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The Construction and Operation of a Cyclotron to Produce One Million Volt Deuterons

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A cyclotron for producing one million volt deuterons is described. The general magnetic field characteristics, and the effect of shims on the magnetic field have been examined. The production of ions for acceleration with and without filaments is discussed. The operation with a continuous glow discharge in the vacuum chamber is possible only because a transmission line is used to feed power to the dees. Various construction and operation details are given. The cyclotron has been found very reliable in operation and a maximum ion beam of 11 microamperes has been maintained for long periods of time. The beam has been removed in vacuum to a point about four feet from the vacuum chamber and partially focused. This allows bombardment work to be done with little interference from background radiation and high intensity fields.

VARIOUS methods[1–4] for accelerating heavy particles for nuclear disintegration work have been devised. A consideration of them led the authors to choose the cyclotron, or magnetic resonance accelerator. Two of its chief advantages are that a cyclotron yielding 2 Mev deuterons and 4 Mev protons or α-particles can be housed easily in a room approximately 15 feet by 20 feet and 15 feet high, and that voltages no larger than 50,000 volts need be applied to obtain the above effective potentials. The latter condition greatly reduces, as compared to other methods, the insulation problems which must be solved.

At the time the present installation was commenced, the high velocity beam of particles from the cyclotron could not be removed from the vacuum chamber and on this account the utility of the apparatus was limited. It seemed to the authors that this apparent disadvantage could be removed, an opinion which has been substantiated by Lawrence and his co-workers, and by the experience described below.[5]

Several descriptions of the cyclotron, its operation and fundamental characteristics have been discussed by other authors[4, 6, 7] so that it is unnecessary to give here an account of the general ideas involved. However, during the construction and operation of our small cyclotron (1 Mev deuterons) several new features have been introduced and since a number of investigators have requested information on these points, it is the chief purpose of this paper to discuss these new features in detail.

The size of the cyclotron is essentially the same as that designed by Livingston,[7] and from whom several important points on design were obtained prior to publication. The length of the Armco iron magnet is approximately 88 inches, the height 48 inches, and the pole face diameter 16 inches. A view of the whole unit is shown in Fig. 1.

The energizing coils of the magnet have 1248 turns of $\frac{1}{4}$-inch copper tubing and take a current of 100 amperes so that the magnetomotive force is 124,800 ampere turns. The magnet coils are cooled by a 12 gallon per minute flow of distilled water. The distilled water is cooled by tap water flowing through a copper radiator in a heat exchanger.

The intensity of the magnetic field in the accelerating chamber is 12,400 gauss at a current of 100 amperes and is essentially uniform over a radius of 16 cm as is shown in Fig. 2. Fig. 2 also depicts the effect of placing ring shims of various widths above and below the vacuum chamber. With no shims the field is flat and uniform except for a hump just inside the point where the field falls off rapidly. This hump may be due to the fact that the lid and bottom of the vacuum chamber are $\frac{1}{4}$-inch larger in diameter than the poles of the magnet. A ring shim ($\frac{1}{16}$ in. thick,

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[1] Cockcroft and Walton, Proc. Roy. Soc. **A129**, 477 (1930).

[2] Van de Graaff, Compton and Van Atta, Phys. Rev. **43**, 149 (1933).

[3] Crane, Lauritsen and Soltan, Phys. Rev. **45**, 507 (1934).

[4] Lawrence and Livingston, Phys. Rev. **40**, 19 (1932); Phys. Rev. **45**, 608 (1934).

[5] Kruger and Green, Phys. Rev. **51**, 57 (1937).

[6] Lawrence and Cooksey, Phys. Rev. **49**, 866 (1936); Phys. Rev. **50**, 1131 (1936).

[7] Livingston, Rev. Sci. Inst. **7**, 55 (1936).

