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I.

Apparate zur Erzeugung energiereicher Teilchen und von Neutronen

High Energy Accelerators

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For the purpose of the following discussion we shall use a special definition of "high energy", since the nuclear physicist's idea of high energy may seem low to a cosmic ray investigator, making a numerical definition difficult. Accordingly, we shall call a "high energy accelerator" any device in which essential use is made of time-varying fields for the acceleration of particles. Energies up to a few million electron volts can be obtained by the use of constant electrostatic fields, and according to our present definition anything above this range is high. There are in use at present two general types of high energy machines, the resonance accelerator and the induction accelerator. In the resonance accelerator the particle passes through a series of electrodes (or repeatedly through a single set of electrodes) on which are applied oscillatory potentials so timed that the electric field seen by the particle while crossing the gaps between electrodes is always in the right direction to cause an increase in energy. The fact that a particular time relation is required between the motion of the particles and the variation of the electrode potentials leads to the use of the descriptive term "resonance". In the induction accelerator, on the other hand, the accelerating electric field is derived from a varying magnetic flux which is always changing in the same sense throughout the motion; therefore the force is always in the same direction, and the time relation is not important.

The general idea of resonance acceleration is best illustrated by the linear accelerator in its early form, resulting from the proposal of G. Ising and developed by R. Wideröe, E. O. Lawrence and D. Sloan, and others. In this device, the ions pass successively through a series of hollow cylindrical electrodes arranged in a straight line. The first, third, fifth, etc., electrodes are connected to one side of a source of high frequency voltage, while the even numbered electrodes are connected to the other side. Suppose that the ion is in the gap between electrodes 1 and 2 at a time when the electric field in that gap is to the right, so that the ion is accelerated. At this time the field in the gap between 2 and 3 is in the opposite direction, but by the time the ion has traversed the length of the second electrode the field has reversed and the ion is again accelerated. Thus if the lengths of the electrodes are properly proportioned, the "resonance" between the high frequency oscillation and the times of crossing the gaps is maintained and the final energy is limited only by the gap voltage and the number of gaps. A practical limitation of the above design is given by the difficulty of obtaining high radio frequency potentials with that kind of circuit, making the number of gaps (and the overall length) very large if really high energies are to be produced. This situation has been changed by certain wartime radar developments, in particular the new high power high frequency oscillators and the experience in the use of wave guides and cavity resonators. These have led to a rebirth of interest in linear accelerators, and the recent development of the traveling wave accelerator for electrons and the standing wave accelerator for protons. The former (W. W. HANSEN in the U.S.A. and the group at T.R.E. in England) uses a corrugated wave guide carrying a wave with its phase velocity adjusted to the electron velocity; the electrons go along the axis of the guide, "riding the crests" of the waves. The latter will be described in more detail later.

The best-known type of resonance accelerator is the cyclotron of E. O. LAWRENCE, which uses a magnetic field to make the ions move in circular paths, and a set of hollow half-cylindrical electrodes ("dees") as accelerating electrodes. The ions circulate with the angular velocity ω, which is related to the magnetic field H and the ion charge and mass e and m by the familiar equation:

$$\omega = \frac{eH}{mc}. \tag{1}$$

If the frequency ν applied to the dees is equal to $\omega/2\pi$, it is apparent that the ions will cross the gaps between the dees in step with the electric field oscillations, and will continue to be accelerated, describing larger and larger orbits up to a diameter limited by the dimensions of the magnet. This development has been of extremely great importance in the growth of nuclear physics, since it provided the first source of really high energy particles in large numbers.

The induction accelerator, althoug a rather old idea, was first brought to practical form by D. W. KERST as an electron accelerator called the betatron. This device employs a magnetic field to guide the electrons in a circular path, and a changing flux through the path to provide the tangential electric field which gives the acceleration. Since it is desirable to have the orbit radius r remain constant, the magnetic field H at the orbit must increase during the acceleration in a certain ratio to the increase in flux $\varnothing$. This "flux condition" is:

$$\frac{d\varnothing}{dt} = 2\,\pi\, r^2 \frac{dH}{dt}\,. \tag{2}$$

The machine usually operates with a sinusoidal variation of both H and $\varnothing$ at a frequency of the order of power line frequency; electrons are injected from an internal electron gun at a time near the zero point of the cycle, and reach their maximum energy at the peak of the cycle. The mechanism of injection, that is, the means by which the electrons fail to strike the electron gun in the first few turns after leaving it, is still a matter of controversy.

Before going any farther in the discussion of principles of operation, we might now stop to consider the necessary requirements for the practical operation of devices such as those described above at very high energies. One thing that is apparent is that long paths (or very many traversals of a circular path) will be necessary. Therefore the paths must be stable, or as is usually said, there must be focusing of the particles. In the linear accelerator focusing is provided by the electric field in the gaps. This has been discussed so many times that it will only be outlined here. The field lines are curved in such a way that there is a converging force as the particles enter the gap and a diverging force as they leave. Focusing is provided by an excess of the former effect over the latter. This can be obtained in three ways: (1) By the increase in velocity of the particles while crossing the gap, giving the diverging force less time in which to act. This accounts for the entire focusing effect in "steady potential" machines such as the Van de Graaff machine, but is probably not important in linear accelerators. (2) By the change in potential while the particle is crossing, which gives focusing if the particle goes through during a time of decreasing field, and defocusing if the opposite is true. (3) By putting grids or foils over the entrance to one of the electrodes, thus eliminating the diverging part of the field. Mechanisms (2) and (3) will be mentioned again later.

