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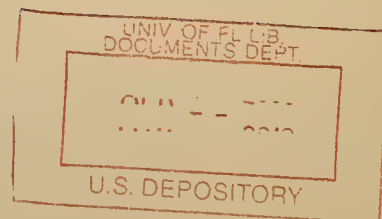
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The maximum energy to which particles can be accelerated in a cyclotron is limited by the maximum value of $H \rho$, where H is the value of the magnetic field at a radius ρ . The maximum value of $H \rho$ occurs at the radius where $\frac{\rho}{H} \frac{dH}{d\rho} + 1 = 0$. If the quantity $n = - \frac{\rho}{H} \frac{dH}{d\rho}$ is defined, then $n = 1$ at the maximum energy (Figure 1).

The point $n = 1$ occurs in the 184-inch cyclotron, at a radius of 85 inches. It was expected, therefore, that the particles would continue to be accelerated until they reached this radius, but it was found that the beam disappeared at a radius of 82 inches. It was suggested that a rapid increase in the vertical oscillations of the ions at the 82-inch radius caused the beam to hit the dee. This theory was checked by a series of experiments using special "c" shaped targets placed at different radii in the cyclotron (Figure 2). Radioautographs of these special targets were taken after they had been bombarded. They showed that at radii less than 82 inches the vertical beam spread was less than 2-1/2 inches and, therefore, was small enough to expand radially through the horizontal slot in the target. However, the vertical spread at the 82-inch radius was large enough to cause the ions to hit the top and bottom of the slot in the target (Figure 3). Also, a sharp peak of radioactivity was found on the dee lip at the 82-inch radius, which gave additional evidence that the beam was spreading vertically in this region. The energy to build up these vertical oscillations seems to arise from the coupling between the vertical and the radial oscillations. These two oscillations go through a harmonic resonance at a radius of 82 inches (Figure 4). The energy of these oscillations can be expressed as

$$W = \frac{m \omega_{\Delta \rho}^2 (\Delta \rho_{\max})^2}{2} + \frac{m \omega_z^2 (Z_{\max})^2}{2}$$

At $n = 0.2$

$$W = \frac{m \omega_0^2 (0.2)}{2} \left[4 (\Delta \rho_{\max})^2 + (Z_{\max})^2 \right]$$

Hence, if all the energy of radial oscillation is converted to that of vertical oscillation, the amplitude of vertical oscillation will be, at times, at least double that of the radial oscillations.

It must be kept in mind for systems having low accelerating voltages similar to the 184-inch cyclotron, that the ions will rapidly increase the amplitude of their vertical oscillations at the point where $n = 0.2$. The solution of the problem of accelerating particles past the radius where $n = 0.2$ in the 184-inch cyclotron has been postponed, since the available energy of the ions at this radius is within 5 per cent of the maximum of the system.

A number of studies have been made using a synchroscope to observe the time structure of the beam current collected by a current reading probe placed in the circulating beam. As was expected, the beam arrives at such a probe in a series of pulses. These pulses are due to the frequency modulation of the cyclotron, one pulse occurring each time the cyclotron goes through an F. M. cycle. However, in addition it was observed that each of these pulses showed a fine structure consisting of a series of amplitude modulated minor pulses (Figure 5). The frequency and number of these minor pulses was found to depend on the probe radius. This fine structure of the beam is apparently caused by the radial oscillations of the ions with respect to the probe. This net oscillation at the probe is the result of two independent oscillations that the ions perform. First, the ions have a radial oscillation, which is due to the center of rotation of the ions being displaced with respect to the magnetic center of the system. These free radial oscillations cause a precession of the centers of rotation, which produces an oscillation of the beam with respect to the probe. Second, the ion undergoes a radial phase oscillation (Figure 6).

The frequency of the minor pulses in each beam pulse agrees quite well with the calculated frequency of precession of the center of rotation of the ions about the magnetic center of the system, which is given by the expression

$$\omega_{\text{prec.}} = (1 - \sqrt{1-n}) \omega_0 .$$

A further condition for the explanation of the fine structure seems to require that the centers of rotation of the ions be bunched azimuthally.

The modulation frequency of the minor pulses agrees quite well with the calculated frequency of the phase oscillations, which is given by the expression

$$* \omega_{\text{phase}} = \left(\frac{eV \cos \phi}{E_S} \frac{K}{2\pi} \right)^{1/2} \omega_0$$

where e = charge on ion

v = max. voltage available per revolution

ϕ = phase of the synchronous orbit

E_S = energy of the ion in the synchronous orbit

$$K = 1 + \frac{n}{(1-n)\beta^2} .$$

This work has been of aid in getting a better understanding of the motion of ions in the cyclotron.