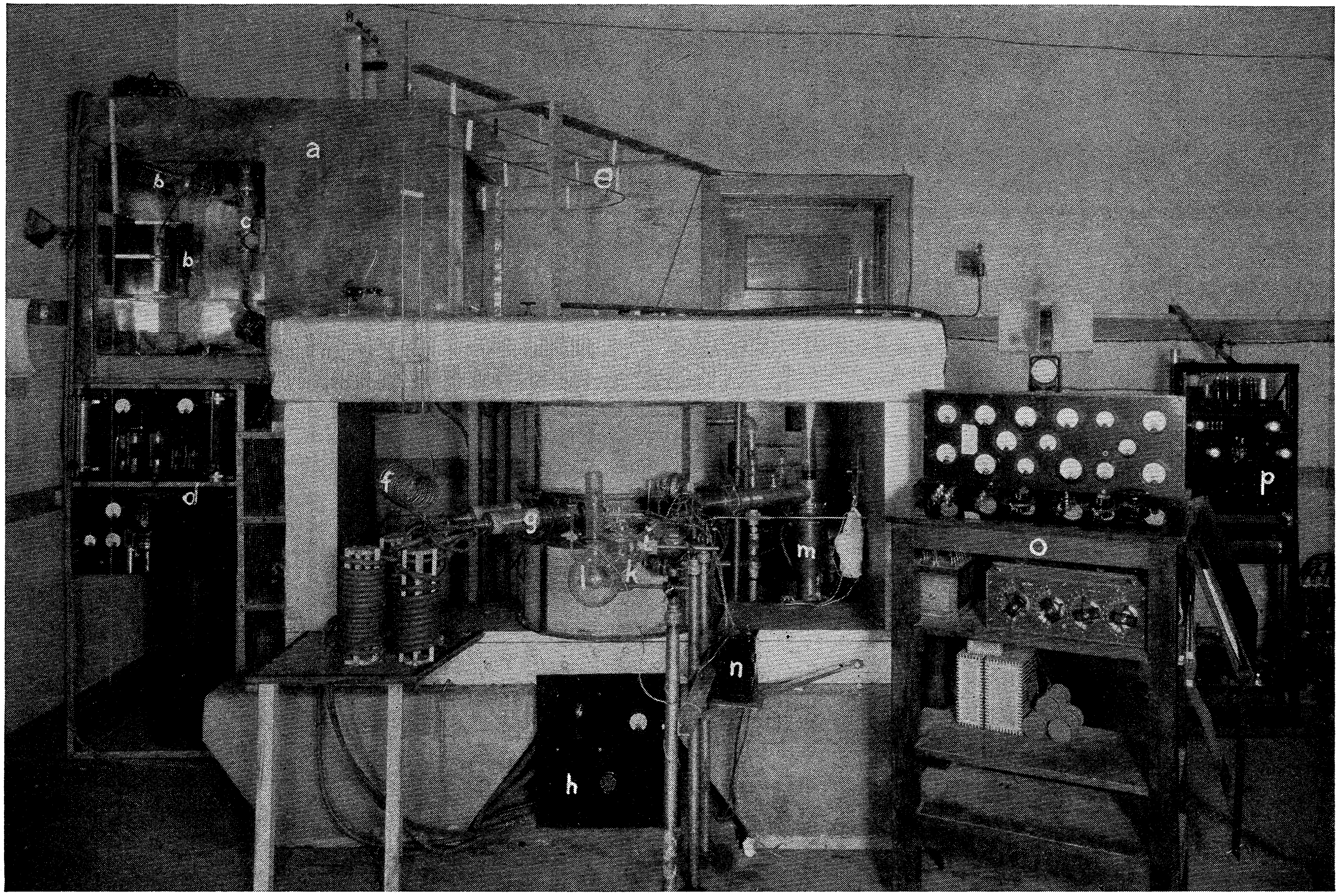

FIG. 1. General view of the cyclotron. (a) Oscillator house; (b) grid condensers; (c) 207 tube and water jacket; (d) oscillator-rectifier control panel; (e) transmission line; (f) dee coil; (g) dee insulators; (h) filament panel; (i) beam exit tube and focusing magnets; (k) stopcock to segregate exposure chamber; (l) exposure chamber; (m) Apiezon oil pump; (n) beam meter box; (o) movable control desk; (p) rack with auxiliary units and controls.

