Nuclear and Particle Physics
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Module – 06
Particle Accelerators
Lecture – 01
Electrostatic Cyclotron

So, today we will discuss the particle accelerator.

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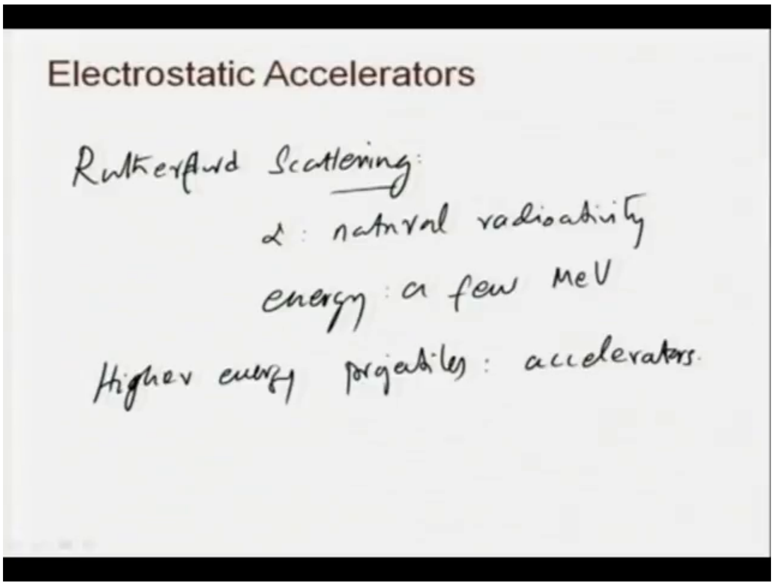

We will start the discussion and then we may continue it to the in next lecture all right. So, first let us see why do we needs particle accelerators if you remember the Rutherford scattering basically we had alpha particles bombarded on a targets like gold and silver or a gold, aluminum, etcetera. So, these alpha particles were obtained naturally from radioactive sources.

So, the limitation the energy available for this alpha particles are limited depending on what the source or the parent that decaying into what daughter the alpha particle energy is fixed and then we can actually expect some kind of order of anomie V energies for this kind of natural radioactive alpha particles.

So, energy of these alpha particles are typically a few mega electron volts. Now as we saw in the case of Rutherford scattering experiment, such alpha particles will not really penetrate the nucleus, but we will actually scatter off the nucleus it gives good information about the atomic structure, but it will not be able to probe the nucleus the interior of the nucleus because the energy of the alpha particle is not enough to penetrate the nucleus and then go inside and then understand the dynamics there inside the nucleus. So, to get higher energy particles let us say not only alpha particle, but any other projectiles, we need to artificially or we have to accelerate them by using some mechanism, we need something like accelerators. So, these accelerators and some particular mechanism using which we can accelerate these particles.

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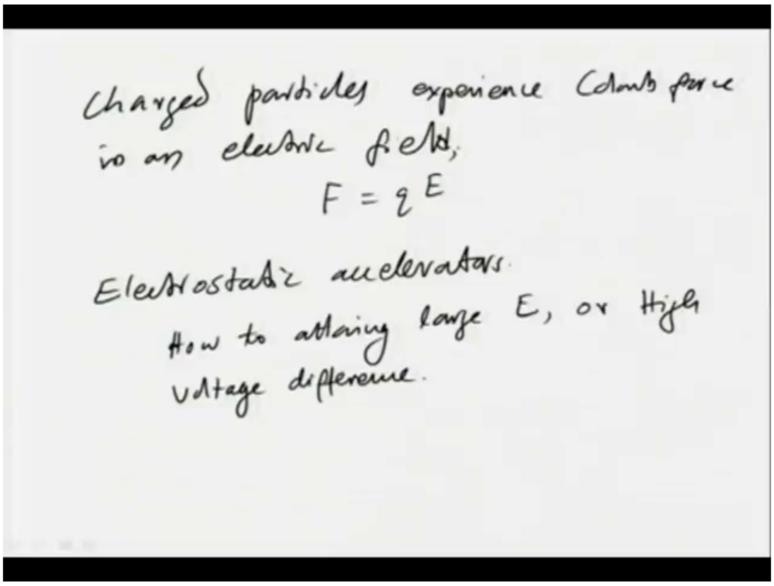

So, most of the time our projectiles are charged particles, let us focus first on charged particles we could also do nuclear experiments with the neutrons which are electrically neutral particles, but we will not talk about accelerators of neutron etcetera, but we will be able to actually talk about accelerators of charged particles. So, charged particle experienced coulomb force in an electric fields and the electric fields if electric field is e the force is q times the charge of the particle times the electric field.

