Nuclear and Particle Physics
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Module – 06
Particle Accelerators
Lecture – 02
Synchrotron, Colliders, LHC

We had discussed the basic electrostatic accelerators and then further cyclotrons which uses the magnetic and electric fields to accelerate the charge particles.

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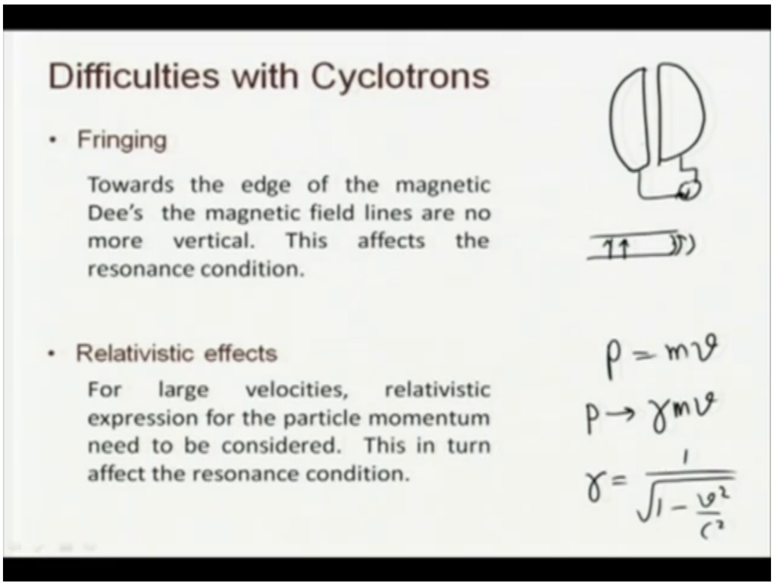

One of the difficulties with cyclotron is that there is a fringing effect towards when particle moves towards the edges of the Dee's that are used. suppose you remember what the configuration was there were two Dee's which were separated two Dee's. Let me draw that here.

So, the two Dee regions which had the magnetic field perpendicular to the plane of Dee's and these two Dee's were separated by a small distance and an electric potential was applied between these two so that whenever a bar charged particle enter a small this gap this small gap then it is accelerated, there is an electric field and the force of electrostatic force will be experienced by the charged particle and it will be accelerated. And then Lorentz force will take over as the particle enters the Dee and then it goes around in a circular path and after a travel of traversing a semicircular semicircle it enters the gap again and by then you can actually reverse the electric field, so that this reverse the electric field between these two Dee’s and then you can actually accelerate the particle again and this goes on.

But then if you look at the transverse direction the one of the Dee’s will look like this and inside this the particle will be actually going around in a plane now perpendicular to the plane of the paper and if you what we want for the entire thing to work properly is a magnetic field. So, it is set so that the magnetic field is perpendicular to the or it is vertical it is perpendicular to the plane of the Dee’s therefore, and the call resonance condition for example, that we had looked at in the last discussion were derived using this. But towards the end of this region the magnetic field actually will not be perpendicular to each other, but will actually have a small bending. So, it will have, it will not be perpendicular to this thing and then that will have an effect on the resonance condition which means the frequency of the or motion of the particle and the frequency of the electrons the potential electric potential which is applied should be in sync with each other and this will be disturbed when the particle and there is a region where the magnetic field is not perpendicular to this thing. Like towards the end of the Dee’s and it.

So, this is one of the problems. The other problem is the relativistic effect that we are not considered from I mean we heard when we derived this resonance condition again we had used an expression for momentum which is equal to m times mass times the velocity of the particle. But in the case of relativistic particles the momentum p will go to gamma m v where gamma is now 1 over, so gamma is 1 over under root 1 minus the speed of the particle squared divided by the speed of light square. So, this effect will also disturb the resonance condition. So, this are some two effects at least which are major in this kind of setup.

