THE BETATRON*

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FROM THE experiments of the past eleven years and from still earlier experiments we have learned a great deal about the phenomena of nuclear disintegration, especially about artificially produced disintegration, which follows as a result of nuclear particles being forced together so that some degree of interpenetration occurs. Since the nuclei of atoms are positively charged, the great repulsive forces arising from a very close approach must be overcome before there will be penetration. One cannot take a hold of nuclear particles or push directly on individual particles; so the method which has been used with such great success is that of impact. Charged nuclei, or positive ions, of one variety are accelerated in a high voltage vacuum tube in which the electrodes are arranged to force them toward a target of a substance containing the other nuclear particles to be bombarded. It is common in these artificial disintegration experiments to reach forces as great as 20 pounds weight between individual nuclei during the impact process. This force is far out of the range of those which occur in the most intense compression that can be produced by other means.

It is only in the case of the neutron, the uncharged nuclear particle, having approximately the same mass as the proton, that penetration into other nuclei occurs easily, and this is because the lack of charge on the neutron makes electrical repulsion impossible.

One other reason for giving one of the nuclear particles a high energy is that when the two nuclei collide certain reactions will not occur unless the energy brought to the collision by the high speed particle is sufficient to supply the energy required for this reaction. It is mainly for this reason that if disintegrations are to be produced by electrons or by the x-rays which they produce, the electrons must have very high energy.

The nuclear physicists who have become high voltage experts in order to do these disintegration experiments make use of several varieties of high voltage apparatus to impart large energies to small particles. Except for disintegrations produced by particles from naturally radioactive substances, the equipment usually used for producing high speed particles has been either a linear accelerator or a cyclotron. In the linear accelerator the charged particles are pushed from electrode to electrode down the axis of a long vacuum tube. The electrodes are generally hollow cylinders connected to successively higher voltages. The voltage is supplied either by a large transformer-rectifier combination or by the Van de Graaff type of electrostatic generator which charges a high voltage electrode by means of long moving belts. One end of the accelerating tube is connected to this high voltage electrode, and the other end is usually at ground potential. This accelerator has been developed to the extent where it produces about 4.5 million volts when confined in a tank no larger than 5.5 feet in diameter and 22 feet long, provided the high air pressure of about 100 pounds per square inch is used for insulation of the high voltage terminal. This type of accelerator has been used to some extent for the study of nuclear reactions produced by electrons and x-rays having energies up to three million electron volts, but most of the work of the electrostatic accelerator has been with positive ions. There is a large number of nuclear reactions called photodisintegrations which can occur by electron or x-ray bombardment, but these require on an average six to eight million electron volts of energy before the reaction can proceed. For these experiments energies greater than those obtained by the electrostatic generator are necessary.

In the cyclotron the positive ions do not follow a linear path. Rather they are bent by a magnetic field into a spiral path, and they are accelerated back and

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forth between two dee shaped hollow metal electrodes. The reason this can be done is that when a group of positive ions are well shielded within one of the dees this electrode reverses potential with the other electrode; and by the time the positive ions are in position to pass to the other dee, the potential is such that they are forced forward to a greater speed. This requires that the dees be connected to a high voltage high frequency oscillating circuit. The final energy which the positive ions achieve is the product of the number of transits from dee to dee and the voltage between dees. With this apparatus deuterons have been accelerated to 16.5 million electron volts, far more than the voltage which can at present be produced on a single insulated electrode such as that used on the electrostatic machine.

However, the cyclotron cannot apply its great voltage to electrons. The reason for this lies in the onset of relativistic behavior of the electron at very low energies. Particles behave in a distinctly relativistic manner when their kinetic energy approaches or exceeds the energy equivalent of their rest mass. For example, the rest mass of a proton is equivalent to about one billion electron volts. Protons of this energy would show pronounced relativistic behavior; however, the electron with a rest mass equivalent to only .5 of a million electron volts will behave relativistically at this low voltage. At .5 of a million electron volts the electron is traveling at approximately .9 of its speed limit, the velocity of light. Since one of the requirements in the operation of a cyclotron is that the accelerated particle increases its speed in proportion to the square root of the number of revolutions, it is impossible for an electron near its speed limit to fulfill this condition. Consequently, a cyclotron could only be used for electrons at voltages well below half a million volts.

