GULABCHAND PRASAD AGRAWAL COLLEGE ,sadma

NILAMBER PITAMBER UNIVERSITY, MEDININAGAR (PALAMU)

नीलाम्बर-पीताम्बर विश्वविद्यालय, मेदिनीनगर, पलामू

तमसो मा ज्योतिर्गमय

A PROJECT ON **'CYCLOTRON'**

SUBMITTED BY :-

NAME : Vandna Kumari

REGISTRATION NO :- NPU/283-70/18

ROLL NO :- 1885 - 5525864

SESSION :- 2018 – 21

PAPER :- DSE-3

ACKNOWLEDGEMENT

I Wish to express my deep sense of gratitude to My guide prof. Rani Srivastva . Under Graduate department of physics for the valuable and inspiring guidance throughout the course of project.

I am gratefull to the chairman and members of a project evaluation committee for providing the opputunity to present the project on this topic.

CERTIFICATE

This is to certify that Vandna Kumari of B.Sc physics UG Department of physics NPU Medininagar has completed his project work successfully on the topic ,

"CYCLOTRON"

During the period of 28/10/2022 to 05/02/2021 under my guidance .

Wish him/her success in all their endeavours.

Prof. Rani Srivastava

CONTENTS :

INTRODUCTION

A **cyclotron** is a type of particle accelerator invented by Ernest O. Lawrence in 1929–1930 at the University of California, Berkeley, and patented in 1932. A cyclotron accelerates charged particles outwards from the center of a flat cylindrical vacuum chamber along a spiral path.The particles are held to a spiral trajectory by a static magnetic field and accelerated by a rapidly varying electric field. Lawrence was awarded the 1939 Nobel Prize in Physics for this invention.

Cyclotrons were the most powerful particle accelerator technology until the 1950s, when they were superseded by the synchrotron, and are still used to produce particle beams for physics and nuclear medicine. The largest single-magnet cyclotron was the 4.67 m (184 in) synchrocyclotron built between 1940 and 1946 by Lawrence at the University of California, Berkeley, which could accelerate protons to 730 million electron volts (MeV). The largest cyclotron

ever built using normal conducting magnets is the 17.1 m (56 ft) multimagnet TRIUMF accelerator at *the University of British Columbia in Vancouver, British Columbia, which can produce 520 MeV protons. Advances in superconductivity have since allowed for the construction of more powerful, yet smaller, cyclotrons.*

FUNDAMENTAL OF CYCLOTRON

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. 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' speeds were 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 voltage creates an oscillating electric field in the gap between the dees that accelerates the particles. The frequency is set so that the particles make one circuit during a single cycle of the voltage. To achieve this, the frequency must match the particle's cyclotron resonance frequency

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. 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 a small voltage on a metal plate deflects the beam so it exits the dees through a small gap between them, and hits a target located at the exit point at the rim of the chamber, or leaves 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.*

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, so the output energy can be many times the accelerating voltage.

PARTICLE ENERGY

Since the particles in a cyclotron are accelerated by the voltage many times, the final energy of the particles is not dependent on the accelerating voltage but on the strength of the magnetic field and the diameter of the accelerating chamber, the dees. The classic cyclotron can only accelerate particles to speeds much slower than the speed of light, nonrelativistic speeds. For nonrelativistic *particles, the centripetal force required to keep them in their curved path .*

The particle's of mass depends on its velocity, and is the radius of the path. This force is provided by the Lorentz force of the magnetic field.

The particles reach their maximum energy at the

periphery of the dees, where the radius of their path is the radius of the dees.

TYPES

- **Classic cyclotron** - *The first type of cyclotron, described in previous sections, which had uniform magnetic field and constant frequency, is mostly obsolete.*