So, q here is the charge of the particle is the electric field and if you place a charge particularly in an electric field. It will experience a force magnitude the amount of the force will be q times e and this force will accelerate this particle and the direction of acceleration is also fixed to be in the direction of the electric field if it is positively charged and if it is negatively charged it will be in the negative direction.

Only question is how much of the wall if a electric field, it can be actually attained in practice and how do we and correspondingly how much of charge energy can be given to this accelerated particles or to what energies can we actually accelerate these particles whether we can take the energy of this projectiles to the 2 ions, which are charged particles to 100s of MeVs or beyond that and what kind of an electric field is needed for that and whether we can achieve this or what kind of another arrangement can actually lead to such high voltages or high electric fields it is the kind of question. So, that one has to ask. So, these kinds of accelerators are based on coulomb force or electrostatic force. So, we call them electrostatic accelerators. So, electrostatic accelerators are based on columbic force experienced by charged particle. So, one such how to as I said how to attain large e or consequently high voltage difference.

Between 2 terminals I mean. So, this is the question that one has to ask. So, one such arrangement is due to cockrofts.

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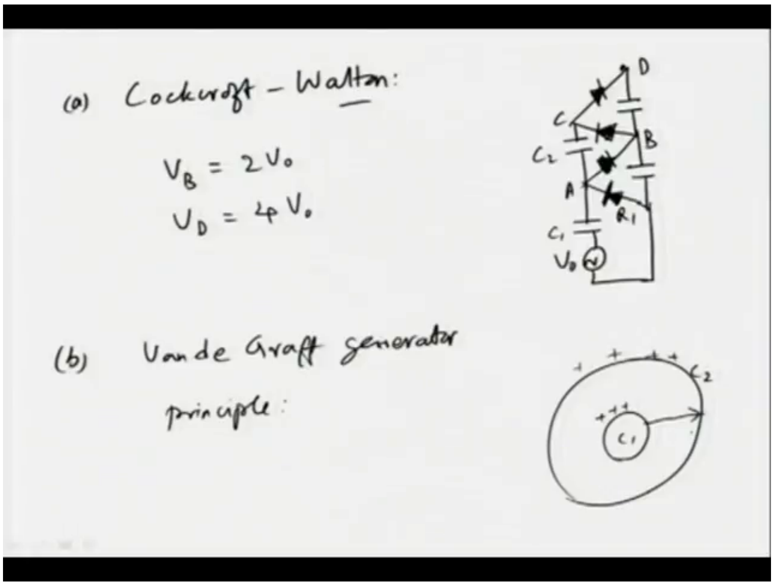

And Walton; what did they do? they used low and low voltage source of alternating current or low voltage low alternating voltage see some low voltage V 0 which is the peak voltage say and made some a range if you look at an arrangement like arrangement of rectifiers and capacitors like this say a capacitor here and then connected through rectifier like this and this one in turn is connected to another axle I mean capacitor through another rectifier and again you can have another capacitor and a rectifier and you can continue in this like this. So, this type of an arrangement will lead to voltage multiplication

So, what happens is let us say this point I call A, B, C, D. So, if you look at this arrangement and then if you know your electronics and how the current flows through a circuit like this alternating with an alternating voltage source or current source then you will see that if V 0 is the peak voltage there when the capacitor C 1 is fully charged point A will have a peak voltage of 2 V 0 because the other rectifier R 1 will actually give a voltage V 0 there and because of the capacitor there will be a voltage alternating voltage V 0 there. So, it will be A, we will have a peak voltage of 2 V 0 and this will be directed to B as a dc voltage and B will experience a DC voltage of 2 V 0.