Fortunately the betatron operates equally well at classical or relativistic energies. The energy which the new betatron gives to electrons is 20 million electron volts. With this source of high energy electrons one can create extremely energetic x-rays, and the nuclear-photo effects requiring on an average 6 to 8 million volts can be produced. Generally in the photo effect an x-ray or gamma ray photon of energy greater than the binding energy of a neutron within the target nucleus reacts with that nucleus and ejects the neutron somewhat like the electrons are ejected from the cathode in an ordinary photo-electric cell. The resulting nucleus is frequently radioactive, and the binding energy of the nucleus to be disintegrated can then be easily determined by finding the energy of the betatron at which production of radioactive material commences. The electrons themselves can be used to eject the neutron for the nucleus responds to the passage of an electron with its associated electric field in the same way but to a lesser extent than it responds to high energy photons.

Since we now have available a source of highly penetrating x-rays and a source of electrons of an energy so great that they can penetrate approximately half way through the human body, the uses to which the betatron can be put are not only experimental but very practical. X-rays are widely used in numerous practical ways industrially, and the radiations from the betatron are more penetrating than any others which have been produced.

The high energy electrons which escape from the accelerator by scattering off of the x-ray target form a very intense but somewhat divergent beam of electrons. Such high energy electrons when sent into the human body would produce a trail of ionization having the same destructive effect as x-rays which are at present used for therapy of deep tissue. One of the disadvantages of x-rays is that they do not stop somewhere within the body, but they penetrate completely through it and produce a biological effect, not only at the entrance surface and at the tissue being treated, but also at the exit side of the body. Various techniques are used in an attempt to create an optimum of ionization at the deep malignant tissue; but the advantage which penetrating electron rays have is that their range is finite and proportional to the energy of the electrons. The 20 million volt electrons from the betatron would penetrate 10 centimeters into the body and no more. Dr. Phillip Morrison estimates that the maximum ionization produced by these rays would be at about 7 or 8 centimeters below the entrance surface of the body. This means that the damage produced by an electron beam