  It was limited to

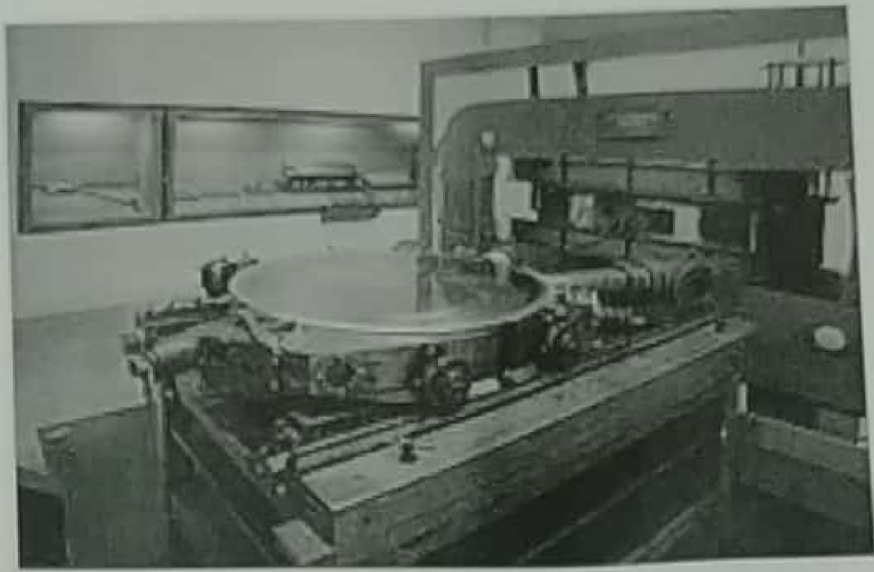
  completely nonrelativistic energies (the output energy small compared to the particle's rest energy), and had focusing problems.

- ***Synchrocyclotron*** - *an obsolete machine which extended energies into the relativistic regime by decreasing the radio frequency of* the oscillator as the orbit of the particle got larger to keep it in synchronism with the particle. This was the most powerful accelerator during the 1950s, before the synchrotron. It operated in pulses, instead of continuously, so its luminosity (beam current) was very low.

- ***Isochronous cyclotron (isocyclotron)*** *- a category which includes most current machines, extends output energy into the relativistic regime by using shaped pole pieces extending outwards from a center to create a nonuniform magnetic field stronger in peripheral regions to increase centripetal force* *on the particle as it gains relativistic mass, with alternating-gradient focusing to keep the beam focused.*

- **"Sector focused", "spiral-ridged", "azimuthally-varying-field"** - *these describe machines in which the pole surfaces have hills and valleys azimuthally, making the field increase and decrease as the particles move in the ring, which keeps the beam collimated by alternating-gradient focusing.*
- ***Separated sector cyclotron*** - *a machine in which the magnet is in separate sections, separated by gaps without field.*

- ***H^- cyclotron*** *- a cyclotron that accelerates negative hydrogen ions, which make it easy to deflect the beam out of the machine. At the beam exit point at the periphery of the dees, a metal foil strips the electrons from the hydrogen ions, transforming them into positively charged H^+ ions. These are bent in the opposite direction by the magnet, so the beam leaves the machine.*



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 non-relativistic approximation, the cyclotron frequency does not depend upon the particle's speed or the radius of the particle's orbit. As the beam spirals outward, the rotation frequency stays constant, and the beam continues to accelerate as it travels a greater distance in the same time period.

In contrast to this approximation, as particles approach the speed of light, the cyclotron frequency decreases proportionally to the particle's Lorentz factor. A rigorous proof of this fact (starting from Newton's second law) is given here: Relativistic mechanics#Force. Acceleration of relativistic particles therefore requires either modification to the frequency during the acceleration, leading to the synchrocyclotron, or modification to the magnetic field during the acceleration, which leads to the isochronous cyclotron.

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 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 kV 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". This solution for focusing the particle beam was proposed by L. H. Thomas in 1938.Recalling the relativistic gyroradius and the relativistic cyclotron frequency , one can choose to be proportional to the Lorentz factor, . This results the relation which again only depends on the velocity , 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. Examples of isochronous cyclotrons abound; in fact almost all modern cyclotrons use azimuthally-varying fields. The TRIUMF cyclotron mentioned below is the largest of its kind 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 and* higher intensity but is smaller because of using a higher magnetic field.

HISTORY

In late 1928 and early 1929 Hungarian physicist Leo Szilárd filed patent applications in Germany (later abandoned) for the linear accelerator, cyclotron, and betatron. In these applications, Szilárd became the first person to discuss the resonance condition (what is now called the cyclotron frequency) for a circular accelerating apparatus.Several months later, in the early summer of 1929, Ernest Lawrence independently conceived the cyclotron concept after reading a paper by Rolf Widerøe describing a drift tube accelerator. He published a paper in Science in 1930,and patented the device in 1932.

