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On the Apparatus for the Multiple Acceleration of Light Ions to High Speeds

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Significant improvements of the apparatus for the multiple acceleration of light ions, now called the "cyclotron," have recently been made. The apparatus produces many microamperes of deuterons having energies up to 6.3 Mev and a few tenths of a microampere of 11 Mev doubly charged helium ions. The means of deflecting the high speed ions from the accelerating system has also been improved, with the result that the ions can now be withdrawn completely from the apparatus into the air through a thin window in the chamber wall. The present paper is devoted to a detailed description of the cyclotron, including its adjustment and operation, with a discussion of the questions involved.

SINCE the first experiments[1] six years ago, work in our laboratory on the development of methods of accelerating charged particles has gone forward steadily with the endeavor of evolving methods and apparatus for nuclear physics that would find wide usefulness. Almost from the beginning, the method of multiple acceleration of light ions, wherein the ions circulate in a magnetic field in resonance with an oscillating electrical field, gave most promise, and accordingly has been given major attention in our laboratory. Four years ago, details of an apparatus that generates 1.2 Mev protons were described,[2] and two years ago an account[3] was given of a much larger apparatus of this type, capable of generating a fraction of a microampere of 5 Mev deuterons. In the meanwhile, significant improvements have been made not only in increasing the output of ions to many microamperes at higher voltages, and in the general convenience and reliability of the apparatus, but also in the means of withdrawing the ions from their spiral paths. It is the purpose of the present paper to describe these recent advances in design and also to discuss some of the questions involved, for some of the changes which we have made suggest the possibility of further improvements.

APPARATUS

A general view of the apparatus, which is now called[4] the magnetic resonance accelerator, or, more frequently, the "cyclotron," is shown in Fig. 1. The magnet which was described in the publication two years ago has not been changed in any respect. For some time we have intended to enlarge the pole faces beyond the original $27\frac{1}{2}''$ diameter, but this change still remains for the future. All of our attention has been given to the improvement of the cyclotron at its present size. The drawing of Fig. 2 is a general view of the chamber with cover removed, showing the ion source, the accelerating electrodes, which are called duants, or dees, the electrode for deflecting the ions from their spiral paths, the rotatable beryllium and tungsten target, and the window in the chamber wall through which the ions emerge into the air. These component parts are discussed in the following paragraphs.

Ion source

As in the original arrangement, the ions are produced in the central region by a beam of electrons passing along the magnetic lines of force between the dees and ionizing the gas filling the chamber at a suitable pressure. Formerly, spiral filaments above and below the central region were mounted on glass tubes in copper pipes which extended from the chamber wall to the center, along a radius between the dees. These tubular shields extended to the center on one side only, thus introducing an undesirable asymmetry in the field between the dees. This has been corrected[5] in the present apparatus by bringing the filaments to the center across one dee, as shown in Fig. 3. Here may be

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[1] E. O. Lawrence and N. E. Edlefson, Science **72**, 376–377 (1930).

[2] E. O. Lawrence and M. S. Livingston, Phys. Rev. **40**, 19–35 (1932).

[3] E. O. Lawrence and M. S. Livingston, Phys. Rev. **45**, 608–612 (1934).

[4] E. O. Lawrence, E. McMillan and R. L. Thornton, Phys. Rev. **48**, reference p. 495 (1935).

[5] In the Cornell cyclotron this correction has been achieved by the symmetrical placing of four filaments (M. S. Livingston, Rev. Sci. Inst. **7**, 55–68 (1936).

