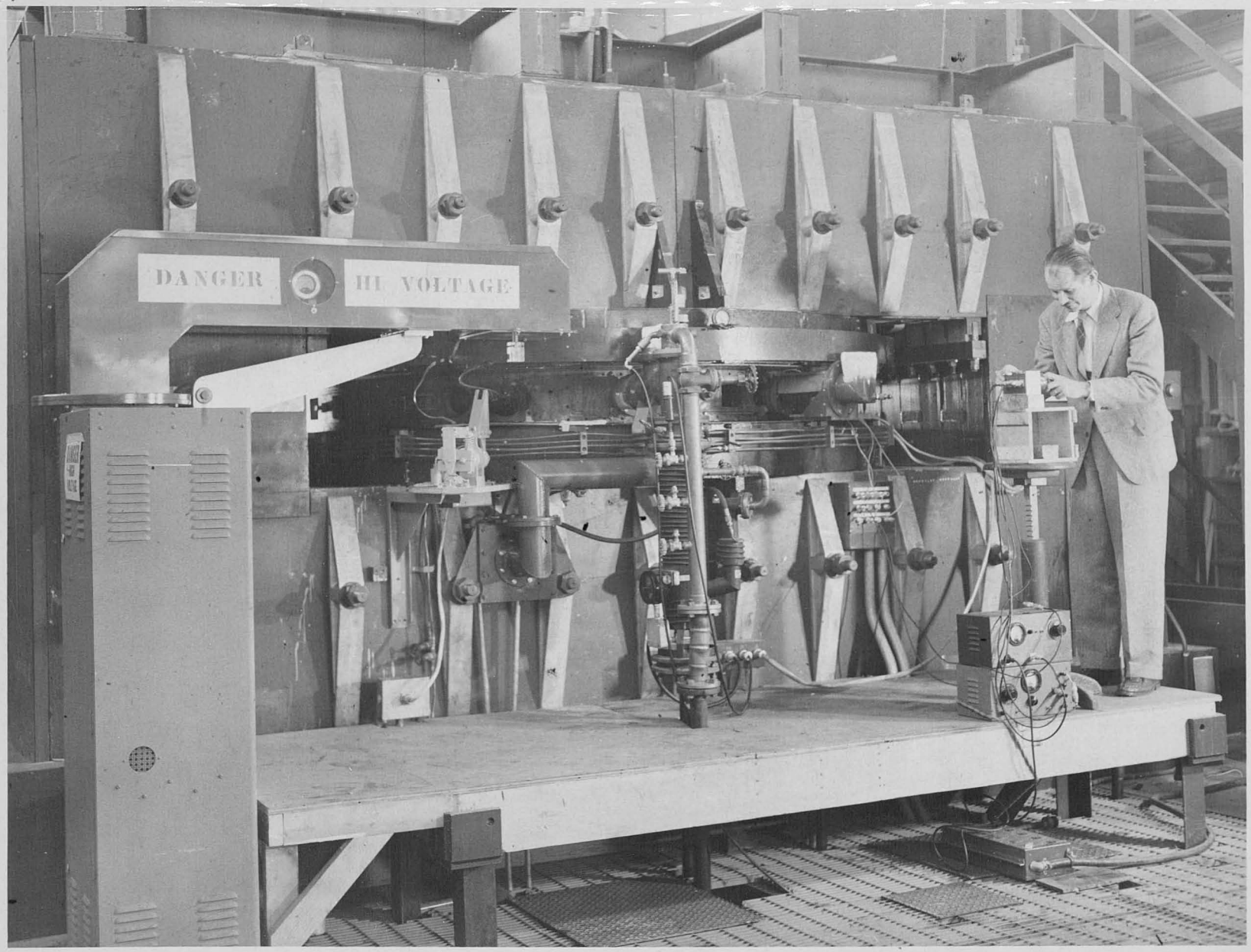
The linear accelerator produces less penetrating neutrons than the cyclotron and to the present time, only the area immediately surrounding the external target has been enclosed. The walls of this enclosure are only about one foot thick and there is no roof. Actually a considerable number of neutrons are produced by protons striking the drift tubes inside the tank and eventually these will have to be restricted by some kind of cover shield.

Summary and Discussion of Research Facilities at Berkeley

The research problems which can be investigated with the three operating high energy accelerators at Berkeley can be, somewhat arbitrarily, divided into three categories. The first is the study of nuclear reactions induced by high energy projectiles. The synchrocyclotron is the most versatile tool in this field, being able to supply internal beams of protons, deuterons, or alphas for bombardments at any energy up to the maximum values listed above. It can produce weaker external beams at the maximum energy. Neutrons of mean energy 90 Mev or 280 Mev can also be produced in the 184-inch cyclotron, as explained in

the next paragraph. The linear accelerator gives protons only, and at a lower energy, but they are available in an intense, well collimated, monoenergetic external beam. Photonuclear reactions can be studied with the gamma rays from the synchrotron. The intensity is low, but with newly developed techniques, not much is needed. Nuclear reactions will be the subject of the next article in this series.

A second field of interest is the interaction between fundamental particles. Leaving out mesons, the four fundamental particles available at Berkeley for experiment are protons, neutrons, photons and electrons. High energy neutrons are most conveniently produced by stripping 190 Mev deuterons in the 184-inch cyclotron. The deuteron is a rather loose combination of neutron and proton, and the proton can be stripped away in a nuclear collision allowing the neutron to continue on with about half the energy of the initial deuteron. This stripping process is itself an interesting nuclear reaction and will be discussed in the next article. Neutrons with mean energy at about 280 Mev are projected forward from nuclei bombarded with the 340 Mev protons. This process will also be discussed. Fast electrons could be obtained indirectly by causing the gamma-rays from the synchrotron to produce positron-electron pairs. There is rarely any advantage in this because the most important interaction of an electron with other particles is via the electromagnetic field. The quanta of the electromagnetic field are, of course, photons, so one may just as well use them directly. The fundamental interactions are usually investigated with appropriate scattering experiments, e.g., neutrons scattered by protons, protons by protons, photons by electrons, and so on. Logically these are just the simplest type of reactions and should be discussed first. In practice, however, they are treated in a quite different and more rigorous way than other reactions and, therefore, will be deferred to the third article of the series.



BERKELEY SYNCHROTRON. X-RAY BEAM WILL EMERGE AT RIGHT FROM DOUGHNUT

FIG. 13

The fourth article will be concerned with mesons, and again the separation is not completely logical. Mesons are believed to be responsible for nuclear forces and occur in many high energy reactions. However, artificially produced mesons are a new phenomenon and of great current interest. In addition, the connection with nuclear forces is not yet understood, and any discussion at this time must be on a semi-empirical basis. Enough information has accumulated, however, to make a separate article worthwhile.

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