To construct the first such device, Lawrence used large electromagnets recycled from obsolete Poulsen arc radio transmitters provided by the Federal Telegraph Company.[He was assisted by a graduate student, M. Stanley Livingston Their first working cyclotron became operational in January of 1931. This machine had a radius of 4.5 inches, and accelerated protons to an energy up to 80 keV..

At the Radiation Laboratory of the University of California, Berkeley, Lawrence and his collaborators went on to construct a series of cyclotrons which were the most powerful *accelerators in the world at the time; a 69 cm (27 in) 4.8 MeV machine (1932), a 94 cm (37 in) 8 MeV machine (1937), and a 152 cm (60 in) 16 MeV machine (1939). Lawrence received the 1939 Nobel Prize in Physics for the invention and development of the cyclotron and for results obtained with it.*

The first European cyclotron was constructed in the Soviet Union in the physics department of the Radium Institute in Leningrad, headed by Vitaly Khlopin [ru]. This Leningrad instrument was first proposed in 1932 by George Gamow and Lev Mysovskii and was installed and became operative by 1937.

Two cyclotrons were built in Nazi Germany. The first was constructed in 1937, in Otto Hahn's laboratory at the Kaiser Wilhelm Institute in Berlin, and was also used by Rudolf Fleischmann. It was the first cyclotron with a Greinacher multiplier to increase the voltage to 2.8 MV and 3 mA current. A second cyclotron was built in Heidelberg under the supervision of Walther Bothe and Wolfgang Gentner, with support from the Heereswaffenamt, and became operative in 1943.

By the late 1930's it had become clear that there was a practical limit on the beam energy that could be achieved with the traditional cyclotron design, due to the effects of special relativity. As particles reach relativistic speeds, their effective mass *increases, which causes the resonant frequency for a given magnetic field to change. To address this issue and reach higher beam energies using cyclotrons, two primary approaches were taken, synchrocyclotrons (which hold the magnetic field constant, but increase the accelerating frequency) and isochronous cyclotrons. (which hold the accelerating frequency constant, but alter the magnetic field)*

Lawrence's team built one of the first synchrocylotrons in 1946. This 184 inch machine eventually achieved a maximum beam energy of 350 MeV for protons. However, synchrocyclotrons suffer from low beam intensities (<1 μA), and must be operated in a "pulsed" mode, further decreasing the available total beam. As such, they were quickly overtaken in popularity by isochronous cyclotrons.

The first isochronous cyclotron (other than classified prototypes) was built by F. Heyn and K.T. Khoe in Delft, Germany, in 1956.Early isochronous cyclotrons were limited to energies of ~50 MeV per nucleon, but as manufacturing and design techniques gradually improved, the construction of "sprial-sector" cyclotrons allowed the acceleration and control of more powerful beams. Later developments included the use of more powerful superconducting magnets and the separation of the magnets into discrete sectors, as opposed to a single large magnet.

PRINCIPLE OF OPERATION

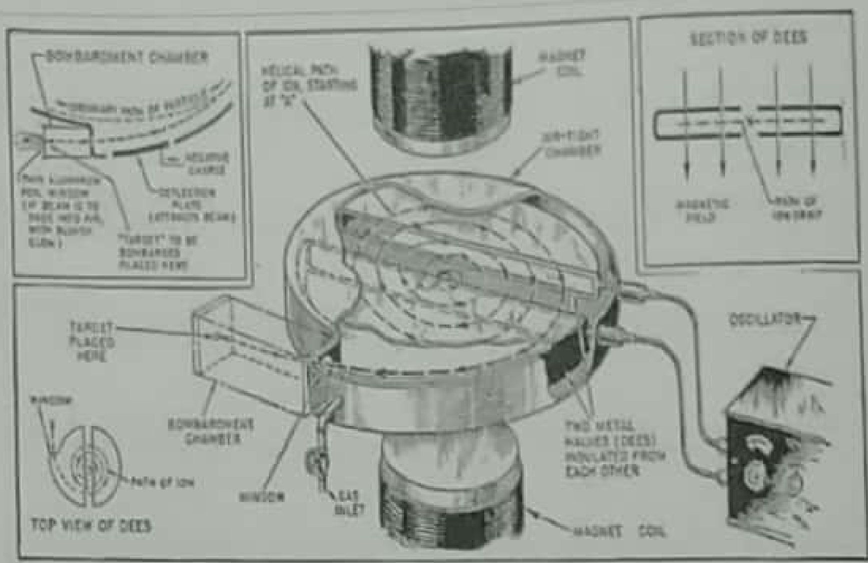
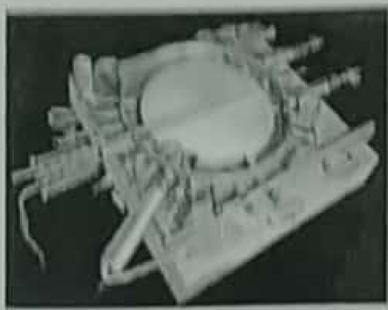