In machines with circular paths in a magnetic field, the chief focusing is provided by the curvature of the magnetic lines or force. In a uniform field, there is obviously no focusing at all; if the field H diminishes with radius r, the lines are curved in such a way that any orbit out of the median plane is pushed toward that plane, and furthermore any orbit which is "off center" will tend to precess about the magnetic center. However, if the rate of decrease of field is too great, the circular orbit becomes a spiral and all stability is lost. The stable limits are most compactly given in terms of the "field index" n, defined by:

$$n = -\frac{r}{H}\frac{\partial H}{\partial r}; \tag{3}$$

the condition for stability is then that $0 < n < 1$.

In the above we have discussed stability in two coordinates only, but a third coordinate is necessary for a complete description of the motion, namely the distance measured along the path of the particle. This coordinate is not important in the case of induction acceleration where the particle is urged on by a steady push, but it is very important in resonance acceleration since it determines the timing of the arrival of the particle at the gaps. Therfore, if the number of gap crossings is to be large, stability in this coordinate is needed too. It was shown independently by V. Veksler in Russia and E. M. McMillan in the U.S.A. that this kind of stability does indeed exist, and the realization of this fact has made possible the recent extension of the energy range attainable by resonance accelerators. In order to illustrate the idea, let us express the position of the particle in terms of a phase angle, which may be the difference between the angular position in a circular orbit and the "electrical angle" of the high frequency oscillation. The value of this "phase" then determines at what time in the high frequency cycle the particle will cross the gap, and therefore the energy gained (or lost) in the crossing. If the resonance condition is exactly satisfied, the phase will remain constant, but if $\omega \neq 2\pi\nu$ it will change with each traversal of the orbit. This change will lead to either an increase or decrease in the energy gain per turn, depending on the initial value of the phase angle. We can now show that if ω depends on the energy E, and if the energy initially has a value which is not exactly right for resonance, the change can act in a direction to counteract the deviation of the energy from resonance, and therefore can lead to a stability in phase and energy. The angular velocity and the total relativistic energy E are related by:

$$\omega = \frac{eH}{mc} = \frac{ecH}{mc^2} = \frac{ecH}{E}. \tag{4}$$

Suppose that the energy is initially too small, so that ω is too high for resonance, and the phase will change in the sense that the particle arrives earlier and earlier at the gap. Suppose further that the initial phase is at one of the two values where the particle crosses the gap at zero field. If it is at the particular one of these for which earlier arrival means a gain in energy, then the changing phase leads to an energy increase, tending to restore the initial energy deficiency. Then the condition for stability is satisfied, and further analysis shows that the phase will oscillate in a way exactly like the motion of a pendulum. If the initial energy error is too large, one has the case of a pendulum swinging over the top, so that true stability exists only within a certain range of energy and phase. For a linear accelerator the linear velocity v, given by:

$$\frac{v^2}{c^2} = 1 - \frac{m_0\, c^2}{E^2}, \tag{5}$$

is the determining factor. This increases with E, so that phase stability exists about an initial phase where the energy gain is greater for later arrival at the gap. This condition for phase stability is incompatible with the requirement for focusing by mechanism (2) described above, leading to some difficulties in the design of high energy linear accelerators.

The discussion just given applies to a case of constant H and ν, as exemplified in the cyclotron. An ion, after leaving the source near the center, goes through a portion of one cycle of phase oscillation on its way to the outer edge. The rest of the cycle, if allowed to take place, would carry it to some maximum energy and then back to the center again, leading to the relativistic limit of cyclotron energy first pointed out by Rose and Bethe. However, if H or ν is made to change continuously during the acceleration, the situation is altered. So long as the change is not too rapid, the stability is not destroyed (in the pendulum model for phase oscillations, it is equivalent to applying a torque to the pendulum, which will not destroy the stable oscillations unless it is too large). The energy tends to oscillate about a "synchronous energy" E_s:

$$E_s = \frac{e\, c\, H}{2\, \pi\, \nu}, \tag{6}$$

while the mean phase shifts to a point where the energy gain in the gap is just enough to take care of the rate of change of E_s. This rate of change must of course be slow enough that the required energy gain does not exced the maximum available at the gap (or gaps). To complete the story, we should say that in the linear accelerator the parameter which changes with time is the spacing of the accelerating electrodes as seen by the moving particle.

Equation (6) leads to three technical modifications, which are especially suitable for different particles and have been given different names. That is, one can vary ν alone, H alone, or ν and H together. For accelerating electrons, the range to be covered by E_t (from something near rest energy to several hundred MeV) is relatively so large that H-variation seems the only practical way. For heavy partcles up to a few hundred MeV, the range can be covered by ν-variation, and the difficulties of H-variation (laminated magnet, storage and transfer of energy of the magnetic field) can be avoided. Finally, for very high energy heavy particles, the combined variation is most suitable. The reason for the latter is best understood if one considers the orbit radius, determined by:

$$r = \frac{v}{\omega}\,. \tag{7}$$

For electrons of a few times the rest energy $v \sim c$, and r is approximately constant for fixed ω, so that a ring-shaped magnetic field can be used. For protons on the other hand v is still changing up to very high energies, so it is worth while to vary ν (and therefore ω) in such a way as to follow the variation in v, thus keeping the radius constant and allowing the great saving in both iron and magnetic energy consequent on the use of a narrow band of field.

