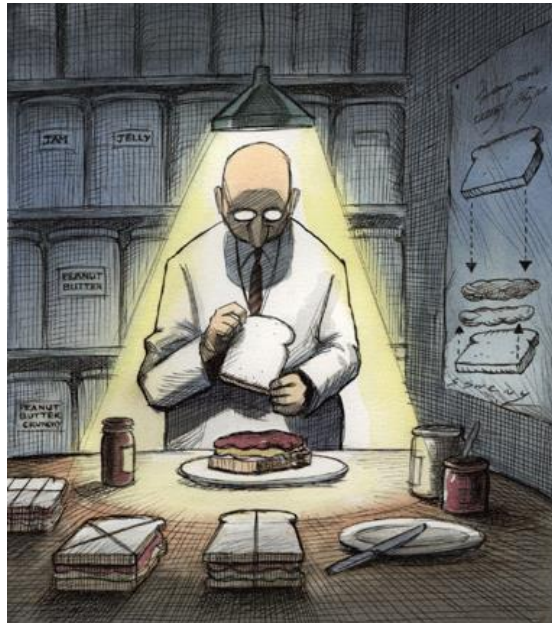


This learning material has been prepared by Prof. David Schlyer (Brookhaven National Laboratory) and the Technical Officers in charge are Mr Amirreza Jalilian (Primary) and Ms Aruna Korde (Alternate) from the Radioisotope Products and Radiation Technology Section, Department of Nuclear Sciences and Applications, IAEA.

Radiopharmaceutical Production

Cyclotron Basics



Assumptions

- The purpose of this presentation is to explain a little about the basic components in cyclotrons. There are certain assumptions that have been made about the background you need to read through this material. For the most part this is strictly descriptive material and you don't need a science background to get something out of it. However, it may help to know a little about physics and have had some exposure to differential equations as least in elementary level. It also will be useful to know rudimentary electrostatics and magnetostatics.
- As you progress through and are interested in what you find, additional material can be found in the literature and in a publication produced by the IAEA on the principles and practice of radionuclide production. That book can be found by following the arrow.



[TRS 465 – Principles and Practice of Radionuclide Production](#)



Cyclotron Components

- A **cyclotron** is a device that can accelerate charged particles to very high speeds
- The energetic particles produced are used to bombard atomic nuclei and thereby produce reactions
- These reactions can be used to produce radionuclides which can be used for medicine, industry or research

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Introduction

E.O. Lawrence - Father of the Cyclotron

- A positive or negative ion is released near the center of the cyclotron and moves gradually outward in a semicircular path due to the effect of a magnetic field.
- A rapidly changing RF field can be used to increase the kinetic energy of the particle with each circulation
- The cyclotron's operation is based on the fact that the time per revolution is independent of the speed of the particles and of the radius of their path
- When the energy of the ions in a cyclotron exceeds about 20 MeV, relativistic effects come into play



For a short presentation on the history of the cyclotron and the early years at Berkeley, Click for More

More [Cyclotron History](#)

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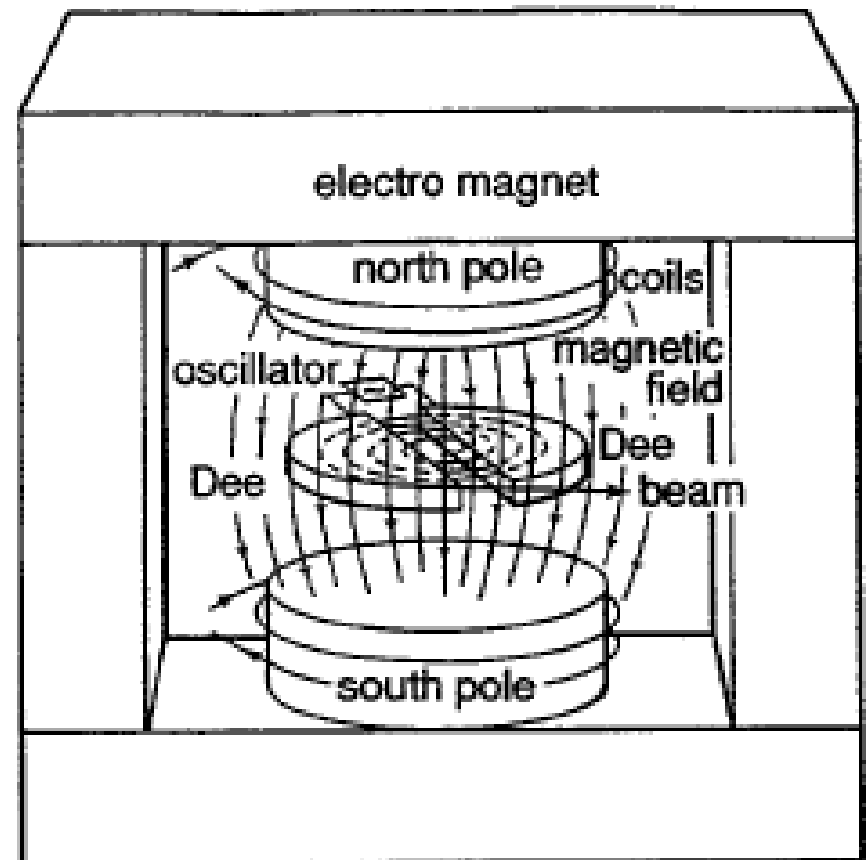
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Introduction

Major Components

- Major components
 - Magnet
 - Ion source
 - RF power
 - “dee” structure



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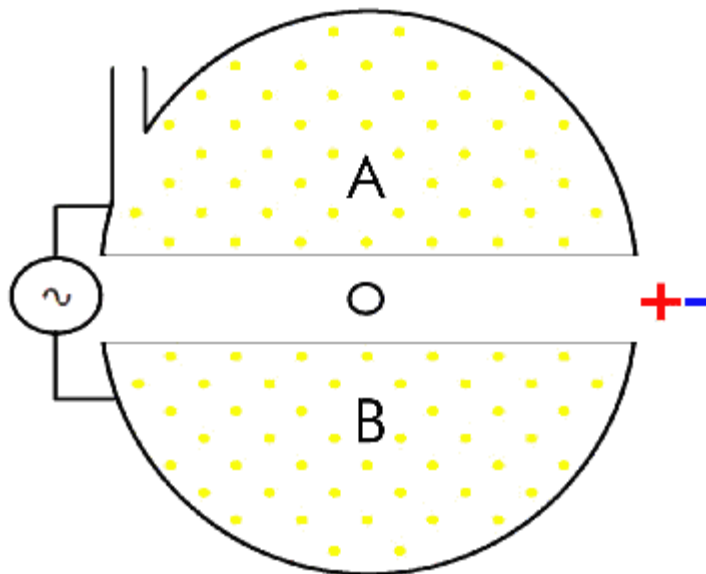
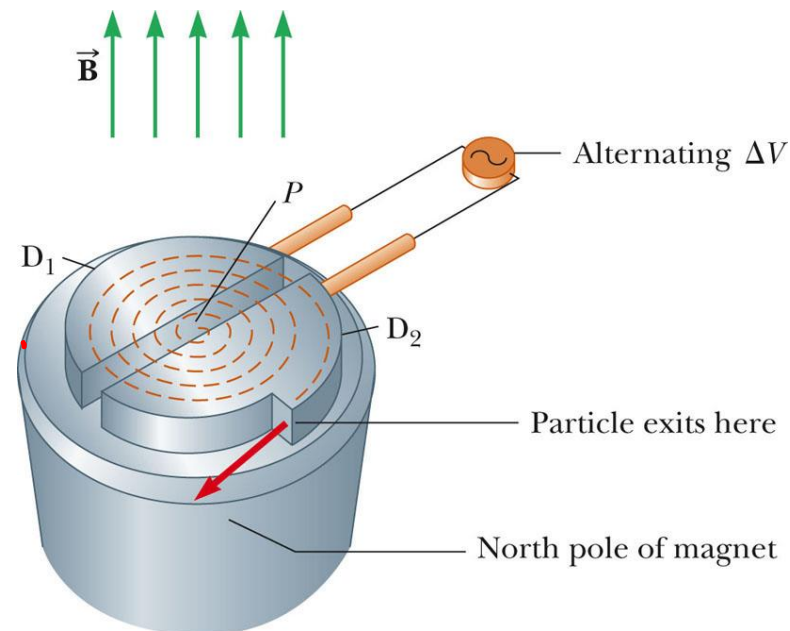
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- D_1 and D_2 are called *dees* because of their shape
- A high frequency alternating potential is applied to the dees
- A uniform magnetic field is perpendicular to them



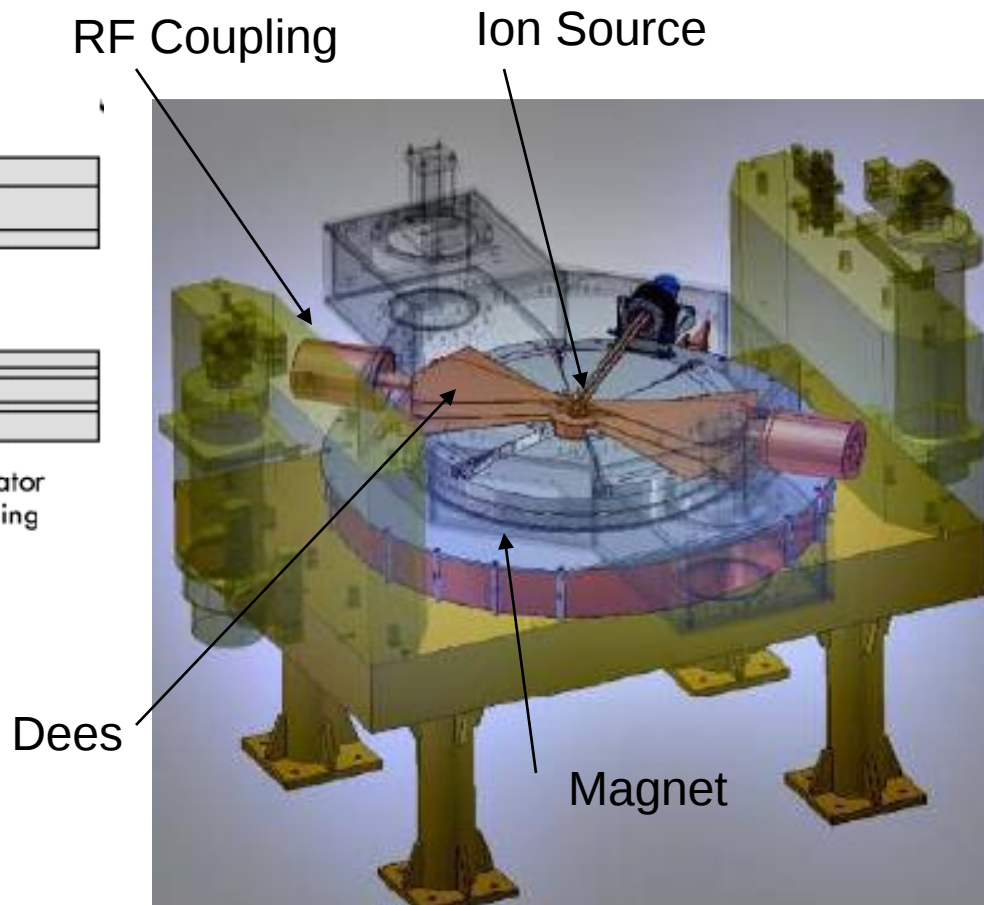
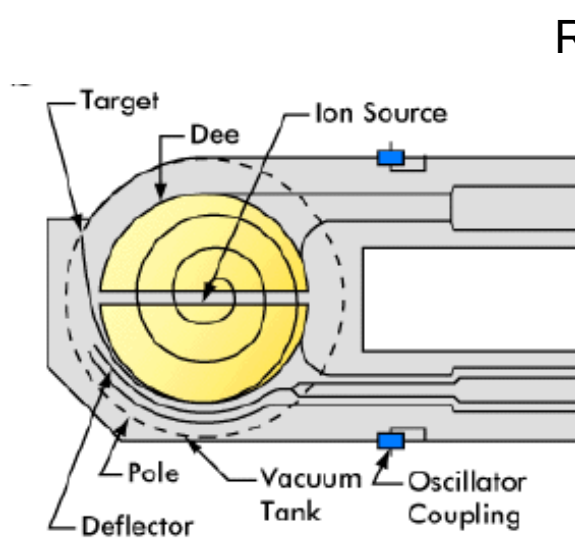
(a)
© Thomson Higher Education



(b)

Cyclotron Progress

Although some components have been significantly improved, the basic structures present in the cyclotron remain the same. The cut away view of the modern cyclotron shows the same ion source, magnet, RF structure and vacuum of the older cyclotron.



