THE CYCLOTRON

By

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During the semesters that I have worked on the cyclotron, I have demonstrated it to perhaps one person per day. These demonstrations have indicated to me what questions the majority of people will ask. The answers, which range from fundamental working principles to somewhat advanced problems, will constitute this article. It is my special aim to satisfy the interests of the technical student, and toward this purpose some detail is included.

The beam produced by the cyclotron consists of ten million volt heavy hydrogen ions. The problem to be solved by any high voltage accelerator in producing such a beam is to guide charged particles through an electric field of tremendous potential. Solutions of this problem have resulted in the different types of linear accelerators, the cyclotron, and the more recent betatron. The ingenious feature of the cyclotron is that it produces a total potential ranging in the tens of millions of volts while operating at only a small fraction of the final voltage.

If reference is made to the diagrams the construction of the cyclotron may be followed graphically. The housing is a cylindrical tank of relatively large radius. It is vacuum sealed and maintained at a pressure of approximately one micron of mercury. At this pressure collisions of the beam with gas molecules are reduced to insignificance. Moreover, the gas, if present, would conduct between the high voltage gap and destroy the charge.

The particles which are to constitute the beam are heavy hydroden (deuterium) nuclei. Heavy hydrogen is chemically the same as ordinary hydrogen. The difference lies in the nucleus where a neutron is present in addition to a proton—making deuterium a heavy isotope of hydrogen. Deuterium gas is introduced into the tank at a pressure only slightly higher than the zero pressure. This beam constituent, when ionized, is to be accelerated.

Suspended in the tank are two copper "dees." Together they would form a flat, hollow cylinder. However, they are separated along a diameter by a spacing of about one inch. The dees, insulated from the tank and from one another, have impressed upon them a high frequency alternating voltage. The frequency is of the order of ten megacycles. The voltage, which may be as low as 17,000 volts, will be as high as 1,000,000 volts in the supercyclotron being built at Berkeley, California. Thus with alternation, one dee is charged positively and the other negatively; an electric field is created in the gap between the dees, and in falling through this field the particles receive their energy.

An electrically heated filament is located at the center of the base of the tank for the purpose of ionizing the neighboring deuterium. The filament itself is placed at a high negative voltage so that the thermal electrons emitted are repelled toward the center of the tank with at least the ionization potential of the deuterium. The atoms thus ionized possess a unit positive charge. The electrons (and their companions with which they collided) are caught by a positive plate toward which they were already speeding and are carried away.

The reader has already seen an example of electric charges—like charges repelling, and unlike attracting. Just such forces are now in operation on the charged deuterium. The nuclei are repelled by the dee which is momentarily positive and attracted by the one which is negative. In falling through this electric field the nuclei receive their initial energy (equal to the voltage across the gap).

Now they are to be brought around to fall through the gap again. For this purpose a magnetic field is created by powerful electromagnets. The tank itself is situated between the gap of the magnet poles. The direction of the field is perpendicular to the base of the tank, and therefore perpendicular to the path of the beam.

Now any charged particles moving, as our nuclei are, perpendicular to a magnetic field are acted upon by a force which is perpendicular both to their velocity and to the lines of force of the field. This force changes the linear path of the particle to a circular one—thus the spiral path seen in the diagram. It is just such a force which is utilized in electric motors: electrons conducted along armature coils are moving perpendicular to a magnetic field, and the armature is forced to turn. The only difference lies in the fact that the electrons are moving in wires, whereas our particles are suspended in free space.

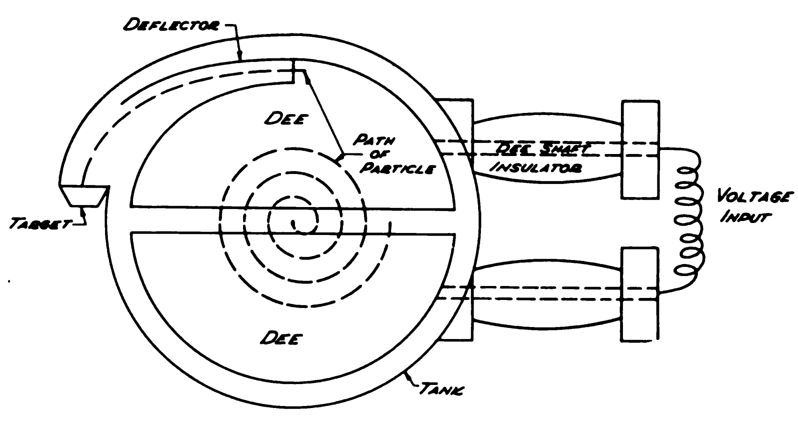

FIG. 1

Drawing by Madison Lent-Koop

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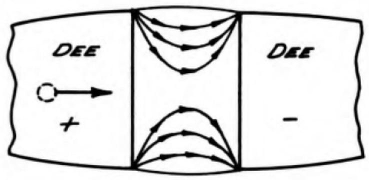
No electric field is present inside a hollow conductor such as the dee, and so the charged particles now move only under the influence of the magnetic field. Their circular path heads them straight for the dee-gap again. The timing is so adjusted that as the particle reaches the gap the formerly positive dee is negative and the formerly negative dee is positive, due to the alternation of the votlage. Here the particles receive another "kick", their second increment of energy.