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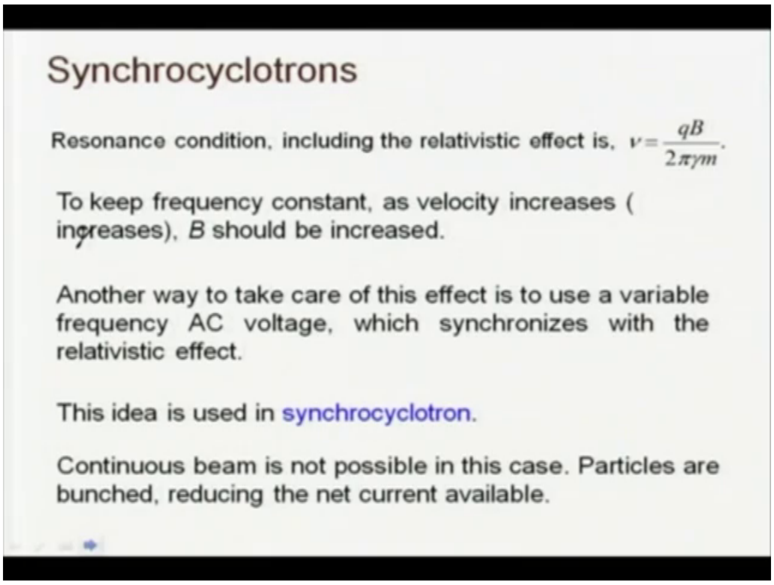

But then the resonance condition including the relativistic effect will now look like the frequency is equal to reference frequency is equal to qB the magnetic field divided by 2 pi gamma the one which we had just now talked about and mass of the particle. To keep the frequency constant as velocity increases which means a gamma is also increased B should be can B, one way to keep the frequency constant is to keep B increased as gamma increases. So, when the velocity is increased gamma will be increased and then accordingly if you change also the binary field then the resonance condition can be kept maintained.

But this is one way of doing it, and another way of taking care of this effect the relativistic effect is to vary the resonance frequency itself or the frequency of resonance frequency or the frequency of the AC voltage which is applied is varied as gamma is changed and therefore, nu is change. So, when gamma increases then nu will decrease. So, as the particle attains larger and larger speed the resonance frequency the B nu will actually decrease if you keep other things constant and therefore, in synchronous synchronizing with this you can actually change the applied AC voltage. So, that whenever the particle come out of this Dee’s into the gap there will be a change in the frequency a change in the AC and then AC direction the voltage direction and you will again accelerate the particle in whichever direction it and there is a gap it will accelerate the particle.

Such way in this way of synchronizing this frequency of the series voltage with the resonance frequency is used in what is called a slightly modified version of the cyclotron which is called synchrocyclotron. So, this in the synchrocyclotron you keep B constant, but change the AC, so that is what you do. But one more disadvantage is that the continuous beams is now not possible that is obvious because the frequency is now different. So, different particle different particles with the different speeds will actually need different frequencies to synchronize it with its resonance frequency. So, this will automatically then bunch the particle into different bunches and therefore, consequently reduce the available current in that this thing. That is a small disadvantage.

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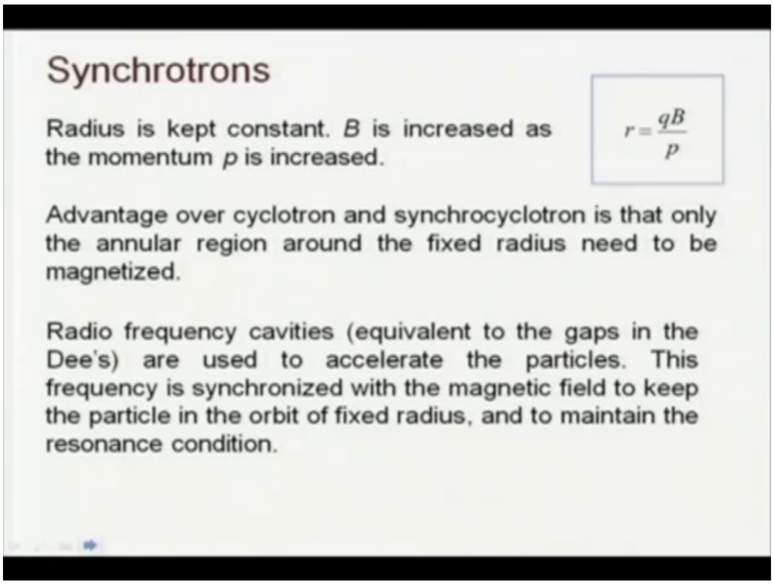

So this is one way of taking care of this thing the other problem with this is that the cost involved in keeping a large region under magnetic field. If you want to actually magnetize a increase the radius to a large extent then in the case of cyclotron or synchrocyclotron you need to keep the under region magnetized the order of these Dee's under that magnetic field is applied.