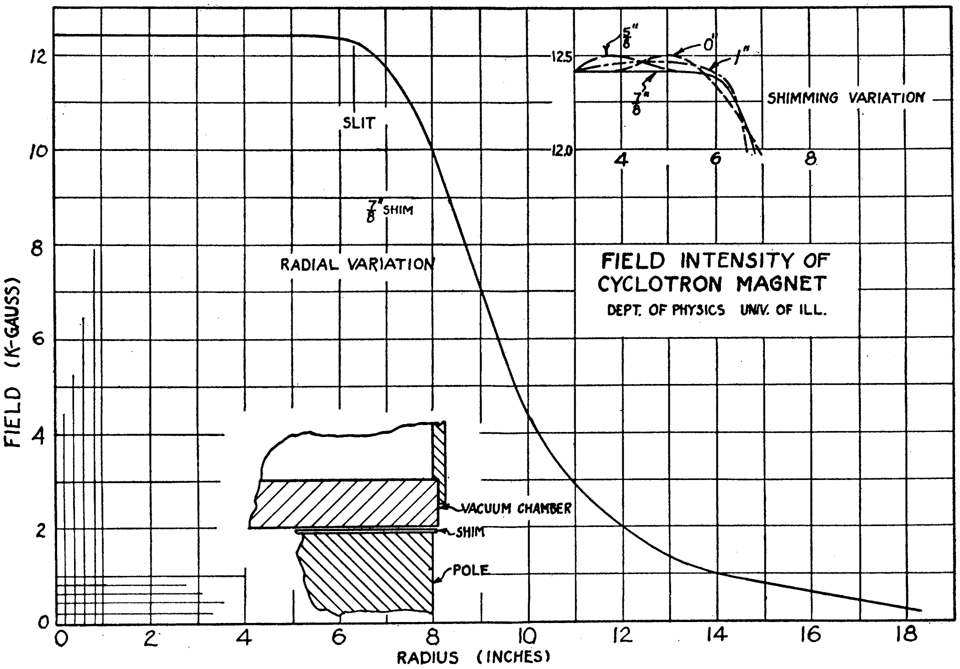

FIG. 2. Magnetic field intensity curve. Insert shows relative position of vacuum chamber and pole edges.

$\frac{7}{8}$ in. wide, 16 in. o.d. $14\frac{1}{4}$ in. i.d.) removes this hump (others do not, see Fig. 2), and gives a uniform field over an area almost 16 cm in radius. For that reason the exit slit in the dee is placed 16 cm from the center of the vacuum chamber. The large field gradient at greater radii makes it easy to remove the beam from the cyclotron chamber.

Fig. 3 shows schematically the vacuum chamber, the dees, deflection electrodes, and exit for removing the ion beam from the region between the poles of the magnet. The dees are one inch deep inside and are essentially the same as the design of Lawrence and Livingston. The vacuum chamber lid and bottom are made of Armco iron and are one inch thick. There is a space of three inches between top and bottom of the vacuum chamber.

During the first months of operation, 10-mil tungsten filaments were used, and a maximum ion beam current of three microamperes obtained at the collector cup (see Fig. 3). Recently a new filament assembly using 40-mil tungsten wire, and similar to the design of Lawrence and Cooksey,[6] has been installed. With this a steady beam current of 11 microamperes has been maintained during continuous operation of several hours. All of our results indicate that the ion beam current is nearly proportional to the filament emission, provided the gas pressure in the vacuum chamber is of the order of 10^{-5} mm Hg or less. At pressures slightly above 10^{-5} mm Hg, space charge limitations occur so that it is necessary to reduce the filament heating current to an optimum value which gives maximum beam current. At still higher pressures a glow discharge occurs between the dees and then the filaments can be turned off and a beam of 5 microamperes obtained.[8] Fig. 4 shows the relation between the ion beam current and the pressure in the vacuum chamber. Two independent sets of data taken under different conditions are represented by the dots and crosses. In taking these data the pressure was increased to about 10^{-4} mm Hg by letting in a burst of heavy hydrogen. Then readings of pressure and beam current were recorded while the pumps reduced the pressure. The right half of the curve represents a condition of gaseous discharge and cold filaments. The use of filaments in this pressure region does not

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[8] Kruger, Green and Stallmann, Phys. Rev. **51**, 291 (1937).

