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ABSTRACT

The structure and operation of cyclotrons are discussed. Factors limiting cyclotron size and energy are given. Improvements to the basic continuous-wave cyclotron are described, including frequency modulation, strong focusing, and variable-energy facilities.

CYCLOTRONS*

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The cyclotron (Fig. 1) invented by E. O. Lawrence in 1932, uses a strong magnetic guide field and one or more accelerating electrodes, called dees, to accelerate charged particles to energies of millions of electron volts. The frequency of the dee voltage is chosen to synchronize with that of the rotation of the charged particles, so that the particles are accelerated each time they cross a dee edge. This condition is called cyclotron resonance. The angular frequency ω_r is

$$\omega_r = (q/m)\,B \qquad (1)$$

where q is the charge and m the mass of the particle, and B is the magnetic field intensity. For protons, this relation reduces to:

$$f_r = 1530\,B, \qquad (2)$$

where B is in gauss and f_r is in cycles per second. As the particles are accelerated, the orbit radius increases until the particles reach the final radius ρ; the momentum p of a particle is then

$$p = qB\rho\,. \qquad (3)$$

*This work was done under the auspices of the U.S. Atomic Energy Commission.

The particle energy is

$$U = U_0 \left[\sqrt{1 + \left(\frac{p}{m_0 c}\right)^2} - 1 \right] \tag{4}$$

where m_0 is the rest mass of the particle, and c is the velocity of light. For protons, Eq. (4) becomes

$$U = 938 \left[\sqrt{1 + 6.61 \times 10^{-13} (BR)^2} - 1 \right] \text{ (Mev)} \tag{5}$$

where R is the final orbit radius in inches.

The particles to be accelerated start from an ion source which is located near the center of the cyclotron. In the ion source, a gas is ionized by a stream of electrons from a hot filament; these ions escape into the accelerating chamber through a hole in the ion-source housing. The type of gas determines the type of particles available. For example, for protons, hydrogen is used; for deuterons, deuterium; for alpha particles, helium. Heavier ions also may be produced by the appropriate choice of gas.

Usually the particles are extracted from the source by the electric field from the dee. The particles cross the dee edges many times; each time they pick up an amount of energy corresponding to the instantaneous potential of the dee at the time of the crossing. Ultimately the particles acquire enough energy to reach the final radius of the magnet. Then they are guided out of the magnet by a deflector.

There are two factors that limit the practical size of cyclotrons. First, as a particle is accelerated to higher energy, its mass increases, and the required

rf frequency decreases as shown by Eq. (1). Thus, the frequency required to accelerate particles at small radii is incompatible with that required at large radii. The second factor is the requirement of a magnetic guide field that provides a focusing force for the beam and a centering force for the orbits. This requirement is accomplished by tapering the magnet poles so that the field decreases slightly with increasing radius. This tapeing causes the magnetic-field lines to bow outward slightly, producing a component of force on the particles toward the median plane (the plane of equilibrium midway between the magnet poles). Like the relativistic mass increase, this decrease in magnetic field also reduces the required frequency for cyclotron resonance at the larger radii. These two factors limit the beam to about 150 turns and restrict the energy of proton cyclotrons to about 20 Mev.

McMillan and Veksler independently discovered the principle of phase stability. One of the consequences of this discovery was the realization that the energy limitation of cyclotrons could be circumvented by frequency-modulating the dee voltage. Machines of this type are called synchrocyclotrons. The frequency of the dee voltage starts at the particle-starting frequency (i.e., the cyclotron frequency corresponding to rest mass) and is swept down to that which is required for full radius. With each sweep, a group of particles is accelerated to full energy. Many synchrocyclotrons are in operation; the highest-energy machine produces 730-Mev protons.

In 1938, L.H. Thomas found another method of circumventing the two limitations of cyclotrons. He showed that by varying the magnetic field azimuthally according to a certain formula, one could achieve isochronism (equal transit times for all orbit) while maintaining focusing of the beam and centering of the orbits. While Thomas' theory preceded McMillan and Vekslers' theory of phase stability

by many years, it was not checked experimentally until 1950 at the University of California Radiation Laboratory in Berkeley. As a result, the synchrocyclotrons preceded the Thomas cyclotrons.

