# Cyclotron

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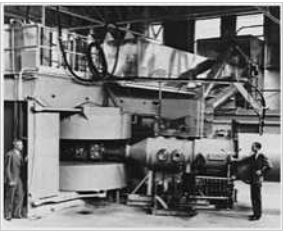
*For other uses, see Cyclotron (disambiguation).*

A **cyclotron** is a type of particle accelerator invented by Ernest O. Lawrence[1] in 1932 in which charged particles accelerate outwards from the center along a spiral path.[2][3] The particles are held to a spiral trajectory by a static magnetic field and accelerated by a rapidly varying (radio frequency) electric field. Lawrence was awarded the 1939 Nobel prize in physics for this invention.[3] Cyclotrons were the most powerful particle accelerator technology until the 1950s when they were superseded by the synchrotron, and are still used to produce particle beams in physics and nuclear medicine. The largest single magnet cyclotron was the 184 inch (4.6 meter) synchrocyclotron built between 1940 and 1946 by Lawrence at the University of California at Berkeley,[3] which could accelerate protons to 730 MeV. The largest cyclotron is the 56 ft (18 meter) multimagnet TRIUMF accelerator at the University of British Columbia in Vancouver, British Columbia which can produce 500 MeV protons.



Lawrence's 60 inch cyclotron, with magnet poles 60 inches (5 feet, 1.5 meters) in diameter, at the University of California Lawrence Radiation Laboratory, Berkeley, in August, 1939, the most powerful accelerator in the world at the time. Glenn T. Seaborg and Edwin M. McMillan *(right)* used it to discover plutonium, neptunium and many other transuranic elements and isotopes, for which they received the 1951 Nobel Prize in chemistry. The cyclotron's huge magnet is at left, with the flat accelerating chamber between its poles in the center. The beamline which analyzed the particles is at right.

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## History

A modern cyclotron used for radiation therapy. The magnet is painted yellow.

The cyclotron was invented and patented,[1] by Ernest Lawrence of the University of California, Berkeley, where it was first operated in 1932.[4]Lawrence went on to actually make a working cyclotron using magnets and field coils provided in part by the Federal Telegraph Company.[5] A graduate student, M. Stanley Livingston, did much of the work of translating the idea into working hardware.[6] Lawrence read an article about the concept of a drift tube linac by Rolf Widerøe,[7][8] who had also been working along similar lines with the betatron concept. At the Radiation Laboratory of the University of California at Berkeley Lawrence constructed a series of cyclotrons which were the most powerful accelerators in the world at the time; a 27 inch (68 cm) 4.8 MeV machine (1932), a 37 inch (94 cm) 8 MeV machine (1937), and a 60 inch (1.5 m) 16 MeV machine (1939). He also developed an 184 inch (4.7 m) synchrocyclotron (1945).

The first European cyclotron was constructed in Leningrad in the physics department of the Radium Institute, headed by Vitaly Khlopin. This Leningrad instrument was first proposed in 1932 by George Gamow and Lev Mysovskii and was installed and became operative by 1937.[9][10][11] In Nazi Germany a cyclotron was built in Heidelberg under supervision of Walther Bothe and Wolfgang Gentner, with support from the Heereswaffenamt, and became operative in 1943.

## Principle of operation

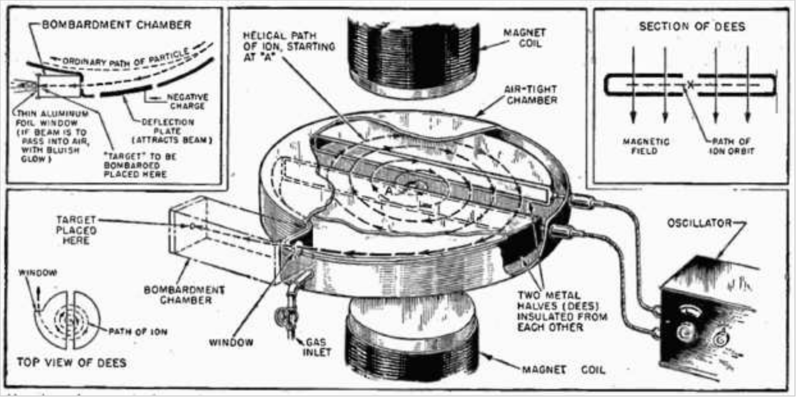
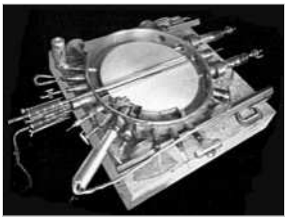


Diagram showing how a cyclotron works. The magnet's pole pieces are shown smaller than in reality, they must actually be as wide as the dees to create a uniform field.