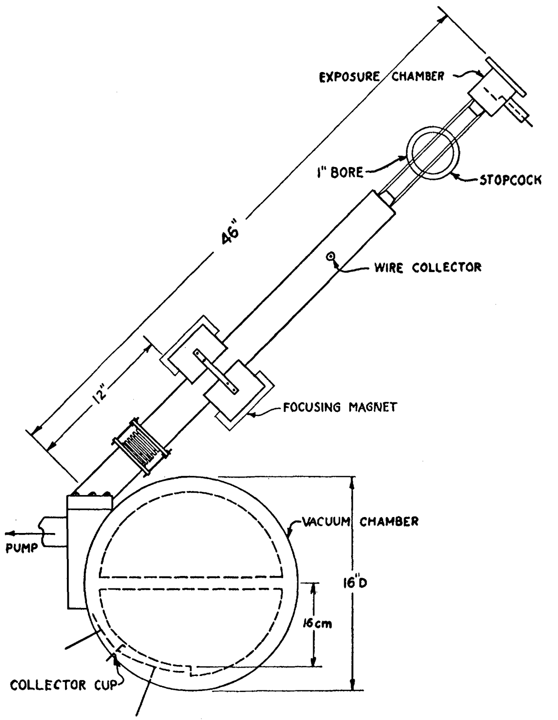

FIG. 3. Schematic diagram of vacuum chamber and beam exit appurtenance.

increase the beam current. The left half of the curve represents a pressure condition so low that no glow discharge occurs and filaments must be used. It will be noticed that the maximum beam current is obtained over a rather limited pressure region.

The electrons from the filament are accelerated by a 0–1800 volt potential applied between the filament and a surrounding shield. The optimum potential[9] is dependent on operating conditions and is set by watching the effect on the beam current. As the accelerating potential is increased the beam current increases up to the optimum value of the accelerating potential and then decreases with any further increase in accelerating potential. At first the electrons were accelerated through a round hole in the filament shield but later a three wire 10-mil tungsten grid was placed over the hole. With this grid the beam current was 2.5 times the current without a grid. We are planning to use six or eight wire grids in the future. This should increase the efficiency of the filaments even more.

The details of the construction of the dee insulators are shown in Fig. 5. Molded Pyrex glass tubing has internal cones ground on both ends. These cones are fitted with brass end cones which are machined to fit the vacuum chamber on one end and the dee support tube on the other, and are cemented to the glass with litharge cement (mixture of PbO and glycerin). This makes a joint which is so stable that a hammer must be used to separate the cones. However, the joint is not strictly vacuum tight and must be painted with shellac or glyptol under vacuum. Aluminum rings, as shown in the figure, are spaced along the glass wall to shield the glass and at the same time provide a sufficiently long glass path for insulation. These rings are split with the ends tapered and overlapping so that the ring is not continuous, and so that the copper dee supporting rod cannot "see" the glass at any point. This prevents sputtering of the glass with copper. The rings also serve two other purposes. They prevent any cold cathode emission from striking the glass and act as a high frequency shield to prevent the glass from heating. One such pair of insulators gave several hundred hours of service between March and November, 1936, without heating or puncture. The second pair has been in service since then.

Removing the beam from the region between the poles of the magnet is very important, because it enables the performance of bombardment and disintegration experiments in a region comparatively free from the disturbing influence of background radiation from the walls of the vacuum chamber. Moreover, detecting devices such as a Wilson cloud chamber or electrical

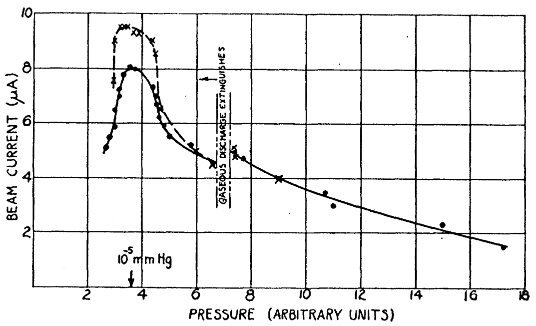

FIG. 4. Ion beam current *vs.* pressure in vacuum chamber.