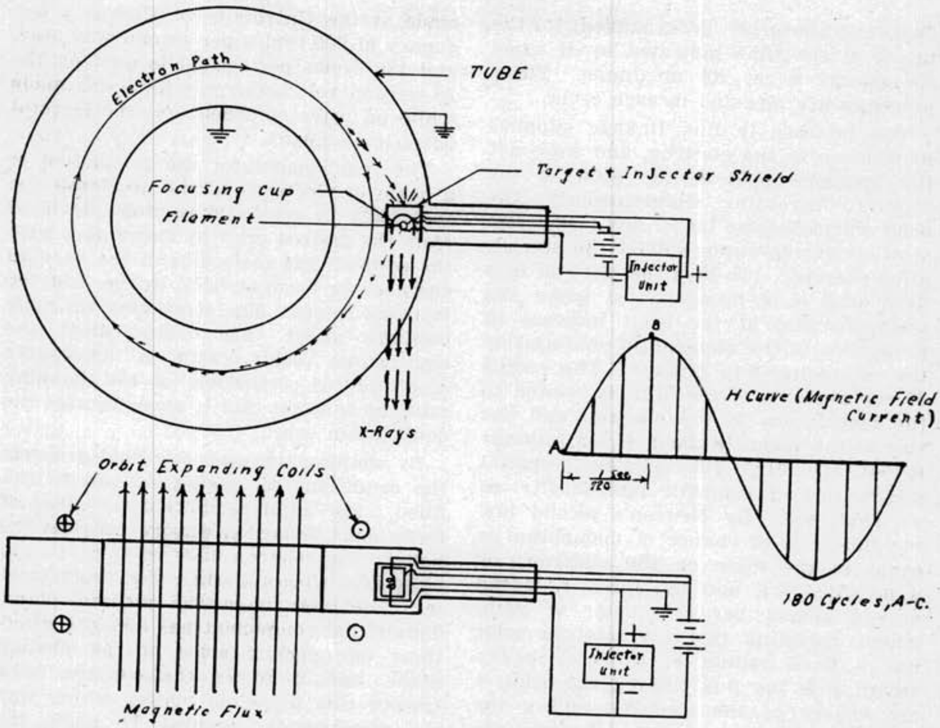

Fig. 1.—The vacuum doughnut in which the electrons are accelerated. Electrons going from the injector to the equilibrium orbit actually circle the tube many times before reaching the orbit. The same is true for electrons leaving the orbit to hit the target. Electrons are injected at A, and the orbit is expanded at B in every cycle.

can probably be localized fairly well on the tissue which is irradiated, a smaller amount of damage being done on the entrance side of the body and no damage being done beyond the tissue irradiated. When the beam of electrons in the betatron can be brought out without being scattered from a target, it will be more homogenous and less divergent, which will make the betatron more applicable to this very practical problem.

OPERATION OF THE BETATRON

The betatron looks in some respects like a miniature cyclotron since it is a magnetic device; but it operates with an alternating magnetic field instead of a uni-directional field. The theory of the betatron shows that relativistic effects encountered when the speed of light is approached do not hinder the operation in any way.[1] Electrons from an electron gun, called the injector, are shot into a circular path in a low intensity magnetic field. As these electrons circulate between the poles of the magnet, the magnetic field increases, and the time rate of change of flux linking the orbit produces a voltage gain per revolution equal to the voltage which would be read on a voltmeter connected to a one-turn coil placed at the orbit and reading instantaneous voltage.

Fig. 1 shows a sketch of the circular vacuum tube or doughnut in which the electrons leave the injector, circulate the magnetic field many times picking up energy at every revolution, and strike the back end of the injector, after they have been accelerated, where they produce x-rays. The orbit expanding coils are energized after the electrons have been accelerated, and they disturb the flux distribution near the electron path causing the electrons to spiral out to the target. The electrons are injected at the time indicated by A on the graph of magnetic

[1] D. W. Kerst, Phys. Rev. 60, 47 (1941). D. W. Kerst and R. Serber, Phys. Rev. 60, 53 (1941).

field, and the orbit is expanded to the target at the time indicated by B when the energy is at its maximum. These processes are repeated in each cycle.

The increase in flux linkage supplies momentum to the electron, and were not the magnetic field at the orbit of the electron increasing simultaneously, the orbit would become larger and larger and soon strike the outer wall of the acceleration chamber. To hold the electron in a fixed orbit it is necessary to make the magnetic field at the orbit increase in proportion to the momentum produced by the increasing flux linkage. The radius of curvature, r, of the orbit is related to the momentum of the electron and the size of the magnetic field, H, as follows: $mv = (e/c)\ Hr$. This calls for a special distribution of magnetic flux density, as we shall see. By Newton's second law the time rate of change of momentum is equal to the force on the electron; or $d(mv)/dt = f$, and the force, f, is the energy gained per centimeter of path, which assuming that the electron orbit has a fixed radius, r, is $(e/c)\ \phi/2\pi r$ where ϕ is the flux linking the orbit, e the charge of the electron, and c the velocity of light. Integrating the time rate equations, we get $mv = (e/c)\ (\phi - \phi_o)/2\pi r$, showing that the momentum is proportional to the change of flux within the circular orbit. Equating this momentum to $(e/c)Hr$ we get $\phi - \phi_o = 2\pi r^2 H$; which shows that if ϕ_o is zero when H is zero, the flux linking the orbit is proportional to the field at the orbit and must at all times have the value twice that which would exist if the field H were uniform within the orbit.