The three modifications are then, in tabular form:

Name	Particles	H	ν	r
synchroton	electrons	varies	constant	$\sim$ constant
synchro-cyclotron or frequency-modulated cyclotron	protons deuterons helium ions	constant	varies	varies
bevatron (Berkeley) or cosmotron (Brookhaven) or proton-synchrotron (Birmingham)	protons or possibly other ions	varies	varies	constant

Finally, as illustrations of some of these devices, we shall use the machines at present operating at the Radiation Laboratory in Berkeley, the 60-inch cyclotron, the 184-inch synchro-cyclotron, the proton linear accelerator, and the synchrotron. The bevatron, now under construction, will be described in the following talk by Dr. HAWORTH.

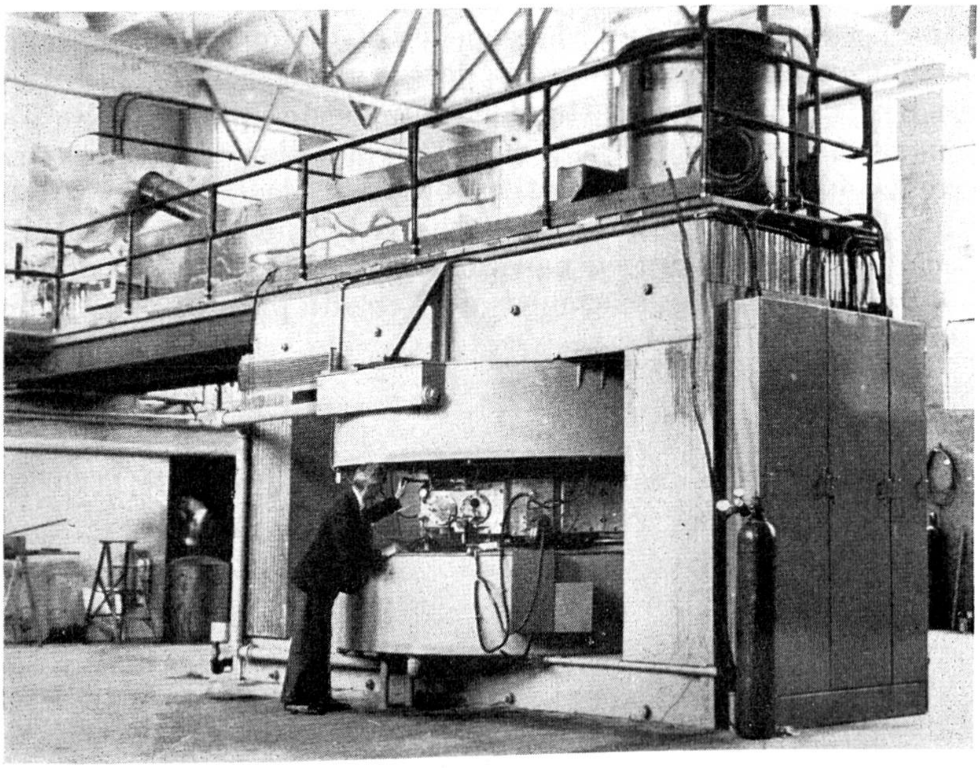

Fig. 1.
The 60-inch cyclotron.

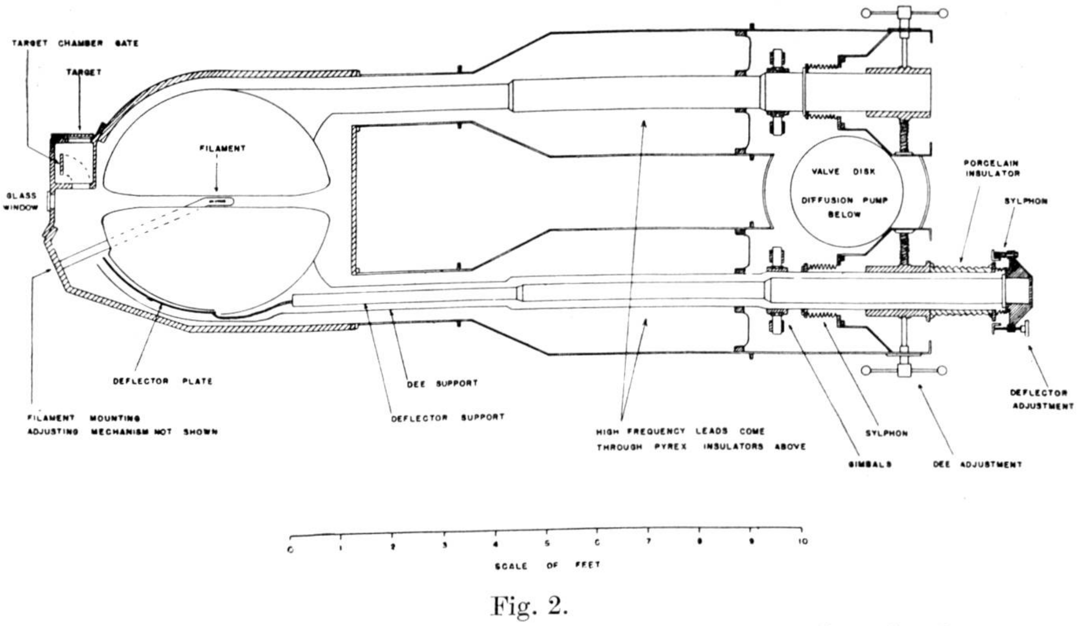

Fig. 2.
Plan view of 60-inch cyclotron vacuum chamber in cross section, showing the method of supporting the dees.