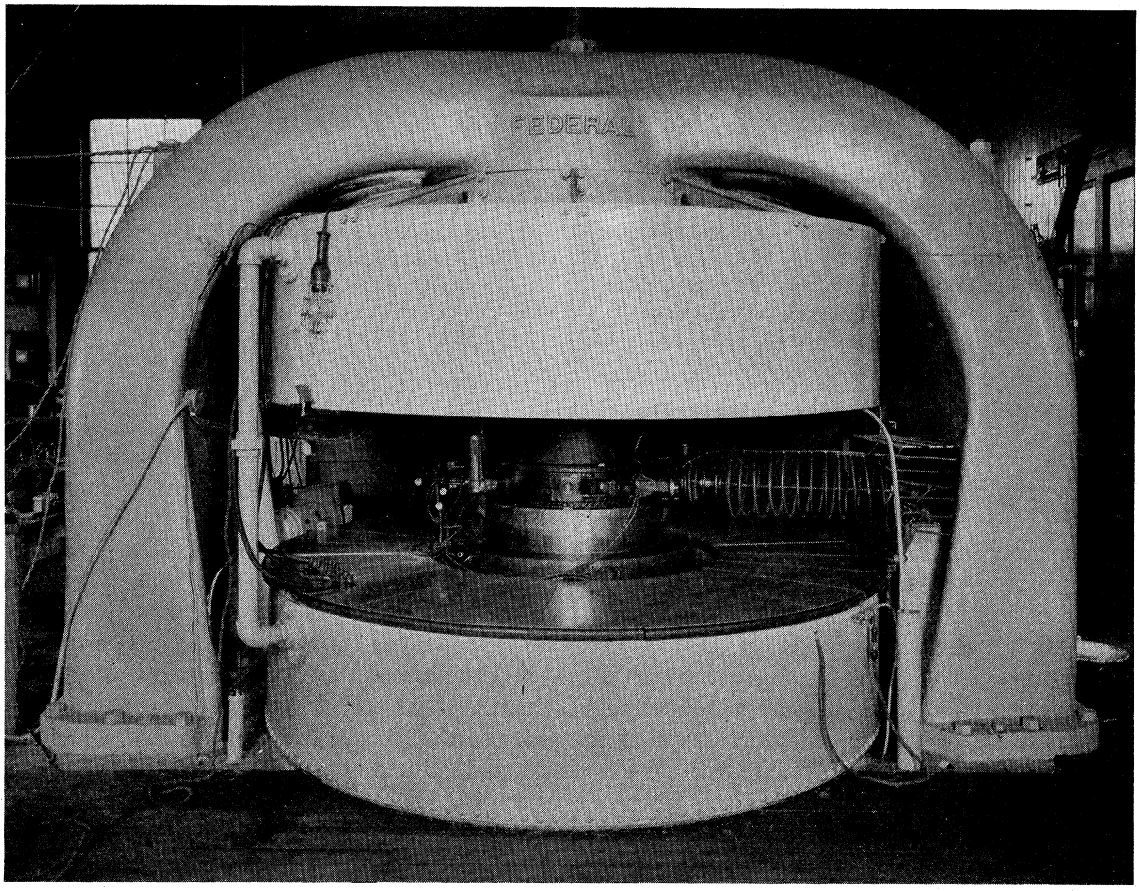

FIG. 1. General view of the cyclotron.

seen two filament supports, one above and one below one of the dees (which in this photograph has been removed). The flat spiral filaments, usually $5\frac{1}{2}$ turns of 30 mil tungsten with an over-all diameter of about $\frac{1}{2}''$, are mounted by clamping to water-cooled copper blocks. The filament support is enclosed in a copper shield

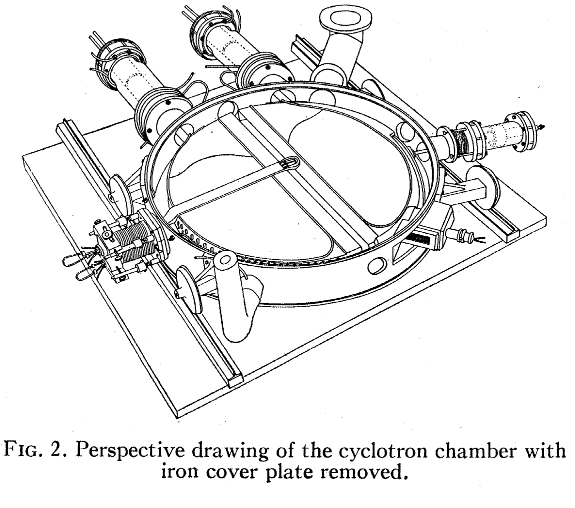

FIG. 2. Perspective drawing of the cyclotron chamber with iron cover plate removed.

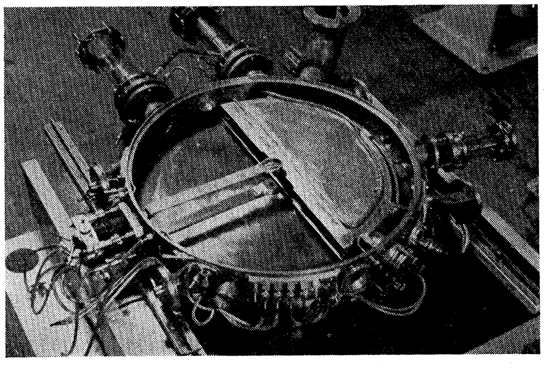

FIG. 3. Photograph of a cyclotron chamber with cover plate and one dee removed. In this apparatus the ions are not withdrawn completely but bombard targets within the chamber wall.

(because of the radio frequency potentials on the dees) and the whole assembly is made as thin as possible for maximum clearance between the dee and the filament structure. In practice, it has been our experience that $\frac{1}{4}''$ vertical or $\frac{1}{8}''$ horizontal clearance is enough to prevent trouble from breakdown discharges.

The filament support is mounted on a sylphon arrangement which permits moving the filament to various places in the central region. Theoretically, the ion source should be near the center of the cyclotron, inasmuch as the ions start their spirals on paths of small radii of curvature in the oscillating electric field between the accelerating electrodes. In practice, however, it is usually found that the optimum position of the filament is not at the center but off the center one way or another. This arises from the circumstance that in general the centers of the successive circular paths migrate from the geometrical center of the apparatus as a result of the lack of complete circular symmetry of the magnetic field. This migration of the paths of the ions can be changed by correcting the asymmetry of the field. This can be done by inserting suitable pieces of iron (which we call "shims") between the cover plates of the vacuum chamber and the magnetic pole faces, but oftentimes it is much simpler to make the correction by shifting the point at which the ions begin their spiral paths.

The whole filament assembly is bolted and waxed to a plate on the side of the chamber wall, and is made conveniently demountable for filament replacement. Water-cooling pipes pass around the filament shield and also are provided for the wax joints. The filament electrodes are insulated from the surrounding shield by glass tubes and emerge from the sylphon assembly through a rubber plug, the arrangement being made vacuum-tight by wax. The insulation is adequate for several thousand volts, but in general the filament is maintained at a negative potential not greater than 1000 volts with respect to the surrounding shield and the walls of the vacuum chamber.

Although there are two filaments (one above and one below) only one at a time is used, the other being moved to one side, to be available when the former burns out. The electron emission from the ion source passing down between the dees, strikes the iron (lid or base plate) and, inasmuch as no water cooling is provided at the point, large electron currents can give rise to excessive heating and evolution of gas. In the future when larger currents are used, it will be necessary to provide water cooling where the electrons strike, but for the currents used until now (less than 500 ma at 1000 volts) this has not been necessary.

From the magnitude of the current of high speed ions arriving at the periphery in comparison to the estimated amount of ionization at the ion source, it is clear that the focusing action of the electric and magnetic fields is such that a very considerable fraction of the ions starting at the center reach the target. Because space charge effects are negligible for such small currents at such high voltages, it is to be expected that the output of high speed ions would be proportional to the production of ions at the center, and therefore, it is of importance to consider means of increasing the source of ions.