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[9] This potential varies from zero to 1500 volts under different operating conditions but normally is about 800 volts.

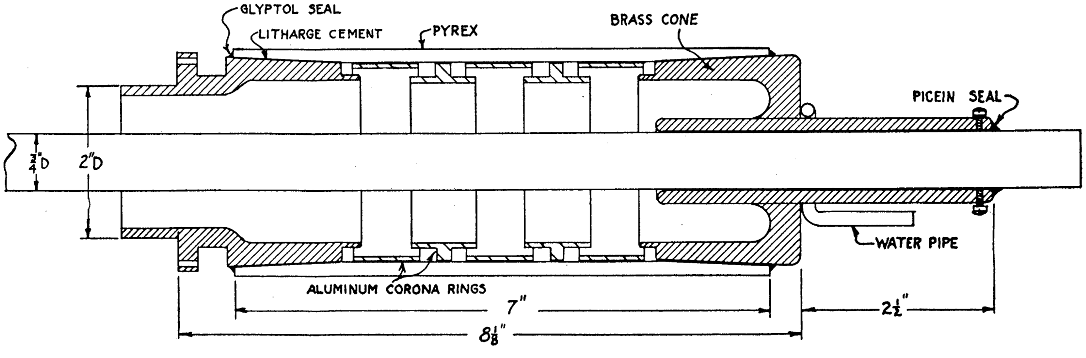

FIG. 5. Dee insulator.

counters can be operated with less influence from intense electric, magnetic and high frequency fields. It is comparatively simple to remove the beam if advantage is taken of the sharp decrease in the magnetic field at the edge of the pole, i.e., if the slit in the dee is placed at the edge of the plateau in the magnetic field curve as shown in Fig. 2. When this is done the ions move in a rapidly decreasing field and consequently a path of increasing radius of curvature as soon as they are pulled a small distance out from their last circle by the deflecting field. The size of the beam was examined at the point where it passed the edge of the vacuum chamber and was found to be 50 mm long by 5 mm high. Thus to remove the beam several feet from the cyclotron, as has been done, it was necessary to prevent further divergence of the beam and focus it. Partial focusing has been accomplished with a pair of small electromagnets.

The high frequency power for accelerating ions is supplied by two PR 207 tubes and is transferred to the cyclotron vacuum chamber by an untuned transmission line (Fig. 6). This method was selected for several reasons: limited space makes it impractical to set the oscillators next to the vacuum chamber; the small output of our rectifier (10 kw) requires the highest possible efficiency; the vacuum chamber can be rotated or removed without disturbing the oscillator system; and during operation the oscillators are not thrown out of oscillation by bursts of gas in the vacuum chamber. Thus the cyclotron can be run with a glow discharge in the chamber in order to outgas the metal surfaces rapidly, and, as described above, can produce a beam without the use of filamentary ion sources.

Greatest efficiency is realized with the oscillator tubes working into a circuit with a high L–C ratio. For this reason the plate tank circuit is made "low C," i.e., high impedance, and matched by the transmission line to the dee tank circuit. This latter resonant circuit may have a relatively low impedance, especially with a glow discharge, which is equivalent to shorting the dees with a resistance. The dee coil is wound with $\frac{5}{16}$ in. copper tubing on a 4 in. form and has ten turns. The transmission line[10] is made with two lengths of $\frac{1}{4}$-in. copper tubing which are supported on 4 in. Isolantite feeder spreaders. (See Fig. 1.) The length of an untuned line does not affect its characteristics and is fixed to accommodate the arrangement of the apparatus. The line tubes, at the terminal end, are clipped across 1.1 turns of the dee coil which matches the line to the dee tank impedance. At the input end the line is coupled to the plate tank by $\frac{1}{2}$ turn of $\frac{1}{4}$ in. tubing wound on a 6 in. form and placed around the center of the plate coil. This plate coil has eleven turns of $\frac{5}{16}$-in. copper tubing wound on a 4 in. form.