The *60-inch cyclotron* (i. e., diameter of magnet poles equals 60 inches) operates at a fixed frequency of 11.4 megacycles per second. The peak potential between dees is about 200 kilovolts, produced by about 60 kilowatts of high frequency power fed into a resonant dee system with a Q of 3500. The following energies and currents (deflected onto a target) are obtained: deuterons, 18.5 MeV, 50 to 100 microamperes; doubly charged helium ions, 37 MeV, 8 microamperes; hydrogen molecular ions, 9.25 MeV per proton, 25 microamperes. This machine is used chiefly for producing radio-

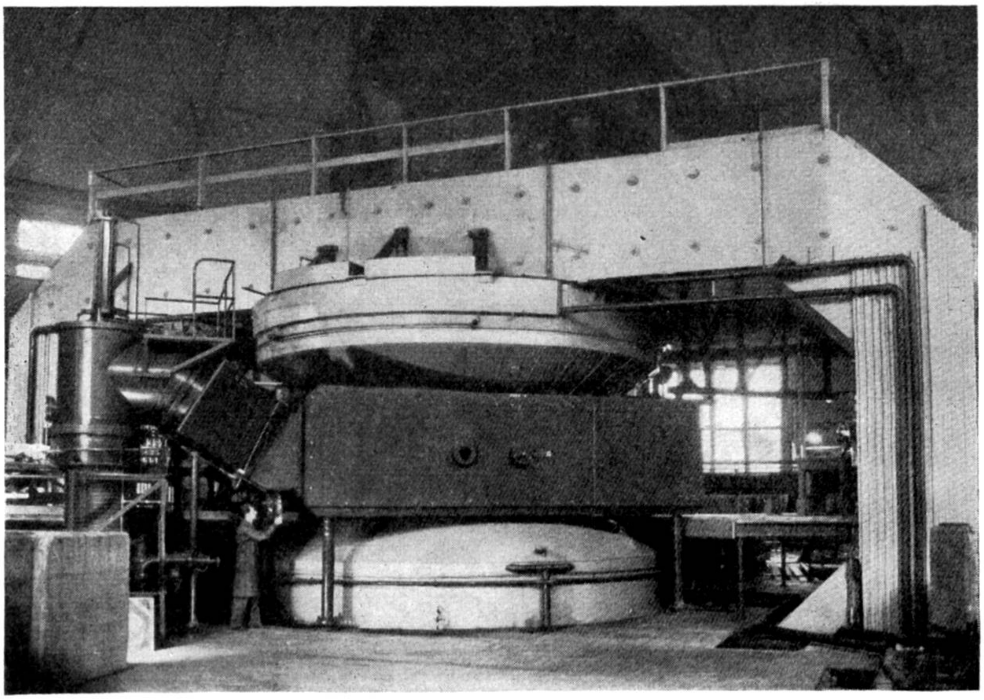

Fig. 3.
The 184-inch synchro-cyclotron without shield, showing magnet yoke and coils, vacuum chamber, and diffusion pumps.

active materials for biological and medical purposes, and in the study of nuclear reactions and their products among the heavy elements. Fig. 1 is a view of the 60-inch cyclotron without its present shield of water tanks. Fig. 2 shows the method of mounting the dees on resonant supports, which avoids the necessity of having the high dee voltage appear across insulators. The power is fed in at points near the grounded ends of the dee supports.

The *184-inch synchro-cyclotron* is shown in Figs. 3 and 4 with and without its concrete shield. Fig. 5 is a vertical section through the single dee and its associated resonant circuit, which consists essentially of a coaxial transmission line with on eend grounded and containing a variable series capacitance. The rotating part of the variable condenser is shown in Fig. 6. The frequency is made to vary from 22.9 to 15.8 megacycles per second when accelerating protons, and from 11.5 to 9.8 megacycles when accelerating deuterons or helium ions, with a repetition rate of 60 per second. The peak dee potential is only 17 kilovolts, since the phase stability allows the ions to make many turns while being accelerated (37,000