The ion current will be proportional to the electron current and therefore it is necessary only to increase the filament emission in order to increase the ion output. Unfortunately, large electron currents are limited by space charge, and it is necessary to increase the accelerating electrical fields in order to increase emissions. In the present arrangement, it is not efficacious to increase the electron emission by increasing the electron accelerating voltage, because the probability of ionization of the gas—for example, the production of protons in hydrogen—falls off with increasing energy of the electrons, as has been shown by Bleakney.[6] The optimum energy of the electrons for the formation of protons or deuterons is in the neighborhood of 200 volts, and accordingly it is desirable to design the source of electrons to yield large currents at low voltage.

One way to accomplish this is to increase the size of the filament, since in practice it has been found that there is a relatively large central region that is suitable for the ion source. Over distances of as much as two inches the output of high speed ions in relation to the production at the ion source does not vary more than 50

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[6] W. Bleakney, Phys. Rev. **35**, 1180–1186 (1930).

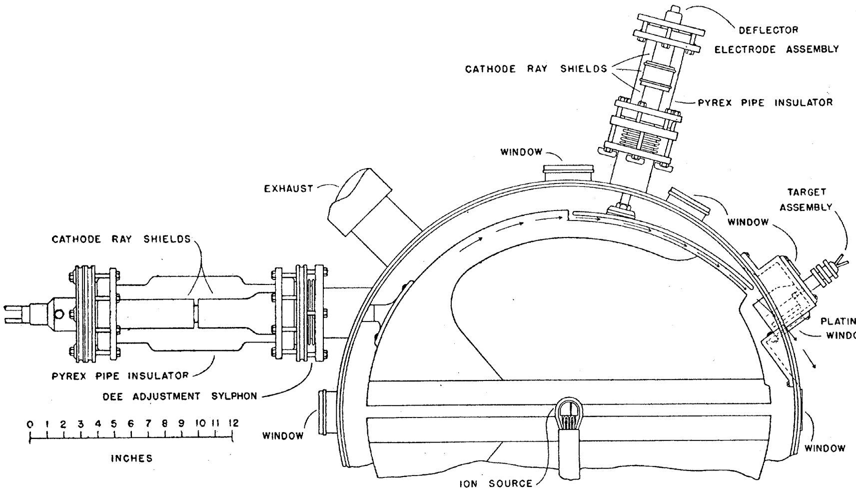

FIG. 4. Detail of accelerator electrodes and mountings.

percent. Space charge effects can be reduced also by the use of an accelerating electrode close to the filament. One suitable arrangement would be that of a heavy (perhaps 50 mil) straight tungsten wire several inches long, extending parallel to the diametrical edges of the dees, midway between them. With such a straight wire filament held accurately in position, it would be feasible to place, very close by, a water-cooled accelerating electrode having a narrow rectangular slot which would produce much higher fields at the filament surface than are obtained in the present arrangement.

Thus it appears that there should be no great difficulty in producing 5 or 10 times as much effective electron current as at present used, and accordingly that much greater output of high speed ions. At the present time, the maximum output current of high speed ions is about 25 microamperes and the usual steady-running currents are about 20 microamperes. With the ion source increased, the output of high speed ions should be more than one hundred microamperes.

The accelerator electrodes

The semi-circular hollow accelerator electrodes or dees, are clearly shown in Fig. 2 and is more detail in Figs. 3 and 4. They are made entirely of copper, copper sheeting being soldered to a heavier copper frame, with water-cooling pipes to take care of the heating due to the high frequency charging currents and the bombardment by the circulating ions. The dees have an over-all diameter of $24\frac{1}{4}''$, while the exit slit, as may be seen in the drawing of Fig. 4, is such that the diameter of the final circular path of the ions is $23''$. The dees have a width at the center of $1\frac{3}{4}''$ which uniformly decreases to $1\frac{1}{4}''$ at the periphery. The widening of the dees at the center favors the production of ions there without unduly increasing the capacity of the system.

The dees are supported on the ends of $1''$ copper rods $22''$ long, which are in turn supported by means of Pyrex pipe insulators, the details of which are shown in the drawings of Figs. 2 and 4 and the photograph of Fig. 3. The insulators are standard $\frac{1}{4}''$ wall Pyrex glass flange pipes of $3''$ inside diameter which have been blown out in the central region to $4''$ diameter (the insulators shown in Fig. 3 are not blown out to $4''$), the glass being connected to the metal parts by fuse wire gaskets, according to the suggestions of D. L. Webster and P. A. Ross.

From a mechanical standpoint this arrangement for supporting the dees is very satisfactory, but there have been troubles with cathode-ray punctures of the insulators and high frequency hysteresis heating. These troublesome matters, however, have been practically eliminated by providing the cathode-ray shields shown in the drawings and also by providing air cooling of the glass. This geometry of the electrode arragement not only practically eliminates cathode rays but also distributes the high frequency electric fields in such a way as to minimize hysteresis heating effects; but nevertheless there remains enough heating of the glass to make it necessary to provide jets of air on the glass surfaces to keep them cool. With air flowing over the glass insulators, we have had no trouble with insulator breakdown for several months, and presumably the insulators will last indefinitely.

Of course, the endeavor always will be to produce larger numbers of high speed ions, at ever higher energies, and this will mean an ever-increasing applied high frequency voltage, so that doubtless the point will be reached where it will be difficult to prevent breakdown of the insulators. It will then be desirable to eliminate them practically altogether. This can be accomplished by mounting the dees on heavy and rigid inductance coils in vacuum. The high frequency power for such a circuit could be introduced through insulators at relatively low voltage and thereby it would be possible to increase the power input many fold without insulator difficulties. This arrangement, which makes use of vacuum insulation in the manner of the Sloan[7] radio frequency high voltage generator, will doubtless be used in our laboratory sometime in the future.