FRONT VIEW OF DEE-GAP & ELECTRIC FIELD

FIG. 2

Drawing by M. Lent-Koop

In the simplicity with which the timing problem may be solved lies the real success of the cyclotron. The fundamental equation for the motion of the particles is

$$Hev = mv^2/r$$

where H is magnetic field strength,
e is charge on the particles,
v is velocity of particles,
m is mass of particles,
r is radius of path,

The second term of the equation is seen to be the centrifugal force of the particles. Hev is the opposing centripital force. Solving the equation for the radius, we find r equals $\frac{mv}{He}$. The time required for the particle to traverse one half circle is the distance divided by the velocity or T equals $\pi r/v$. This in turn equals $\pi\frac{\frac{mv}{He}}{v}$ or simply $\frac{\pi m}{He}$ The period is therefore a constant to the extent that the last term is constant, and is independent of velocity or radius. Therefore, the voltage oscillator may be adjusted to a single proper frequency, and all the particles, whether just starting or at a great radius, will cross the gap at the correct time. When the timing is so adjusted the apparatus is said to be in resonance; thus the term "magnetic resonance accelerator," which is sometimes applied. In practice the oscillator is adjusted to about the desired frequency and the magnetic field is varied to correspond.

By Newton's second law, force equals mass times acceleration. The amount of acceleration derived from a given force is no function of velocity. Therefore the particles can always receive additional acceleration equal to that initially imparted only by falling through the gap again. Every kick accelerates the particles and their velocity soon becomes tremendous. If the dee voltage is 20,000 and if the particles fall through the gap 500 times, as is the case in the University of Michigan cyclotron, the particles acquire 10,000,000 volts of energy.

From the formula for the radius, it is seen to increase with velocity. The spiral path of the particles becomes wider until they reach the inner radius of the dees. At this point they are ready to be deviated from their path and thrown toward a target. This is accomplished by a deflector plate (see figure 1) extended outside this radius immediately before the target. It is negatively charged at about 20,000 volts potential pending on its position. Particles reaching the critical radius fall under the influence of this attracting field and are deviated from their path. The target to be bombarded is placed in line with their new path.

We have followed a complete cycle of the events in the cyclotron and have thus explained its fundamental principles. However, we have postponed some important problems which any sincere treatment of the subject should contain.

The forces which operated on the particles in the horizontal plane in which they move are clear. But what forces guarantee that the particles will remain in that plane? After all, they had a random motion to start with. Moreover, the groups consist of positively charged particles all of which repel one another, a tendency toward dispersion. The first force effective in maintaining the horizontal position is that of the electric field itself. The shape of the lines of force are shown in Figure 2. The particles in following these lines through the first half of the gap are drawn toward the center. However, in following the lines through the last half of the gap they are pulled away from the center—an adverse effect. Nevertheless, if it is remembered that the particles are accelerated across the gap, it will be seen that they spend less time traversing the latter half than the first half. They are therefore under the influence of the converging force longer than under the diverging force, and the effect is a focusing one.

As the particles go faster, this effect becomes less significant, because the per-

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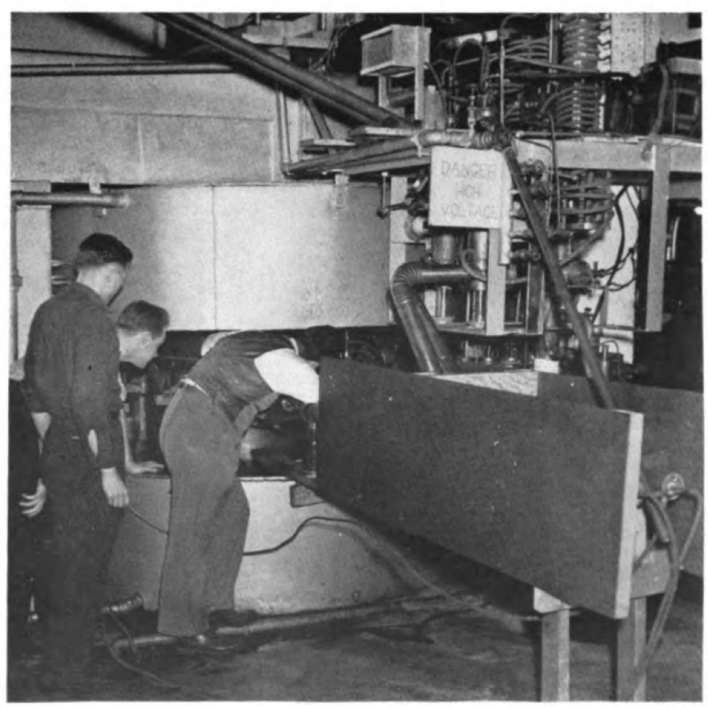

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(*continued from page 13*)

centage increase of speed becomes less less even though the increase is the same every time. Here a compromise in the cyclotron is invoked. Rather than produce a uniform magnetic field, which would be ideal as pointed out above, a field of strength decreasing slightly toward larger radii is produced. In the diagram of the resulting field (Figure 3), a familiar pattern is seen. The field, being more intense at the center, bulges out at the edges. If the particle tended to move up or down in such a field it would encounter a vertical opposing force, since it would have to cut lines of force to maintain its radius. An analogy would be a small ball bearing speeding inside a hollow doughnut. It would tend to follow the largest circumference.