A cyclotron accelerates a charged particle beam using a high frequency alternating voltage which is applied between two hollow "D"-shaped sheet metal electrodes called "dees" inside a vacuum chamber.[12] The dees are placed face to face with a narrow gap between them, creating a cylindrical space within them for the particles to move. The particles are injected into the center of this space. The dees are located between the poles of a large electromagnet which applies a static magnetic field *B* perpendicular to the electrode plane. The magnetic field causes the particles path to bend in a circle due to the Lorentz force perpendicular to their direction of motion.

If the particles' speed was constant, they would travel in a circular path within the dees under the influence of the magnetic field. However a radio frequency (RF) alternating voltage of several thousand volts is applied between the dees. The frequency is set so that the particles make one circuit during a single cycle of the voltage. Each time after the particles pass to the other dee electrode the polarity of the RF voltage reverses. Therefore each time the particles cross the gap from one dee electrode to the other, the electric field is in the correct direction to accelerate them. The particles' increasing speed due to these pushes causes them to move in a larger radius circle with each rotation, so the particles move in a spiral path outward from the center to the rim of the dees. When they reach the rim the particles exit the dees through a small gap between them, and hit a target located at the exit point at the rim of the chamber, or leave the cyclotron through an evacuated beam tube to hit a remote target, various materials may be used for the target, and the nuclear reactions due to the collisions will create secondary particles which may be guided outside of the cyclotron and into instruments for analysis.



Vacuum chamber of Lawrence 27 in. 1932 cyclotron with cover removed, showing the dees. The 13,000 volt RF accelerating potential at about 27 MHz is applied to the dees by the two feedlines visible at top right. The beam emerges from the dees and strikes the target in the chamber at bottom.

The cyclotron was the first "cyclical" accelerator. The advantage of the cyclotron design over the existing "electrostatic" accelerators of the time such as the Cockcroft-Walton accelerator and Van de Graaff generator, was that in these machines the particles were only accelerated once by the voltage, so the particles' energy was equal to the accelerating voltage on the machine, which was limited by air breakdown to a few million volts. In the cyclotron, in contrast, the particles encounter the accelerating voltage many times during their spiral path, and so are accelerated many times,[1] so the output energy can be many times the accelerating voltage. To achieve this, the voltage frequency must match the particle's cyclotron resonance frequency

$$f = \frac{qB}{2\pi m},$$

where *B* is the magnetic field strength, *q* is the electric charge of the particle, and *m* is the relativistic mass of the charged particle. This frequency is given by equality of centripetal force and magnetic Lorentz force.

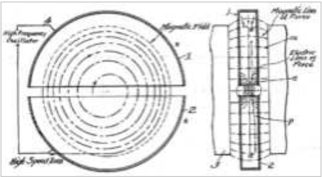


Diagram of cyclotron operation from Lawrence's 1934 patent. The "D" shaped electrodes are enclosed in a flat vacuum chamber, which is installed in a narrow gap between the two poles of a large magnet.

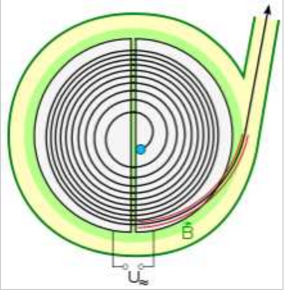
## Particle energy

Since the particles are accelerated by the voltage many times, the final energy of the particles is not dependent on the accelerating voltage but the diameter of the accelerating chamber, the dees. Cyclotrons can only accelerate particles to speeds much slower than the speed of light, nonrelativistic speeds. For nonrelativistic particles, the centripetal force $F_C$ required to keep them in their curved path is

$$F_C = \frac{mv^2}{r}$$

where $m$ is the particle's mass, $v$ its velocity, and $r$ is the diameter of the path. This force is provided by the Lorentz force $F_B$ of the magnetic field $B$

$$F_B = qvB$$



Sketch of a particle being accelerated in a cyclotron, and being ejected through a beamline.