The question of the effect of dee width (i.e., height of opening) on the output of high speed ions is one of much interest and importance. The fact that many microamperes of high speed ions are obtainable indicates that the focusing action of the curved electrical fields between the dees is very good, but it is impossible to predict exactly the effect on the focusing action of the geometry of the accelerating electrodes. Of course, it can safely be argued that the number of ions produced at the center will be at least a linear function of the dee width at the center, but whether the peripheral width of the dees affects the ion output very much can only be determined by experiment.

To examine this question we have recently tried dees having a uniform internal width of 2″ and have found that steady output currents of $50\mu A$ are obtainable under approximately the same conditions that $20\mu A$ are obtainable from the narrower dees. Thus it seems that the output of ions increases somewhat faster with dee width than proportionally, and therefore a cyclotron designed for very large current output should not only have an ion source capable of giving large electron emissions, but also should have very wide dees.

Withdrawing the ions

The arrangement for withdrawing the ions is shown in Figs. 2 and 4. The ions emerging from one of the dees are deflected by a transverse electrostatic field and travel between the deflector plate and the dee on an approximately cricular path of radius 30 percent greater than the final circular path within the dee (of radius $11\frac{1}{2}''$). Since the magnetic force acting on the circulating ions is equal to the centrifugal force, which is equal to twice the energy of the ions divided by the radius of curvature, it follows that the magnetic force on 5 Mev ions traveling on a radius of 30 centimeters would correspond to an electrical field of about 330,000 volts per centimeter. Thus, an applied electrostatic field of the order of magnitude of 100,000 volts per centimeter is used in the present arrangement. Since the pole face diameter is $27\frac{1}{2}''$, the ions emerging from the interior of the dee are at a distance of $2\frac{1}{4}''$ from the wall of the vacuum chamber and with the deflecting fields used in the present experiments they are brought to the tank wall in a distance less than one-fourth of the circumference. As may be seen in Figs. 2 and 4, a water-cooled target mounted on a ground joint may be rotated in and out of the beam. Usually two targets make up the assembly, one of tungsten and one of berryllium, the former being used mainly for test purposes (to measure the beam intensity with a minimum of neutron background) while the latter is used as a source of neutrons. The arrangement of the inset in the chamber wall adjacent to the target makes it possible to place objects near to and directly in front of the source of the neutrons. Since the neutrons partake of the momenta of the bombarding deuterons, in general there is an enhancement of the intensity of the neutrons in the forward direction so that there is real advantage for investigations with neutrons to be able to place objects near and directly in front of the beryllium target.

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[7] D. H. Sloan, Phys. Rev. **47**, 62–71 (1934).

It is frequently desirable to expose objects directly to the deuteron beam and for this purpose it is convenient to bring the beam out into the air. A thin platinum window is provided for this purpose. The platinum foil 0.0001″ thick (stopping power, 1.5 centimeters of air) is soldered to a brass grid which is water cooled and able to dissipate the heat liberated by the deuteron beam striking and passing through the window into the air. The holes in the grid are such as to allow a little more than half of the beam to pass through. A beam of several microamperes of deuterons emerging into the air produces a luminosity of lavender color of considerable intensity and a photograph of a 5 microampere beam of 5.8 Mev deuterons passing out into the air from the window to a distance of 25 centimeters is shown in Fig. 5.

Although the arrangement here shown is quite convenient and useful in many investigations, for some purposes it would be desirable to withdraw a beam of ions through a vacuum tube to a point which is at a considerable distance from the accelerator system, in order to remove background radiations, produced by ions circulating between the dees that strike parts of the apparatus other than the intended target. This can be readily accomplished by attaching a vacuum tube of any desired length in place of the platinum window, and putting the platinum window on the other end of the tube. If no attention is given to refocusing, the ion beam will progressively diverge as it passes through such an extended vacuum tube, partly on account of the inhomogeneity of the magnetic fields external to the vacuum chamber. However, it is not a difficult matter to correct this inhomogeneity; in fact, pieces of iron can be placed around the tube in such a way as to refocus the beam of ions at the extended exit window. This has not actually been done as yet in our laboratory, but we intend to do so very soon for the purposes of certain experimental investigations in progress.

Oscillators

The source of high frequency power is a self-exciting (tuned grid—tuned plate circuit) oscillator which has the advantage of simplicity involving a minimum of equipment. Two oscillator tubes of our construction which have been recently described,[8] are used in a push-pull circuit. These tubes are rated at 30 kilowatts, although in practice much smaller powers are used. The anodes are supplied with three phase full wave rectified voltage up to a voltage of about 10,000 volts. The rectifier consists of three 220 volt to 6600 volt transformers connected for three phase full wave rectification with 872A rectifier tubes. In order to draw as large currents as might be desired, 12 of these rectifier tubes are actually used, parallel groups of two being connected with suitable stabilizing resistances in series. When the cyclotron is running, delivering 20 microamperes of 5.5 Mev deuterons, the anode voltage on the oscillators is about 8000 with an anode current of about three amperes. Of the total input power of about 25 kilowatts, it is found that about 12 kilowatts of high frequency power is delivered to the "tank circuit."

Although the simplicity of the self-exciting oscillator commends itself for many practical purposes, it has the disadvantage of inconstancy of frequency and a certain instability in operation; for variable frequency means variable output of high speed ions and for many purposes it is desired to have as great constancy as possible in the energy and intensity of the beam. We are at the present time engaged in the construction of a new oscillator system, using a master oscillator and successive stages of power amplifiers, an arrangement which should deliver to the accelerating system radio frequency power of constant frequency and great stability. With the present arrangement, it is possible to keep the beam steady within 10 percent by adjusting the magnetic field from time to time. The new oscillator should make it possible for the cyclotron to deliver a steady and homogeneous beam of high speed ions for considerable periods of time, perhaps hours, without requiring attention.