This result was obtained by making the assumption or r constant. Naturally the converse must be established and was established before the accelerator was built, that is, given this flux distribution, then the orbit has a fixed radius.

No mention has been made of the time dependence of the flux and field. It is merely necessary that the flux increase with time and that the field increase proportionately. This is easily accomplished by having both H and ϕ produced in an air gap by the same magnetic circuit. In practice the magnet and its coils correspond to an inductance in a resonant circuit. A great number of condensers are used to produce resonance at the desired frequency. On the original betatron made at the University of Illinois a frequency of 600 cycles per second was used, and 180 cycles per second is used on the 20 million volt betatron which was made while on leave of absence at the General Electric Company.

The requirement for the production of a beam of electrons in the accelerator is that stray or scattered particles deviated from the desired orbit by encounters with the residual gas molecules in the vacuum chamber be brought back to the orbit by focusing forces. The stray electron must oscillate about this orbit, called the equilibrium orbit, with a decreasing amplitude of oscillation, or the damping must be so great that it never crosses the equilibrium orbit.

By shaping the magnetic field properly the conditions for oscillation can be fulfilled. For axial oscillation the lines of force must bulge outwardly between the poles. The electron finds itself in a magnetic field with a slight radial component if it deviates from the median plane. This radial component has opposite directions on opposite sides of the median plane, and it forces the electron back toward this plane no matter which way the displacement occurs. To make the field bulge outwardly between the poles it is merely necessary to have the air gap increase with increasing radius. In practice this is done with approximately conical pole faces except for a slight lip at the rim of the pole face to correct for the rapid drop in field intensity which occurs at this point.

The condition for radial oscillation is that the magnetic field must not decrease more rapidly than 1/r. This can be understood from Fig. 2 which shows the curve of required centripetal force to hold the electron in the radius, r, as a function of r. This is a hyperbolic curve, since $F_c = m\ v^2/r$. The magnetic force Fm which is supplied by the magnetic field is $F_m = (e/c)\ H\ v$. In the betatrons which have been made, v changes so slightly during several focusing oscillations that this change can be ignored for the present. Consequently, if the radial dependence of Fm, and hence of H, is as shown in Fig. 1, it will supply more than the required centripetal force when r is greater than r_o and less when r is less than r_o. Should an electron be outside the equilibrium orbit, it would be in a region where the magnetic field was stronger

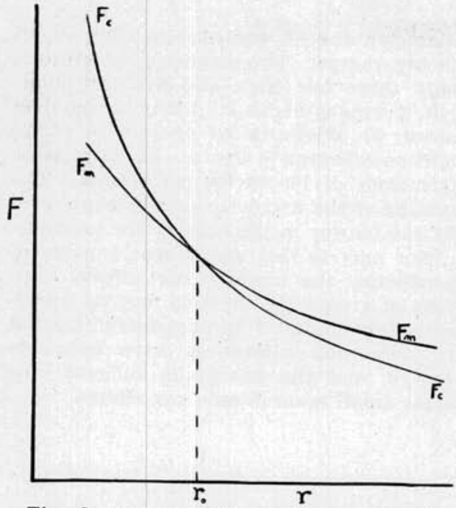

Fig. 2.—$F_c = mv^2/r$ is the centripetal force required to hold the electron in a circle of radius, r. $F_m = (e/c)Hv$ is the magnetic force which is actually supplied to the electron. The equilibrium orbit is at r_o.

than that necessary to cause a circular path. Its orbit would bend in toward the equilibrium orbit and, on crossing, the electron would find itself in a region where the magnetic field does not quite supply the required centripetal force; so the electron goes outwardly. This oscillation about the equilibrium orbit eventually dies out. The decrease in the amplitude of oscillation is a result of the increase in the magnetic field during the period of oscillation. The amplitude is proportional to $H^{-\frac{1}{2}}$. To a certain extent this is analogous to the stiffening of a spring which holds an oscillating mass. The damping properties of the increasing magnetic field make possible the whole process of injecting electrons so that they are trapped in a fixed orbit.