where $q$ is the particle's charge. The particles reach their maximum energy at the periphery of the dees, where the radius of their path is $r = R$ the diameter of the dees. Equating these two forces

$$\frac{mv^2}{R} = qvB$$

So the output energy of the particles is

$$E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

Therefore, the limit to the cyclotron's output energy for a given type of particle is the strength of the magnetic field $B$, which is limited to about 2 T for ferromagnetic electromagnets, and the diameter of the dees $R$, which is determined by the diameter of the magnet's pole pieces. So very large magnets were constructed for cyclotrons, culminating in Lawrence's 1946 synchrocyclotron, which had pole pieces 184 inches (15 feet or 4.6 m) in diameter.

# Relativistic considerations

A French cyclotron, produced in Zurich, Switzerland in 1937. The vacuum chamber containing the dees *(at left)* has been removed from the magnet *(red, at right)*

In *the nonrelativistic approximation*, the frequency does not depend upon the radius of the particle's orbit, since the particle's mass is constant. As the beam spirals out, its frequency does not decrease, and it must continue to accelerate, as it is travelling a greater distance in the same time period. In contrast to this approximation, as particles approach the speed of light, their relativistic mass increases, requiring either modifications to the frequency, leading to the *synchrocyclotron*, or modifications to the magnetic field during the acceleration, which leads to the *isochronous cyclotron*. The relativistic mass can be rewritten as

$$m = \frac{m_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{m_0}{\sqrt{1-\beta^2}} = \gamma m_0,$$

where

$m_0$ is the particle rest mass,
$\beta = \frac{v}{c}$ is the relative velocity, and
$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$ is the Lorentz factor.

The relativistic cyclotron frequency and angular frequency can be rewritten as

$$f = \frac{qB}{2\pi\gamma m_0} = \frac{f_0}{\gamma} = f_0\sqrt{1-\beta^2} = f_0\sqrt{1-\left(\frac{v}{c}\right)^2},\text{ and}$$
$$\omega = 2\pi f = \frac{qB}{\gamma m_0} = \frac{\omega_0}{\gamma} = \omega_0\sqrt{1-\beta^2} = \omega_0\sqrt{1-\left(\frac{v}{c}\right)^2},$$

where

$f_0$ would be the cyclotron frequency in classical approximation,
$\omega_0$ would be the cyclotron angular frequency in classical approximation.

The gyroradius for a particle moving in a static magnetic field is then given by

$$r = \frac{v}{\omega} = \frac{\beta c}{\omega} = \frac{\gamma\beta m_0 c}{qB},$$

because

$$\omega r = v = \beta c$$

where v would be the (linear) velocity.

## Synchrocyclotron

*Main article: Synchrocyclotron*

A synchrocyclotron is a cyclotron in which the frequency of the driving RF electric field is varied to compensate for relativistic effects as the particles' velocity begins to approach the speed of light. This is in contrast to the classical cyclotron, where the frequency was held constant, thus leading to the synchrocyclotron operation frequency being

$$f = \frac{f_0}{\gamma} = f_0\sqrt{1-\beta^2},$$

where $f_0$ is the classical cyclotron frequency and $\beta = \frac{v}{c}$ again is the relative velocity of the particle beam. The rest mass of an electron is 511 keV/c$^2$, so the frequency correction is 1% for a magnetic vacuum tube with a 5.11 keV/c$^2$ direct current accelerating voltage. The proton mass is nearly two thousand times the electron mass, so the 1% correction energy is about 9 MeV, which is sufficient to induce nuclear reactions.

### Isochronous cyclotron

An alternative to the synchrocyclotron is the *isochronous cyclotron*, which has a magnetic field that increases with radius, rather than with time. Isochronous cyclotrons are capable of producing much greater beam current than synchrocyclotrons, but require azimuthal variations in the field strength to provide a strong focusing effect and keep the particles captured in their spiral trajectory. For this reason, an isochronous cyclotron is also called an "AVF (azimuthal varying field) cyclotron".[13] This solution for focusing the particle beam was proposed by L. H. Thomas in 1938.[13] Recalling the relativistic gyroradius $r = \frac{\gamma m_0 v}{qB}$ and the relativistic cyclotron frequency $f = \frac{f_0}{\gamma}$, one can choose $B$ to be proportional to the Lorentz factor, $B = \gamma B_0$. This results in the relation $r = \frac{m_0 v}{qB_0}$ which again only depends on the velocity $v$, like in the non-relativistic case. Also, the cyclotron frequency is constant in this case.