ADJUSTMENTS

The dees

The sylphon arrangement in the dee supports makes it possible to change the position of the

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[8] D. H. Sloan, R. L. Thornton and F. A. Jenkins, Rev. Sci. Inst. **6**, 675–82 (1935).

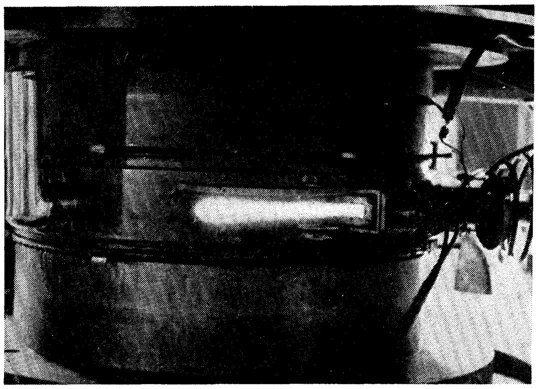

FIG. 5. Photograph of 5μA of 5.8 Mev deuterons (range 25 cm) emerging from platinum window of cyclotron.

dees during operation. As would be expected, it is often found that the optimum position is that in which the dees are accurately parallel to each other and symmetrically placed with respect to the magnetic field. Deviations from this symmetrical adjustment, of one millimeter for example, are sometimes detectable by as much as a 10 percent reduction in the output of ion current. This fact emphasizes the importance of constructing the dees so that they do not tend to wobble or sag out of position, and also the desirability of the sylphon arrangement for making adjustments. In this latter regard, it is found that a slight lack of parallelism of the dees can be partly compensated by adjustments of their relative position. The sylphons make it possible also to vary the separation of the dees, which when parallel are about $\frac{3}{4}''$ apart. No great variations are produced by varying the separation, but it does seem in general that the further the dees are apart the less the output of high speed ions. It is not known whether this is due to change in the production of ions at the center or to the focusing action of the fields out toward the periphery.

In the light of the above remarks, it would seem that with dees and supports of sufficient rigidity, the sylphon on the supports would not be needed, as the dees could be placed accurately in the optimum symmetrical positions at the time of assembly and would keep these positions during the course of operation. It is difficult to say whether in practice the simplification of the dee supports obtained by eliminating the sylphons would more than compensate the loss of the possibility of making dee adjustments.

The magnetic field

Neglecting relativity corrections, which are unimportant, the simple theory of operation of the cyclotron would suggest that the ideal magnetic field is uniform over the whole accelerating system. In practice, this ideal is not achieved, partly because of the imperfections of the geometry and the inhomogeneity of the iron of the magnetic circuit, and partly because the saturation of the iron pole pieces results in a decrease of the magnetic field toward the periphery of the dees; this latter, surprising as it may seem, is an inhomogeneity that is really desirable. The actual variation of the magnetic field from the center outward in the present cyclotron is shown in Fig. 6, where it is seen that from the center to the edge of the magnetic pole faces, the field falls off 25 percent, while even from the center to the point where the ions are withdrawn from the accelerating electrodes, radius $11\frac{1}{2}''$, the field actually diminishes by 7 percent. At first sight, one would think that such a marked radial inhomogeneity of the magnetic

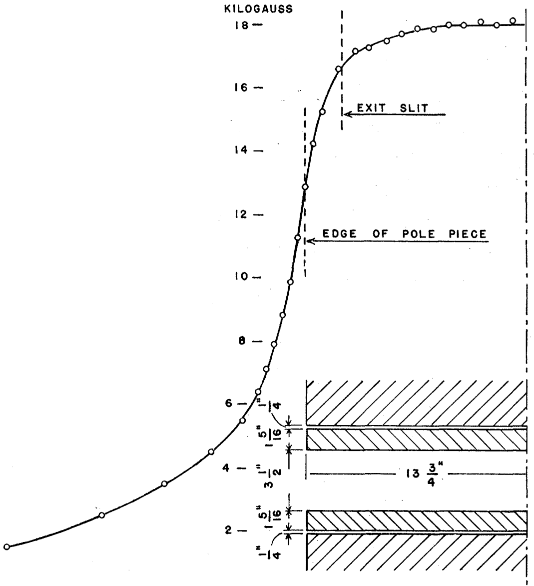

FIG. 6. The radial distribution of the magnetic field. The shaded areas indicate the magnet pole faces and the iron plates of the cyclotron chamber.

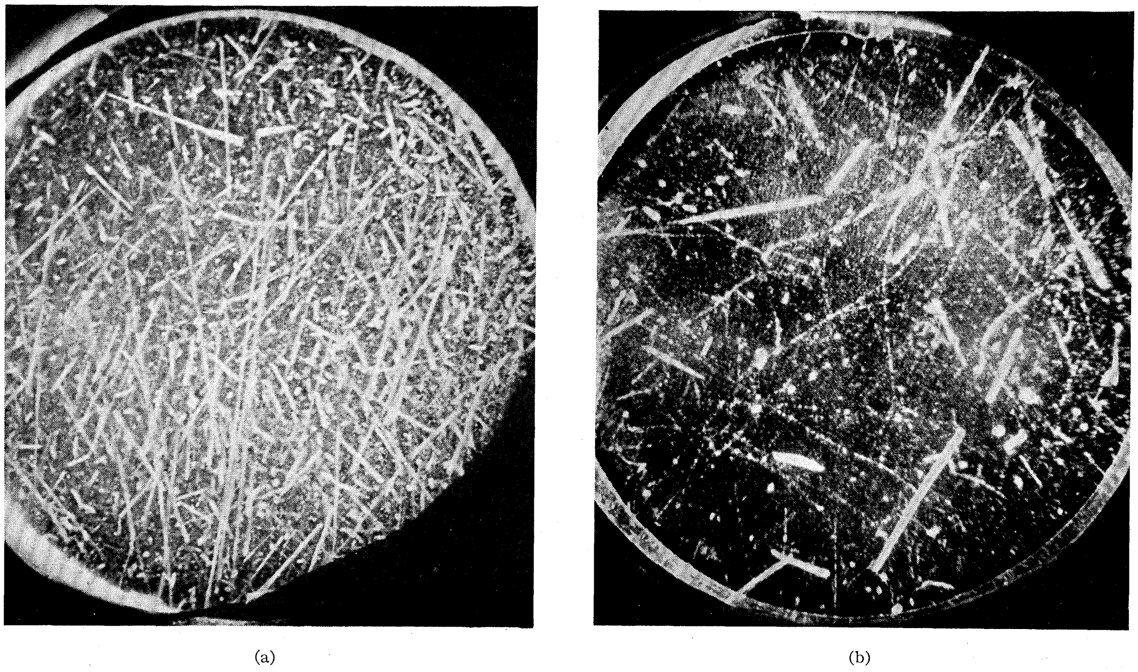
(a) (b)