Diagram showing how a cyclotron works. The magnet's pole pieces are shown smaller than in reality; they must actually be as wide as the dees to create a uniform field.



Vacuum chamber of Lawrence 69 cm (27 in) 1932 cyclotron with cover removed, showing the dees. The 13,000 V 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.

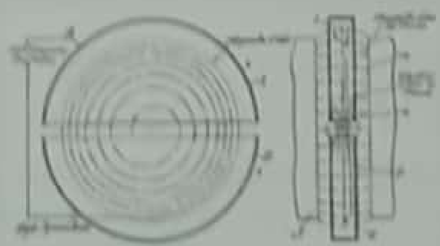


Diagram of cyclotron operation from Lawrence's 1934 patent. The "D" shaped electrodes are enclosed in a flat vacuum chamber, which is installed in a narrow gap between the two poles of a large magnet.

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. 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' speeds were 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 voltage creates an oscillating electric field in the gap between the dees that accelerates the particles. The frequency is set so that the particles make one circuit during a single cycle of the voltage. To achieve this, the frequency must match the particle's cyclotron resonance frequency 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. 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 a small voltage on a metal plate deflects the beam so it exits the dees *through a small gap between them, and hits a target located at the exit point at the rim of the chamber, or leaves 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.*

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, so the output energy can be many times the accelerating voltage.

MECHANISMS OF CYCLOTRON

The theory of cyclotron is based on the interaction of a charged particle with electric and magnetic *fields. The magnetic force on a particle of charge q, moving with velocity v due to a uniform magnetic field B is given by,*

$F = q\, v \times B$

When a charged particle moves perpendicular to a constant magnetic field with speed v, the magnitude of the magnetic force is,

$F = q$

B sin 90°

F = q

VV

B

This force acts in a direction perpendicular to both the velocity of the particle and the magnetic field.

The Circular Path of a Charged Particle

The particle starts to rotate in a circular path of radius r such that the magnetic force serves as the centripetal force of that circular path. The centripetal force

FcFc has magnitude,

Fc= mv2rmv2r

Here, m is the mass of the particle and r is the radius of the circular path. The centripetal force is equal to the magnetic force i.e.

FcFc= Fmv2rmv2

= qvvBvv

= qBrmqBrm

The angular velocity (cyclotron angular frequency) is given by,

ωω= vrvr

$$\omega\omega = qBmqBm$$

The frequency of the rotation namely cyclotron frequency is,

$$f = \omega 2\pi \omega 2\pi$$

$$f = qB2\pi m qB2\pi m$$

This is the cyclotron frequency formula.

OPERATING PRINCIPLE OF CYCLOTRON

- a cyclotron, two hollow "D" shaped electrodes are placed face to face with a small gap, inside a vacuum chamber. An alternating voltage is applied between the "dees" across the gap. A uniform magnetic field is applied perpendicular to the plane of the electrodes. The "dees" have a cylindrical In space for the particles to move.
- Charged particles are injected at the center of the cylindrical space (shown by a dot in the figure). If the particles would have a constant velocity, they would rotate in circles of constant radii. But an alternating voltage of high frequency is applied across the gap. The frequency is set such that the charged

particles make a semicircle during a single cycle of the alternating voltage. In other words, the frequency of the ac voltage must match with the cyclotron frequency of the particles given by the cyclotron formula,

f = qB2πmqB2πm

Here, q is the charge, is the mass of the particle and B is the magnetic field strength.