The transverse de-focusing effect of this radial field gradient is compensated by ridges on the magnet faces which vary the field azimuthally as well. This allows particles to be accelerated continuously, on every period of the radio frequency (RF), rather than in bursts as in most other accelerator types. This principle that alternating field gradients have a net focusing effect is called strong focusing. It was obscurely known theoretically long before it was put into practice.[14] Examples of isochronous cyclotrons abound; in fact almost all modern cyclotrons use azimuthally-varying fields. The TRIUMF cyclotron mentioned below is the largest with an outer orbit radius of 7.9 metres, extracting protons at up to 510 MeV, which is 3/4 of the speed of light. The PSI cyclotron reaches higher energy but is smaller because of using a higher magnetic field.

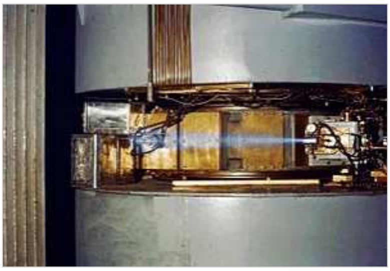
## Usage

For several decades, cyclotrons were the best source of high-energy beams for nuclear physics experiments; several cyclotrons are still in use for this type of research. The results enable the calculation of various properties, such as the mean spacing between atoms and the creation of various collision products. Subsequent chemical and particle analysis of the target material may give insight into nuclear transmutation of the elements used in the target.

Cyclotrons can be used in particle therapy to treat cancer. Ion beams from cyclotrons can be used, as in proton therapy, to penetrate the body and kill tumors by radiation damage, while minimizing damage to healthy tissue along their path. Cyclotron beams can be used to bombard other atoms to produce short-lived positron-emitting isotopes suitable for PET imaging. More recently cyclotrons currently installed at hospitals for particle therapy have been retrofitted to enable them to produce technetium-99m.[15] Technetium-99m is a diagnostic isotope in short supply due to difficulties at Canada's Chalk River facility.

## Advantages and limitations

The cyclotron was an improvement over the linear accelerators (*linac*s) that were available when it was invented, being more cost- and space-effective due to the iterated interaction of the particles with the accelerating field. In the 1920s, it was not possible to generate the high power, high-frequency radio waves which are used in modern linacs (generated by klystrons). As such, impractically long linac structures were required for higher-energy particles. The compactness of the cyclotron reduces other costs as well, such as foundations, radiation shielding, and the enclosing building. Cyclotrons have a single electrical driver, which saves both money and power. Furthermore, cyclotrons are able to produce a continuous stream of particles at the target, so the average power passed from a particle beam into a target is relatively high.


Lawrence's 60-inch cyclotron, circa 1939, showing the beam of accelerated ions (likely protons or deuterons) exiting the machine and ionizing the surrounding air causing a blue glow.

The spiral path of the cyclotron beam can only "sync up" with klystron-type (constant frequency) voltage sources if the accelerated particles are approximately obeying Newton's Laws of Motion. If the particles become fast enough that relativistic effects become important, the beam becomes out of phase with the oscillating electric field, and cannot receive any additional acceleration. The classical cyclotron is therefore only capable of accelerating particles up to a few percent of the speed of light. To accommodate increased mass the magnetic field may be modified by appropriately shaping the pole pieces as in the isochronous cyclotrons, operating in a pulsed mode and changing the frequency applied to the dees as in the synchrocyclotrons, either of which is limited by the diminishing cost effectiveness of making larger machines. Cost limitations have been overcome by employing the more complex synchrotron or modern, klystron-driven linear accelerators, both of which have the advantage of scalability, offering more power within an improved cost structure as the machines are made larger.