So, this is a very costly thing as you increase the radius. So, what is done in synchrotrons is to keep the radius constant now. How do you keep the radius constant? You look at the relation between radius of the particle which is moving in a magnetic field under Lorentz force and the magnetic field and discharge and momentum you see that r is actually equal to q times B over p. So, as p is increased you can change your magnetic field. So, that r remains the same q is for a particle remains the same. So, only B and p have to be related to each other. So, that r is kept constant, this can be done. And advantage here is that you need to keep the magnetic field only over the annular region around this one and whenever and to increase p what do you do to increase p you have to actually increase or you have to apply the magnetic electric field somewhere. So, what is done is basically some radiofrequency cavities in different regions along the annular region along the radius I have kept which will the frequency of which is in sync with the is synchronized with the magnetic field and the speed of the particle etcetera so that they will accelerate this particle will be accelerate whenever they pass through this RF or radio frequency cavities. So, they are the equivalent of the gaps in the Dee's in the case of cyclotrons.

So, the whole idea is to keep only the annular region under magnetic field and use the RF cavities to accelerate it. The frequency of that is linked or synchronized with the magnetic field so that everything is actually kept in the same radius and acceleration happens each time this particle enrich the cavities. So, these are some of the basic ideas in accelerator physics although we have said it in the we have only discussed the simple basics of this and make it in practice lot of things to be worried about and then a lot of work need to be done in for example, maintaining the resonance between the RF frequency and the magnet or the particles orbiting frequency etcetera.

Now, what are these particles useful I mean the aim idea to start with was we have to have a accelerated very high energy particles so that we can actually make them collide with something other particles either atoms or whatever which will then give us information about the interaction of this particle when they collide with each other. Like the case of Rutherford scattering and from the scattering experiments we can derive information or we can infer what is going on at the microscopic level when these particles interact with each other. So, that is the idea.

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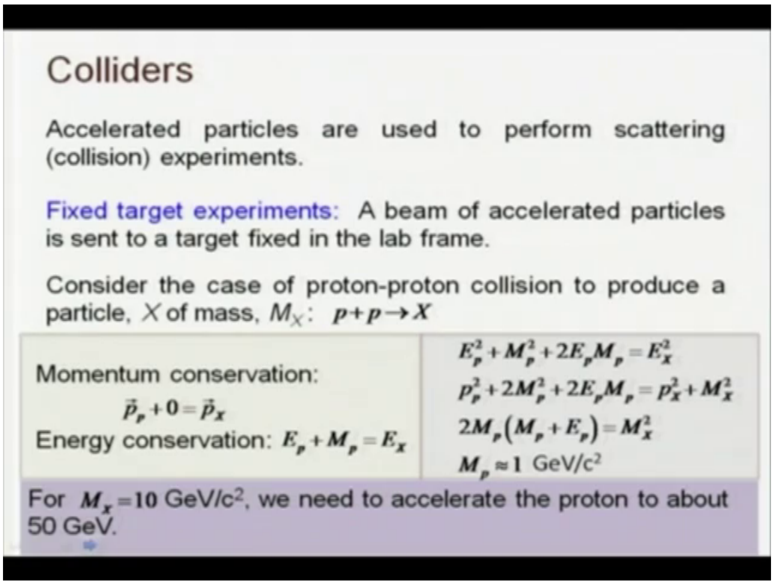

So, we have to use this accelerated particles in scattering experiments. So, when we come to scattering experiments there are two basic types of these experiments. So, one is called fixed target experiment as the name suggests these are very similar to what Rutherford’s experiment was where the target particle is fixed in the frame of lab. So, you keep it there on the table or somewhere and then generate or how the accelerators charged particle like the alpha particle and then collimate that and then make them fall on this target.

Similar thing is done in the case of these accelerated particles like protons when you accelerate in a accelerator and you can actually have a hydrogen target for example, hydrogen gas condensed to the high pressure the hydrogen gas which is not moving or at rest in the laboratory frame and make these protons collide on this. So, that there can be proton proton collisions for example, and you can actually have instead of protons you can have proton ion collision or you can have alpha particle accelerated and alpha particle and ion collisions or whatever you like, or electrons can be accelerated and made to fall on the protons which are basically the hydrogen nucleus and all these things are possible.