. Each time a particle completes a semicircle inside a dee and approaches the other dee, the polarity of the voltage flips. The particle gets accelerated towards the other dee due to the electric field created by the ac voltage and its velocity increases.

- Since the frequency remains constant, the particle starts to move in a circle of a larger radius. The particle's trajectory takes the shape of a spiral of increasing radius. With each full cycle, the radius increases, and the velocity also increases. This process continues until the radius of the trajectory approaches the radius of the cylinder and the accelerated particles are passed through an exit at the end of the cylinder. The radius of *the cylinder must be set such that the desired velocity of the particles can be reached.*

APPLICATIONS OF CYCLOTRON

Cyclotrons are much more effective than linear accelerators because cyclotrons accelerate the particles several times in a single set up and due to their cylindrical shape, less space is required as compared to linear accelerators. Some of the uses of cyclotron are listed below,

- *Cyclotrons are widely used to accelerate charged particles in nuclear physics* experiments and use them to bombard atomic nuclei.

- *For radiation therapy in the treatment of cancer, different cyclotrons are used.*
- *Cyclotro*
- *ns can be used for nuclear transmutation (change of the nuclear structure).*

Limitations of Cyclotron

- *Neutral particles (e.g. neutron) do not interact with electric or magnetic fields. So, cyclotrons cannot be used to accelerate them.*

- *Since electrons have very small mass, their speed increases very rapidly and soon the resonance between the high voltage and the particle becomes lost. Hence, a cyclotron cannot accelerate electrons.*
- *Cyclotrons can accelerate particles to speeds much less than the speed of light (in the non-relativistic regime).*

WHAT EXACTLY IS A CYCLOTRON?

A cyclotron is an apparatus for increasing the energy of charged particles or ions. E.O Lawrence and M.S Livingston devised it in 1934 to examine the nuclear structure. The cyclotron boosts the energy of charged particles by using both electric and magnetic fields. Cross fields are named such because both fields are perpendicular to each other.

Charged particles accelerate outwards from the centre of a cyclotron along a spiral route. A static magnetic field keeps these particles on a spiral route, while a rapidly shifting electric field accelerates them.

CYCLOTRON PRINCIPLE OF OPERATION

- *A charged particle beam is accelerated in a cyclotron by applying a high-frequency alternating voltage between two hollow "D"-shaped sheet metal electrodes inside a vacuum chamber called the "dees."*
- *Dees are situated between the poles of an electromagnet, which produces a perpendicular static magnetic field B.*
- *The Lorentz force perpendicular to the particle's direction of motion causes the particle's path to bend in a circle due to the magnetic field.*
- *Between the dees, an alternating voltage of several thousand volts is supplied. By creating*

an oscillating electric field in the region between the dees, the voltage accelerates the particles.

- The voltage is set at a frequency that allows particles to complete one circuit in a single cycle. The frequency must be tuned to the particle's cyclotron frequency to achieve this situation.

CYCLOTRON FREQUENCY EXPRESSION

f = $qB2\pi m$qB2πm

- The magnetic field strength is denoted by the letter B.

- *q is the particle's electric charge.*
- *m is the relativistic mass of the charged particle.*

PARTICLE ENERGY EXPRESSION

The particles' energy is determined by the magnetic field's strength and the diameter of the dees.

The formula for calculating the centripetal force required to keep the particles in a curved path is:

$$Fc = mv2rmv2r$$

Lorentz's force FB on the magnetic field B provides the force. we get,

$$F = mv2rmv2r$$

$$Nv = qBRmqBRm$$

Hence, the output energy of the particle is given by the expression

$$E = q2B2R22mq2B2R22m$$

CYCLOTRON APPLICATIONS

These were the best sources of high-energy beams for nuclear physics investigations for decades. These are, however, still used in this type of research.

IS THERE ANYTHING THAT CYCLOTRON CAN'T DO?

- *cyclotron cannot accelerate them.*
- *The use of a cyclotron to accelerate neutral particles is not possible.*

- Due to the relativistic effect, it cannot accelerate Because electrons have such a little mass, a
- positively charged particles with enormous masses.

