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Publication Date
1964-07-06

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The Encyclopedia of Physics

UCRL-11554

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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July 6, 1964

*Article to be published by THE ENCYCLOPEDIA OF PHYSICS, Reinhold Publishers.

UCRL-11554

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The cyclotron is an accelerator of ions widely used to study the nucleus, to produce radioactive substances, and to study the interactions of ionizing radiation with living systems and with inert matter. It is equally important as the first of a class – Magnetic Resonance Accelerators – which includes the various kinds of synchrotron (see synchrotron) as well as synchrocyclotrons and sector focused cyclotrons. The essential feature of this type of accelerator is that acceleration of charged particles to high energies is achieved by a successive application of small accelerations in synchronization with the rotational period of the particles in a magnetic field. The condition for synchronization is simple and can be derived as follows: A charged particle moving perpendicular to the lines of force in a magnetic field will describe a circle which is defined by the equilibrium between the Lorentz force $F_\ell = eBv$ and the centrifugal force $F_c = m\frac{v^2}{r}$. Equating these gives the rotational frequency of the particles which is set equal to the frequency of the accelerating field. This is the Cyclotron Resonance Condition:

1) $$f_a = f_o = \frac{eB}{2\pi m}$$

f_a, frequency of accelerating field

f_o, rotational frequency

e, charge of ion

m, mass of ion

B, magnetic field strength

The important fact is that the rotational frequency is independent of the energy of the particle and depends only on quantities which are (approximately) constant. In 1929 the possibility of using this relationship as the basis for an accelerator occurred to Ernest O. Lawrence, who like many other physicists at the time had been inspired by Rutherford's success in disintegrating atoms with alpha particles from natural sources to seek a means of producing a controlled beam of high energy particles. The practicability of the idea was demonstrated and most of the essential features of the cyclotron were developed by Lawrence, M. Stanley Livingston, N. E. Edlefsen, and others during the next few years.

Fig. 1 is a schematic diagram showing the principle components of a cyclotron. The dees are two hollow semicircular electrodes in a vacuum tank located between the poles of an electromagnet which provides an approximately uniform magnetic over the entire region. The dees are part of an electrical resonant circuit which may be excited by an oscillator whose frequency is adjusted to the rotational frequency given by equation (1). Ions are produced by an electric discharge in a source located at the center. They are drawn from the source and accelerated into a dee while it is negative, they follow a semicircular path in the field free interior of the dee and again arrive at the gap between the dees where by that time the voltages are reversed in sign and they are accelerated again. The ions describe semicircles of increasing radius as their velocity and energy increase as a result of repeated accelerations. When they reach the maximum radius of the dee they enter a channel between a septum in one of the dees and the deflector. The deflector is charged negatively and draws the particles out where they may strike a target in the target chamber or they may travel some distance as a beam outside the cyclotron before they are used.

The kinetic energy of the accelerated particles is given by:

$$2) \quad T = \frac{1}{2} \frac{B^2 R^2 e^2}{m}$$

T, kinetic energy

R, radius of ion path at point of extraction

For protons, equation (1) reduces to $f = 1.52\ B$ megacycles per second and equation (2) to $T = 3.12 \cdot 10^{-4}\ B^2 R^2$ MeV with B in kilogauss and R in inches. The usual values of B are from 15 to 22 kilogauss.

In addition to the resonance condition a successful cyclotron requires that the orbits be stable, that is, they must remain in the median plane and at the appropriate radius. The first is achieved by introducing in the magnetic field a small negative gradient with respect to radius. The field lines are then bowed as shown in Fig. 2, and the Lorentz force on a particle off the median plane has a vertical focusing component. Radial stability results from the fact that the orbit of the particle is an equilibrium orbit with the inward Lorentz force predominating at radii larger than the equilibrium orbit and the centrifugal force predominating at smaller radii. Ions which are displaced either vertically or radially then execute oscillations about the equilibrium orbit. If the magnetic field is described by the index:

$$3) \quad n = -\frac{r}{B} \frac{\partial B}{\partial r}$$

r, radius

Then it can be shown that for $0 < n < 1$ stable oscillations occur with frequencies:

(4) $f_z = f_o \sqrt{n}$ and f_z, frequency of vertical oscillations

$f_r = f_o \sqrt{1-n}$ f_r, frequency of radial oscillations

The negative gradient in the magnetic field results, however, in the situation that the rotational frequency, equation (1), is not exactly the same at all radii. In addition, it must be noted that the mass in equation (1) is the relativistic mass, $m = m_o + \frac{T}{c^2}$ and increases with energy. The result of these two discrepancies is that the rotational frequency of the ion decreases as it is accelerated and there is an accumulated phase lag between the ion and the accelerating field which when it approaches π radians, results in no further acceleration. The energy limit of the conventional cyclotron can be shown to be proportional to the square root of the accelerating potential and to be about 30 MeV for protons with a dee-to-dee potential of 200 kV. It has not been possible to reach the theoretical maximum energy in practice, and for reasons made clear in the next sections the incentive to do so has disappeared. The maximum energy which has been attained with protons is 22 MeV and that required about 500 kV on the dees. Currents in cyclotrons are usually of the order of 100 μa but up to 1 ma has been attained. The most commonly used ions are protons, deuterons, and alpha particles, although heavier ions such as carbon nitrogen and oxygen ionized to plus three or four have also been accelerated.

A possibility of achieving higher energies with cyclotrons was opened up in 1945 when V. Veksler and E. M. McMillan independently pointed out the phase stable characteristic of the cyclotron resonance condition 1) which is apparent if the equation is rewritten in terms of particle energy:

5) $f_o = \frac{Be\ c^2}{2\pi\ (E_o + T)}$ E_o, rest energy of particle

Consider a particle rotating in a cyclotron at the resonant frequency and crossing the accelerating gap at a phase such that it gains no energy and that a later arrival causes it to lose energy. If this particle is perturbed by an excess of energy, f_o decreases and the particle loses energy. If the particle is perturbed in phase so that it arrives at the accelerating gap too early it gains energy, f_o decreases and the phase slips back. Perturbations in energy or phase thus result in oscillations about the equilibrium phase. Under these conditions if the accelerating frequency of a cyclotron is slowly decreased, the ions will execute stable oscillations about that phase which will give sufficient energy gain so that the radius and energy are matched as the orbits expand. This is the Principle of Phase Stability as applied to the Synchrocyclotron. It completely removes the energy limitation of the cyclotron previously discussed. This principle was immediately exploited and synchrocyclotrons (also sometimes called Frequency Modulated or FM Cyclotrons, and in the U.S.S.R. Phasotrons) have been built which give protons up to 700 MeV. The only limit is the economic one due to the large size of the magnet.

The important structural difference between a synchrocyclotron and a conventional cyclotron is in the provision for a variable frequency. This is accomplished by placing a variable capacitor in the resonant dee circuit. Rotary blade capacitors have been in common use for this purpose but in more recent designs, vibrating blade capacitors have been preferred. The required frequency swings are about two to one and the usual modulation frequencies are about 60 to 100 cycles per second. The ions are accelerated in pulses as the accelerating frequency sweeps through its modulation cycle in contrast to the continuous acceleration in a conventional

cyclotron. The result is that average currents in synchrocyclotrons are about 1% of cyclotron currents, thus removal of the energy limit has been accomplished at the expense of a current limitation.

Another method of circumventing the energy limit of the cyclotron was proposed by Thomas in 1938, seven years before the principle of phase stability was enunciated. In the Thomas proposal the average magnetic field increases with radius so that the resonance condition may be exactly matched by a constant accelerating frequency as the ion gains energy. The axial focusing force is supplied by an azimuthal variation of the magnetic field which may be obtained by using sectored magnet poles, Fig. 3. The ion orbits are then no longer circular and the radial component of velocity interacting with the azimuthal component of magnetic field produces an axial focusing force. This is the "edge focusing" which occurs when an ion crosses a fringe field obliquely and has long been used in mass spectrometers and other devices.