So, V B is equal to 2 V 0 and this continues this is directly transferred to 2 in a C k 2 V 0 and the other capacitor C 1 and C 2. C 2 will actually give an external oscillating potential voltage of 2 V 0 there. So, peak will there be four V 0 and this is directed to point D to the rectifier connecting C and D and V D will have dc voltage of four V 0 and then if you continue this arrangement you can get multiples of this V 0 higher multiples of this V 0 at other points.

So, this way one can think about getting a large voltage from A so small voltage. So, this is the arrangement that was primarily used by Coccraft and Watton and in their experiments and then a lot of modifications to this; this is one such arrangement then you can have select modified versions of this improved versions of this and usually the voltage that you will achieve is something like one thousand kilo volt etcetera with this kind of arrangement or of that order and the simplicity of this is the issue here I mean it is very simple. So, even now we can think of using it for small voltage I mean small accelerators or where you need not. So, high acceleration, but at the primary level of different accelerators also this can be thought of as using ok.

Then another kind of accelerator is called Vande Graff accelerator or a generator. So, Vande Graff generator which generates high voltage; so, the principle here is simple if you have a conductor C 1 and another hollow sphere conducting hollow sphere C two. So, there are 2; there is an inner conductor conducting spheres C 1 and then outer conducting shell C 2 ok.

So, now if you have some charge on C 1 say some positive charges here and if you connect these 2 electrically then properties of electrostatics that we know tells us that all the charge on a conductor now is will reside on the outer surface of this conductor this is because there cannot be any electric field inside the electric the conductor.

So, if there is a electric field inside the conductor because the conductor has free electrons in it a free charge in it. It will actually make it flow from one point to the other and attain some kind of an equilibrium where the surface of the electric the conductor is an equipotential and it should be you. If you look at it properly you will see that the inner surface of a hollow conductor we do not have any charge or in this arrangement when they are connected C 1 and C 2 are connected they are become part of a single unit and C 1 can be thought of as an inner part of the whole arrangement and therefore, there would not be any charge on it and all this charge will actually flow to the outer surface of this arrangement which is the C 2.

So, the charge will flow and it does not matter if there are already a already some charge on that and then what is a already some charges residing on C 2 it does not matter all the charge from C 1 will flow to C 2 this is a property of conductor now you think of a an arrangement.

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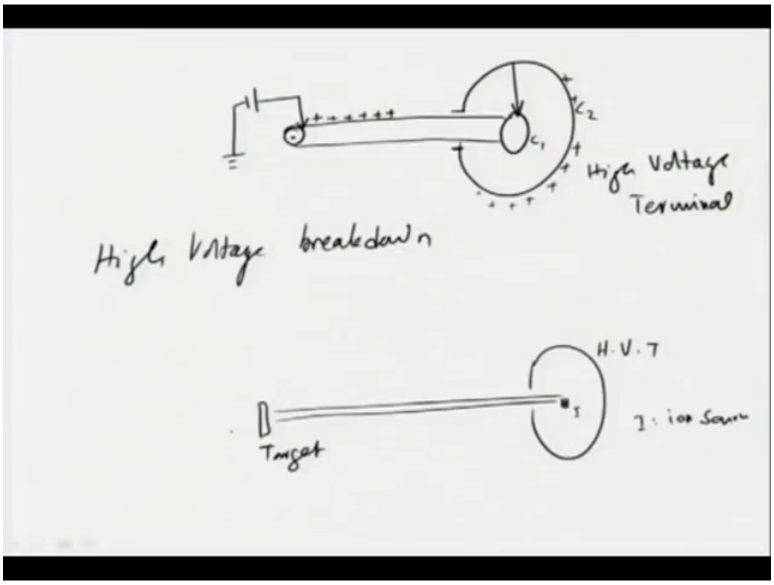

By which you will actually have kind of a big conducting dom; we will not cross it fully, but kind of a almost full spiracle shell, but with an opening and in a sphere conducting sphere same arrangement C 1 and C 2 say that sphere.

