

very good morning to all of you we will continue with our discussion in magnetostatics we started looking at motion of charged particles in magnetic fields

so let me recall that the force on a charged particle consists of two parts the electrostatic force plus the magnetostatic force $q \cdot e$ this is electrostatic force and that is the magnetostatic force

so ah the electrostatic force as we have seen is directed along the electric field and the force due to the magnetic field is perpendicular to the directional magnetic field

so we saw a motion of a charged particle in a uniform magnetic field

so let me take a uniform magnetic field say pointing into the page which i draw as crosses here

so b is downwards

so let me assume i have a positively charged particle which is which is directed with a velocity b in this direction positively charged particle q with a velocity v in this direction now let me assume there is no electrostatic field at all

so the only force that will act on the charge particle is the magnetostatic force

so according to this equation the force is perpendicular to the velocity and to the magnetic field and it is along the direction $v \times b$

so v is in this direction b is into the page

so as you can see here $v \times b$ is upwards

so the force that is acting on the particle is like this this is the magnet of magnetic force

so the particle tend to curve upwards but as the particle curves the direction of velocity keeps changing

so at this point the force is directed like this

so the particle as we have seen before executes a circular motion and the magnetostatic force provides the centripetal force for this circular motion and we can write for example as we have seen before the centripetal force $m v^2$ by r is equal to $q v b$ here the velocity and magnetic field are perpendicular to each other

so $v \times b$ is simply b times v that gives me the radius of the circular orbit as $m v$ by $q b$

so that's the radius of this of the circular orbit

so the particles will keep circulating along a circle you can similarly do the same problem assuming that the charge is negatively negative with the same direction of magnetic field and find out what is the direction of motion of the charged particle this radius also tells me that the angular velocity angular velocity of the motion is nothing but v by r which is equal to $q b$ by m angle velocity is $q b$ by m and its independent of the radius of the charged particles motion or of the velocity and this gives me a frequency of number of revolutions per unit time as f is equal to ω by 2π which is equal to $q b$ by $2 \pi m$ and this as we have seen before is called the cyclotron frequency and is independent of the radius of the circular orbit thats a very very important aspect and we will use this property to consider an accelerator particle accelerator called a cyclotron a little later

so in the presence of a uniform magnetic field a charged particle here as we have seen if the velocity of the particle is perpendicular to the direction of the magnetic field but forms a circular orbit on a plane and that plane is perpendicular to the magnetic field now the if you have both a magnetic field and an electric field as we have seen last time suppose i have a plate here which is positively charged and i have another plate here which is negatively

charged here

so it's like a parallel plate capacitor and i have an electric field pointing downward here and suppose i have a magnetic field pointing inwards and if i project a particle here then as you can see here if the charge particle is positive then the electrostatic force on this particle is downward which is equal to q times e and if the charge particle is positive then the velocity is in this direction magnetic field is downward v cross b is upward

so the magnetic force is upward

so this is q b times b

so magnetic field is uniform and pointing inwards into the page and the particle comes from here

so the net force acting on the particle is q e minus q v b or q v b minus q e and it is it is perpendicular to the direction of this now if the magnetic force is larger than the electric force if q v b is greater than q e the particle will tend to occur upwards if q e is bigger than q v b the particle will down tend to curve downwards but if q e is equal to q v b then the net force acting on the particle becomes zero and then the particle will go undeflected straight and that means the particle if the particle has a velocity v is equal to e by v then the particle will go undeflected along a straight line

so only those particles which have a velocity equal to e by b is electric field which is applied between the parallel plates and b is a uniform magnetic field perpendicular to the electric field and perpendicular to the motion of the particle then those particles will go straight and if i happen to for example put a slit here then those particles whose velocity is up higher will be tending to go upwards those particles which are velocity lower will go downward and only those particles which are velocity v equal to e by b will go straight through the slit and

so what will happen is the particles coming out from here the charge particles coming from out from here will have a velocity defined by v is equal to e by b

so it's like a velocity selector you may have particles entering this region in this direction with different velocities but only those particles with the velocity equal to e by b will be able to cross through the slit and i will be able to select from these given set of particles those particles which have a different velocity is equal to e by b

so that's like acting like a velocity selector now the motion of this particles in electric and magnetic fields was used by j j thompson joseph john thompson 1856 to 1940 also referred to as j j thompson who discovered the first subatomic particle namely the electron he did experiments on cathode rays and showed that there are particles which are propagating in the cathode rays consist of particles which are which have much less mass than the known particles at that time and and he discovered the electron for the first time and for this discovery he was awarded the nobel prize in 1906.