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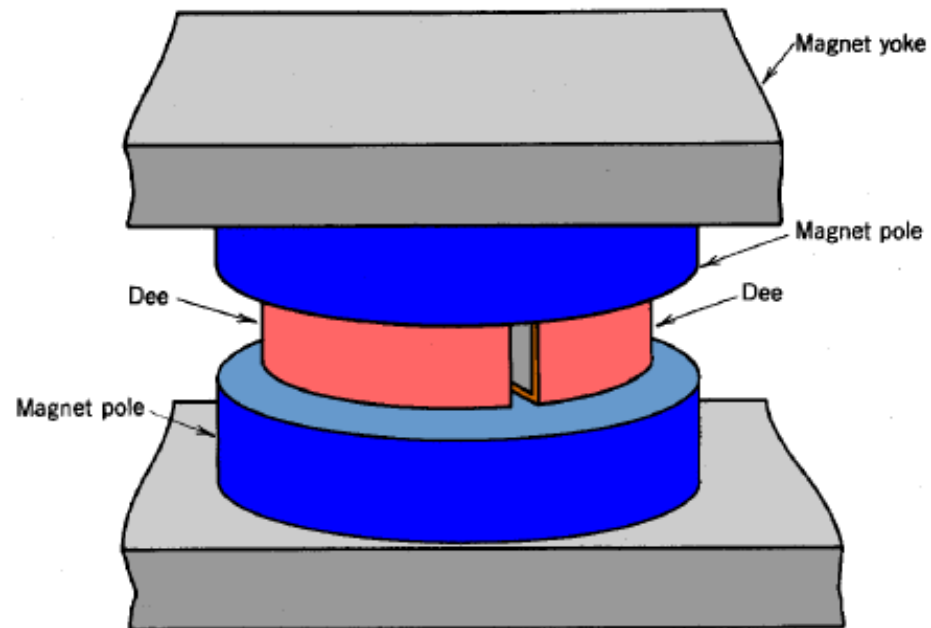
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- Just as charges set up an electric field, and other charges in the vicinity feel an electric force due to that electric field ($F_{el} = qE$), we can work with the idea that magnets set up a magnetic field in space, and charges moving through that field experience a magnetic force.
- In addition to the necessity of moving, there is one more difference: the direction of the magnetic force is perpendicular to the magnetic field direction, and perpendicular to the velocity of the moving charge!
- The magnetic field causes the charged particle to bend in accordance with the “right and rule”.



Motion in a Magnetic Field

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For a B field in the y direction

A positively charged particle with charge q
moving with velocity v in the x direction will
feel a force

$F = qvB$ in the z direction

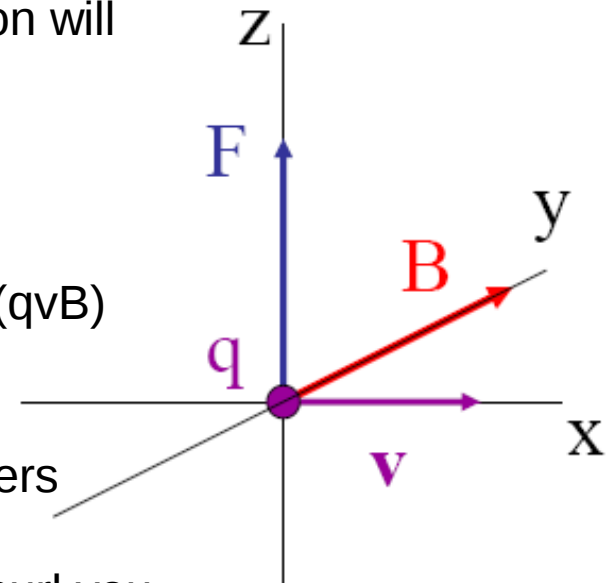
This is called the Lorentz force

magnitude: $F_{\text{magnetic}} = q v B \sin(qvB)$

direction:

right hand rule: thumb = hand x fingers

Point your hand in the direction of v , curl you
fingers in the direction of B , and the force will be
in the direction of your thumb; if the charge is
negative, the force direction is opposite that of
your thumb (or use your left hand).





An Example

To see if this is really feasible, let's try using realistic numbers to see what the radius should be for a proton moving in a B field:

$q = 1.6 \times 10^{-19}$ Coul; $B = 1$ Tesla $m = 1.67 \times 10^{-27}$ kg;
the radius is:

$$r = mv/qB = (1.67 \times 10^{-27} \text{ kg}) * (3.0 \times 10^7 \text{ m/s}) / (1.6 \times 10^{-19} \text{ Coul}) * (1 \text{ T})$$

$$r = 0.313 \text{ meters}$$

Now let's look at the other parameters of our cyclotron

$$\bullet \quad r = mv/qB \quad \text{and} \quad T = 2\pi m / qB$$

To accelerate a proton to 1/10 the speed of light (3×10^7 m/s) using a magnetic field of 1 Tesla, we would need an r of:

$$r = \mathbf{0.313 \text{ m}}$$
 (determined above)

$$T = [(2 * 3.1415 * 1.67 \times 10^{-27} \text{ kg})] / [(1.6 \times 10^{-19} \text{ C}) * (1 \text{ T})] = \mathbf{6.6 \times 10^{-8} \text{ sec}}, \text{ or}$$

$$f = 1/T = \mathbf{15 \text{ MHz}}.$$

You can continue this exercise to see how many turns it would take at what RF voltage to get to this velocity and how long that would take. (Hint: Typical dee voltages are on the order of 50 kV)

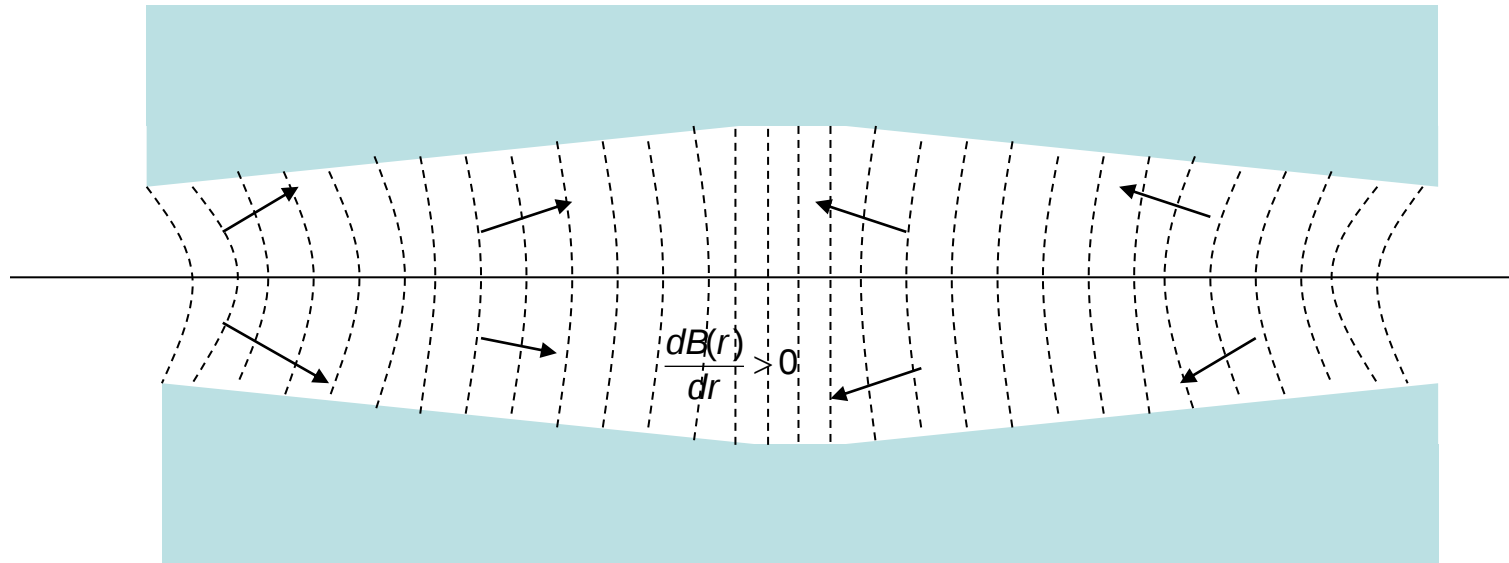


Field Gradient

- As the particle goes faster and faster, it starts to experience relativistic effects that cause the mass to increase.
- One way to keep the particle traveling at the same orbital frequency is to increase the magnetic field as the radius of the magnet increases
- There are detrimental consequences of using this type of field gradient in the path of the particles as the velocity increases since increasing the magnetic field in a gradient fashion defocuses the beam
- It is possible to keep the beam focused by decreasing the magnetic field as the orbital radius increases, however, decreasing the magnetic field is inconsistent with isochronous orbits
- These two situations are shown on the following diagrams.

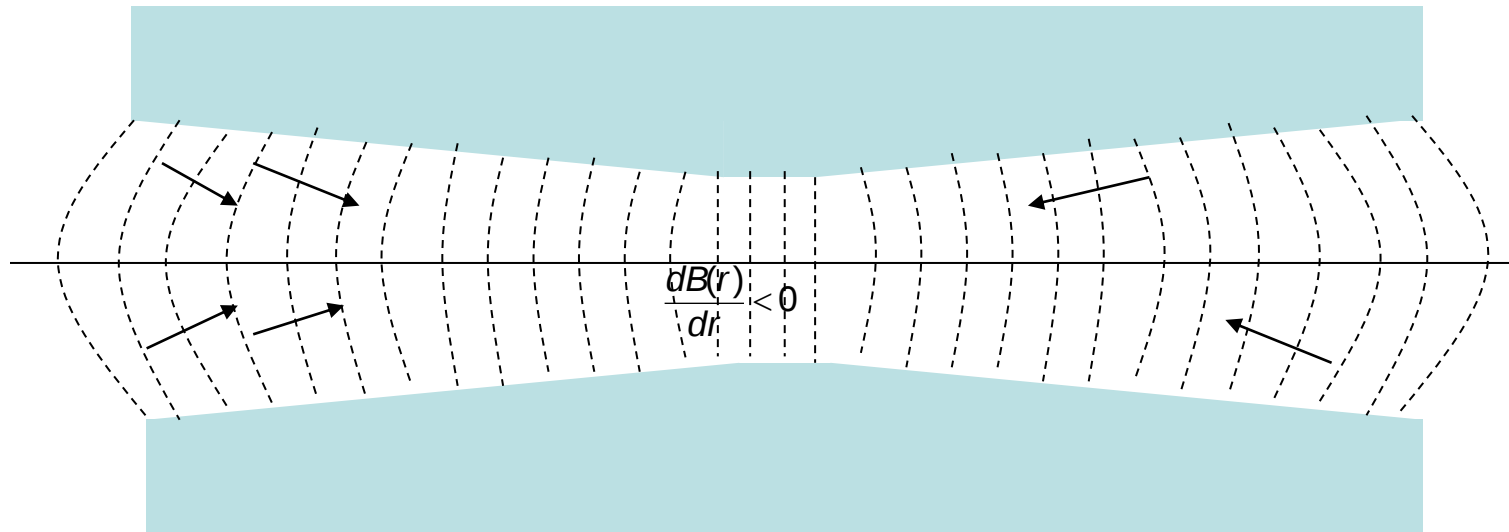
Vertical Defocusing

An increasing magnetic field with increasing radius maintains the orbital frequency, but defocuses the beam



Vertical Focusing

Decreasing the magnetic field with increasing radius focuses the beam, but the orbital frequency is no longer constant.