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 some cyclotrons currently installed at hospitals for radio isotopes production have been retrofitted to enable them to produce technetium-99m.Technetium-99m is a diagnostic isotope in short supply due to difficulties at Canada's Chalk River facill.

WORKING

- *A cyclotron accelerates a charged particle beam using a high frequency alternating voltage which is applied between two hollow "D"-shaped sheet metal electrodes known as the "dees" inside a vacuum chamber.*

- *The dees are placed face to face with a narrow gap between them, creating a cylindrical space within them for particles to move. Particles are injected into the center of this space.*
- *Dees are located between the poles of electromagnet which applies a static magnetic field B perpendicular to the electrode plane.*
- *The magnetic field causes the path of the particle to bend in a circle due to the Lorentz force perpendicular to their direction of motion.*
- *An alternating voltage of several thousand volts are applied between the dees. The voltage creates an oscillating electric field in*

the gap between the dees that accelerates the particles.

- The frequency of the voltage is set so that particles make one circuit during a single cycle of the voltage. To achieve this condition, the frequency must be set to particle's cyclotron frequency.

EXPRESSION FOR CYCLOTRON FREQUENCY

f=qB2πmf=qB2πm

B is the magnetic field strength

q is the electric charge of the particle

m is the relativistic mass of the charged particle.

Expression for Particle Energy

The energy of the particles depends on the strength of the magnetic field and the diameter of the dees.

The centripetal force required to keep the particles in a curved path is given by the formula:

Fc=mv2rFc=mv2r

The force is provided by the Lorentz's force F_B on the magnetic field B

$$FB=qvBFB=qvB$$

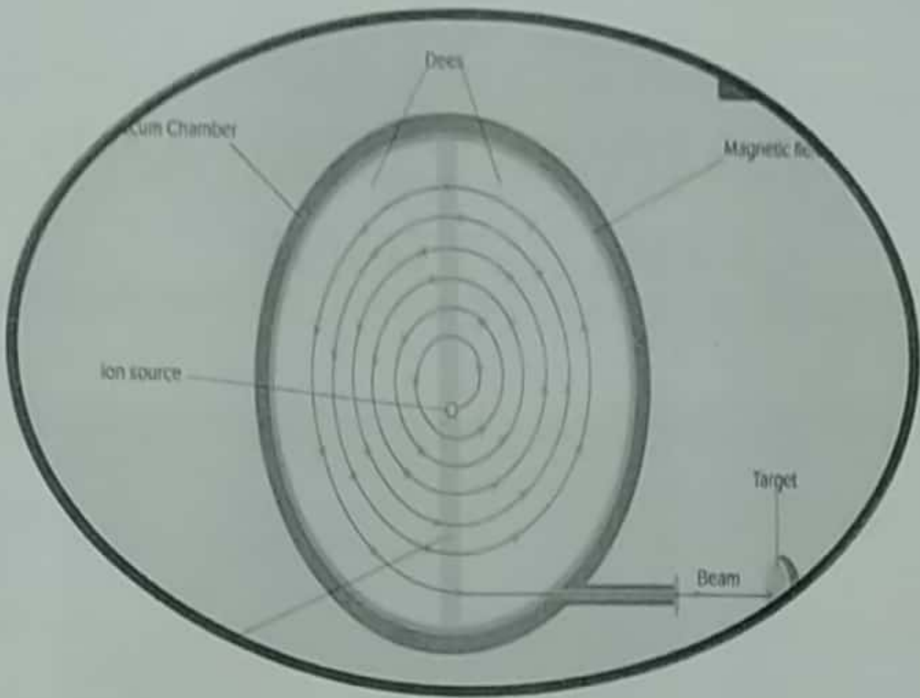
Equating these equations, we get

$$mv2r=qvBmv2r=qvB$$

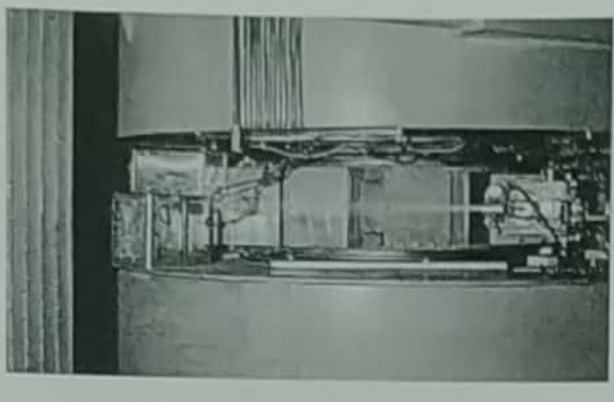
$$v=qBRmv=qBRm$$

Hence, the output energy of the particles is given by the expression

$$E=q2B2R22mE=q2B2R22m$$


Dees
Magnetic fie
Ion source
Target
Beam

ADVANTAGES AND LIMITATIONS



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 cyclotron was an improvement over the linear accelerators (linacs) 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.

M. Stanley Livingston and Ernest O. Lawrence (right) in front of Lawrence's 69 cm (27 in) cyclotron at the Lawrence 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.

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 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.

NOTABLE EXAMPLES

One of the world's largest cyclotrons is at the RIKEN laboratory in Japan. Called the SRC or Superconducting Ring Cyclotron, it has six 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 T, yielding a bending ability of 8 T·m. The total weight of the cyclotron is 8,300 t. The Riken magnetic field covers from 3.5 m radius to 5.5 m with the maximum beam radius of about 5 m (200 in). It has accelerated uranium ions to 345 MeV per atomic mass unit.

TRIUMF, Canada's national laboratory for nuclear and particle physics, houses the world's largest cyclotron of its kind. The 18 m diameter, 4,000 t 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 813 cm (0 to 320 in) radius with the maximum beam radius of 790 cm (310 in). Its large size is partly a result of using negative hydrogen ions rather than protons; this requires a lower magnetic field to reduce EM stripping of the loosely bound electrons. 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 a non-profit incorporation with charitable status located at the University of British Columbia.

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.

CYCLOTRON RADIATION

Cyclotron radiation is electromagnetic radiation emitted by non-relativistic accelerating charged particles deflected by a magnetic field. The Lorentz force on the particles acts perpendicular to both the magnetic field lines and the particles' motion through them, creating an acceleration of charged particles that causes them to emit radiation as a result of the acceleration they undergo as they spiral around the lines of the magnetic field.

The name of this radiation derives from the cyclotron, a type of particle accelerator used since the 1930s to create highly energetic particles for study. The cyclotron makes use of the circular orbits that charged particles exhibit in a uniform magnetic field. Furthermore, the period of the orbit is independent of the energy of the particles, allowing the cyclotron to operate at a set frequency. Cyclotron radiation is emitted by all charged particles travelling through magnetic fields, not just those in cyclotrons. Cyclotron radiation from plasma in the interstellar medium or around black holes and other astronomical phenomena is an important source of information about distant magnetic fields.

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.

CYCLOTRON RESONANCE

Cyclotron resonance describes the interaction of external forces with charged particles experiencing a magnetic field, thus already moving on a circular path. It is named after the cyclotron, a cyclic particle accelerator that utilizes an oscillating electric field tuned to this resonance to add kinetic energy to charged particles.

CYCLOTRON RESONANCE FREQUENCY

The **cyclotron frequency** or **gyrofrequency** is the frequency of a charged particle moving perpendicular to the direction of a uniform magnetic field B (constant magnitude and direction). Since that motion is always circular the cyclotron frequency is given by equality of centripetal force and magnetic Lorentz force

with the particle mass m, its charge q, velocity v, and the circular path radius r, also called gyroradius.

The angular speed of the rotation is then:

Giving the rotational frequency (being the cyclotron frequency) as:

It is notable that the cyclotron frequency is independent of the radius and velocity and therefore independent of the particle's kinetic energy; all particles with the same charge-to-mass ratio rotate around magnetic field lines with the same frequency. This is only true in the non-relativistic limit, and underpins the principle of operation of the cyclotron.

The cyclotron frequency is also useful in non-uniform magnetic fields, in which (assuming slow variation of magnitude of the magnetic field) the movement is approximately helical - in the direction parallel to the magnetic field, the motion is uniform, whereas in the plane perpendicular to the magnetic field the movement is, as previously circular. The sum of these two motions gives a trajectory in the shape of a helix.