This idea was well in advance of the theory and practice of the cyclotron art at the time and was not immediately exploited. Development began in 1949 and extending to recent years has resulted in a whole subclass of cyclotrons characterized by a fixed rotational frequency and focusing forces derived from spatial variation in the magnetic field. For example, if the sectors are spiral shaped as in Fig. 3, additional focusing forces of the alternate gradient type are developed. These cyclotrons are variously called Sector Focused, Isochronous, and AVF (azimuthally varying field) cyclotrons. They have energies well beyond the energy limit of the conventional cyclotron and at the same time are capable of high average currents because they operate at a constant frequency. Provision of auxiliary magnet coils on the pole tips to trim the field shape over a range

of values of average field and adjustable frequency oscillators to provide for different ions and a variation in maximum energy have made the modern cyclotron of this type very flexible.

The following table gives a comparison of the salient features of examples of each of the three main types of cyclotron.

	CYCLOTRON 60 inch Cyclotron University of Washington, Seattle	SYNCHROCYCLOTRON 184 inch Cyclotron Lawrence Radiation Laboratory, Berkeley	SECTOR FOCUSED CYCLOTRON 88 inch Cyclotron Lawrence Radiation Laboratory, Berkeley
Magnet	60 inch pole diameter, 19 KG maximum field, 218 tons.	189 inch pole diameter, 23.4 KG maximum field, 4300 tons.	88 inch pole diameter, 3 sector, 17 KG maximum average field, 300 tons.
RF	Fixed frequency 11.6 Mc/s, two dees, 250 KV.	Variable frequency, 18–36 Mc/s for protons, Modulation frequency 64 cps, single dee, 9 KV.	Fixed frequency, adjustable 5.5 – 16.5 Mc/s for various particles, single dee, 70 KV.
Beam	Protons 11 MeV, Deuterons 22 MeV, Alpha Particles 44 MeV, 1 ma maximum current.	Protons 730 MeV, Deuterons 460 MeV, Alpha Particles 910 MeV, 1 μa maximum average current.	Protons 50 MeV, Deuterons 65 MeV, Alpha Particles 130 MeV, 1 ma maximum current.

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Cross reference to any of the following entries which may be in the Encyclopedia:

Accelerator
Synchrotron
Alternate Gradient Focusing or Strong Focusing

Revised: June 17, 1964

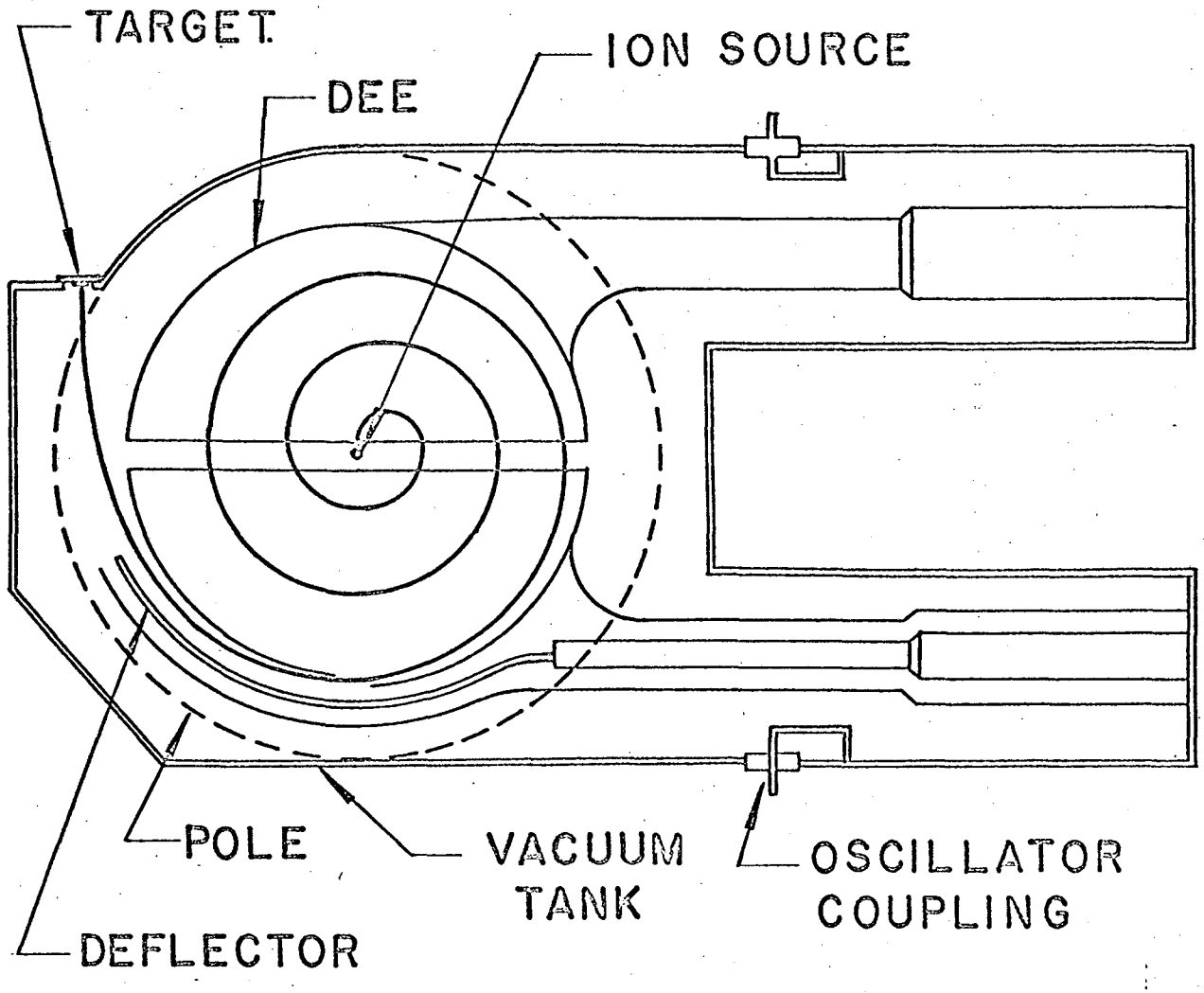

TARGET
DEE
ION SOURCE
POLE
VACUUM TANK