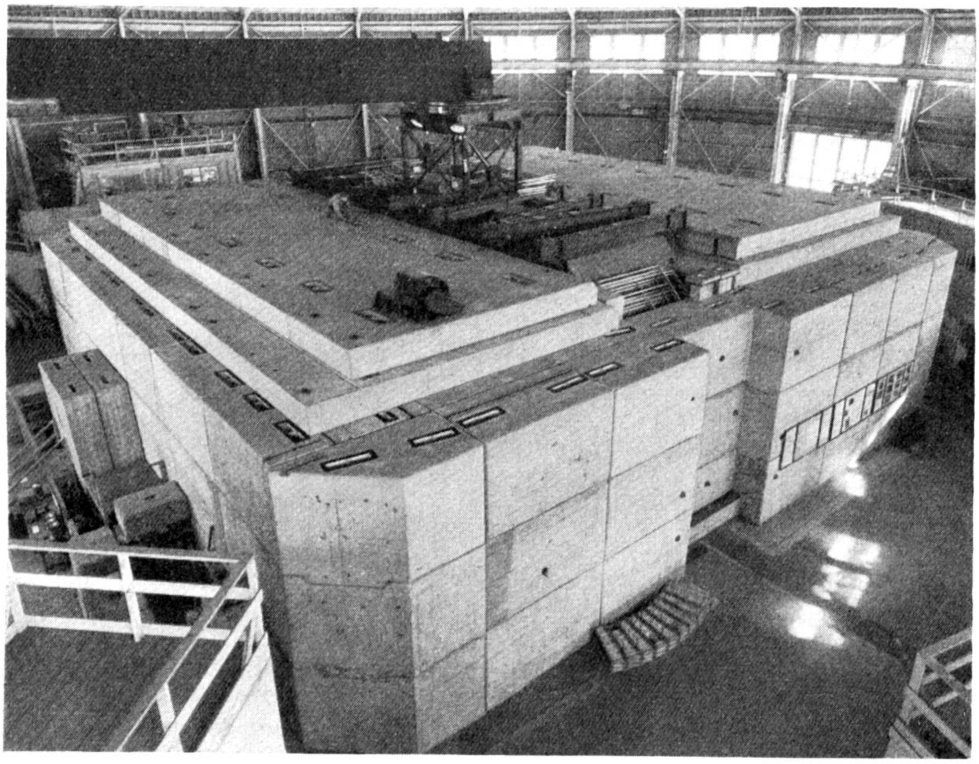

Fig. 4.
Same as Fig. 3 with 10 foot thick concrete shield in place.

in the case of protons). The magnetic field is 15,000 gauss at the center, 14,175 gauss at the final radius of 81 inches. The energies and currents (time average on an internal target) are: protons, 350 MeV, 0.75 microampere; deuterons, 195 MeV, 0.75 microampere; helium ions, 390 MeV, 0.1 microampere. These particles can be used directly to bombard internal targets, or a portion of the currents can be brought out by a deflecting system for experiments outside. Also, the neutrons produced by "stripping" of deuterons or exchange collisions of protons in the internal target can be allowed to emerge through a hole in the concrete shield, providing a well-collimated beam of high energy neutrons. The experiments performed or in progress with this machine cover a wide range of high energy processes, which we shall not have time to describe here; probably the most striking are the studies of meson production, including the recent evidence for the production of neutral mesons of mass comparable to the π-meson.

The *linear accelerator* of Professor Alvarez uses standing waves inside a cylindrical resonant cavity to accelerate protons. Fig. 7 shows the general arrangement, and Fig. 8 is a photograph of the completed machine, looking toward the beam-exit end. The cavity,

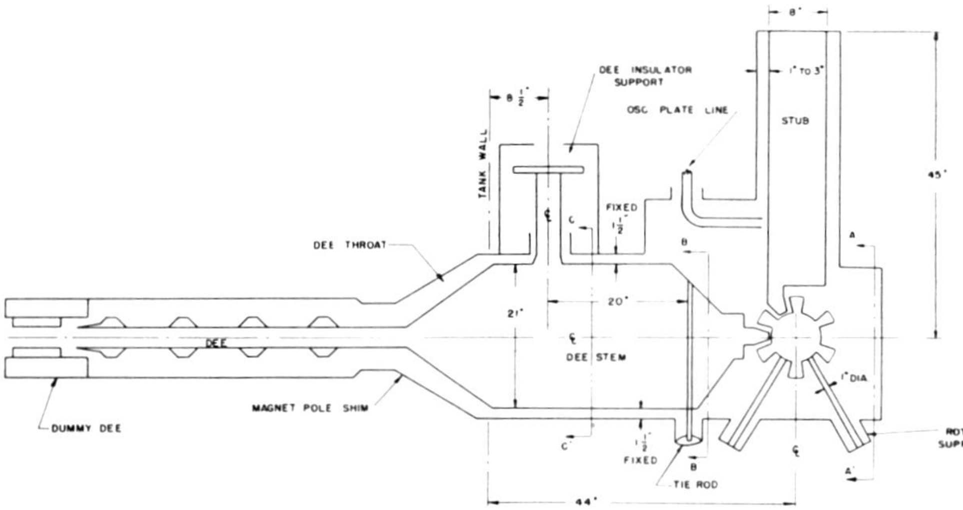

Fig. 5.

Vertical section through high-frequency resonant system of 184-inch synchrocyclotron. The rotary part of the condenser is in effect insulated from ground. The edge of the dee is at the center of the magnetic poles.

40 feet long and 3.2 feet in diameter and having a Q of 70,000, is excited at 202.6 megacycles per second in a mode for which the electric field is parallel to the axis, and uniform along the axis. It is driven by 28 converted radar sets operating in parallel, delivering pulsed high frequency power at an instantaneous rate of 2.5 megawatts, which provides a total potential drop along the cavity of 36 million volts. Protons are injected into the cavity at 4 MeV from a VAN DE GRAAFF machine. They are shielded from the effect of alternate half cycles by metal "drift tubes" arranged along the axis, as shown; these can be (and are) mounted on conducting radial supports, since the electric field is entirely longitudinal. The final proton energy is 32 MeV and the time average current is 0.1 microampere, delivered in 15 pulses of 400 microseconds length per se-

cond. The drift tubes are provided with grids in order to produce focusing by mechanism (3) discussed above, since mechanism (2) seems to be incompatible with phase stability. (Note added since giving the talk: Recently the machine has been operated successfully without the grids; apparently this possibility is allowed by its shortness compared to the period of a phase socillation.) The great advantage of the linear accelerator lies in the easy accessibility and good collimation of the beam; it has been used for measurements of *p-p* scattering and excitation curves of nuclear reactions, the discovery of some new light radioactive isotopes, etc.