Focusing of the Beam

In order to maintain the orbital frequency and keep the beam focused, there are several approaches we can use.

Axial (Vertical) focusing of the beam can be provided in three different ways.

- Decreasing the magnetic field as the radius increases
 - Azimuthally varying magnetic field i.e., magnet sectors creating hills and valleys of the magnetic field
 - Spiralization of magnet sectors.
-
- We have already seen that the first solution does not work for a cyclotron so that the other solutions must be used.

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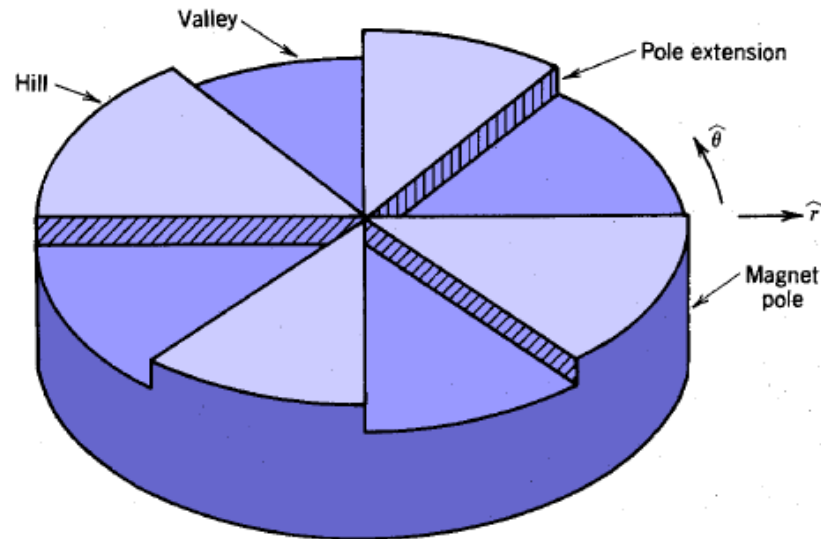
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AVF Cyclotron

- Azimuthally varying magnetic field (AVF) Cyclotrons
- We begin by considering extensions with boundaries that lie along diameters of the poles;
- Focusing by fields produced by wedge-shaped extensions is usually referred to as *Thomas focusing*
- The raised sections are called hills and the lower sections are called valleys



Hill and valleys on magnet pole with no spiral angles

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Hill Valley Map

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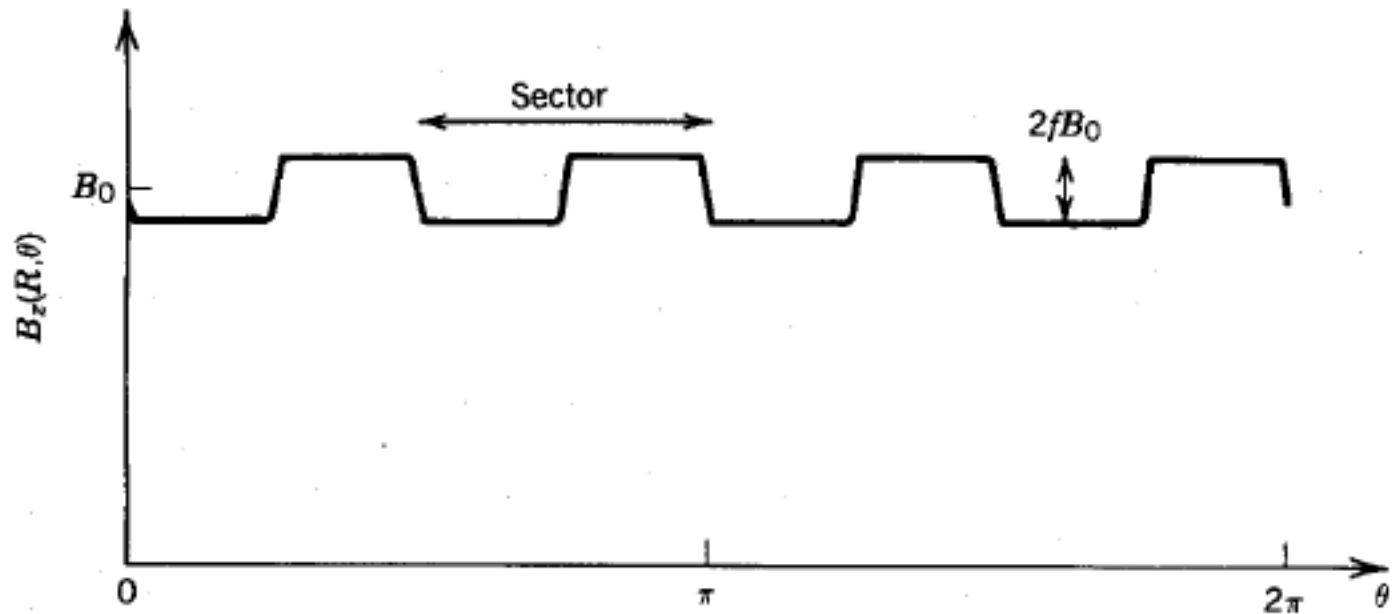
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Magnetic Vertical Field Amplitude as a function of azimuth at constant radius. This figure illustrates an AVF cyclotron field generated by circular magnet poles with wedge-shaped extensions attached.

Magnet Hills and Valleys

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An example of hills and valleys cut into the magnet pole face

Magnetic Field Gradients

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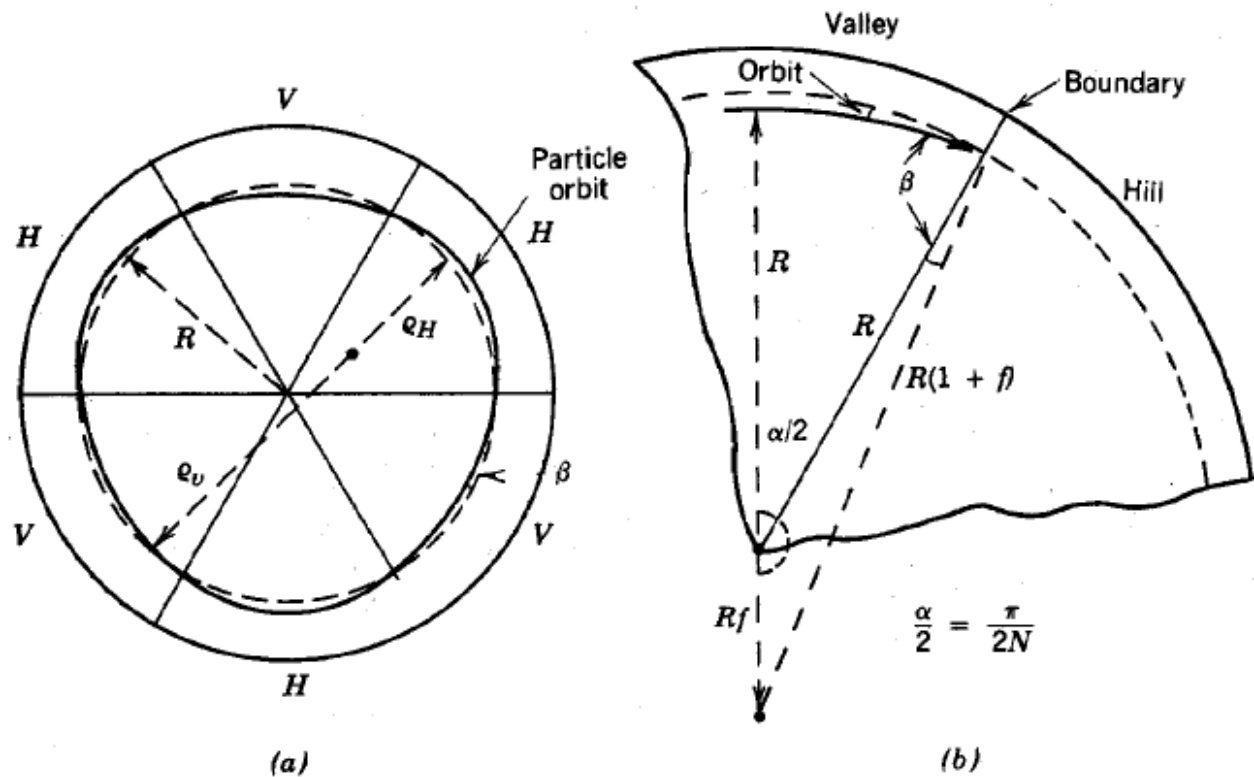
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- With variations in the field, the equilibrium orbit is changed from the circular orbit to the orbit shown in the figure
- Inspection of the Figure shows that the equilibrium orbit crosses between hill and valley regions at an angle to the boundary.
- The vertical forces acting on the particle are similar to those encountered in edge focusing and result in an overall focusing of the beam.



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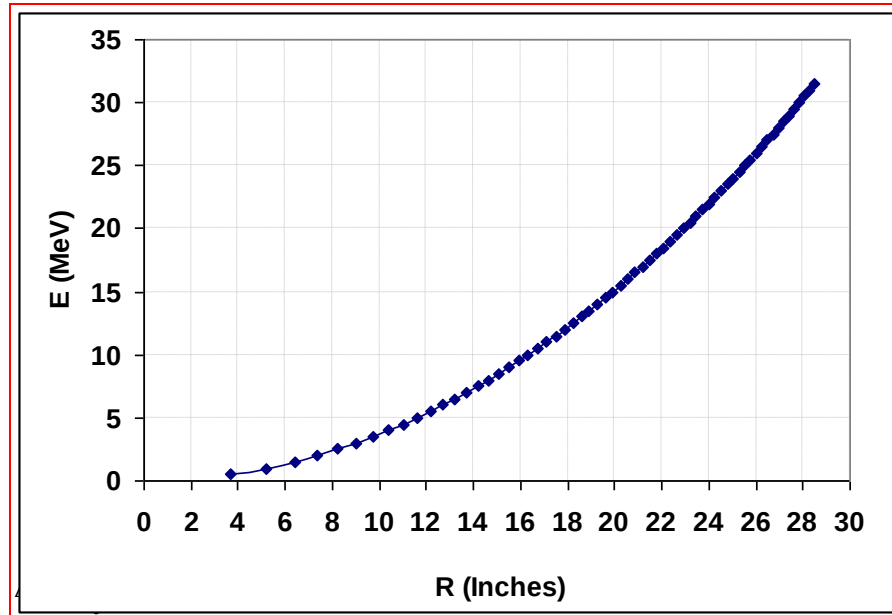
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- The kinetic energy of a charged particle is increased by electric fields according to where the integral is taken along the particle orbit.
- An electrostatic accelerator consists basically of two conducting surfaces with a large voltage difference V_0 . A particle with charge q gains a kinetic energy qV_0 .
- The energy of the beam should be a smooth increase from the center to the outer edge.