The cooling water exhausts from the oscillator tube jackets into the plate coil ends and leaves the coil through its center tap. This arrangement

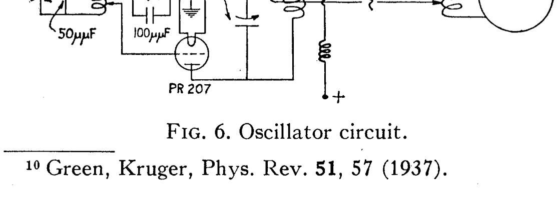

FIG. 6. Oscillator circuit.

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[10] Green, Kruger, Phys. Rev. **51**, 57 (1937).

saves three hose reels, which in our installation contain 16 feet of hose, each. The tank coil is tuned by double concentric cylindrical condensers whose stationary elements are 6.5 in. i.d. by 12 in. long, and have cylindrical corona rings around bottom and top. The movable elements are 4.75 in. o.d.×15 in. long, with copper hemispheres over their tops, and their positions controlled by racks and ganged pinions. The grid tank consists of a seven turn, water-cooled coil of $\frac{1}{4}$ in. tubing wound 2.5 in. i.d. and a conventional type variable condenser built in our shop. The condenser has five $3\frac{1}{2}$ in. radius rotor plates, and four stator plates, spaced one inch apart and is paralleled by a fixed air condenser having three 11 in.×11 in. plates spaced 1 in. (see Fig. 1). All condensers are supported on Isolantite pillars. The grid coil center tap connects to a grid condenser made of glass plates and sheet copper, and a grid leak consisting of three 200 watt 2000 ohm vitreous enameled resistors in series. The oscillator tubes have a low grid plate impedance so that it is necessary to tap the grid leads about a turn in from the coil ends to keep the excitation and d.c. grid current low enough. This tapping gives a transformer action causing a high peak voltage across the grid condenser, which arcs between plates occasionally. It may be necessary to introduce a small amount of cross neutralization to prevent arcing when using higher power. The filaments of the two tubes are connected in parallel with copper rods which conduct the circulating current. This eliminates by-pass condensers, and reduces parasitic oscillations.

The high frequency system is supplied with power by a three-phase full wave rectifier having a high voltage transformer rated at 10 kva. Rectification is provided by six FG 19A (same as 872A) carbon anode mercury vapor tubes. A small filter is connected in the rectifier output, mostly for high frequency and surge protection.

When making either the initial or subsequent adjustments, the dee circuit is tuned to the desired frequency by varying the number and spacing of turns, of the tank coil. The resonant frequency is determined by finding the point at which a small, calibrated, oscillator delivers load to the tank when coupled loosely to it. The power oscillators are then tuned to this frequency and the transmission line connected at both ends with turn ratios determined by a rough impedance calculation. Operating with reduced input energy, the plate condenser is varied over the region in which the plate current peak occurs, and the characteristics of this current peak observed. This operation is repeated for a series of grid condenser positions and the grid and plate condensers adjusted to give the best peak obtainable. The coupling at the dee end of the line is then varied to find the best plate current peak. Finally the coupling at the tank end is adjusted to give the desired power transfer. When the tuning is correct, varying the plate condenser will give a smooth plate current peak and a neon lamp touched to the line will glow with an intensity independent of the point touched. (Such tests may be made with a neon glow lamp fixed to the end of a clean glass tube about a meter long. This sort of indicator should never be put in contact with any part of a circuit at very high radiofrequency potentials.) The potential developed across the dees is directly proportional to the square root of the high frequency power they absorb. In normal operation the oscillators are supplied with 10 kw of d.c. power at 9600 volts, of which about 60 percent appears as high frequency power in the dee tank. This produces a peak voltage of 50 ± 5 kv across the dees, as measured with a cathode-ray oscilloscope and capacity voltage divider. The relation between beam current and peak voltage across the dees is shown in Fig. 7.