So, let us consider the case of a proton proton collision. Say imagine that there is one beam of protons are accelerated to a high energies to high energies and there is condensed or high pressure hydrogen gas sitting somewhere in the lab and you make the accelerated protons fall on this thing. And when you collide these things have in the case of Rutherford scattering what happened is this was an elastic scattering and then you had initial particle alpha particle and the target particle and after the scattering you had in the final state again the alpha particles and the target particles there. This was basically a kind of elastic collision only coulomb interaction was present there etcetera.

But we will touch upon these towards the end. Well, in the case of very high energy particles mashing on each other proton proton or electron proton or electron electron etcetera we will learn that quantum field theory is the one which actually a comes into play there and then it actually suggests that you can create new particles according to the special theory of relativity. So, energy can be converted into mass or mass can be converted into energy and then you can actually have a mechanism under quantum field theory to generate particles which were not present otherwise earlier.

So, in a pp collision you can imagine that you and you can also destroy the particles in a similar way you can annihilate particles and create energy out of this. So, we can think about proton proton colliding with each other and then just vanishing and then creating some new particles. Just let us imagine that there is only one particle which we are producing in this case. Just to simplify our picture and their understanding.

In that case we can write the equation as p plus p going to X, X is some new particle which has a mass say M x and momentum and energy linear momentum and energy need to be conserved in these cases and then energy meaning not just the kinetic energy. So, it need to be its not need not to be an elastic collision we are talking about the total energy including the mass of the particle and then the kinetic energy. So, in that case momentum conservation will certainly tell us that there is only one particle which is moving initially. So, let me denote that by p subscript p vector and with the other particle other proton is at rest and I say its particle is a proton belonging to the target. So, we have 0 for its momentum and that is equal to the final momentum again where there is only one particle that we are going to assume here p x.

And energy conservation will tell you that initially there was energy of the proton the projectile proton was E p say and the target protons energy is only its mass it was not moving it has no kinetic energy, only M p. So, E p plus mp is equal to energy of the final particle E x and simple algebra by squaring E p plus mp square and equating it to E x square will tell you that and then substituting for E p square any considering the energy momentum relation indicated by the special theory of relativity E square is equal to linear momentum square plus square of the mass, mass square c square etcetera. So, basically this will tell you that P p square plus M p square plus another mp square which is already sitting there. So, that makes it 2 M p square plus the last term 2 E p M p is equal to E x square is P x square plus M x square. To be completely correct I should have put the powers of c along with this thing. So, for energy is equal to, is equal to M c square energy current of mass is M c square. So, wherever there is an E square and then when I add the mass equivalent of the energy to that I should be adding not just M square, but M square c square.

Similarly and the energy equivalent of the kinetic energy is p times c. So, I should be adding c square along with P x square and c power four along with an M square. But once we know how to take care of this thing we can actually say that we will set for the time being c equal to 1 or will not worry about that factor of c, we will put that back at the end. Wherever there is an m in the energy relation we will put a c square along with that wherever there is a p we will put a c along with that that is all need to be done. So, assuming that we have this in equation in this fashion and you see that because of the momentum conservation P p square is equal to P x square coming on the left hand side and the right hand side respectively which can be cancelled.

And then you have the rest of it 2 M p times mp plus E p equal to M x square. And now proton mass let us assume that it is equal to 1 Gev per c square k approximately it is 938.5 Mevs right, to be more accurate, but let us take it to be approximately 1 Gev square.

If we put M p is equal to 1 you will immediately see that M x square is 2 times E p plus 1 and assuming that we want to produce we want to we are interested in, we let us say we have a theoretical understanding or some theoretical model which actually suggests that when you collide a proton and the proton you can produce say form a particle of mass say 10 Gev. If you want to produce it mass energy momentum conservation relations will tell you that you need to have protons to be accelerated to 50 Gev in a fixed target proton proton collision experiment to produce. So, you have to have protons of very high energy compared to the energy mass of the particle 5 times than this thing.