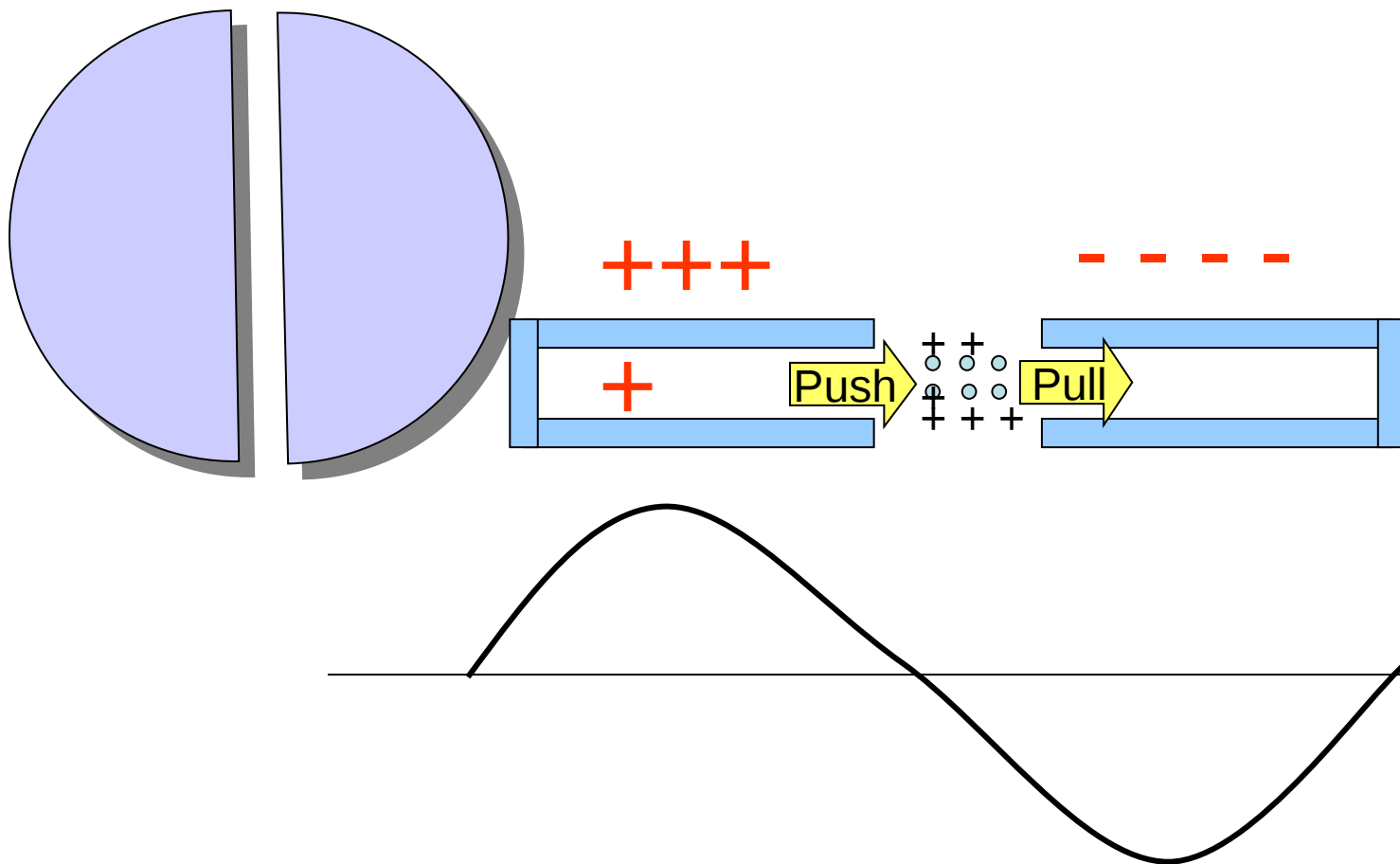


Beam path from the central region to the edge. Note the slight fluctuation in the orbit path as the beam nears the edge of the acceleration zone.



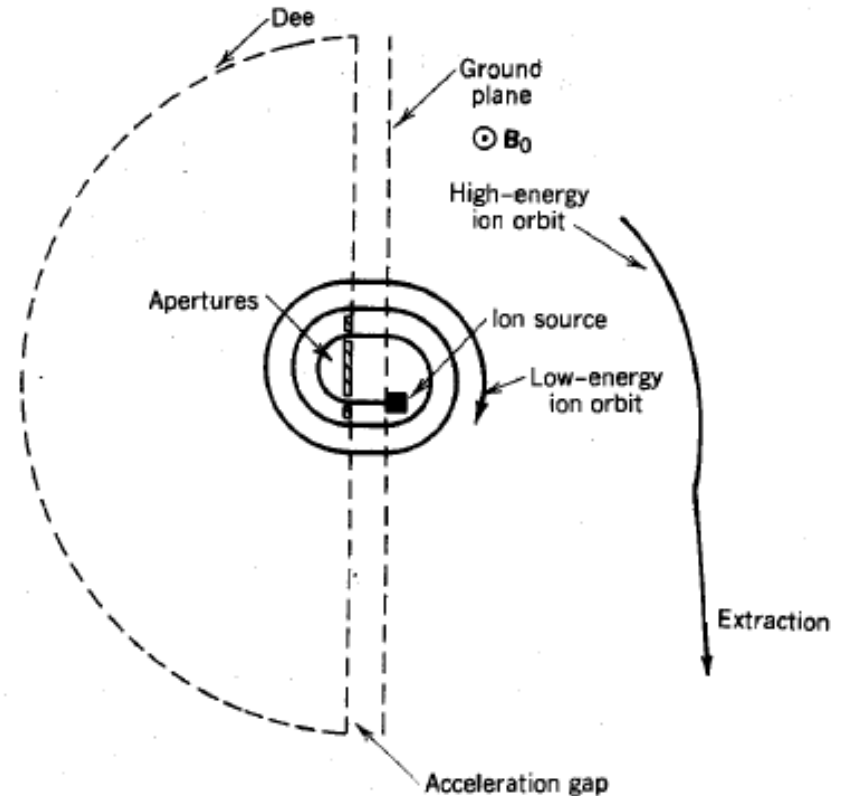
Acceleration Effects

The first cyclotrons had two dees for acceleration and each occupied half of the acceleration chamber. As the charged particle exited from one dee, it was pushed by that dee and pulled by the other dee. The sign of the RF field is given below the diagram.



Ion Path

Each time the beam passed through the gap, it is given a boost in energy close to the dee voltage. As the energy increases, the path becomes longer, but as noted before, the time required to make one loop remains the same because the velocity increases in exact proportion to the increase in distance.



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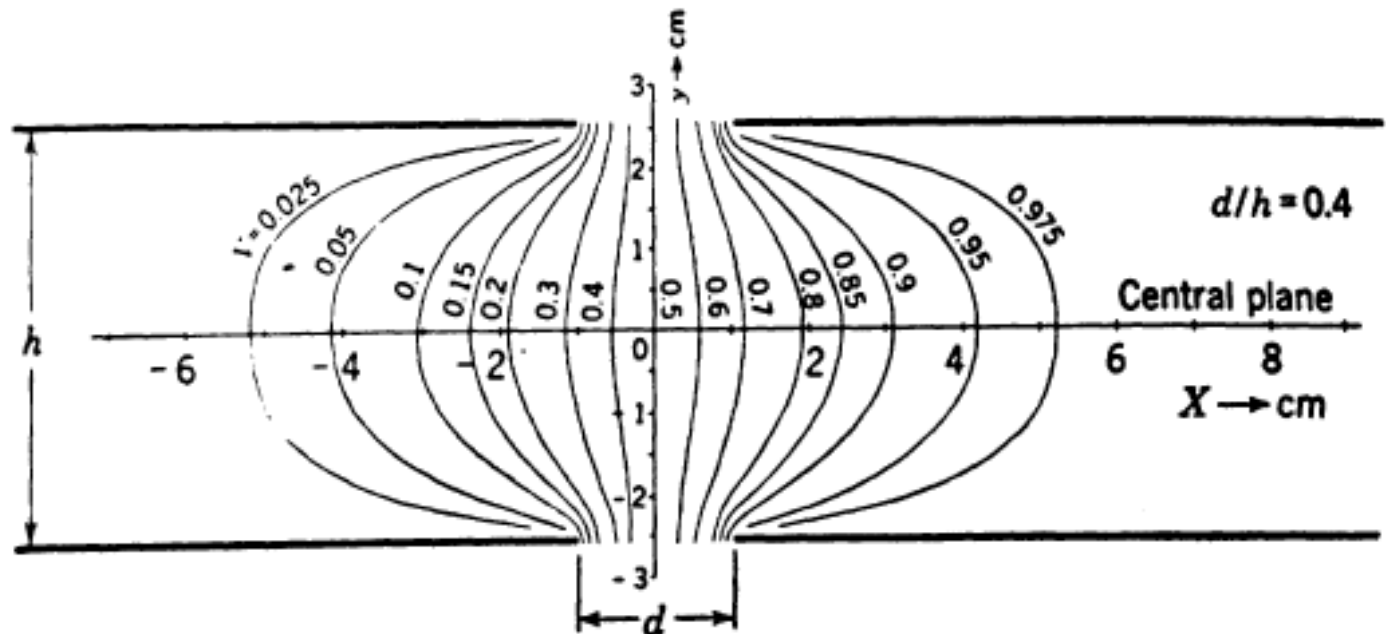
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Dee Gap

The electric field lines have a certain geometry which has an influence on the boost given to each particle as it passes through the gap between dees.