Ion beam current is measured with a vacuum tube voltmeter indicating the potential drop

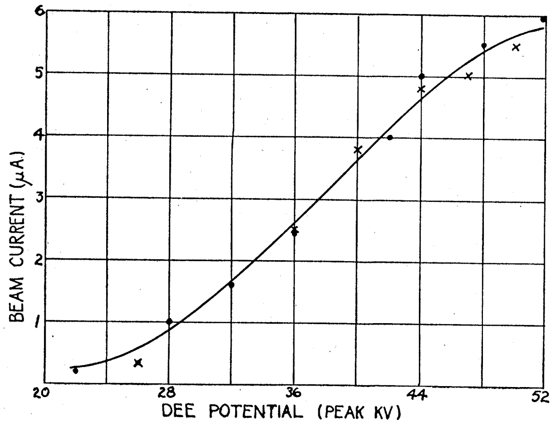

FIG. 7. Beam current *vs.* dee potential.

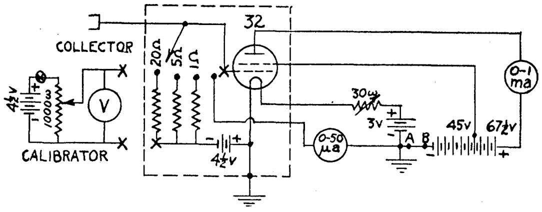

FIG. 8. Beam meter circuit.

across a high resistance. The meter, Fig. 8, is cheap and rugged, and holds calibration for long periods. A permanent calibrator is built to clip on at points X so that a calibration requires less than five minutes. The type 32 tube obtains filament current from two No. 6 dry cells and its plate and screen grid current from batteries which also supply the grid and plate potentials for the ionization vacuum gauge. The insulated metalized type resistors are calibrated and will hold their value for a long period. With 20 megohms, 10^{-8} amperes gives one scale division deflection on the 0–1 ma plate current meter. This has been found to be adequate sensitivity. The above milliameter is mounted on the movable control panel with about 60 feet of shielded cable to the tube and resistors, which are in a shield box near the beam collectors. Shielded rubber covered hookup wire makes a satisfactory grid lead. Several feet of lead wire can be used if the shield is carefully grounded.

A 0.25 megohm resistor has been inserted at AB and a cathode-ray oscillograph connected across it to photograph the wave form of the ion beam. When doing this it is best to increase the plate battery voltage to 90 volts. An oscillogram taken in this manner shows about 10 percent beam current ripple caused by the 360 cycle ripple in the input to the oscillators.

All operating controls and meters are built into a desk (see Fig. 1) mounted on castors and connected by a long cable to a terminal box into which all control and indicating leads are run. This has been especially convenient for developmental and adjustment work when the controls need to be moved to any desired region. Two keys, on the panel, control motor driven resistors in the magnet generator field. One resistor has a low value and gives a fine adjustment, which can be controlled by a balanced-galvanometer and photo-cell system (similar to that of Wynn-Williams[11]) so that the magnet current is held constant. The other resistor has a higher value, for coarse adjustment, and is controlled by a push button so that the generator shunt field circuit is broken when the resistance is all in. The relatively low inductance of the magnet and generator allows these resistors to function with small lag in the generator field circuit, whereas the 200 ampere magnet current makes control in the magnet coil circuit impractical. Both resistors have auxiliary contacts which energize neon bulbs on the panel to indicate their positions.

In operation, the cyclotron has been very reliable. Outgassing is easy because one can let the oscillators run with gas in the vacuum chamber and pump until the gas cleans up. Then a beam can be obtained in a few minutes. When the vacuum chamber is clean, a small amount of air introduced and immediately pumped out does not impede operation. For instance, by closing the big glass stopcock in the beam exit line (Fig. 1) one can change the target in the exposure chamber and within ten minutes be in operation bombarding the new target.

Some rectangular shims are used in addition to the ring shims described above. However, with magnetic field deviations of the order of one percent, such as are present over the area of the dees, very little empirical shimming is necessary.

The authors wish to express thanks to their laboratory colleague, Mr. F. W. Stallmann, for his cooperation and help in the assembly of the cyclotron. The senior author also wishes to acknowledge a grant-in-aid from the National Research Council and generous support from the Graduate School Research Board of the University of Illinois.

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[11] Wynn-Williams, Proc. Roy. Soc. **145**, 250 (1934).