So, suppose I mean if we connect these 2 right if we connect C 1 and C 2 electrically then if C 1 is somehow charged suppose we can charge the C 1 though all those charge will go to C 2. So, only question is to charge this C 1 for that people thought about some arrangement like this they connected C 1 with the some insulating belt and this insulating belt is connected to some other drum and it can be now continuously you rotate let us say right the belt can move continuously by rotating this using a motor and if we can pump in charge here and if we can actually charge this belt.

The belt is made of insulating material the charge will be fixed on that it will continue carry this charge to C 1 and when it reaches C 1 since C 1 is a conductor it will take the charge it will then transfer this charge to C 2 through the connector only question is to charge this one and then there can be some kind of a arrangement to charge this belt by applying some voltage difference between these 2 and then ionizing the air or gas at that point near the belt and the charge the positive charge is repetitive from this thing because of the battery there in the voltage is. So, that it repel this positive charge it is one particular way of thinking about it and then that positive charge can be deposited onto the belt and since the belt is continuously moving it will carry this charge to C 1.

When C 1 is connected to C 2 and then C 2 will get this charge. So, C 2 will be continuously charged like that and then there will be lot of charges here and with respect to ground and therefore, this will have a very high voltage. So, now, one of the problems that you can think about is the breakdown if you keep this arrangement in air high voltage breakdown or sparks will be there.

So, you can ask the question what is the voltage that I can achieve if I keep this in air and you can take this voltage even to higher energy the higher voltages by actually keeping the whole C 2 arrangement in a C 1 and C 2 arrangement in a container which has insulating gas not air; air also breaks down at some high voltage and if you have some other gas insulating gas which will not break down at higher voltages compared to that of air and then you can fill this container with such insulating gas and put this C 1 and C 2 arrangement this terminal let us say this is called this high voltage terminal.

So, high voltage terminal inside such pressurized in a nor I mean insulating gas and then we may be able to achieve even higher pressure. So, that is what is practically done and how do you use this to accelerate particles. So, what you have to do is to take this arrangement. So, now, let me know let me in draw the you know I mean schematics of this high voltage terminal here and if I have source ion source say let us say I want to accelerate some particular ion. So, I keep this ion source inside this high voltage terminal and generate this let us say it is a positive ion. So, if this positive ion it will be repelled by this high voltage and it will push it down through the tube accelerating tube and you can keep your target at t. So, target at the other end of the accelerating tube and these ions will hit the target with high energy.

This is one way of thinking about it now one drawback of this arrangement is that you are keeping the ion source inside the high voltage terminal then only it will push this voltage these ions down to the target. Now supposing you want to change the source change your experiment and then you want to actually use a different source or supposing something happens to the source and then you want to take that out. So, the access to the source is very much restricted in this kind of an arrangement because if you want to take it down you have to discharge the high voltage terminal which must have taken some time to charge it to high voltage firstly.

So, now, you had to discharge it completely then only and then again we said that usually we keep this in a high pressured in insulating gas. So, you have to actually pump the gas out and then open that time and then only you will be able to access the ion source then if you want to actually replace this by a different source or the same source and then you will have to again do the process redo that. So, this is actually not very a convenient arrangement. So, people thought about a different way of doing it. So, that takes us to tandem accelerator.

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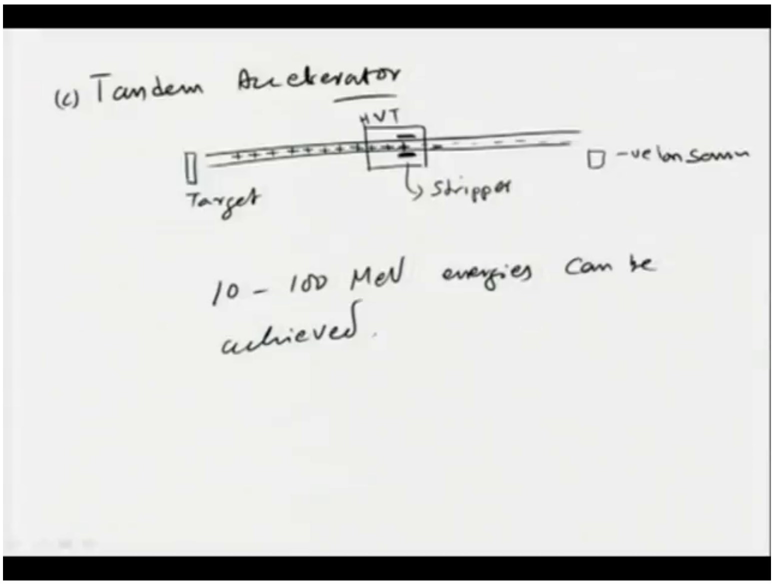