so what is this experiment i see his experiment

so there is a discharge tube

so let me draw a discharge view here and then you have

so this is a tube which has low pressure gas there is a metal electrode here called cathode and then you have an anode here and between these two we apply a potential difference then you have another aperture here and here i have a pair of plates in which i apply a positive voltage here and a negative voltage here and there is also a magnetic field into the plane of the paper here now what happens is this cathode emits when the cathode is heated it emits particles which are which we now know are electrons these electrons then get accelerated in the electric field existing between the cathode and anode and the after the

anode through the hole in the anode the electrons pass through the hole and then pass through this aperture here and enter a region in which there is crossed electric and magnetic fields

so the electrons are entering from here with a certain velocity now if i do not apply any electric or magnetic field then the particles will go straight and hit this point and this point there is phosphorescence in this point and you see a green spot of light generated by the electrons which are striking the end of the tube if you apply an electric field then because the electrons are negatively charged the the electrons will move like this and go here and hit some other point here

so in the presence of electric field only you will see that the particles are bending and hitting another point on the exit end of the tube now if i apply a magnetic field you see the electrons are moving in this direction

so because this is positively charged here the plate

so the electron electrostatic force is upward $v \times b$ is downward but because the electron has a negative charge the magnetic force is downward please note the magnetic force is $q v \times b$ v is in this direction b is downward

so $v \times b$ is upward because charge is negative $q v \times b$ is in the minus direction here in the downward direction the electrostatic force is upward

so if i have a velocity equal to e by b then the particle will go straight and hit the same place as at the at the same place where there was no electrical magnetic fields

so what i can do is the following that for example first let me consider the situation when i had only the electrostatic force

so let me draw a figure here

so i have positively charged plate here negatively charged plate here and the electron this is the axis here the electron comes from here and go like this and go straight

so in this length overall length l of this electrode the electron has a net electrostatic force in the upper direction which is ah

so the force on the electron is equal to ah

so let me in the upward direction

so let me just write the scalar is equal to $\text{mod } e$ times e in the upper direction now this force will tend to shift the electron trajectory in the upper direction

so this is similar to a motion of a particle in a in a gravitational field

so the net acceleration in the upward direction is equal to $\text{mod } e$ e by m force by mass that is the acceleration in the upward direction

so remember the particle had zero velocity in upward direction here and it moves like this

so let me call this displacement as b

so what is the displacement

so this is the part this is the a particle moving in a the acceleration is upward direction the initial velocity in the upper direction is zero

so you can calculate the ah the displacement

so if the velocity of the particle is v in this direction time taken to propagate a length l is equal to l by v that is the time taken for the particle in going from here to here within this time the particle has a force applied in the upper direction

so it will accelerate in the upper direction with the net result that the displacement d can be calculated as d is equal to half of acceleration into t square remember the formula s is equal to $u t$ plus half $a t$ square the initial velocity in the upper direction is zero the acceleration is $\text{mod } e$ e a e e by m and the time taken is given by l by v

so i can substitute all this here

so i get half of the acceleration is $\frac{eE}{m}$ into t^2 is $\frac{l^2}{v^2}$

so i can relate this equation as $\frac{eE}{m}$ is equal to $\frac{2dv^2}{l^2}$ of the particle is equal to $\frac{2dv^2}{e l^2}$ and if i had chosen

so i can now calculate the velocity of the particle by finding out what is the magnetic field required to bring the particle back at this point

so i have an electric field here in the absence of magnetic field the particle trajectory is upwards it displaces by displacement d here then i apply a magnetic field and bring the point back here

so i know the magnetic field is required to bring the point back at this point and that magnetic field must be related to velocity and electric field through this equation v is equal to $\frac{e}{b}$