Equipotential lines for dee geometry in which dee-to-dee gap is 0.4 of the dee height. From Wilson

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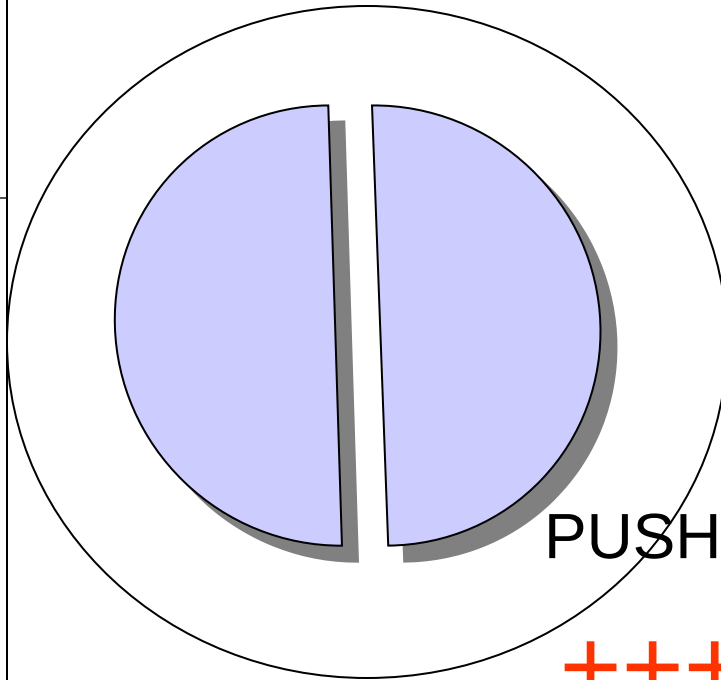




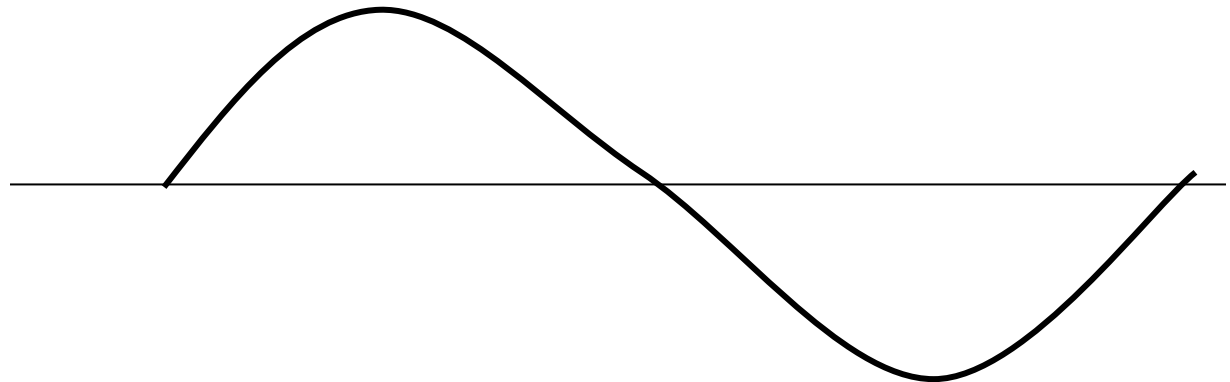
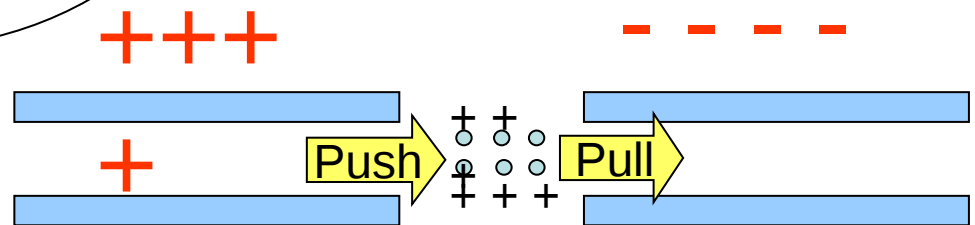
RF Harmonics

- It is usually considered that particles can only be accelerated in the cyclotron by frequencies which are either equal to, or an odd multiple of, the frequency of revolution of the particles in the magnetic field.
- The particles then require $1/2$, $1\ 1/2$, $2\ 1/2$ etc., cycles of the radio-frequency field between successive crossings of the gap between the dees.
- In each case, therefore, they maintain the correct phase relations for continuous acceleration in the alternating radio-frequency field.
- These modes are often called fundamental, third harmonic, fifth harmonic, etc.
- In the case of even harmonics, the particles will take whole numbers of cycles between successive gap transits and therefore will alternately gain and lose energy without any permanent gain.
- Examples of these situations are shown on the following slides.

Acceleration Effects 1st Harmonic



PUSH – PULL Acceleration



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Acceleration Effects Field Harmonics

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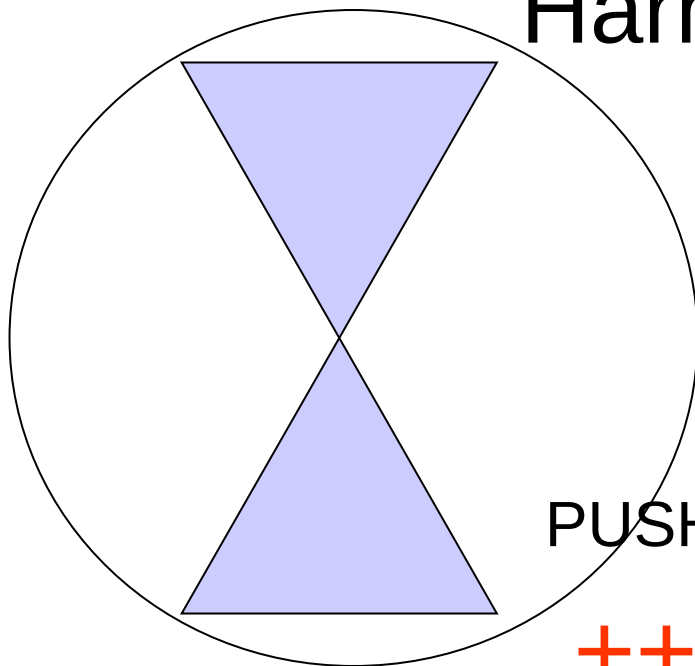
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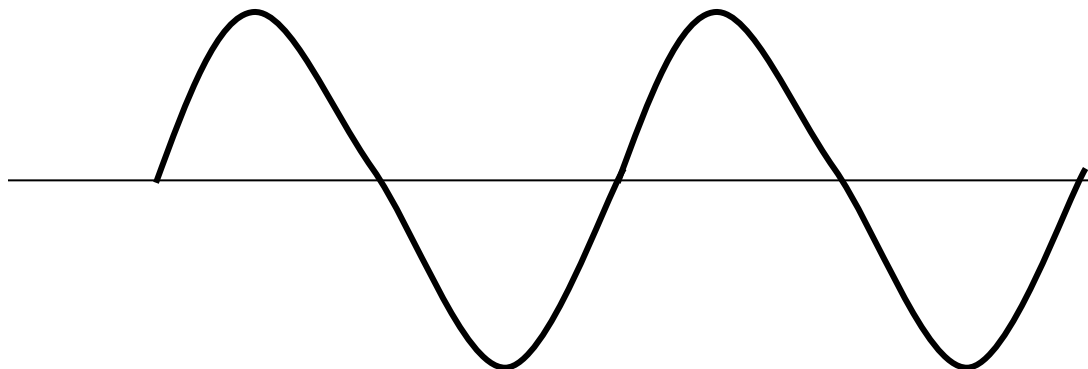
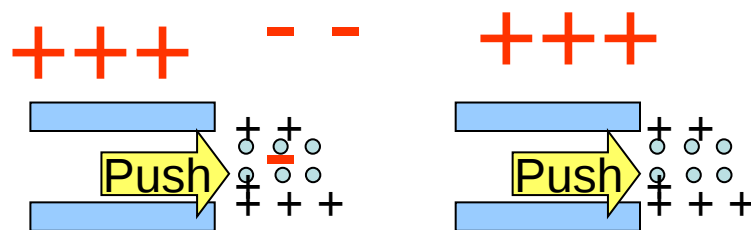
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PUSH – PUSH Acceleration



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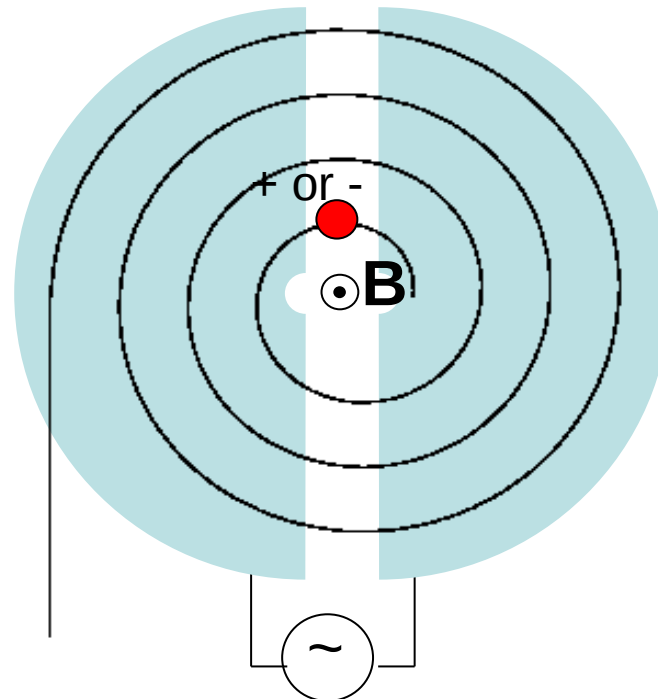
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- RF acceleration
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Ion Sources in Cyclotrons

Cyclotrons use magnetic fields to force **charged particles** to pass through accelerating gaps periodically



R.F. electric field

In order for the particles to be charged, they must be ionized somehow. This is the purpose of the ion source

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- The purpose of the ion source is to create either positive or negative ions to be accelerated
- The ions are usually generated in a plasma discharge
- The ion source can be either external or internal
- In most ion sources a gas of neutral atoms or molecules is “heated” into a *plasma* state where ions and electrons are dissociated and move independently as free particles.
- The heating mechanism can be of various kinds. It can be thermal, electrical, or use laser light.
- Once the ions are created in the source, they are then extracted from the plasma and accelerated



External Ion Source

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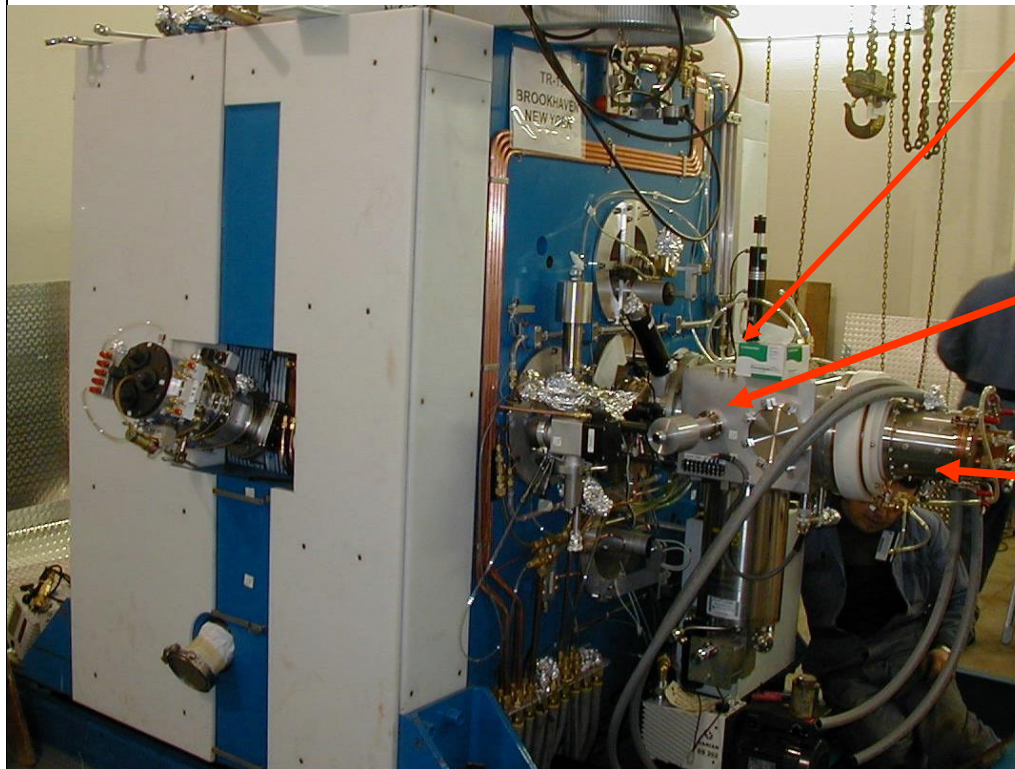
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Box of Kim-Wipes