GAUSSIAN UNITS

The above is for SI units. In some cases, the cyclotron frequency is given in Gaussian units.In Gaussian units, the Lorentz force differs by a factor of 1/c, the speed of light,

which leads to:

For materials with little or no

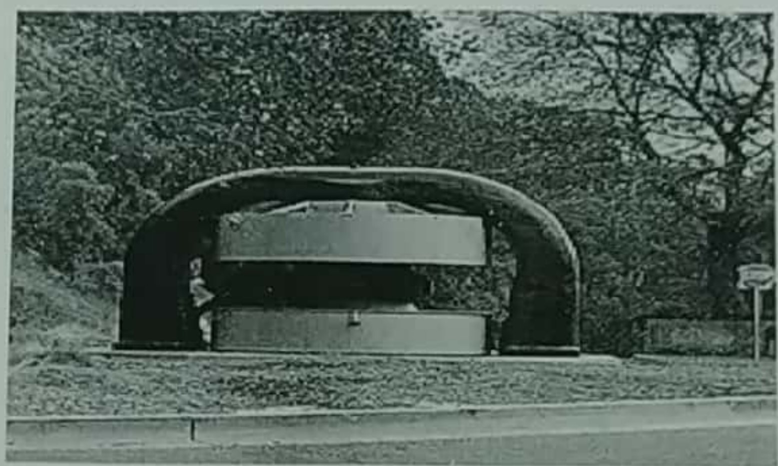
magnetism so we can use the easily

measured H instead of B.

Note that converting this expression to

SI units introduces a factor of

the vacuum permeability.



Why Cyclotron is important ?

Cyclotron – it sounds like a character from a science fiction film. It's actually a particle accelerator, a machine that uses electromagnetic fields to propel charged particles to very high speeds and energies, used to produce radioisotopes for a type of medical drugs called radiopharmaceuticals, which diagnose and treat cancer. There are over 1500 cyclotron facilities around the world, and the IAEA has recently updated its interactive map and database featuring 1300 of these cyclotron facilities from 95 countries.

First published in 2019, the Database of Cyclotrons for Radionuclide Production is a tool to *help experts such as radiopharmacists and owners and users of medical cyclotron facilities to find and exchange technical, utilization-related and administrative information on operating cyclotrons. It forms part of the IAEA's commitment to enhancing countries' capabilities in producing radioisotopes and applying radiation technology in health care.*

"Cyclotrons are developing rapidly and will play an increasingly important role in the health care sector, especially in advanced medical imaging procedures, because cyclotron-produced radiopharmaceuticals are very efficient in detecting various cancers," said Amir Jalilian, Radioisotope and Radiopharmaceutical Chemist at the IAEA.

Medical imaging techniques such as positron emission tomography (PET) and single photon emission computed tomography (SPECT) rely on cyclotron-produced radioisotopes. Unlike research reactors – which also produce radioisotopes – cyclotrons do not use nuclear materials and are not subject to the same radiological safety and security considerations as reactors.

The IAEA database enables users to search for details about each facility, including type, size and number of cyclotrons. Professionals in the field can connect and share expertise and information on their radiopharmaceutical products. The platform also features upcoming IAEA events and publications on the installation and application of cyclotrons.

The database forms part of the IAEA's work supporting countries in radionuclide production. The IAEA provides expert advice and technical guidance related to radiopharmaceutical production facilities; develops human resource capabilities through training courses and education programmes and promotes research and development through coordinated research projects.

Owners and users of medical cyclotrons can contact the IAEA Division of Physical and Chemical Sciences to send up-to-date information on their facilities by filling out a form and submitting it online.

For more information, visit the Database of Cyclotrons for Radionuclide Production. To find out more about accelerators and their applications, visit the IAEA Accelerator Knowledge Portal (AKP).

In fiction

The United States Department of War 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. In

1950, however, in Atom Man vs. Superman, Lex Luthor uses a cyclotron to start an earthquake.

In Ghostbusters a miniature cyclotron forms part of the proton pack used for catching ghosts.

Refrence:-

Prof. Rani Srivastava, UG Department of physics ,

GCPA Sadma,

THANKS