so i can substitute this v into this equation and i get $\frac{eE}{m}$ is equal to $\frac{2d}{e l^2} \times \frac{e^2}{b^2}$ which is equal to $\frac{2d}{l^2} \times \frac{e}{b^2}$

so note here that by knowing this quantity is on the right hand side the displacement d of the particle the applied electric field the applied magnetic field and the length over which the particles are propagating we can calculate $\frac{e}{m}$ and this is what Thomson did he could actually obtain the values of $\frac{e}{m}$ of these particles which were at that time not known the particles coming out from the cathode are accelerated down and by doing this experiment he could find out what is the value of $\frac{e}{m}$ of these particles and he found out that $\frac{e}{m}$ has a certain value now what he also discovered is that this value of $\frac{e}{m}$ is independent of the kind of electrode that we was using independent of the type of gas that is contained within the tube independent of the pressure of the gas independent of the velocity of the particle etcetera and he obtained the same value of $\frac{e}{m}$ for all these particles and from which he concluded that this must be another particle a particle which is there which is a component of all atoms and that is the electron that is the electron and he obtained the value of $\frac{e}{m}$ which happens to be now given by $\frac{e}{m}$ approximately 1.759×10^{11} coulomb per kilogram he found that the mass of this

the charged mass ratio is very very large compared to the charged mass ratio of a of a ionized hydrogen atom for example and he concluded that this must be particle subatomic particles which are extremely light and that is the electron

so that was the first time a subatomic particle was discovered by Thomson and for which he was awarded the nobel prize in 1906.

so that's a very very important discovery at that time to show that electron is a constituent of all atoms and forms a very fundamental particle now continuing with this experiment he and his students developed another instrument called the mass spectrometer

so let me draw the schematic of the experiment of the apparatus here so i have a slit here and i have ions coming from here these are positive ions let me assume the charge is q and mass is m

so these are positive ions these are ionized by some mechanism and these positive ions are coming through the slit here and i have in this region again just like before an electric field this is positively charged here let me assume and this is negatively charged and i have a magnetic field pointing towards me uniform magnetic field pointing towards me and i am another slit here

so as we discussed just now only those ions

so there are ions these are possibly charged ions which are coming down

so the electrostatic force on them will be to the right because they are

possibly charged they are attracted to the negative plates of the of the capacitor here and because they are going downwards and the magnetic field is coming towards me and they are positively charged $q v \times b$ is to the left so magnetic force is to the left electric force is to the right and if i satisfy the equation v is equal to e by b only those particles which which have this velocity will be able to go through the slit and come out from the other side of the slit these particles are coming out from here any particle whose velocity is different from this number will either be deflected less to the left or to the right and will not be able to pass through the slit so this is as i said a velocity selector it picks up those particles which have a very different velocity equal to e by b so these particles are coming out from the lower slit and i have a region here in which there is an again a magnetic field so let me draw a region here this region has a magnetic field magnetic field again pointing upwards towards me let me assume a uniform magnetic field throughout here so this magnetic field could be the same as the earlier magnetic field or could be different so let me just assume that there is some magnetic field here p prime the people are magnetic field pointing upward source v now in this region there is only a magnetic field and there is no electric field so as we have discussed before this particles will now have a circular trajectory so as you can see here so v is downward p is upward the char particles are charged positively so $v \times b$ is to the left and these particles will now have a circular path like this that's a semi-circular path here from here it comes like this and comes here and so let me call this distance as x and x must be equal to two times the radius of the circular orbit of the particle and we have already seen the radius is $m v$ by q times b prime here p prime is a magnetic field and so i get x is equal to two $m v$ by $q b$ prime so the position at which the particles will come and hit on this on this plane here is determined by two $m v$ by $q b$ prime x is the distance from this slit here so that distance depends on the charge present in the ion the mass of the ion and the velocity and b prime now velocity is already known to be e by b so i get the displacement x is equal to two $m e$ by $q b p$ prime so knowing the values of for example if i if i measure x in this experiment if i can measure x if i if i know the value of x then i can find out ah so usually these ions are having a charge plus e that means from these atoms one electron has been removed resulting in a an ion which has one point six times minus 19 coulombs of positive charge it's a it has one electron left it was neutral you remove one electron and it has positive remaining positive charge of plus e so this q is q is equal to mod e and so i get m is equal to mod $e b b$ prime x by two times e so as you can see here if i can measure all these quantities if i know that it is a singly charged ion if i know the magnetic fields $b b$ prime and electric field e which i have applied here and the displacement x i can measure the mass of the particle so if you now have ions here entering with different masses for example another ion with a slightly different mass will have a different radius of curvature and come and hit here so if your if the mass is less x is less and l lower lower mass ion will come