D. W. Kerst in 1955 extended Thomas' theory by showing that forming the magnet-pole hills into spiral ridges results in stronger focusing and more economical use of the magnet steel. Machines of this type are called spiral-ridge cyclotrons. Being cw machines, they produce very large beam currents -- several orders of magnitude larger than those of synchrocyclotrons.

In 1954, a second generation of cyclotrons started. At Livermore, California, Rochester, New York, and Los Alamos, New Mexico, variable-energy cyclotrons were built so that physicists and chemists could study nuclear reactions in much more detail. These first machines covered the range from 1 to 15 Mev. All of the cyclotrons that have been built since have been variable-energy machines. Those nearing completion at present will extend the range of variable energy beams to 75 Mev.

To produce a variable-energy external beam, the rf frequency and magnetic field must be adjustable so that cyclotron resonance can be maintained. In addition, sufficient precision of the magnetic field must be maintained throughout its range. Production of such magnets has become a fine art and field ranges of 5 or 10 to one are readily produced.

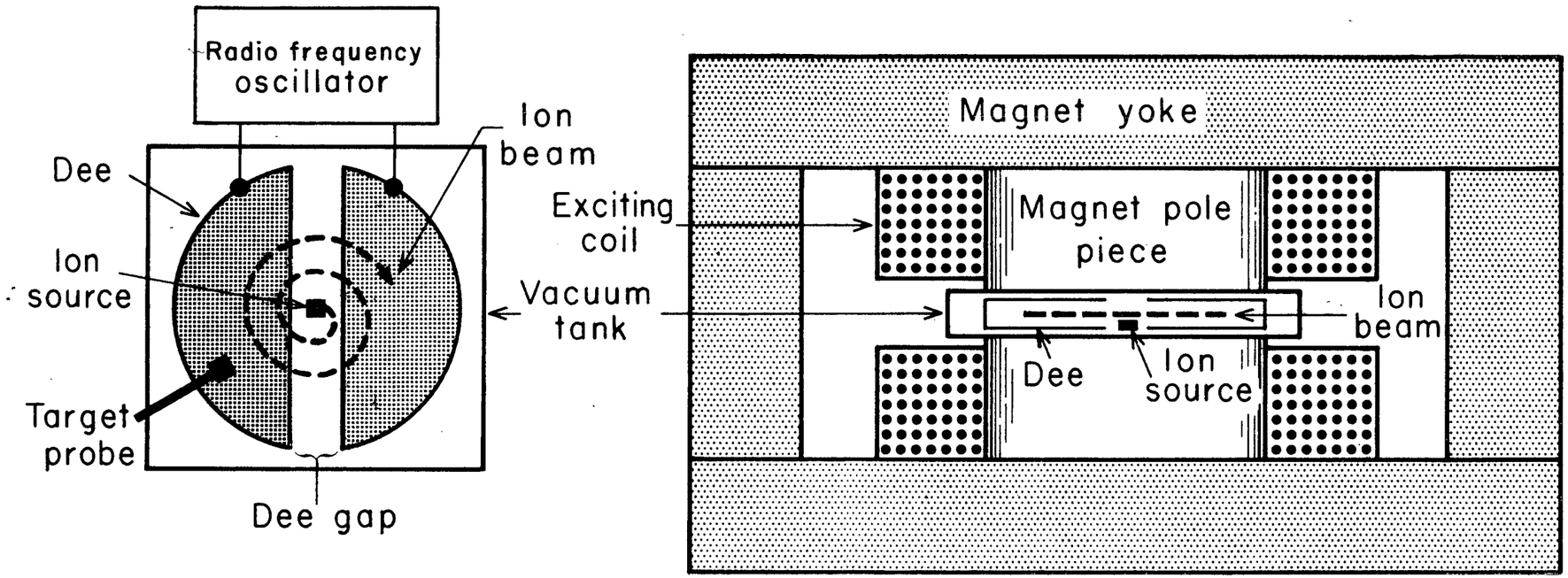

Radio frequency oscillator
Dee
Ion source
Target probe
Dee gap
Ion beam
Vacuum tank
Exciting coil
Magnet yoke
Magnet pole piece
Ion beam
Dee
Ion source

Fig 1
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