So, tandem accelerator principle is the same as the Vande Graff generator accelerator the only difference is that now you have the accelerating tube suppose you were interested in some kind of a particular positive ion; what you do is to actually generate the corresponding negative ion source ion basically I mean you can actually deposit electrons by some mechanism we will not discuss how it is done and to the items of interest and you can have the ions there indirectly negative ions.

So, now, if the tube is; so, that you have the high terminal high voltage terminal somewhere in the middle of this tube the 2 passes through this high voltage terminal. So, then this high voltage terminal now will attract these negative early charged ions. So, it will accelerate this right accelerate this and then you keep some electron stripper. So, this is the stripper. So, what does the stripper it is stripper let us say by some way strips the ion of the electrons.

So, it will take away their electrons let us say not only the excess electrons which makes the negative ion, but also some additional electrons. So, that it is now a positive ion. So, the stripper strips of some of the electrons and makes it a positive ion and then these positive ions are now in the high voltage terminal it will actually repel it. So, it will actually be a repel and then let us say it has already a speed with which it is coming in and it will continue moving in that, but because of the high voltage terminal it will actually be pushed out. So, it will be pushed out through its high again some force and therefore, it will change it will increase its energy increases and then target can be kept at the other end of the tube and then it can actually the high energy ions can now hit the target here and then we can perform our experiment.

So, this arrangement is called the tandem accelerator. So, here the ion source is outside the arrangement of high voltage terminal etcetera. So, it is easily accessible and then we can actually have a easy replacement etcetera let us say. So, one can achieve something of the order of 110 to 100 MeV energies can be achieved with this kind of this thing with this kind of arrangement this is another electrostatic accelerator.

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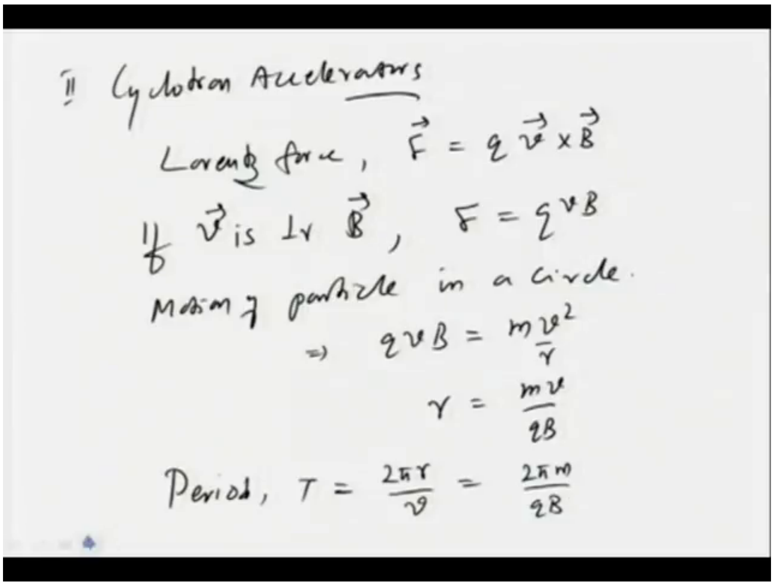

Now, moving away from electrostatic accelerators we can think about cyclotrons what are cyclotrons. So, these cyclotrons accelerators use not only the electrostatic force, but also make use of the Lorentz force experienced by moving charged particle inside a magnetic field. So, we know the Lorentz force on a moving charge particle moving with velocity V in a magnetic field B is q V cross B if V and B are perpendicular to each other then we can say the magnitude is simply V B times q; this will be acting perpendicular to both V and B.