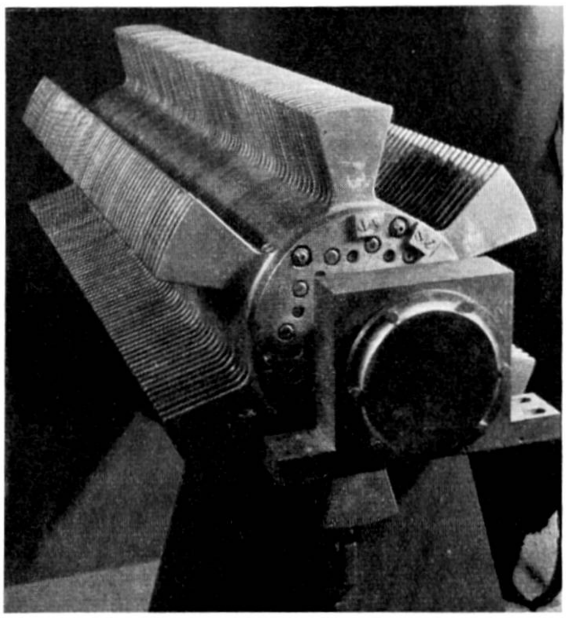

Fig. 6.
Rotating part of variable condenser indicated in Fig. 5.

The *synchrotron* accelerates electrons to 335 MeV. The magnet of this machine must be laminated because of the time-varying magnetic field, and therefore it is constructed entirely of transformer iron. It is excited by means of a condenser bank and an electronic switch consisting of four ignitrons. The condenser bank stores 124000 joules of energy at 17.8 kilovolts; this is discharged into the magnet coils when the switch is closed. The discharge is oscillatory with a frequency of 30 cycles per second, and after the completion of one cycle the switch is opened. This process is repeated at the rate of 6 times per second; the acceleration takes place during the first quarter cycle, and the only function of the second half cycle is to restore the condenser charge to its original polarity. A charging rec-

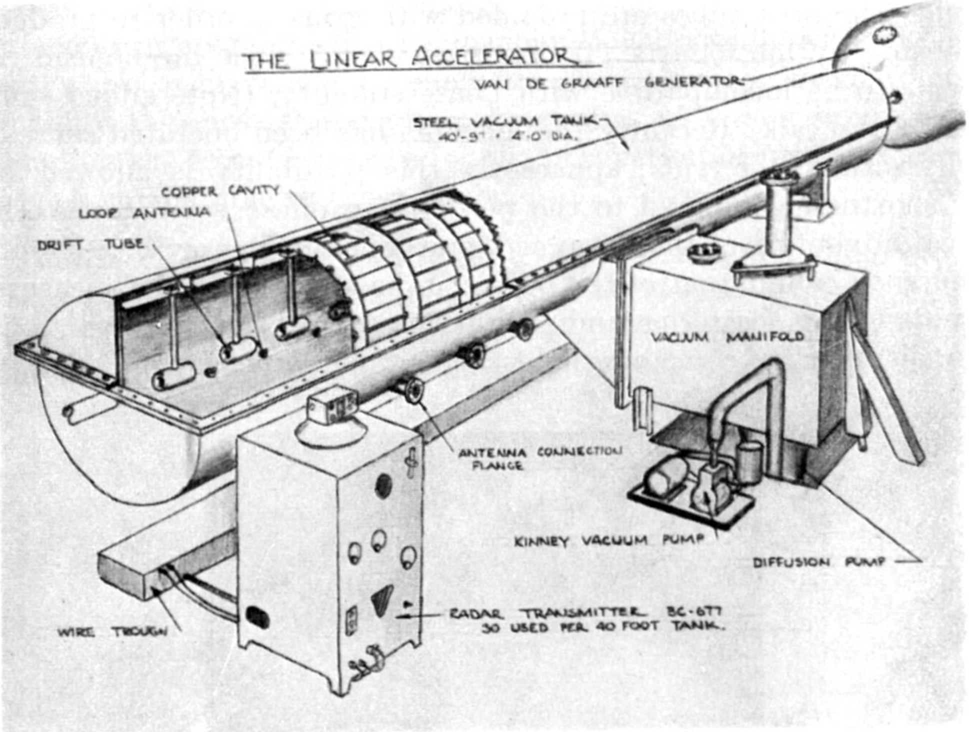

Fig. 7. Cutaway drawing of the linear accelerator.