FIG. 7. Photographs of recoil protons in Wilson cloud chamber filled with hydrogen at pressure of 100 cm Hg produced by neutrons from Be target bombarded with 7μA of 5.5 Mev deuterons. Distance of cloud chamber from Be target, (a) 6 ft., (b) 40 ft.

field would make it impossible to accelerate the ions to the periphery, but on second thought it is realized that if the high frequency accelerating voltage is of the order of magnitude of 100,000 volts in the production of 5 Mev deuterons, the ions circulate only about 25 complete revolutions and under these circumstances an inhomogeneity toward the periphery of only 7 percent would not seriously affect the synchronization of the circulating ions with the oscillating field. The high frequency voltage used in the present cylotron has not been measured reliably, but it is estimated to be somewhere between 50,000 and 100,000 volts.

This radial gradient of the magnetic field, which becomes quite large near the periphery, has the effect of opening up the spiral paths. Instead of traveling on circles within the dees, the decreasing field toward the edge causes the ions that do not have their path centers exactly at the center of the field, to spiral around on continuously increasing radii of curvature. The extent of this effect of the field gradient for the present cyclotron is illustrated by a simple approximate calculation of the path of an ion, on the assumption that the center of the spiral for the revolution, just before the ion is withdrawn from the dee, is $\frac{1}{8}''$ off center, and that the high frequency accelerating voltage is 50,000. The path of the ion, as approximately determined in this way, makes its exit from the dee at a distance of more than $\frac{1}{2}''$ from the previous spiral path. Thus it is seen that this outward field gradient produces a very considerable opening up of the spirals. This is obviously a desirable characteristic, inasmuch as it facilitates the withdrawal of the ions from the accelerating system.

But the fact that a shift of the center of the circuit of the spirals by $\frac{1}{8}''$ produces such a large effect on the spiral paths imposes a rigid requirement that the magnetic field be highly homogeneous in azimuth. If the average value of the magnetic field in one quadrant were appreciably different from that in the others, the effect would be to produce a migration of the centers of the spiral paths, and in turn, serious distortion of the paths, greatly magnified by the spiraling action of the radial field gradient. In adjusting the magnetic field of the cyclotron, therefore, it is necessary to insert pieces of iron between the pole faces and the bottom and top of the cyclotron chamber (as indicated in Fig. 6, $\frac{1}{4}''$ gaps are provided for this purpose) in a purely empirical manner to correct the azimuthal inhomogeneity. In general, it may be said that increasing the magnetic field, let us say on the southern portion of the pole faces, has the result of causing the centers of the spiral paths to migrate toward the east, for clockwise rotation as seen from above. If it is found, therefore, that the ion beam emerging from the exit slit of the dee has an energy less than that to be expected, the presumption is that the centers of the spiral paths have migrated toward the exit slits so that the final radii of curvature are less than the distance from the exit slit to the center of the apparatus. Under such circumstances, the energy of the particles could be increased by inserting shims to increase the magnetic field in a particular region, which would cause the spiral paths to migrate back toward the center, and hence increase the radii of the final paths. Of course, it should be emphasized that in practice the adjustment of the magnetic field by the insertion of shims is largely an empirical matter. Although the effects of the shims cannot always be understood, the shim adjustment is fortunately not difficult to make; inasmuch as without any shims at all, a beam of ions is obtainable. Thus, the homogeneity, intensity and energy of the ion beam can be observed continuously as the magnetic field adjustment is carried out.

PERFORMANCE

Hydrogen ions

The present cyclotron delivers several microamperes of 5 or 6 million volt deuterons without any adjustments after the vacuum chamber has been placed between the poles of the magnet. In the beginning of operation, the circulating ion beam liberates gas from the various metal parts of the apparatus, so that during the first few hours of operation, the output beam of ions steadily increases as the gas liberation decreases. It is found that for satisfastory operation, the pressure of foreign gases must be kept below 10^{-5} mm Hg, and that the largest currents are obtained when the hydrogen pressure is of the order of magnitude of 10^{-4} mm Hg. By making the various adjustments (i.e., the deflecting potential and the magnetic field distribution with shims and the position of the dees, the deflecting plate, and the ion source filament, which usually is at the center) the ion currents are usually built up to optimum values of 20 to 25 microamperes of 5.8 Mev deuterons, when using dees having an internal peripheral width of $1\frac{1}{4}''$, or about 50 microamperes of 4.3 Mev ions when using $2''$ width dees of smaller radius. It is found that the obtainable current is not appreciably dependent upon the output energy of the ions, as we have, when using the narrower dees, obtained just as large currents above 5 Mev as below 5 Mev. The maximum energy of deuterons that has been produced by the present cyclotron is 6.3 Mev.

The obtainable beams of high speed protons are usually equal in current to the deuterons, but less in energy on account of the required higher frequency of the electric oscillations.