and hit here a higher mass ion will go here even a higher mass ion will go with a larger radial curvature now

so actually what you are finding is on the screen now on this on on a screen here you will see particles hitting at different points depending on their masses if all of them have the same charge q particles having different masses will come and hit diff at different points here and by knowing the position of these particles which are appearing here i can actually estimate their masses

so if you have ion source here in which there are ions with multiple masses coming then this particular structure will separate these masses into different points on the screen and you can actually find out what are the types of masses present here and

so on and

so forth in fact this is the mass spectrometer which tells you what are the mass components present in the ion source that you are having and incidentally this is the first experiment that led to the discovery of isotopes the isotopes you know are the same atoms with different number of neutrons the same number of protons and electrons

so you can have for example hydrogen tritium deuterium they are all isotopes similarly you have isotopes of other elements and j.

j thomson along with a student francis aston did experiments using this kind of a setup and discovered the first isotope of neutron new neuron sorry neuron and

so because they obtained for the same neon they obtained two spots of two points where the ions were coming and hitting and that implied that there were two kinds of ions and they found their masses are slightly different and that led to the discovery of the isotopes itself

so looking at motion of particles in charge in electric and magnetic fields gives us very interesting techniques to to understand their behavior and also to analyze ions and measure their charge to mass ratios or muscles if you know the charges and

so on and

so forth

so now all this time we have been looking at a situation where the velocity of the particle is perpendicular to magnetic field now what happens if the velocity is not perpendicular magnetic field but is at an angle

so i will now discuss what we what results is a helical path

so i want to consider a situation

so suppose i had a magnetic field coming pointing towards me and if i had a charge particle which is going up here if this is a possible charge particle you see that this will just have a circular motion like this q a possibly charge particle it will have a circular motion and the radius is determined by r is equal to $m v$ by q times b that is if the velocity of the particle is perpendicular to the magnetic field now what happens if the velocity is not perpendicular but is at some angle

so let me draw a magnetic field here like this let me call this a z axis and ah let this be the x axis here let me assume i launch a particle with a velocity like this and this angle is fine as you can see here the velocity is not at right angles to the magnetic field but i'm i'm shooting an arc a particle with a charge q let me assume a positive charge positive charge q at an angle θ will be perpendicular to the v vector

so i can write here v vector is equal to b times k cap v vector has now two components x component which is $v \cos \phi$ and a z component which is $v \sin \phi$ velocity of the particle has two components one perpendicular to magnetic field which is $v \cos \phi$ one which is parallel to the magnetic field which is $v \sin \phi$

so what is the magnetic force on the particle $q \mathbf{v} \times \mathbf{b}$ which is equal to $q b \cos \phi \mathbf{i} \cap + b \sin \phi \mathbf{k} \cap \times \mathbf{b} \mathbf{k} \cap$ now $\mathbf{k} \cap \times \mathbf{k} \cap$ is zero $\mathbf{i} \cap \times \mathbf{k} \cap$ is minus $\mathbf{j} \cap$

so this is equal to minus $q v b \cos \phi \mathbf{j} \cap$

so the magnetic force on the particle is minus $q v b \cos \phi \mathbf{j} \cap$ it is a minus y direction

so y direction is pointing upwards here

so the minus y direction is pointing downward here

so if i use the right handed coordinate system x is like this y must be towards me

so that z axis is like this

so the magnitude the force on this particle is downward and remember here the force only depends on $v \cos \phi$ and what is $v \cos \phi$ $v \cos \phi$ is a component of the velocity perpendicular to the magnetic field

so this force will now make the particle go in a circular orbit circular path but remember the particle also has a velocity along the magnetic field direction