Acceleration
Chamber

Ion Source

Gaseous Ion Sources

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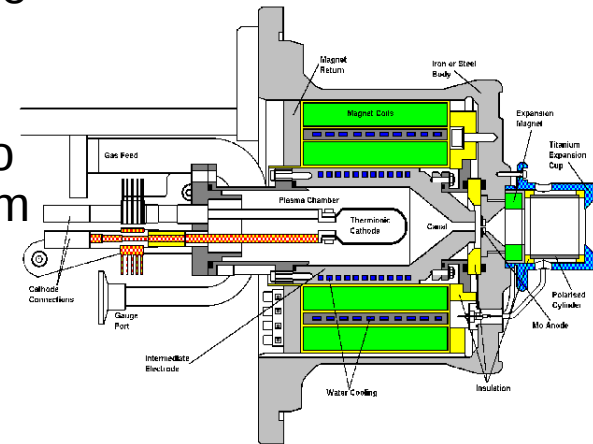
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- In any gaseous discharge, both positive and negative ions exist in approximately equal numbers
- The objective of ion source design is to optimize the desired ion yield and beam quality
- Electron bombardment of the neutral atoms in the plasma is the most usual method for creating ions
- Increasing energy is required to remove increasing numbers of electrons from the atom so multiply charged ions require much higher ionization energies
- The two main types used in cyclotrons are the hot cathode and cold cathode types.
- In the hot cathode, a heated filament is used to maintain the arc.
- In the cold cathode, once the discharge is initiated, no hot filament is used to maintain the plasma during normal operation of the ion source.



**Duoplasmatron
External Proton Ion
Source**

Courtesy of CERN

Ion Source Basics

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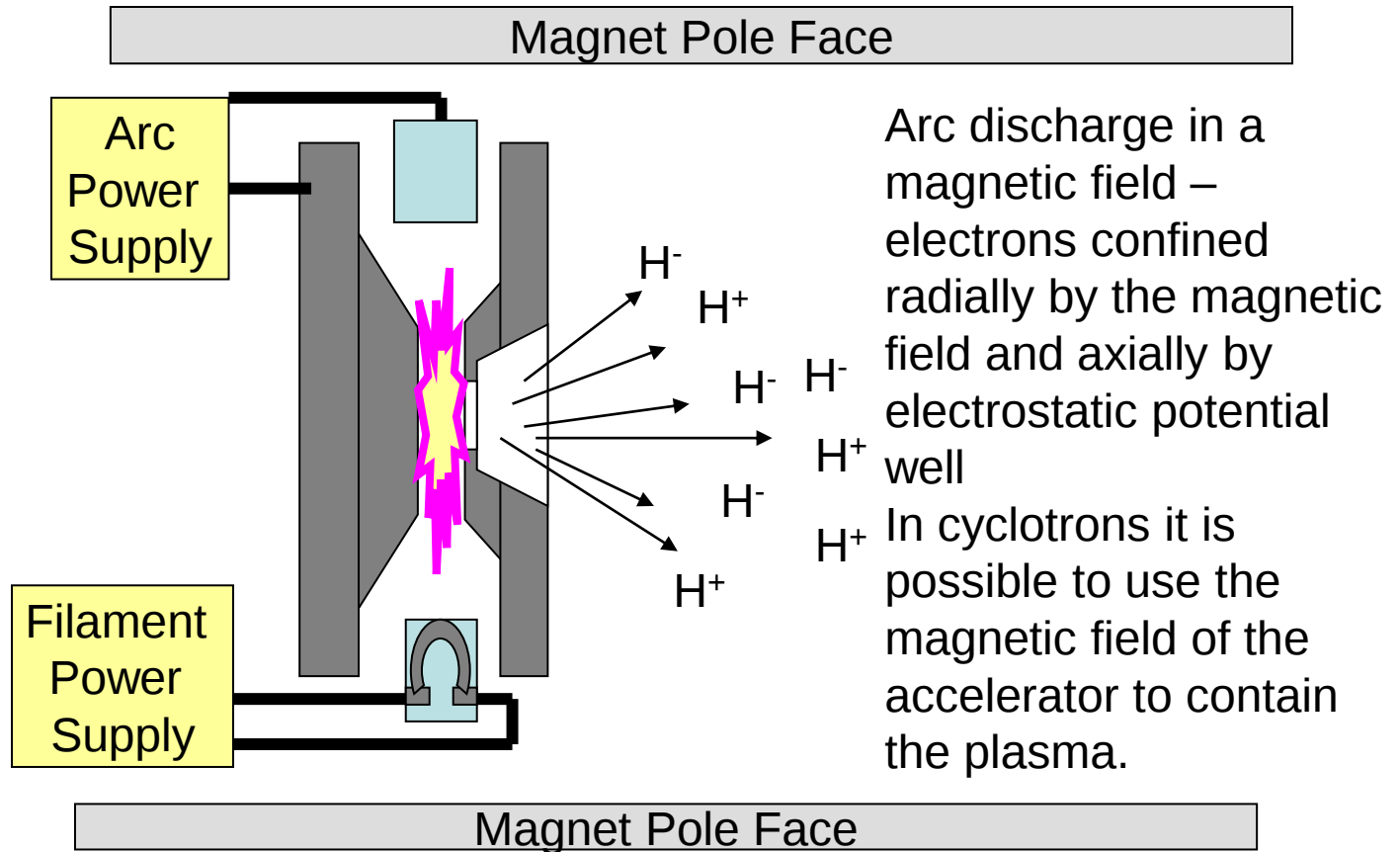
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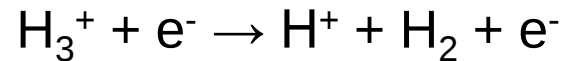
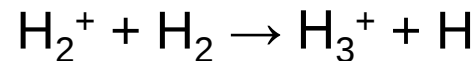
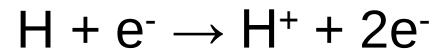
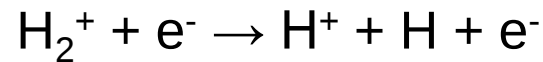
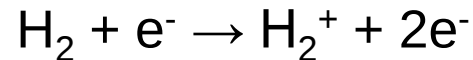
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Hydrogen Ionization Process



The last two reactions are particularly important for the production of protons (positively charged particles)

Simple Hot Cathode Ion Source

- Water lines for cooling the ion source

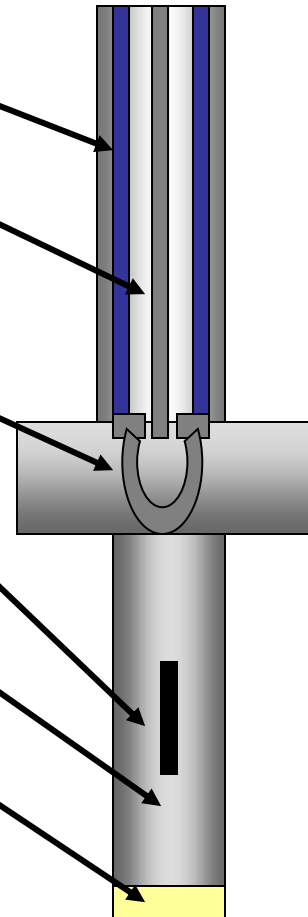
- Hydrogen inlet line

- Filament

- Slit for ion extraction

- Plasma chamber

- Ceramic end piece



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Ion Source in the Cyclotron

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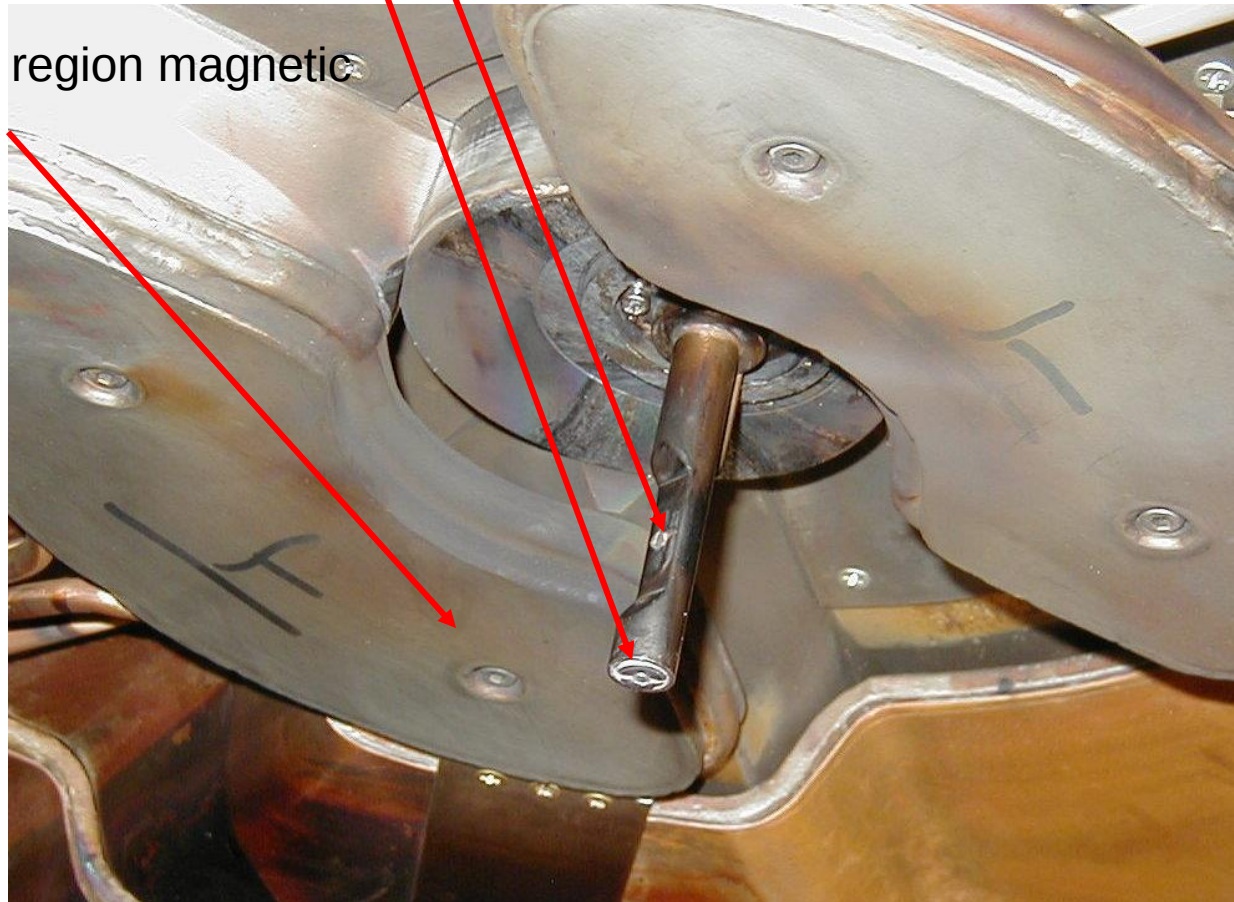
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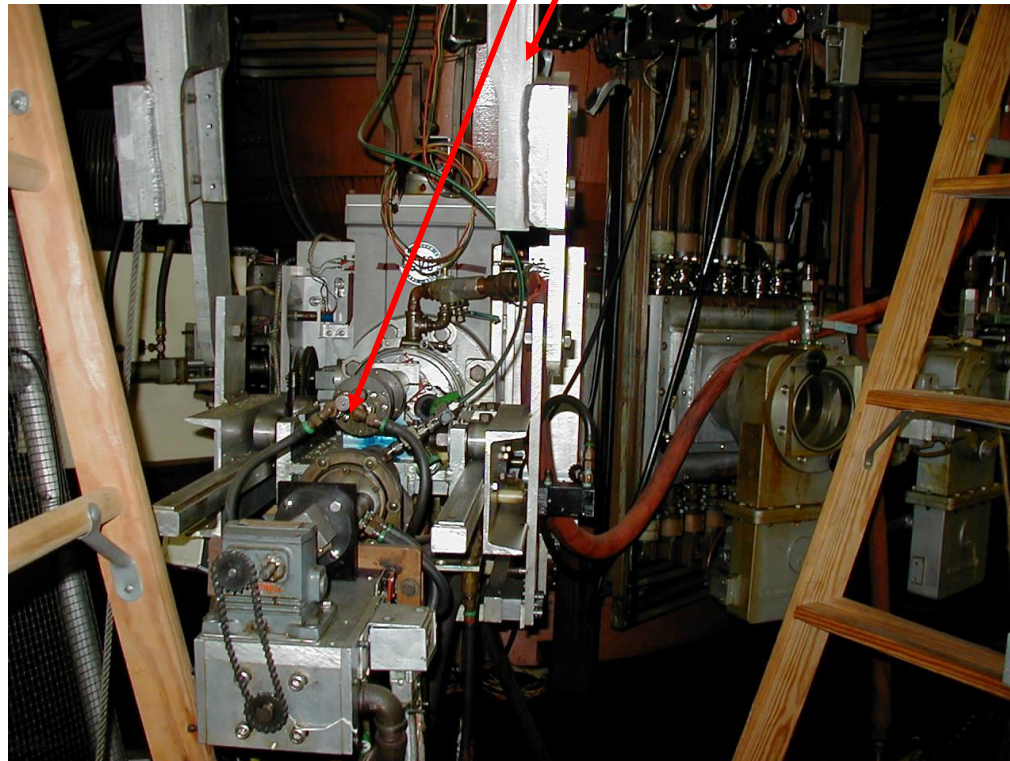