Helium ions

The cyclotron, when adjusted for deuterons, is also in adjustment for doubly charged helium ions. The helium ions having twice the charge and mass relative to deuterons, receive twice the increments in energy each time they pass between the dees and arrive at the periphery with twice as much energy. Thus, apart from difficulties of producing doubly charged helium ions at the center, the cyclotron produces 10 Mev alpha-particles as readily as 5 Mev deuterons.

On one occasion, we replaced the deuterium with helium in the cyclotron chamber and obtained $1/10\mu$A of 11 Mev alpha-particles. (Several times larger currents doubtless could have been obtained by completing the adjustments.) That the beam of high speed ions was really made up of such high speed helium ions rather than deuterons of lower energy was definitely established in several ways. Thus, for example, it was observed that the alpha-particle beam attained its maximum intensity at a magnetic field slightly lower than that for the deuteron beam, had a range one-half that of the deuteron beam under similar circumstances, and produced a luminosity in the air in intensity equivalent to that of 4 times as large a deuteron current.

As yet we have not carried out experiments with these energetic alpha-particles, excepting to observe that they do not give rise to as large a neutron emission from a bombarded beryllium target as deuterons of half their energy.

Neutrons

Among the many elements that emit neutrons under deuteron bombardment, beryllium is particularly noteworthy. The neutron emission from a beryllium target bombarded by 7μA of 5 Mev deuterons is indicated by the cloud chamber photographs of Fig. 7. With the hydrogen-filled cloud chamber at a distance of 6 feet from the target, the number of recoil protons is too great for counting purposes, and a more suitable number is obtained at 40 feet. Although it is difficult to compare vastly different numbers of neutrons, estimates made in several ways indicate that the emission of neutrons from the beryllium target of the cyclotron is more than 10^5 times that from a mixture of one curie of radon and beryllium.

This great neutron intensity facilitates many nuclear studies, but on the other hand, hampers some investigations. Among the practical difficulties, there are the biological effects produced by the neutron rays, which make it necessary to provide considerable protection for the investigator. Some biological studies[9–11] have already been carried out which have shown that, in biological action, the usual neutron emission from the beryllium target of the present apparatus is equivalent to the gamma-radiation from 100 grams of radium. Accordingly, at the present time, for the protection of the operator, the cyclotron is controlled at a distance of 40 feet from the target with suitable intervening absorbing material. As the intensity of the neutron source is further increased, it will be necessary to provide additional absorbing screens.

Artificial radioactive substances

With 5 Mev deuterons, it has been found possible[12] to produce radioactive isotopes of many of the elements throughout the periodic table. In many cases, the yields of the radioactive substances are quite large; as for example, a day's bombardment of sodium metal with 20 microamperes of 5 Mev deuterons produces more than 200 milligrams—equivalent of radio sodium,[13] i.e., an amount of radio sodium having a gamma-ray activity equivalent to that of 200 milligrams of radium. That such large amounts of radioactive forms of many of the elements can be manufactured in the laboratory is of much importance in opening up new avenues of research both in the physical and the biological sciences.

We are greatly indebted to our laboratory colleagues, who have contributed so much to the work here reported. We acknowledge with thanks also the continued support of the Research Corporation, the Chemical Foundation, and the Josiah Macy, Jr., Foundation.

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[9] J. H. Lawrence and E. O. Lawrence, Proc. Nat. Acad. **22** (2), 124–1933 (1936).

[10] R. E. Zirkle and P. A. Aebersold, Nat. Acad. Sci. **22** (2), 1934–138 (1936).

[11] J. H. Lawrence, P. A. Aebersold and E. O. Lawrence, Proc. Nat. Acad. **22**, 543–557 (1936).

[12] J. M. Cork and E. O. Lawrence, Phys. Rev. **49**, 788 (1936). J. J. Livingood, Phys. Rev. **50**, 425 (1936).

[13] E. O. Lawrence, Phys. Rev. **47**, 17 (1935).