so what is going to happen is the particle will be made to rotate in a circle because of the magnetic field and the perpendicular component $v \cos \phi$ it will be projected in the directional magnetic field because of this component $v \sin \phi$ and

so it will form what is called as a helix

so it will look something like this

so the particle will move something like this is magnetic field

so this circular path is because of the component of velocity perpendicular magnetic field the motion along the magnetic field is because of the parallel component magnetic field

so we have for example $p \cos \phi$ is v perpendicular and $v \sin \phi$ is equal to v parallel this is the perpendicular component perpendicular to magnetic field component of velocity the component velocity parallel to the magnetic field

so the radius of the of this circular path is equal to $m v$ perpendicular by q times b that is the radius of this path now the particle completes one revolution in a time t given by 2π by angular velocity which is $2\pi r$ by v perpendicular which is equal to $2\pi m$ by q times b it is this is inverse of the cyclotron frequency the time taken by the particle in completing one circular path is t is equal to $2\pi m$ by $q b$ and in this time the particle would have moved a certain distance here and

so ah distance moved along z direction in time t is equal to b parallel into t which is equal to $2\pi m v$ parallel by q times p this is called the pitch of the ellipse of the helix pitch of the helix

so i have a demonstration here which will show you what is the meaning of particle motion in a helix

so i have actually i brought a a coil here and i have a small ah nut in that which is as you can see which is moving downward that is the motion of the particle along the helix as you can see here the particle is rotating along a circular path but is also moving horizontally vertically in this case here this motion is of course not due to electric and magnetic fields but it is primarily because of the gravitational force here and i am restricting the particle to move along the helix by simply having a spring here

so that is a good way to imagine the motion of a particle in helix as you can see here that dark nut which is moving here is something like what the electron will be doing as it moves

so that's the helical part of the particle here

so particle moves like this in a helix and that is the motion of a of a charged particle when the velocity of the particle is not perpendicular to the magnetic

field but has a component also parallel to the magnetic field

so the perpendicular component of the magnetic field decides the radius and the time taken to complete the one circle the parallel component decides how fast it moves in the velocity direction of v let me take an example here let me take a particle with velocity of about 10^6 meters per second a charge which is the electron which is one electronic charge and let me assume an angle of ϕ is equal to 45 degrees a magnetic field of 5×10^{-5} tesla and the mass of the particle is 9.1×10^{-31} kilogram

so the pitch is equal to $2\pi m v \cos \phi / q B$ is equal to $2\pi \times 9.1 \times 10^{-31} \times 10^6 \times \frac{1}{\sqrt{2}} / (1.6 \times 10^{-19} \times 5 \times 10^{-5})$ and that comes out to be about 5.1 centimeter

so that the pitch that is the distance Δh moved along the directional magnetic field in one circular revolution and

so that is a typical example where you can see here the particle will do like this and go upwards along the direction of the magnetic field Δh the helix will be oriented along the directional magnetic field

so that's the trajectory of a particle in a when the particle is not having a velocity perpendicular to the magnetic field but has also a component parallel with magnetic field the perpendicular component makes it rotate in a circular orbit here and the parallel component makes it move in the hop the directional magnetic field

so it goes like this and that's the helix

so we have seen some examples of Δh practical trajectories in the presence of magnetic fields in the presence of cross electric and magnetic fields in the presence of a magnetic field and the velocity not being perpendicular to the magnetic field but in some other orientation now

so as you can see here the in the the electro electric field can actually actually the has a force which is along the direction of velocity of the of the most of the particle and

so it can accelerate the particle the magnetic field has a force which is perpendicular velocity component and cannot speed the particle up now there are what are called as particle accelerators which i would like to discuss particle accelerators have been investigated for the past more than 80 years there are many many accelerators in various countries and these accelerators are used to accelerate particle charge particles for various applications these have applications in semiconductor industry they have applications in medical diagnostics they have applications in cancer therapy their application is pharmaceutical research and

so on

so there are very many applications of particle accelerators and the most famous accelerator is the accelerator in sun where the discovery of the higgs boson was made this is an acronym for constant european poor law fisher nuclear it's in english it's a european council for nuclear research

so in this this is an accelerator which is Δh in the in geneva Δh in the border between france and switzerland and it is an isolator which is used to accelerate protons and it is interesting to know that the particles are accelerated protons are accelerated to to a velocity to a speed which is 0.9999990 times the velocity of light in free space 0.999999990 times velocity of light and free space and that is only 3.1 meters per second slower than speed of light in free space extremely high acceleration actually extremely high energy these particles are having extremely