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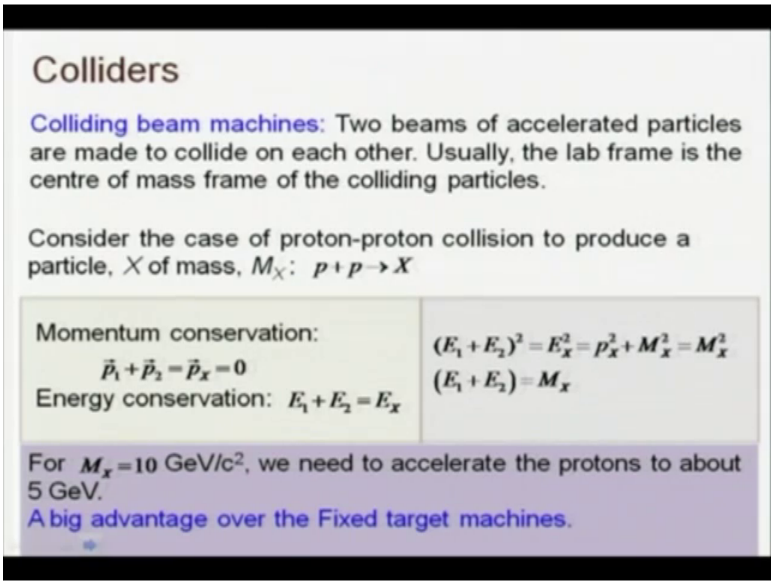

And now, let us keep that in mind and then go ahead and then look at the other type of accelerator collider machines which are called colliding beam machines. Instead of a target fixed target and a colliding beam projectile beam you have two beams which are actually two protons both of both the protons are now accelerated and now they are made to collide on each other and the lab frame is usually the center of mass frame of these to me, if both of these particles are accelerated at the same speed, and moving in the opposite directions then you have the lab frame as the center of mass frame of this proton proton. Again consider a particle of mass M x produced in a p-p collision.

Now in this case the initial momentum both the particles have mass more initial momentum p 1 and p 2 and because of the momentum conservation if we consider p 1 to be minus p 2 if they are moving opposite to each other then you have a p x equal to 0. And energy conservation will tell you that E 1 plus E 2 is equal to E x.

And again putting this back in the same in the like the earlier calculation, we will see that E 1 plus E 2 square is equal to E x square which is equal to P x square plus M x square which is equal to M x square because P x is equal to 0 and we have E 1 plus E 2 equal to M x and you see that to produce a particle of mass M x equal to 10 Gev similar to the earlier case we need to accelerate the protons to about 5 Gev because M x is now equal to E 1 plus E 2. This is a big advantage over the fixed target machines. In that case you had to actually accelerate it that 5 times more than this thing and here you need to accelerate it only half of the energy.

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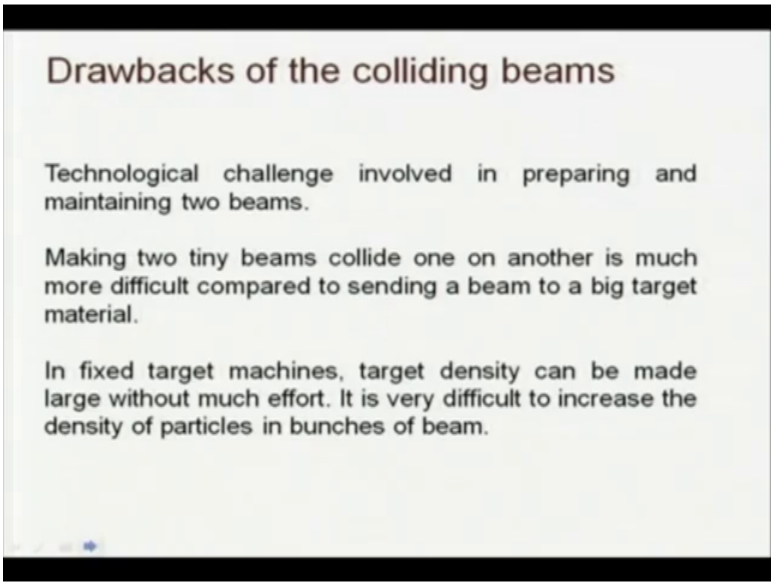

But there are drawbacks also here. In the case of a fixed target machine as we said we can keep target a big target and then beam can be sent to that like Rutherford did. What Rutherford did? There is a gold foil which is reasonably big in size compared to the alpha particle beam and then you send the alpha particle to that. But imagine you want to you have 2 alpha particles which are small in size and then you want to focus them align them so that they will collide with each other which is a technologically challenging thing compared to sending an alpha particle or beam of alpha particles to a fixed target they are big fixed target.