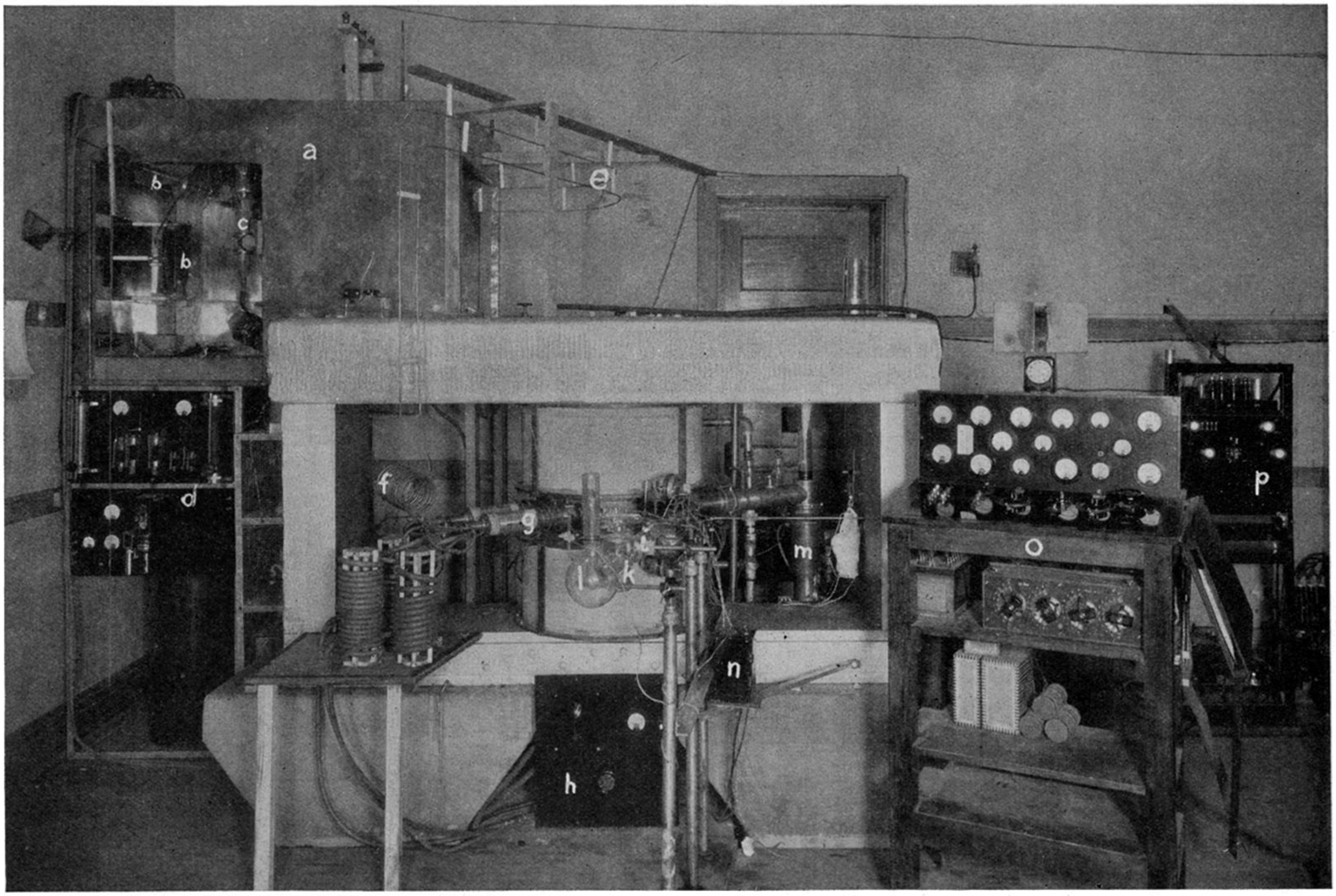

Fig. 1. General view of the cyclotron. (a) Oscillator house; (b) grid condensers; (c) 207 tube and water jacket; (d) oscillator-rectifier control panel; (e) transmission line; (f) dee coil; (g) dee insulators; (h) filament panel; (i) beam exit tube and focusing magnets; (k) stopcock to segregate exposure chamber; (l) exposure chamber; (m) Apiezon oil pump; (n) beam meter box; (o) movable control desk; (p) rack with auxiliary units and controls.