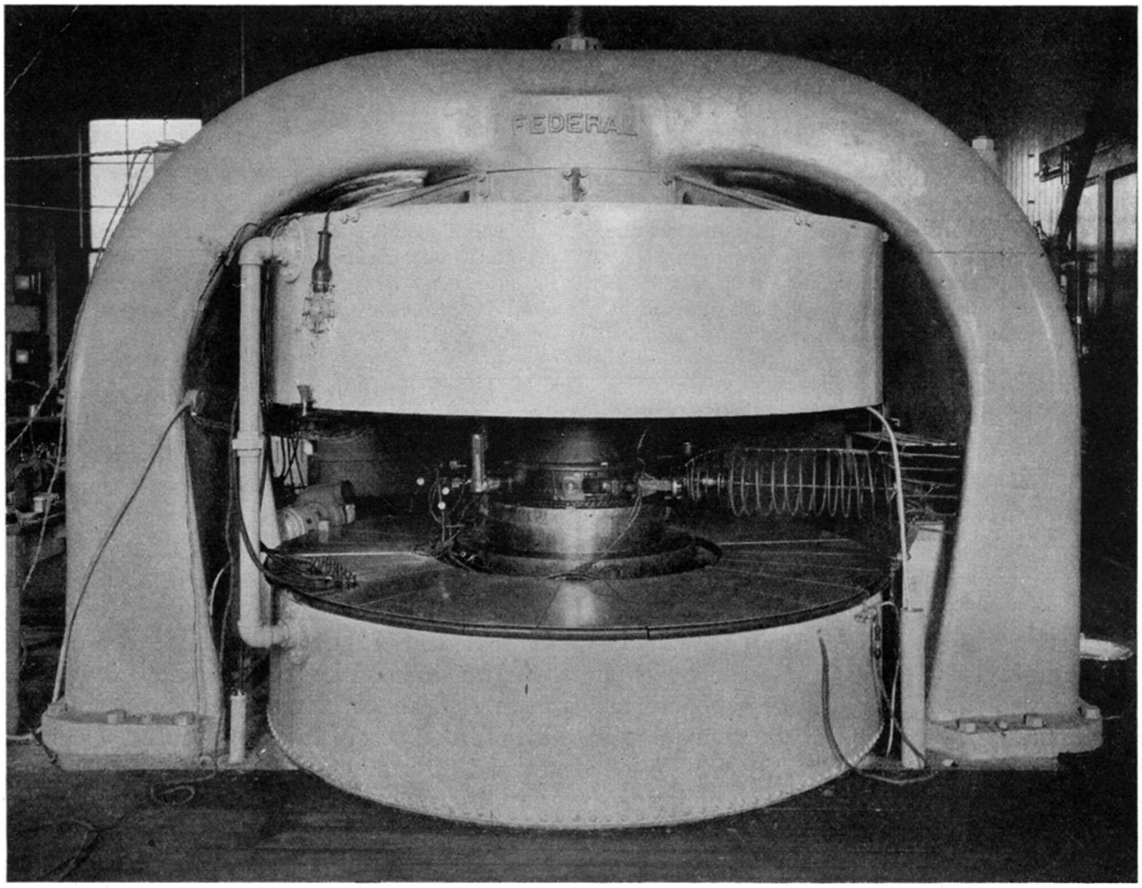

FIG. 1. General view of the cyclotron.

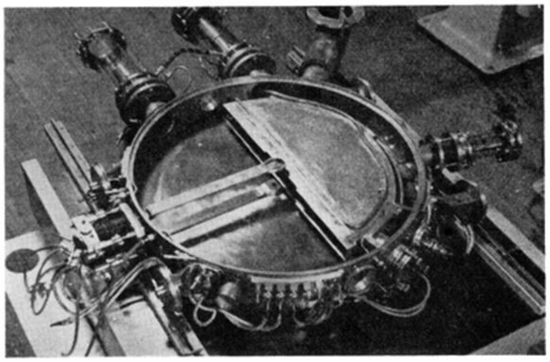

FIG. 3. Photograph of a cyclotron chamber with cover plate and one dee removed. In this apparatus the ions are not withdrawn completely but bombard targets within the chamber wall.

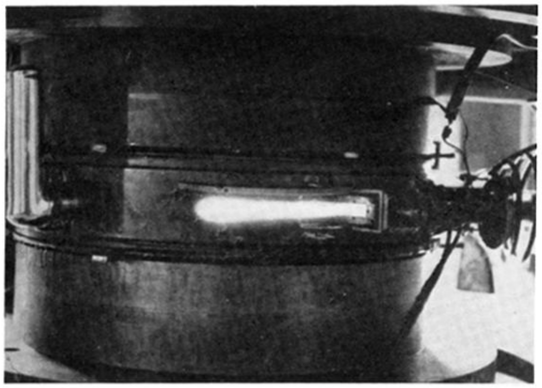

FIG. 5. Photograph of 5μA of 5.8 Mev deuterons (range 25 cm) emerging from platinum window of cyclotron.

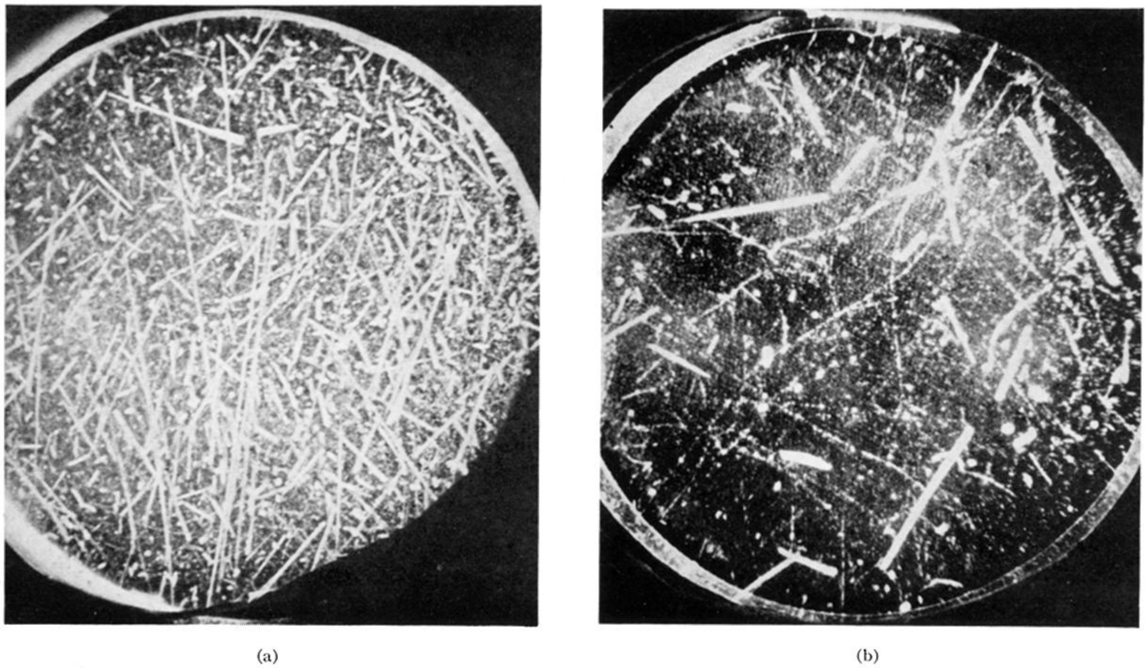

FIG. 7. Photographs of recoil protons in Wilson cloud chamber filled with hydrogen at pressure of 100 cm Hg produced by neutrons from Be target bombarded with 7μA of 5.5 Mev deuterons. Distance of cloud chamber from Be target, (a) 6 ft., (b) 40 ft.