I mean you have now two beams to handle rather than one beam so that itself is a disadvantage and then the (Refer Time: 23:16) and then make. So, the size of the whole accelerator and collider complex can be different and etcetera. So, this is one of the disadvantages compared to the fixed target.

The other is that in the case of fixed target you see most of the times is keeping a giving a large density target particles is much much easier compared to keeping large density particles in the bunches of colliding beams. So, when you keep colliding particles in a bunch close to each other very closely packed protons, then they will suddenly repel each other and then there will be a defocusing effect as they propagate whereas, in the case of target particles you can actually keep reasonably large target density. These are some of the disadvantages.

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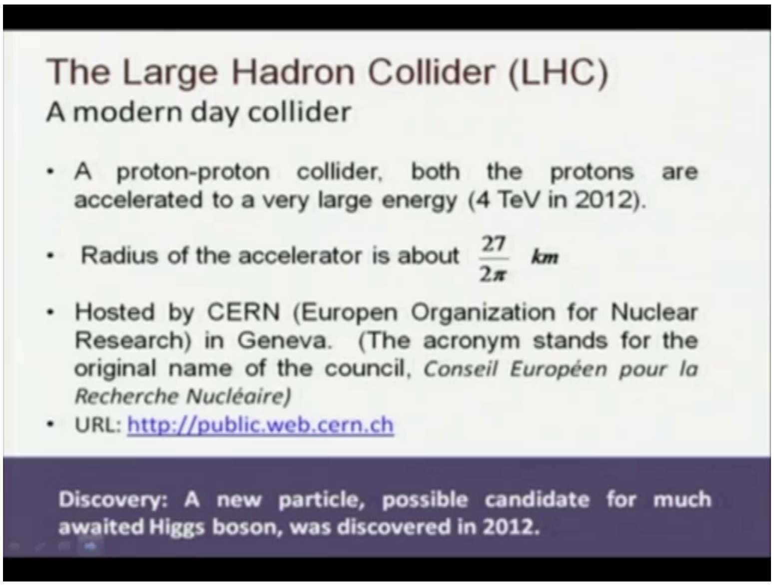

In that case, we will come to one of the basically new recent modern day collider as an example of this kind of collider machines colliding beam machines ok.

So, let us see which was in news recently The Large Hadron Collider where 2012, a new particle was discovered which has mass of about 125 Gev per c square and this is a probable candidate for the particle which all the particle physicists and other ways also generally physicists and then many people have been expecting for many years now. So, this law this, this is called the Higgs particle and the Higgs particle is needed as per the standard model to generate mass to the particles any particles, how to get general random mass to the particle is one of the mechanisms is what is called the Higgs mechanisms as per the standard model and this consequently gives rise to physical scalar particle spin 0 particle which is called the Higgs particle.

So, let us look at this from the point of view of what we had have discussed so far. It is a proton proton collider and the energies of each of this proton beam until now was 4 Tev that is 4000 Gev each of these beams. So, total center of mass energy is 8 Gev Tev and the radius of the accelerator it is a cyclotron, it is a synchrotron. So, therefore, only the annular region has all these electric magnetic field the bending magnetic field etcetera and the accelerating cavities etcetera are only in the annular region. And the radius of this ring is 27 over 2 pi kilometer or the perimeter is 27 kilometer.

It is hosted by CERN which is with the CERN stands for the English name European organization for nuclear research which is situated in Geneva at the border of France and Switzerland. The acronym actually CERN stands for the original name when they started the whole idea which is a French name here given here. And I will advise you to actually visit this, the public web page of CERN which actually gives enormous amount of information for students, for teachers, for general public and for serious researchers. So, as I said the new particle was discovered which was expected to be the candidate of much awaited Higgs Boson all right.