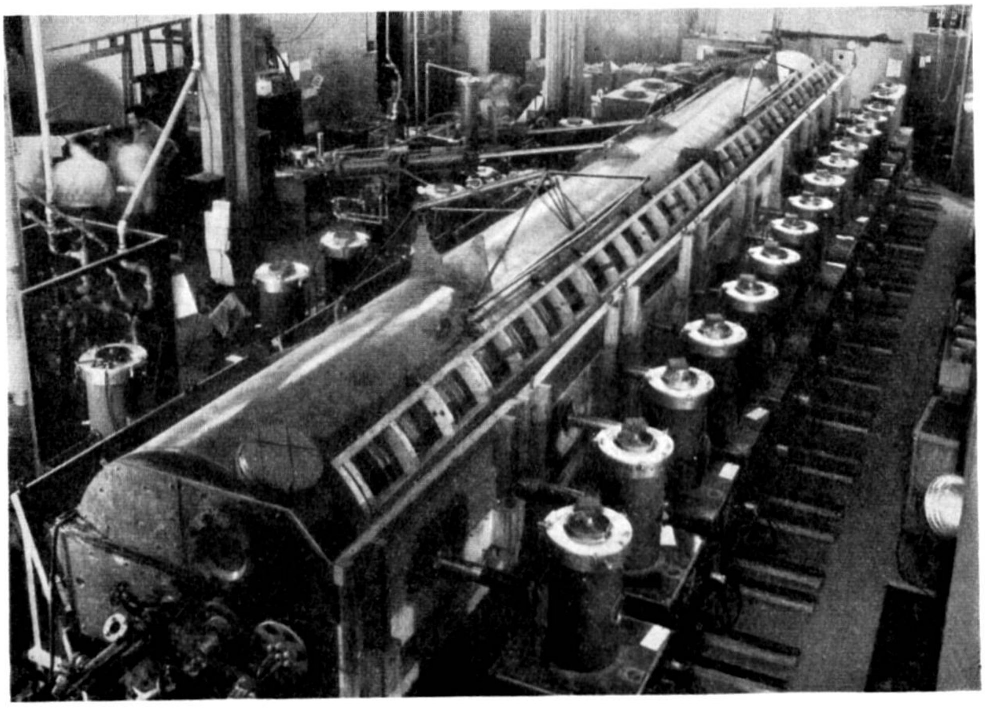

Fig. 8. The linear accelerator. The Van de Graaff machine used as an injector is out of the picture toward the observer.

tifier makes up for the losses in the discharge cycle. Fig. 9 is a drawing of the machine with a portion of the magnet cut away. It shows the rectangular yoke and the circular pole pieces, with the toroidal quartz vacuum chamber between them. Through the hollow center of the magnet pass laminated iron "flux bars" whose purpose is to provide flux for betatron-type acceleration during the early part of the operating cycle. To the right (not shown) is the electron gun that injects electrons into the orbit, and to the left the oscillator and resonant cavity that furnish the synchrotron-type acceleration. Fig. 10 shows the resonant cavity in more detail. A one-eighth segment of the quartz vacuum chamber is plated inside and out

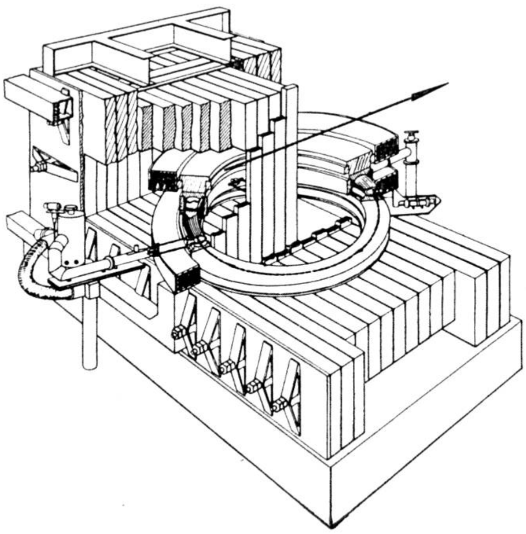

Fig. 9.
Cutaway drawing of the synchrotron.

with copper, and a gap is cut in the inside coating near one end, as shown. The conducting surfaces then form a quarter-wave resonant line, which is driven at 47.8 megacycles per second, corresponding to the circulation frequency of electrons at the velocity of light in an orbit of one meter radius. The peak voltage across the gap is 2 kilovolts.

The operating cycle is as follows: When H reaches 11 gauss, a pulse of 100 keV electrons is injected. The action of the changing flux accelerates these, bringing them to about 2 MeV by the time H has reached 80 gauss; at this time the oscillator is turned on, and most of the circulating electrons are caught into phase stable orbits. Shortly after this the flux bars become saturated, but their action is no longer needed. The electrons are then carried to their peak energy of 335 MeV at the peak field of 11,200 gauss, when the oscillator is turned off. Radiation losses cause the orbit to contract rapidly until the electrons strike a platinum target 0.020 inch thick, producing a narrow beam of x-rays. No attempt has as yet been made to bring the electrons out. The time average x-ray intensity is around 100 roentgens per minute at one meter from the target, corresponding to about 10^8 electrons per pulse striking the target. The normal pulse length is 10 microseconds, but this can be extended to 3000 microseconds by turning off the oscillator slowly, which reduces the random coincidence problem in counter experiments. The most formidable operating problems are concerned with the errors in the field at the time of injection. These errors affect both

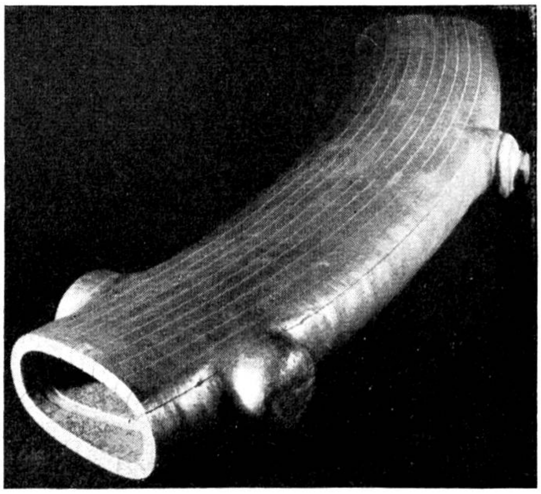

Fig. 10.