These axial and radial focusing actions succeed in forming a minute electron beam which strikes the target at a small focal spot. The x-rays produced cast very sharp shadows because the rays come from practically a point source.

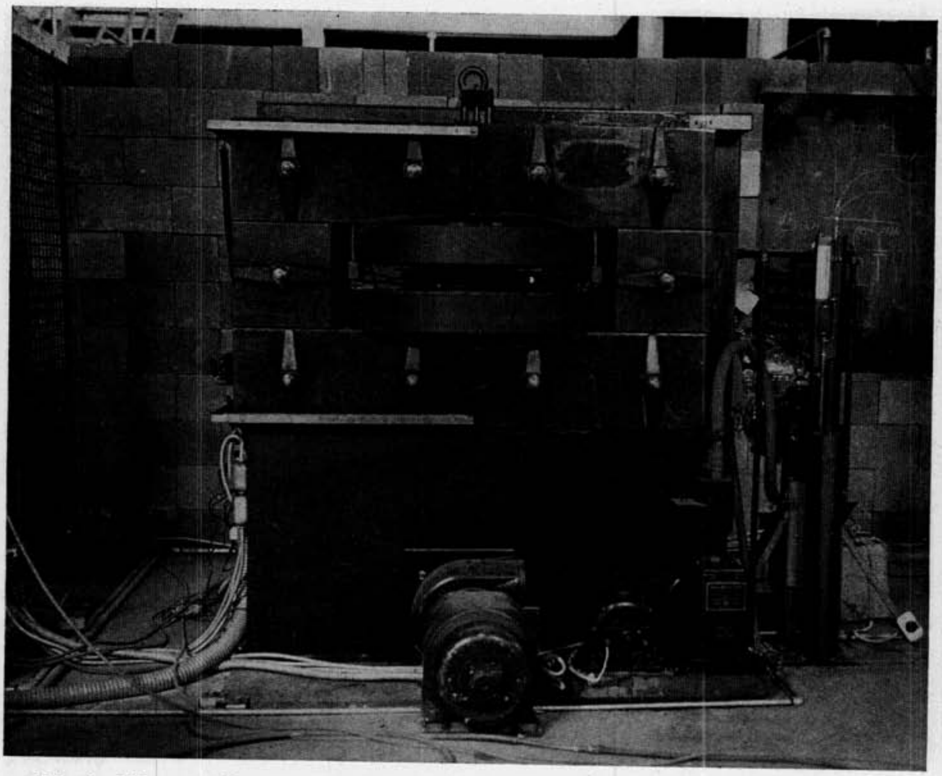

Fig. 3.—The new 20 million volt betatron. The light showing in the doughnut between the poles is from the injector.

The target is not melted by this fine beam because very little current is used. Approximately one microampere in the 20 Mev betatron suffices to produce 16 r per minute at one meter. The total number of watts in the beam is thus 20 and at this high energy the efficiency of x-ray production is so great that about 65 per cent of this beam energy is given off in x-rays and only the remainder heats the target.

The photograph in Fig. 3 shows the new 20 million volt betatron with the light coming from the injector at the edge of the doughnut between the poles. This accelerator has a 19-inch pole face diameter and an equilibrium orbit of 7.5 inches radius. The magnetic structure is only three feet high and five feet long; but it weighs about 3.5 tons. It requires about 25 kilowatts to operate it at 20 million electron volts at an oscillating frequency of 180 cycles per second. The cooling of the magnetic circuit is provided by the blower in the base of the magnet.

Not only is this accelerator capable of producing the usual x-ray effects with rays of greater penetration, but the radioactivities produced by photodisintegration in numerous substances have been observed, and the energy is sufficient for some small scale cosmic ray effects.