The H, therefore, which we hoped would be constant for the sake of the frequency, is varied somewhat for a focusing effect. Some particles at the larger radii will find themselves slightly out of step, and the efficiency is in this way reduced. But another variation in the formula for T is encountered at high velocities—a variation in the mass of the particles. In the ordinary range of experience, a body weighs the same amount whether it is moving or at rest. However, at very high velocities the mass turns out to be a very definite function of velocity, a function depending on the ratio of the velocity of the body to the velocity of light. The relationship due to Einstein is

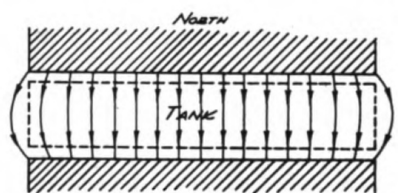
$$\text{mass} = m/[1-(v/c)^2]^{1/2}$$

where m is the mass of the body at rest, v is velocity of body, and c is the velocity of light.

Obviously, since the ratio of common velocities to the velocity of light is extremely small, the correction is insignificant. But as the velocity of light is approached, the correction becomes great, and the mass approaches infinity as the velocity approaches that of light asymptotically. In this region of high velocities developed in the cyclotron the formula for constant frequency is again violated. As such velocities are reached more and more particles will get out of step. A point will be reached where the efficiency would become prohibitive.

Upon the invention of the cyclotron, papers appeared announcing severe limitations on it because of this phenomenon. Since then, the limitations have been far surpassed. The solution of the problem has been by the use of brute force. By applying very high voltages on the dees, the number of revolutions the particles must make is reduced. Smaller chance is given them to lag behind the particles which are in perfect resonance.

Although the concern of this article is the construction and operation of the cyclotron, the resulting beam and its properties and uses present an even larger topic. A statement of the purpose in producing a beam of particles of such tremendous energy may be made here. In the artificial production of elements, elementary particles are added to the nuclei of the stable elements. If one is to add say, a proton to a nucleus, the coulomb repulsion between the positively



Magnetic Field Pattern
Fig. 3

Drawing by M. Lent-Koop

charged nucleus and the proton must be overcome. The force is

$$F = \frac{q \times q'}{d^2}$$

where q represents coulomb charge and d represents the distance between the charges. It is to be expected from this formula that as d approaches zero, the force would become infinite. In the atomic ranges the relationship breaks down, but the force to be overcome in shooting one of the particles into the other is still great. The momenta of the particles has to be in the region of the momenta developed in the cyclotron before the force is overcome and the projectiles pierce the bombarded nuclei.

When a deuteron—a proton plus a neutron—penetrates a nucleus, the nuclear charge is increased by one unit, and the mass by two units; and a new element is formed.

(*continued on page 28*)

SERVICE UNITS

(*continued from page 16*)

strip the usual engineering program down to technical essentials."

Despite all these extra demands, it has been necessary to continue the ESMWT (Engineering, Science and Management War Training) program which is carried on by the College of Engineering under the sponsorship of the U. S. Office of Education.

With Professor Robert H. Sherlock as the co-ordinator, the ESMWT program on the campus provides for the training of ordnance material inspectors for the Detroit Ordnance District, aircraft inspectors for the Army Air Forces, and ordnance engineering aides for the Office of Chief of Ordnance. Students for the latter course are selected from the women employees of the various arsenals in the country.

Technical training also is provided in Detroit and several other Michigan cities under the ESMWT program with approximately half of the teaching burden for these off-campus courses falling on the College of Engineering faculty. During the winter, enrollment in the off-campus ESMWT courses was approximately 1,250, but it is doubtful that the summer total will be that high.

Due to the increased demands on the College of Engineering, Professor Sherlock says it was felt at one time that the ESMWT courses, at least those on the campus, would have to be discontinued. However, the Detroit Ordnance District, the Army Air Forces, and the Office of the Chief of Ordnance made such vigorous protests and effectively stressed the need for the training programs that it was decided to continue them.

All of this means that the College of Engineering Classification Committee which is in charge of assigning space and faculty, headed by Professor Clarence F. Kessler, must continue to do the same skillful work which it has been doing thus far. If necessary, any rooms in other University buildings not being used on a full-time basis may be requested for some engineering courses.

The Army and Navy training programs for engineers require lots of cooperation from the College of Literature, Science and the Arts, particularly in history, geography, English, mathematics, physics, and chemistry, and also the Department of Physical Education.

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