Copper-plated quartz section forming the accelerating unit of the synchrotron. The gap is visible just inside the end. Power is fed in through the far stub; the projections at the near end have no function. The longitudinal cuts reduce eddy currents caused by the changing magnetic field.

the radial and azimuthal field distributions, and are corrected by sets of coils (20 in all) carrying self-induced currents adjusted by variable series resistors. In our experience, the adjustments are best made empirically by observing the output during operation; since they are rather critical, the beam was first found by operating at low magnet excitation (200 volts) where the field errors are small. A view of the machine from the same aspect as in the drawing is shown in Fig. 11; the other side is shown in Fig. 12. The x-ray beam emerges normal to the flat side of the magnet, coming toward the observer in this view. Along the beam are arranged experimental equipment, collimators, and intensity monitors. A cloud chamber is placed 86 feet from the target. The experimental work with the

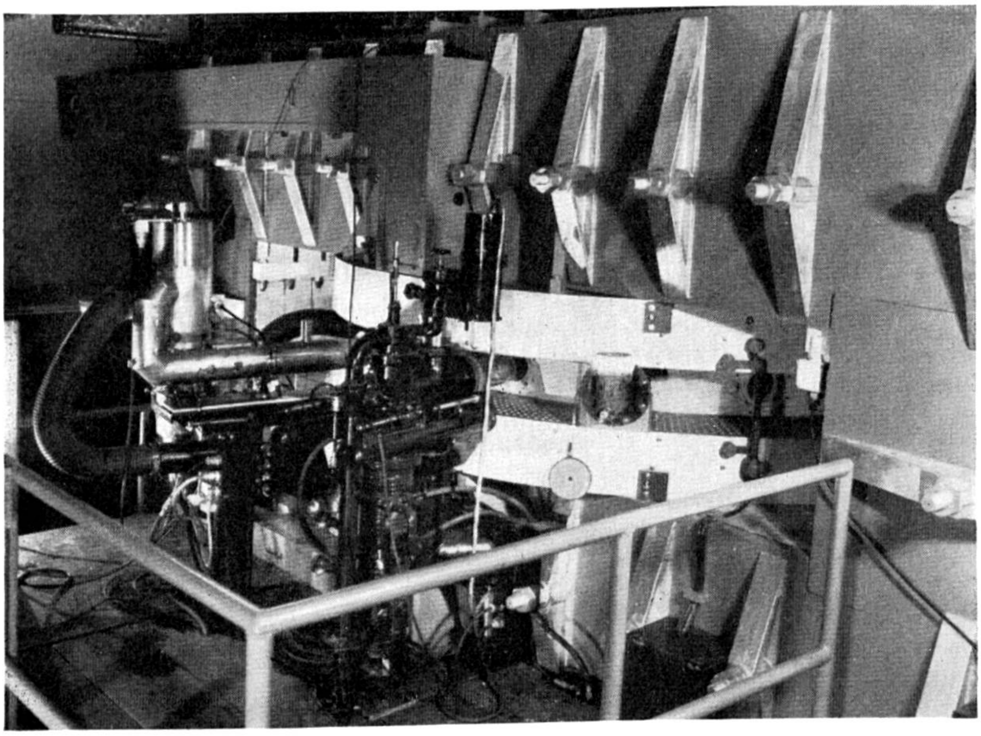

Fig. 11. View of synchrotron, showing at the left the oscillator (vertical brass cylinder) and the transmission line feeding power to the accelerating section.

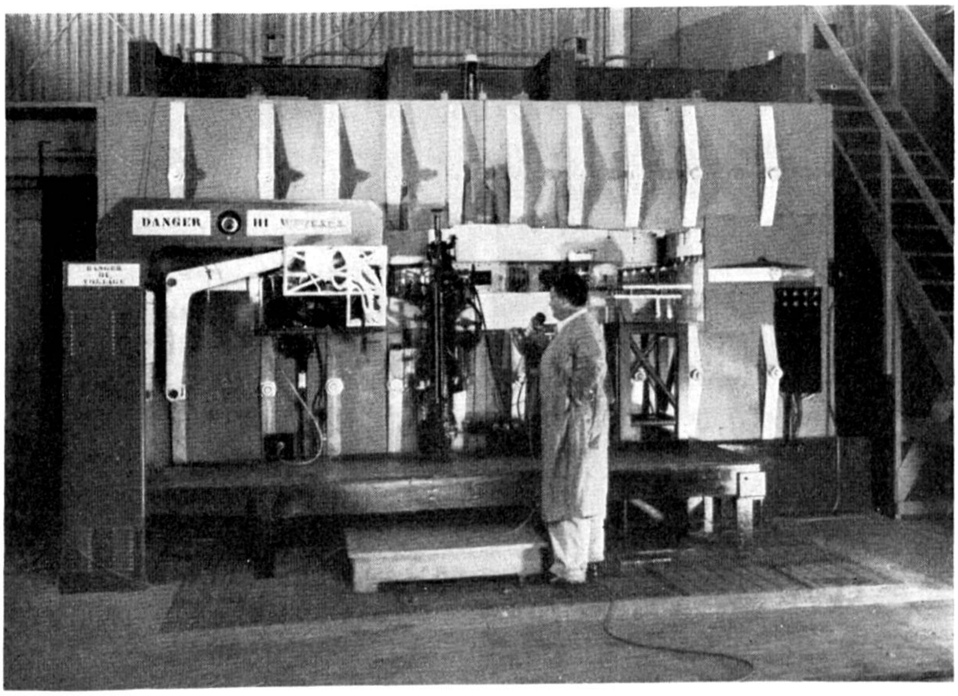

Fig. 12. Other side of synchrotron. The injector and its power supply are at the left, the x-ray beam emerges at the right, toward the observer.

machine has been concerned with measurements of the x-ray yield and spectrum, transition effects in ionization chambers, x-ray induced radioactivity, studies of the Compton effect at high energy, and observations of meson production.

As to the future of high energy accelerators, the next stage is represented by the bevatron, to be discussed by the following speaker. One should not forget, however, that this may not be the best machine for the purpose; it is the best that we know of, but our knowledge is finite, and it is always possible that some new combination of known principles, or some altogether new principle, may make possible the attainment of still higher energies.