So, let us look at the magnitude of this value since F is perpendicular to V it will not actually accelerate it. So, it will not increase [vocalized-noise], it will actually make it bend and move in a circle. So, the particle will be moving in a circle all right motion of particle in a circle and the centripetal acceleration is V square over r here and that should be equal to the force. So, that is equal that will give us q VB which is the force here and some force acting on that charged particle this should be equal to mass times the acceleration. So, it does not really increase the speeds, but it actually does something else it does not change the energy as such it, but changes the direction of the motion. So, it will actually move in a circular path.

So, qV B is equal to m V square by r. So, r the circular radius of the circular path is equal to m V over q B, it is a circular motion and what is the period of this circular motion it is 2 pi r is the distance that it will cover once it moves around in a complete circle that divided by V will give you the time taken for that or V times whatever is T capital T the period is equal to the distance 2 pi r.

That is what we call period. So, this if I put the expression for r in terms of m V and q B is equal to 2 pi m divided by q B V and V cancels and then T is equal to 2 pi m over let us keep this in mind how do we use this to accelerate particles all right. So, for this we will think about the following arrangement.

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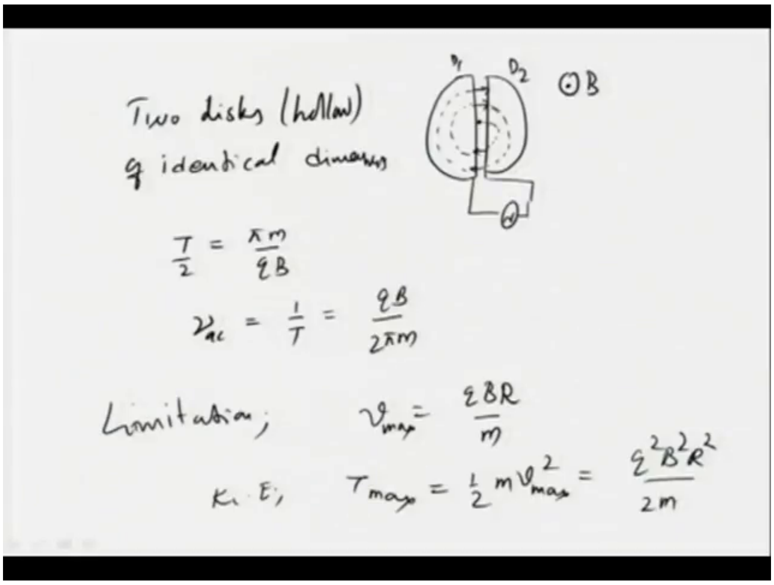

We will take 2 circular disks we will take some kind of a hollow disk and call it D one and D 2. So, let me draw that. So, this is actually a disk. So, one is D one the other is D 2. So, 2 identical 2 disks of identical dimensions say they are hollow disks of identical dimensions.

Placed with some little separation between them well disks meaning these are semi circular disks and now let us say that it is in a plane keep it on a horizontal plane for example, then apply magnetic field perpendicular to the plane of the disk. So, keep this D one and D 2 in a region with magnetic field b. So, that the plane of the disks is perpendicular to the direction of B or the direction of B is perpendicular to the plane of the disk.

Now, if you have an electric connection between this D one and D 2 suppose you connect this D one and D 2 through some voltage alternating ac voltage and then you will see that there will be electric field generated between in the gap between D one and D 2 this electric field will be oscillating the oscillation frequency will depend on them is equal to the oscillation frequency of the source or the source.

And now let us say we place a charged particle in the region we were in the gap in the region between the disks what will happen the electric field will apply a force on this and the charged particle let us say we take a charged particle with positive charge and when it is placed there in the gap the electric field direction is from D 1 to D 2 and then it will move in that direction when it moves in that direction it will enter D 2 with some speed of course, the magnetic field will also be acting on that, but in the gap.

So, the when the electric field is acting on it the magnetic field the force due to magnetic field is negligible you can check that out, but once inside D 2 there is no electric field because if the adhere D 2 is the electron and all of that say is. So, this is basically you will assume that it is a conducting is an electrode it is a conducting disk.