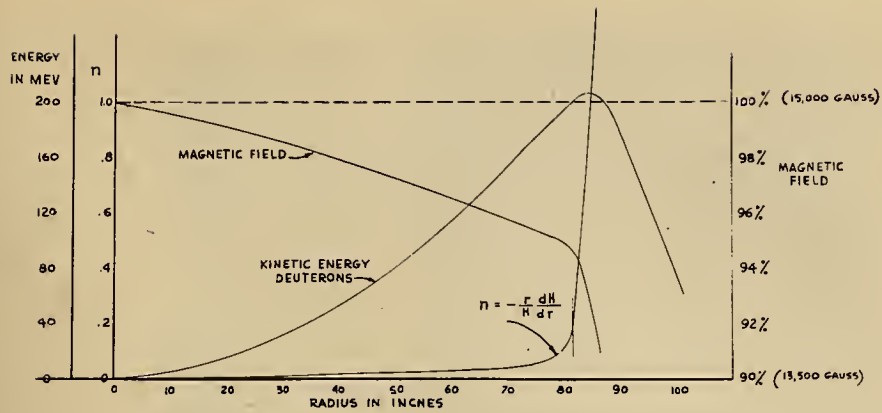


Figure 1

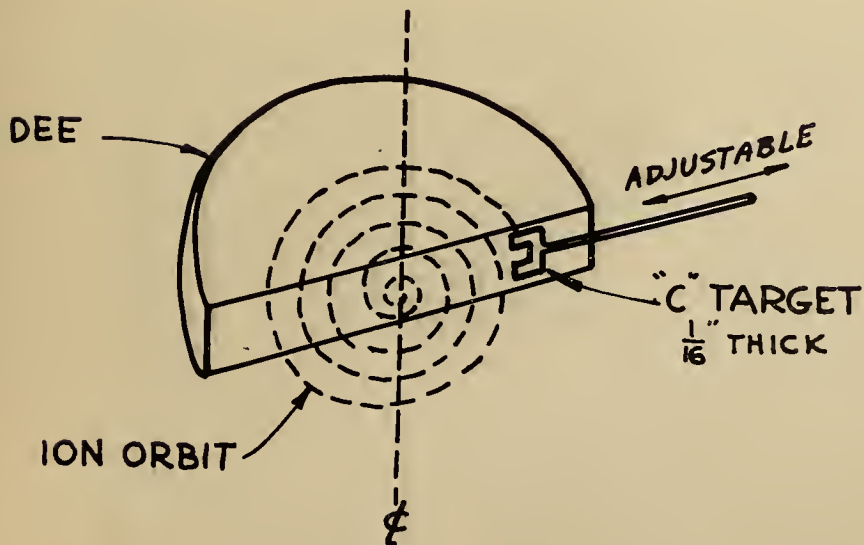


Figure 2

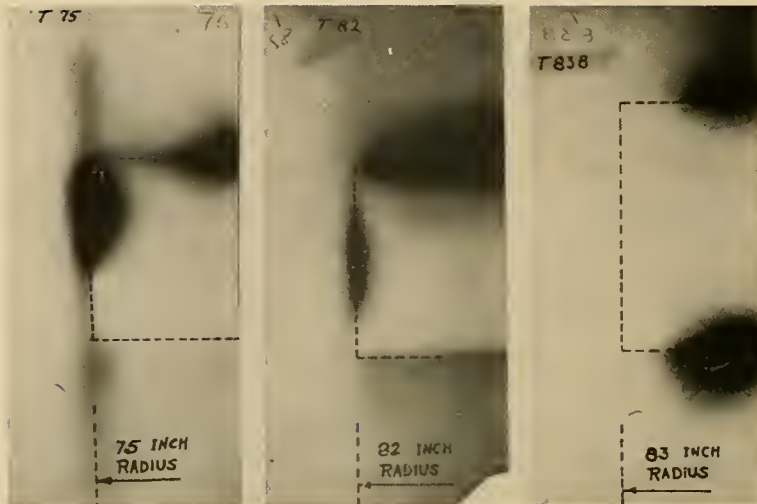
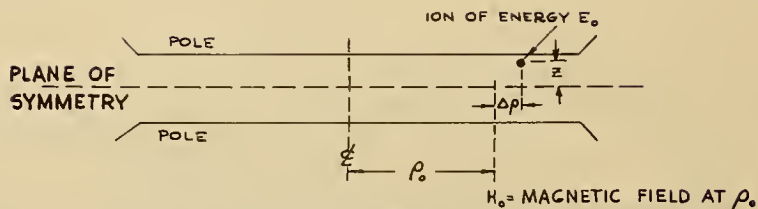


Figure 3



ρ_0 = EQUILIBRIUM RADIUS, OR RADIUS OF ION OF ENERGY E_0 ,
IN MAGNETIC FIELD OF H_0 .