- Slit for extraction of ions
- Ceramic insulator
- Central region magnetic shims



Classical Ion Source

- Ion Source carrier
- Track support ion source during maintenance
- The tank vacuum does not need to be broken for work on the ion source



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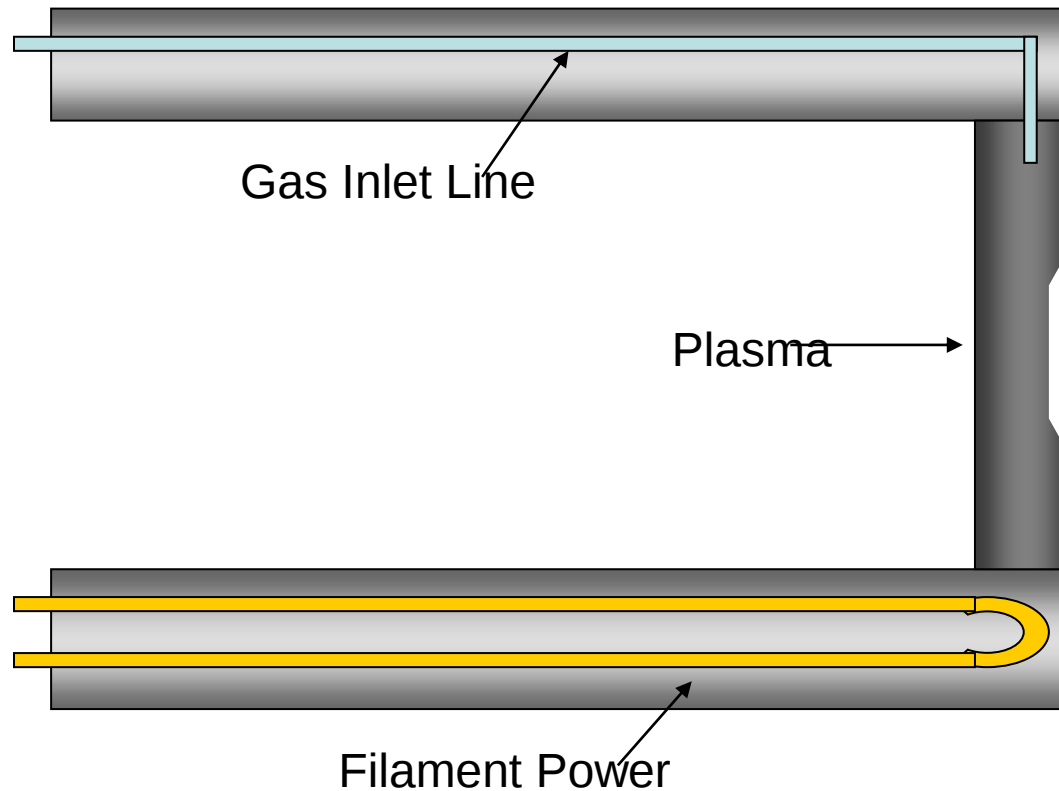
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Chimney Type Ion Source



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Ion Source Types

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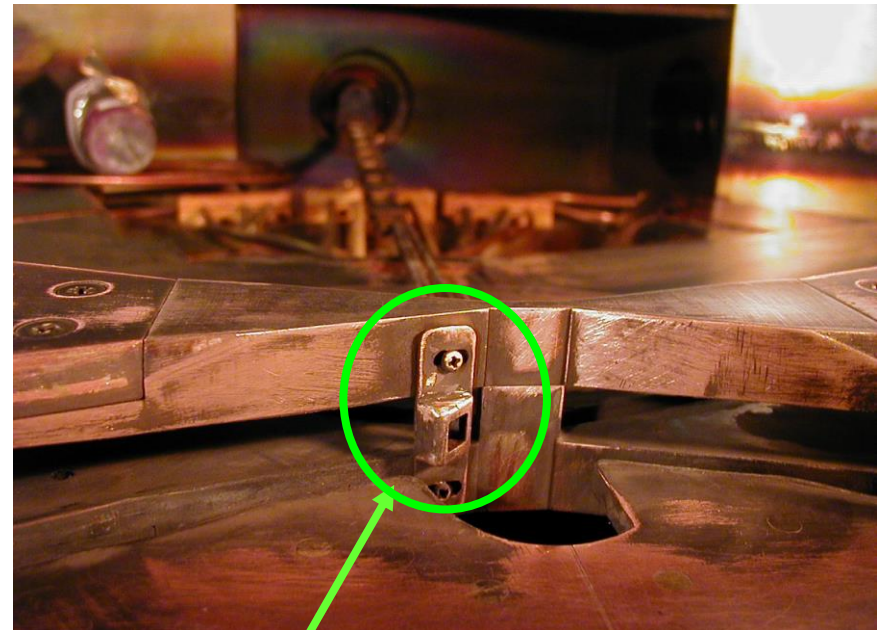
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- The spatial distribution and output of an internal source is not well defined and the ions usually have a broad distribution of energies.
- These problems are usually overcome by using slits on the ion source which decrease the beam intensity but produce a well defined beam profile.

Once the ions are out of the ion source, the path of the beam is further defined with a "puller". This is a small slit in a metal plate which accepts only those ions with the proper energy and position to continue past the first orbit



Puller

Ion Source Positioning

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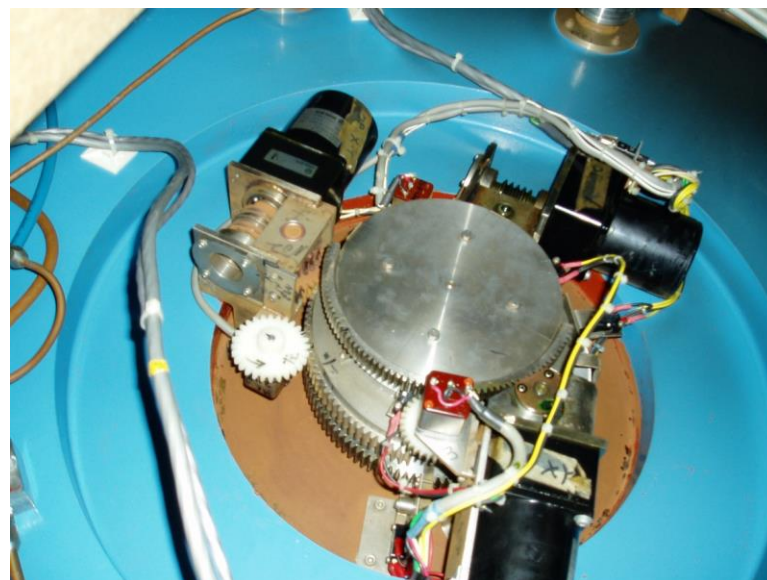
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- The position of the ion source is critical to an efficient beam extraction
- The relationship between the slit on the ion source, the puller, and the magnetic field in the central region must be in the proper alignment in order to achieve efficient extraction of the beam into the first orbit for acceleration.
- Three motor drives control the position of the ion source in three dimension and in rotational position