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high energies their velocities are very close to the velocity of light and free space there are many accelerators in india and i would just like to mention to you main main accelerators here there is iuac which is inter university accelerator center in delhi there is becc variable energy cyclotron in kolkata then this is an accelerator in rrcat raja ramana center for advanced technology there is an activator in tifr barc it is tata institute of fundamental research and bhabha atomic research center this is in mumbai and this is the indoor these are some of the major accelerator facilities in india and many of these accelerators are extremely efficient and highly functional and are used by various researchers in the country for various applications i want to show you the construction of a cyclotron

so let me draw it here there is a cylindrical structure like this this is let me draw the complete figure here

so this is and there is another one like this and then there is a magnetic pole piece here there is another magnetic pole piece on the bottom

so these are electromagnets is also electromagnet then you have a source of particles here and the particles as we will explain go in a part like the helical part like this and come out and these two are called these they are the shape of a d but there are actually its a made of copper and in the hollow space between the two upper and bottom copper plates the particles are revolving around and these two magnets create a magnetic field perpendicular to the path of the particles and there is a these two are connected to a an alternating current source

so the electromagnet produces a magnetic field perpendicular to this these the electric field is applied between the two ds here and as we will explain the particle then can be accelerated in this path and comes out of the of this device in this target and these are the charged particles this charged particle path of the yeah

so we now discuss about the how does the cyclotron work remember we had defined a cyclotron frequency before

so this is a an accelerator which is called the cyclotron and let me just draw you the construction of the cyclotron

so there are there are there are two what are called as these which are made of copper

so they are they are thin cylindrical thin structures and they have a there is a magnetic field applied perpendicular to this plates

so these are these are two thin sheets here between copper copper sheets here and the space in between them and the particle is actually moving within the plate and these two plates are connected to an oscillator which actually applies an electric field between these two ds and weighing time varying electric field a sinusoidally time varying electric field between the two plates

so the potential is positive negative the negative positive positive negative sine is slightly oscillating just like our alternative current that we get in our power power supply

so here is an oscillator which applies an electric field between these two d's there is a magnetic field perpendicular to the to the d's here here i have drawn coming out of the page

so let me assume that there is a source of protons here at the center

so let me start by seeing what happens initially let me assume that this is negatively charged on the left side

so proton being possible charge gets accelerated towards this d now it enters this d within within the two copper plates and because they are made of copper there is no electric field within the volume of within the space between the two copper plates

so there is no electric field penetrating this and
 so this region of the d actually contains only magnetic field inside
 so being a positively charged particle and a magnetic field pointing up there
 is a magnet of magnetic force applied on this particle which makes it rotate
 along the circle and comes from here its a circular orbit of a certain radius
 which you have calculated before once it comes here at this point what happens
 is i ensure that this now becomes negatively charged this has a negative
 potential compared to this
 so this proton gets accelerated towards this when it enters this d this d again
 does not allow any electric field to be present inside now the velocity is
 slightly higher than before
 so it makes a circular orbit like this
 so larger radius of curvature by the time it arrives here i ensure that this
 plate is this side is negatively charged
 so the proton gets again accelerated and then now the velocity is higher
 so its radius curvature is larger by the time it comes here this is negatively
 charged it accelerates
 so what the particle will do if i if i write conditions it rotate like this and
 finally i can take it out of the of the system at some point
 so what we are seeing is i am using the electric field to accelerate the
 particle when it appears between the space between the two d s i am using the
 magnetic field to make it circle along this circular path magnetic field does
 not speed up the particle but allows the particle to take a circular orbit can
 come back to the space between the two d s the electric field between the two d s
 ensures that the particle gets accelerated every time it comes to the space now
 this we have seen before that the radius of the orbit is $m p$ by q times b and
 that radius depends on the charge mass and the velocity and the magnetic field
 between them and we also have a frequency cyclotron frequency which we have
 defined before is $q p$ by two π what is the frequency the free this frequency
 the time taken for one complete number of revolutions per unit time or one by f
 will be the time taken for completing one revolution and as you can see here
 this frequency is independent of the radius of the orbit
 so the particle will take the same time to come from here to here to the
 semicircle as you will take from for the semicircle as it will take for the
 semicircle all that is happening between the semicircles is the energy is
 increasing velocity is increasing as velocity increases the radius increases but
 because the frequency is independent of radius every the time taken for this
 particle to come from here to here is the same at the time taken for the
 particle to come from here to here
 so now i must make sure that whenever the particle appears here between them
 the electrodes have the right potential difference
 so that the particle gets accelerated rather than getting decelerated
 so if it part if when the particle arrives here when it is coming out from this
 first circle this part this part of the d must be negatively charged negative
 potential
 so that it gets accelerated now it comes here and when it arrives here this
 this must be negative potential
 so it gets again accelerated and every time it appears in the spacing between
 them the potential must be such that the particle gets accelerated and because
 the radius the the time taken for making this half a circular path here is
 independent of the radius of the curvature radius of the particle motion here
 this frequency is independent of the radius whether you are looking at this
 particular path or this path now only under one condition that is none of these
 quantities on the right hand side change with the energy now we all know that