EQUATIONS OF OSCILLATION :

$$\left. \begin{aligned} \frac{d^2 \Delta \rho}{dt^2} &= -w_0^2 (1-n) \Delta \rho + \frac{1}{2} w_0^2 \left(\frac{\rho}{H} \frac{d^2 H}{d \rho^2} \right)_{\rho_0} z^2 + \dots \\ \frac{d^2 z}{dt^2} &= -w_0^2 n z + w_0^2 \left(\frac{\rho}{H} \frac{d^2 H}{d \rho^2} \right)_{\rho_0} z \Delta \rho + \dots \end{aligned} \right\} n = -\frac{\rho}{H} \frac{dH}{d\rho}$$

HORIZONTAL OSCILLATION FREQUENCY ABOUT ρ_0 : $w_{\Delta \rho} = \sqrt{1-n} w_0$

VERTICAL OSCILLATION FREQUENCY : $w_z = \sqrt{n} w_0$

$$\text{WHEN } n = 0.2 : \frac{w_{\Delta \rho}}{w_z} = \frac{\sqrt{1-n}}{\sqrt{n}} = \frac{\sqrt{0.8}}{\sqrt{0.2}} = 2$$

Figure 4

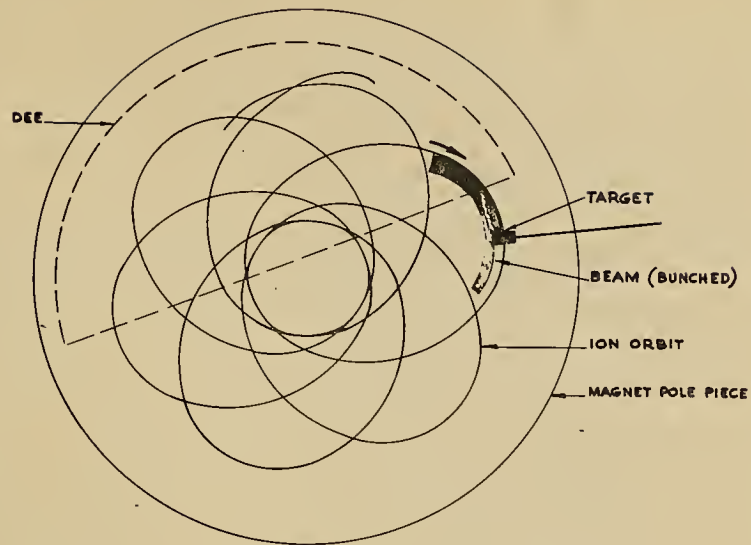


Figure 5

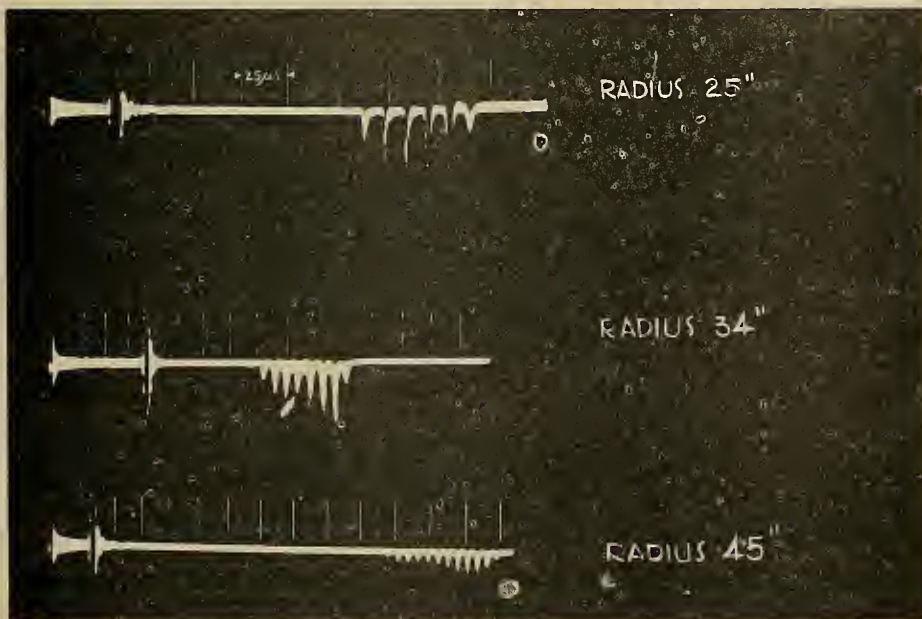


Figure 6

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