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Central Region Beam Path

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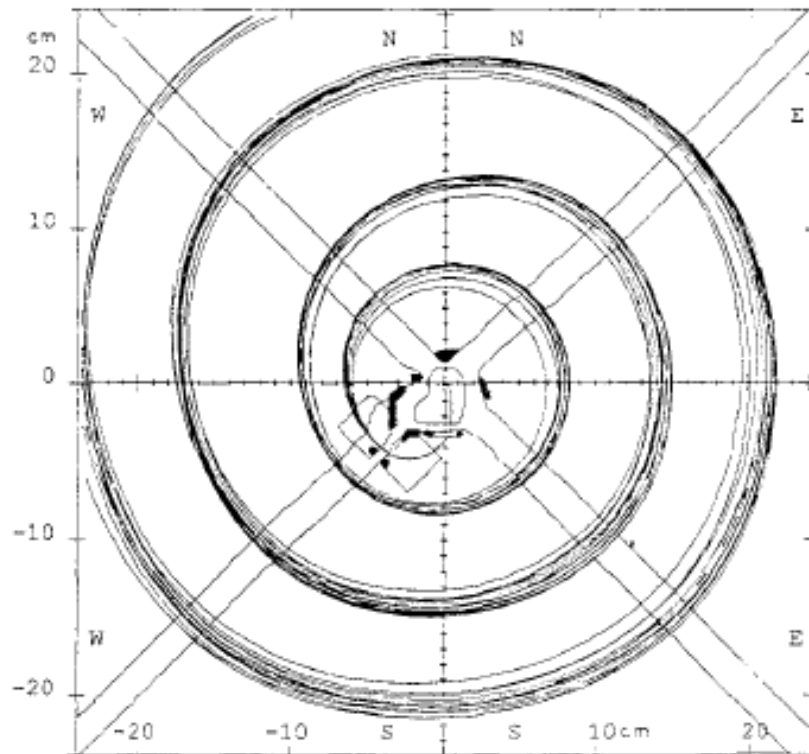
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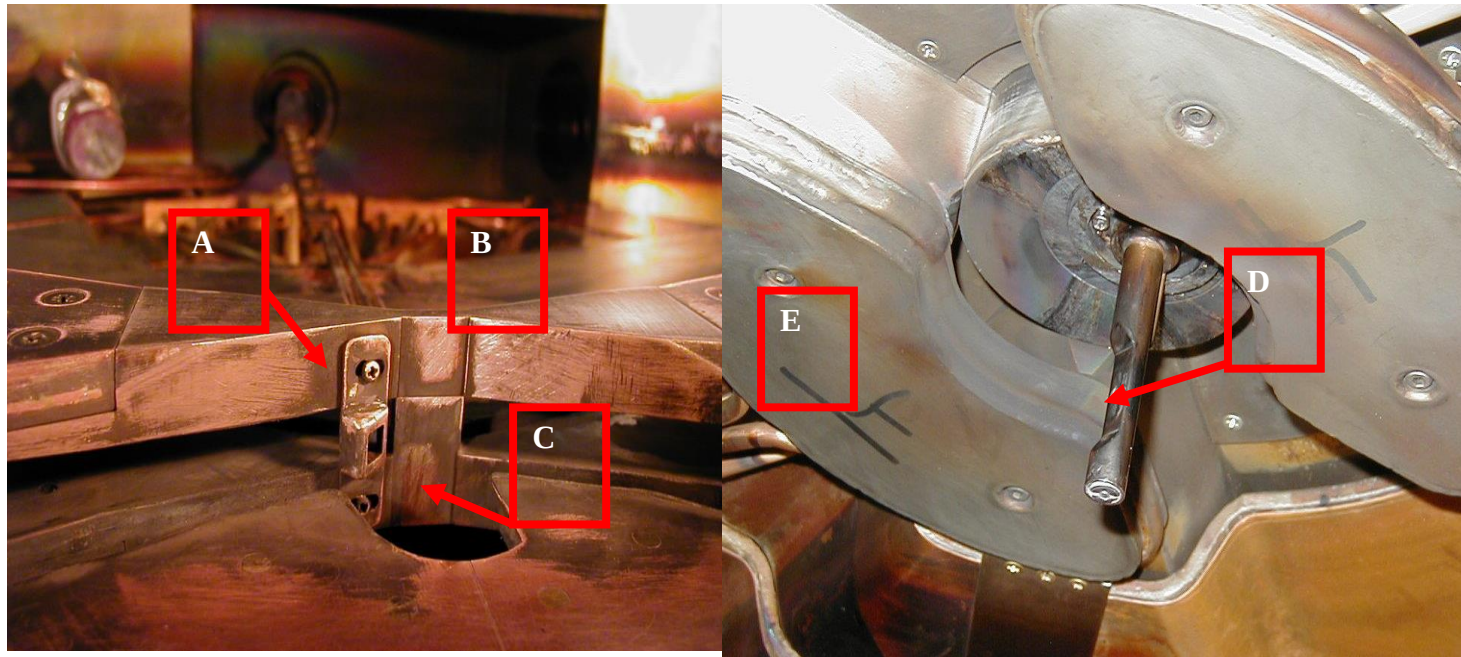


- As the ion exits the ion source the path it takes is determined by the environment of the central region. This includes the magnetic and electric fields in the region which pull the ions from the plasma out of the ion source and into the first orbit.
- As shown in the diagram, the orbit through the puller determines the exact beam path as the beam starts to accelerate.



Central Region

One of the critical parameters in ion sources is shaping the electric and magnetic fields so that the ion are drawn out of the plasma and into the dee region where they can be accelerated. Even with modern modeling of fields, this is often a trial and error sequence in order to maximize the efficiency.



Axial ion source configuration showing the puller (A), dee (B), central region where the ion source is lowered into place (C), the ion source cone (D) and the magnetic central region (E)

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Ion Extraction

- Once the beam has been accelerated to the desired energy, it usually must be extracted from the cyclotron in order to bombard a target and create the radionuclide.
- There are two major methods for extracting the beam from the cyclotron and the choice depends on the charge of the particle being accelerated. Positive ions (e.g. H^+) are extracted by electrostatic deflection of the beam from their normal orbits. Negative ions (e.g. H^-) are usually extracted by stripping the electrons off the ion and creating a positive ion which then magnetically deflected from the orbit out of the machine.
- Examples of these two modes are given in the following slides.

Positive Particle Extraction

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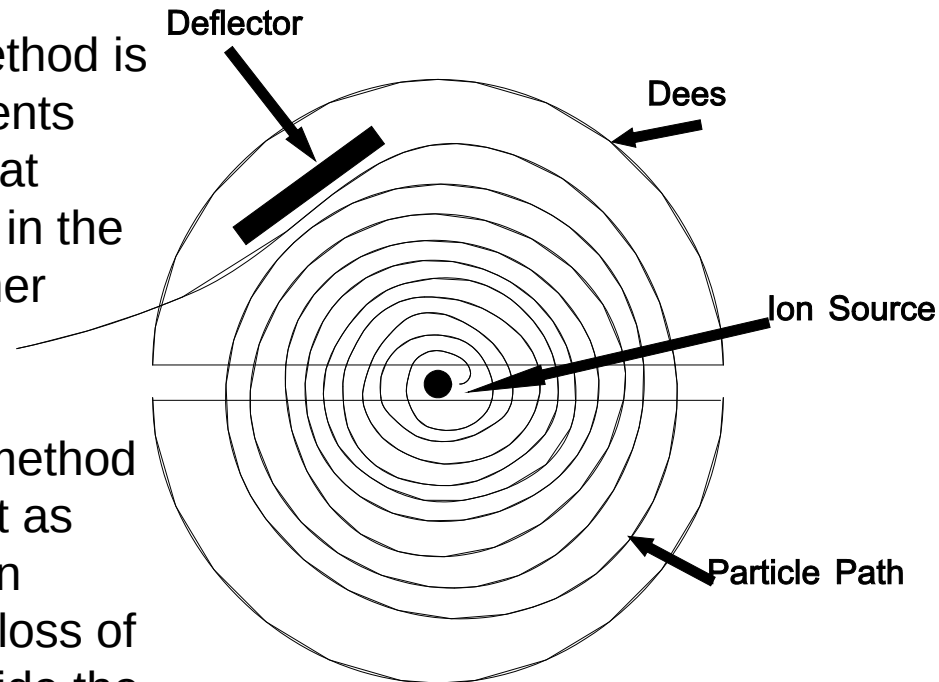


The beam is deflected by an electric field out of the cyclotron.

The advantages of this method is that the vacuum requirements are not as stringent and that positive ion sources have, in the past, been capable of higher beam currents.

The disadvantage of this method of extraction is that it is not as efficient as the negative ion extraction. This results in loss of beam and in activation inside the cyclotron which can result in a higher radiation dose to the cyclotron operators during internal maintenance.

Positive Ion Cyclotron



Positive Ion Extraction

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Deflector with split septum used for positive ion extraction

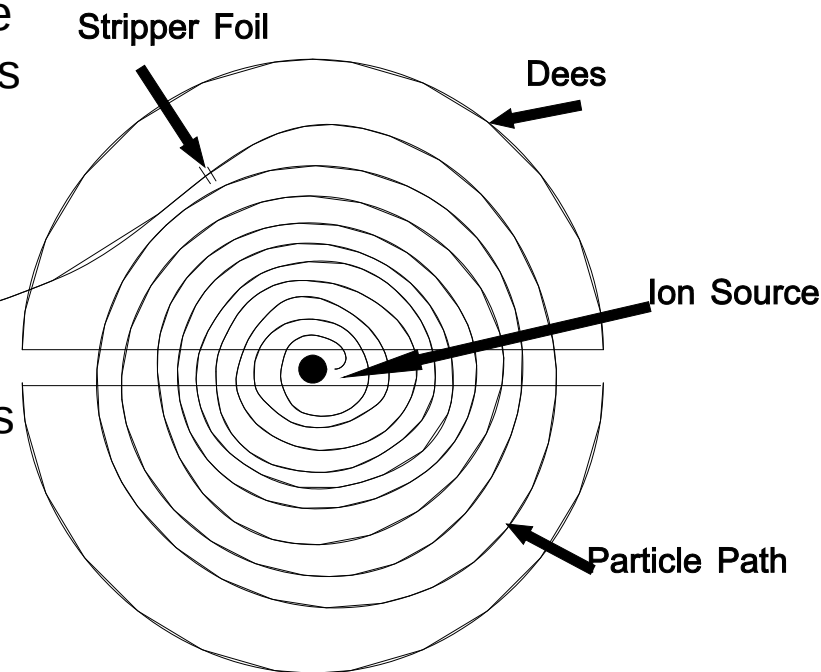
Particle Extraction

Negative Ion Cyclotron

In the negative ion extraction, the electrons are stripped off the accelerated ions and this causes them to be directed out of the cyclotron by the magnetic field acting on them.

The advantages of this system is that the extraction efficiency is very high and there is very little internal activation of the cyclotron

The disadvantages is that the vacuum requirements are slightly higher than for a positive ion machine and the stripping foils need to be changed regularly.



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Negative Ion Extraction

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Carbon foil used to extract negative ion beam

Ion Extraction Summary

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- Most modern cyclotrons use negative ion acceleration with stripper foils for extraction of the beam. The vacuum systems have improved such that vacuums of 10^{-7} torr are common and vacuum pumps such as turbo pumps and cryopumps which do not use oil are in common use.
- The added advantage of very little activation of the interior of the cyclotron makes the radiation dose received by the operators during maintenance much lower.
- Improvements in ion source technology have produced negative ion sources which are capable of producing beam currents of the same order as positive ion sources so the limitations on beam current no longer exist.



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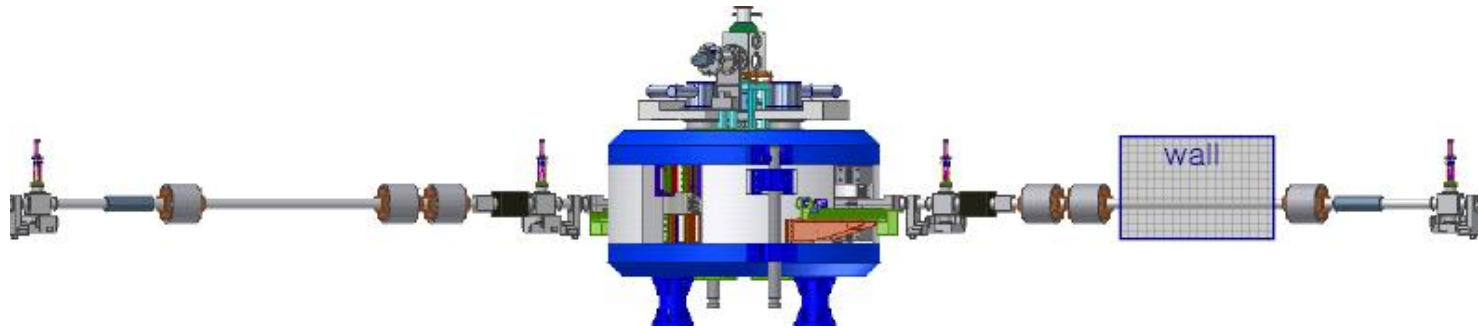
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On negative ion cyclotrons, there can be two or more beam lines from different ports on the machine. Each beam line may be further split to several target stations.

Positive ion cyclotrons can only support one exit and therefore one beam line. This beam line can be split into several target stations using a switching magnet.

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- A switching magnet can be used to divide the beam line into several target stations
- Each target station can hold several targets
- Each beam line will usually have focusing and steering magnets in it to ensure a good beam profile at the target stations



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