M. Stanley Livingston and Ernest O. Lawrence *(right)* in front of Lawrence's 27 inch cyclotron at the Lawrence

## Notable examples

One of the world's largest cyclotrons is at the RIKEN laboratory in Japan. Called the SRC, for Superconducting Ring Cyclotron, it has 6 separated superconducting sectors, and is 19 m in diameter and 8 m high. Built to accelerate heavy ions, its maximum magnetic field is 3.8 tesla, yielding a bending ability of 8 tesla-metres. The

Radiation Laboratory. The curving metal frame is the magnet's core, the large cylindrical boxes contain the coils of wire that generate the magnetic field. The vacuum chamber containing the "dee" electrodes is in the center between the magnet's poles.

total weight of the cyclotron is 8,300 tonnes.The Riken magnetic field covers from 3.5 m radius to 5.5 m with the maximum beam radius of about 5m or 200 inches. It has accelerated uranium ions to 345 MeV per atomic mass unit.[16]

TRIUMF, Canada's national laboratory for nuclear and particle physics, houses the world's largest cyclotron.[17] The 18 m diameter, 4,000 tonne main magnet produces a field of 0.46 T while a 23 MHz 94 kV electric field is used to accelerate the 300 μA beam.The TRIUMF field goes from 0 to about 320 inches radius with the maximum beam radius of 310 inches. This is because it requires a lower magnetic field to reduce EM stripping of the loosely bound electrons. Its large size is partly a result of using negative hydrogen ions rather than protons. The advantage is that extraction is simpler; multi-energy, multi-beams can be extracted by inserting thin carbon stripping foils at appropriate radii. TRIUMF is run by a consortium of eighteen Canadian universities and is located at the University of British Columbia, Vancouver, Canada.

## Related technologies

The spiraling of electrons in a cylindrical vacuum chamber within a transverse magnetic field is also employed in the magnetron, a device for producing high frequency radio waves (microwaves). The synchrotron moves the particles through a path of constant radius, allowing it to be made as a pipe and so of much larger radius than is practical with the cyclotron and synchrocyclotron. The larger radius allows the use of numerous magnets, each of which imparts angular momentum and so allows particles of higher velocity (mass) to be kept within the bounds of the evacuated pipe. The magnetic field strength of each of the bending magnets is increased as the particles gain energy in order to keep the bending angle constant.

## In fiction

The United States Department of Defense famously asked for dailies of the Superman comic strip to be pulled in April 1945 for having Superman bombarded with the radiation from a cyclotron.[18] In 1950 however, in Atom Man vs. Superman, Lex Luthor uses a cyclotron to start an earthquake.

## See also

- Cyclotron resonance
- Gyrotron
- Cyclotron radiation
- Particle accelerator
- Synchrotron
- Beamline
- Bremsstrahlung (radiation)
- Radiation reaction
- Fast neutron therapy
- Sándor Gaál

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# Further reading

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# External links

## General

Look up ***cyclotron*** in Wiktionary, the free dictionary.

- Particle Accelerators (https://www.dmoz.org/Science/Physics/Particle/Research_Groups_and_Centers/Accelerators/) at DMOZ
- Cyclotrons.net (http://cyclotrons.net/)—A forum for builders of small cyclotrons
- The Cyclotron Kids Project (http://thecyclotronkids.org/)—A pair of high school students building their own 2.3 MeV cyclotron for experimentation.

## Facilities

- The 88-Inch Cyclotron (http://user88.lbl.gov/) at Lawrence Berkeley National Laboratory
- The first Cyclotron in Amsterdam, Netherlands (1964) (http://www.cyclotron.nl/__5_3_2_2), at the site of the Free University
- National Superconducting Cyclotron Laboratory (http://www.nscl.msu.edu/) of the Michigan State University—Home of coupled K500 and K1200 cyclotrons; the K500, the first superconducting cyclotron, and the K1200, formerly the most powerful in the world.
- Rutgers Cyclotron (http://www.physics.rutgers.edu/cyclotron/)—Students at Rutgers University built a 12-inch 1 MeV cyclotron as an undergraduate project, which is now used for a senior-level undergraduate and a graduate lab course.
- RIKEN Nishina Center for Accelerator-based Science (http://www.rarf.riken.jp/Eng/)—Home of the most powerful cyclotron in the world.

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Categories: Accelerator physics | American inventions | Particle accelerators | 1932 introductions

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