mass is independent of velocity only at velocity is much less than velocity of light in free space

so as the particle gets accelerated more and more energy increases velocity increases and the mass will start to increase

so until you reach relativistic velocities mass can be assumed to be independent of velocity and in that case the cyclotron frequency is independent of the radius and

so i will need a particular i would need this oscillator to oscillate at this frequency

so that whenever the particle comes here the the particle gets accelerated rather than decelerated

so that is the frequency at which i must operate

so this is the way the cyclotron works a proton which is injected from here first gets accelerated by the this plate being negatively charged it enters this region where there is a magnetic field pointing upwards that leads to a circular path of the proton by the time it arrives here this is this is negatively charged

so the particle gets accelerated again here and then because now its velocity has increased it makes a larger circular orbit v is higher

so radius is larger it comes from here it takes the same time to propagate through this radius here and then by the time it arrives here this d is negatively charged it gets accelerated again velocity increases

so the radius has increased

so this it becomes a path like this and at some point i can take the the particle out by deflector here

so that is the operation of the cyclotron and it is used to accelerate particles and

so let me take a

so the key to operation of this is the fact that this cyclotron frequency is independent of the radius of the orbit

so this ah particle accelerator can be used for accelerating particles to high velocities except that you cannot go to relativistic velocities with these particles

so the oscillator frequency must be equal to f which is equal to $q b$ by two πm and the maximum energy assuming velocity of the particle will be much less than c is equal to half $m v$ maximum square which is equal to half $m q$ square b square r square by m square which is equal to q square b square r square by two m where r is the radius of the d of the cyclotron radius

so the maximum radius that the particle can have is this value of the radius of the d and it comes out of the d with this energy which is q square b square r square by $2 m$ we can look at one example here

so if you take protons q is equal to 1.6×10^{-19} coulomb

so let me take a radius of 0.2 meters

the mass of the proton is 1.67×10^{-27} kilogram

the i leave this calculation to you the

oscillation frequency is 21.4 megahertz

you can calculate the maximum velocity comes out to be 0.27×10^8 meters per second

it is still 1×10^{-8} the velocity of light the maximum energy is equal to 3.75 million electron volts which is 3.75 megaelectron volts

and you can calculate the mass of the particle at this velocity is one point

this is a slight increase in mass because of the velocity being closer to the velocity of light but that increase in mass is very very small compared to the

original mass

so what we have discussed today is motion of charged particles in electric and magnetic fields how the mag the charge particles revolve around the circle if they are moving perpendicular magnetic field and then we looked at helical path and we found that how this uh motion of charged particles and electric magnetic fields can be used to calc where it was used to discover the existence of electrons ah usage the mass spectrometer and how we can accelerate particles using this concepts

so cyclotron is one example you have discussed there are many other kinds of accelerators which you will learn later on in other courses thank you you