So, there is no feel inside their electric field inside that, but there is a magnetic field perpendicular to the speeds the velocity V. So, we will half the motion like moving the charge particle will move towards this inside that it will actually because of the force at first due to the magnetic field it will move in a circle and once it comes out of this after traversing a semi circular this thing it will come out of to the out of D 2 into the gap and let us say.

So, when it comes out it will experience force due to the electric field in the gap, but now this electric field the force due to this electric field depends on the direction and magnitude of the electric fields. So, if we arrange the oscillation of the electric field inside this gap. So, that the electric field switches the direction as the particle comes out from D 2 into the gap then it will continue moving it will be accelerated further and entered even with larger velocity. So, the velocity with which it the speed with which the particle enders D 2 is the same as the speed with which it come out of D 2, but once it comes out of D 2 there is electric field.

Now,. So, that it is it will accelerate it further and it will go in a larger move in a larger circle and as it comes out of D 2 with the same speed, it will again experience the electric field and we will actually switch the electric field at that time and then again it will switch the direction of the electric field and then it will again accelerate towards B 2 and as it endures D 2, it will have a higher speed and higher energy. So, it goes on like that. So, in this way we can get higher and higher accent speeds and over larger and larger energies.

So, let us see; what was the expression for our time period of this time taken, for charged particles to come out of one disk after entering this. So, the time between entering the disk and coming out of the disk is the time period; however, is half the time period of this one. So, the T by 2 is pi m over q B. So, T by 2 is the time taken by the particle to entee this and come out of this you see that this does not depend on the speed it is a constant is the same speed.

The same for any whatever the speed with which it enters it only depends on the charge of the particle which we are not changing the mass of the particle which again we are not changing it is the same particle and the applied magnetic field which we can keep constant. So, the time period or half time period which is needed for the particle to enter a disk and come out of the disk is the same and this is the time with way in which the electric field should be switched right.

So, the frequency of the oscillating field which is the same as the frequency of the ac supplied ac is voltage which is supplied should be. So, the frequency of ac is source should be equal to one over T for this electric field to be switched as it comes out of one disk and then again switched when it comes out of that disk then only this acceleration will work otherwise it will decelerate it or send it back to this one if the electric field is not synchronized like this. So, this should be equal to 2 q B over 2 pi m.

So, we can suddenly adjust our ac voltage frequency. So, that it is equal to q B over 2 pi m or for whatever particle that we are considering and whatever charge of the particle that we are considering and whatever B we are considering and this way we will be able to accelerate this and what is the what did we achieve compared to the earlier accelerators one thing that we have done is we have not I mean in the earlier case electro static case if we want to half higher and higher energy what we had to do is to put half larger and larger potential differences.

So, the main problem there is the high voltage terminal to achieve that high voltage terminal and keep it stable without breaking down even if you use insulating gas still there is a limit to which you can go by that and then again achieving that itself is not a simple job to a very high voltage difference on the other hand this arrangement that we just now discussed which is called the cyclotron accelerator the principle here is very simple we use make use of the magnetic field to make the particle pass through the same electric field same region of where the electric field.

and small or constant electric field again and again and again and again. So, as to achieve larger and larger acceleration larger and larger speed the acceleration remains the same q F is the same F is q times E, but since the initial if the speed is changing. So, we have larger and larger speed and the particle will come out with very high speed with even with small applied electric field the limited limitation of this kind of a cyclotron is the following you need to what is the maximum V that we can think about. So, V the speed we said is equal to q B r over m.

So, if capital R is the if capital R is the radius of the disk that is the maximum speed that we can have which is a q B r over m and the corresponding kinetic energy T max is half m V max square which is q square B square r square over 2 m this is the magnetic large. So, either you apply very large magnetic field which again is costly and or you have a very huge large disk.

Again there is a limitation that we can think about to achieve the same. So, the NDO region has to be magnetized that is again very costly. So, these are the limitations of this and now we have to think about ways to improve that, but this a cyclotron idea is certainly and a betterment or improvement of the simple electrostatic accelerators.

So, we will discuss some other improvements and ways to actually take it to higher energies with some different arrangements and discuss those in the next lecture.