OSCILLATOR COUPLING
DEFLECTOR

Fig. 1

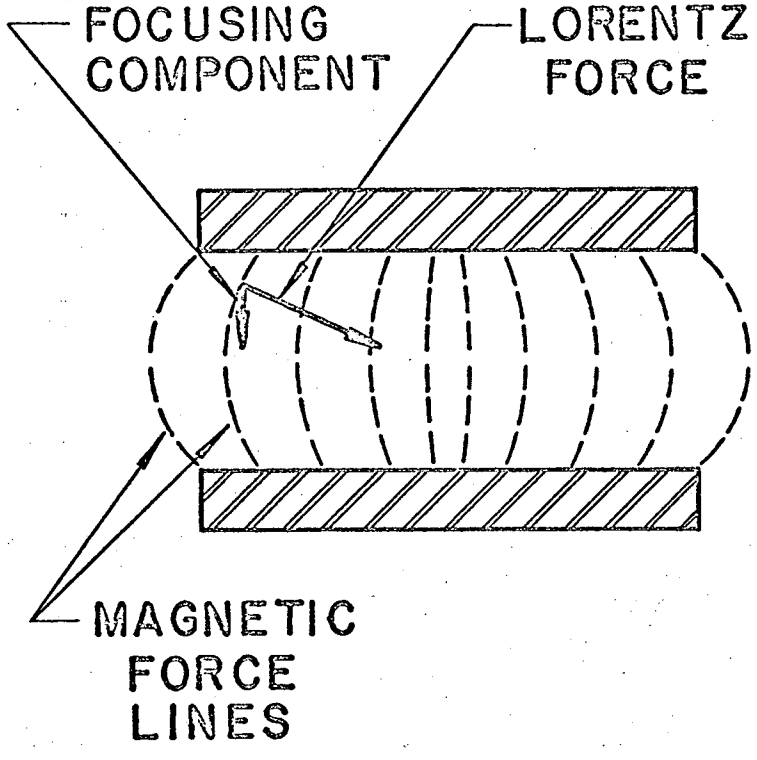


Fig. 2

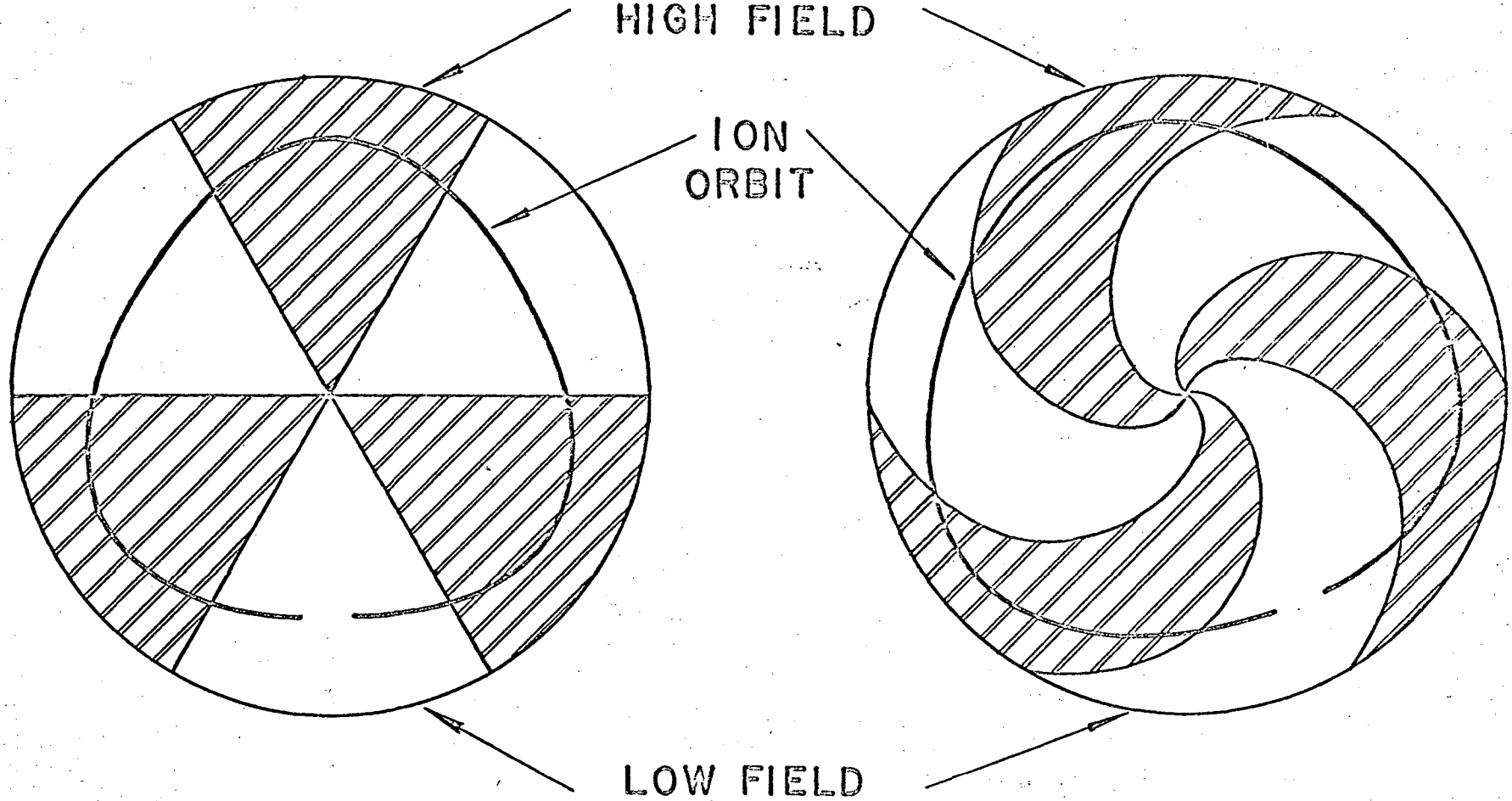


Fig. 3

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