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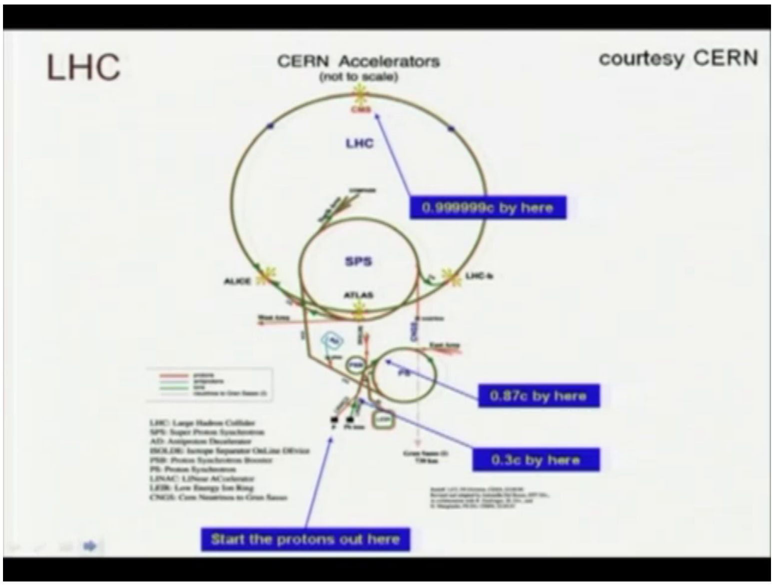

So, if you look at the accelerator complex the schematic diagram of that you will see that there are different stages of this acceleration. So, this is what I said earlier. Although the principles are simple when it when you bring it to practice there are lot of things that one has to worry about, finally, this is the kind of design that the CERN has decided on the LHC.

In fact, the LHC-Before LHC which is actually a proton proton collider at the same side in the same tunnel, in the same accelerator there are a positron and electrons were accelerated and collider. So, that was then called the large electron positron collider or left for short and which was running for a few couple of decades and then which gave a lot of discovery which made lot of discoveries and gave a lot of information about the particle physics interaction, the nature of particle physics interactions including the discovery of what are called the Gauge Bosons. We will come to that soon.

Gauge Bosons which were predicted by the standard model of particle physics and many other things and they can do very very precise they could do very very precise measurement of various physical quantities including the fine structure constant which comes up in atom physics even alpha. So, that is aside. But now coming back to LHC we will see that this complex has different stages of accelerating protons they are produced at some stage start off the production proton out here and then accelerated through a linear accelerator and a ps what is going to be a proton synchrotron and then it is accelerated to some energies and finally, when it comes to the LHCs ring of this 27 kilometer perimeter if the speed of proton is very close to c 0.999999c, its very very close to c proton is not a mass less particle like photon. Proton is having a mass of 1 Gev which is a something like 2000 times heavier than the electron. So, they can be accelerated to that high energies and you see that there are different points which are marked one is CMS, ATLAS, ALICE, LHC-B etcetera these are the places where it is actually colliders are there collider.

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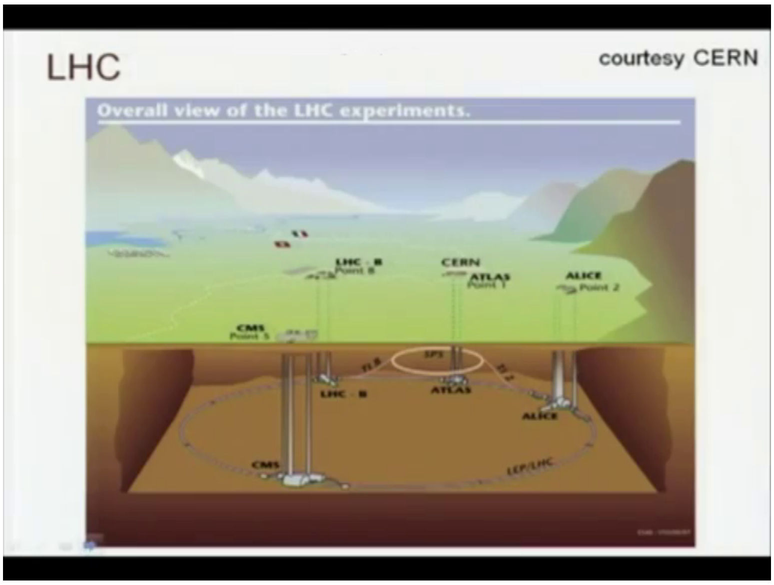

So, and the whole thing is kept below ground, something like 100 meters below ground and this is needed to actually avoid any radiation leak that is one of the reasons. Other things are like any safety for any safety considerations it is better to be under the rear that is one thing you can see some schematic view of this.

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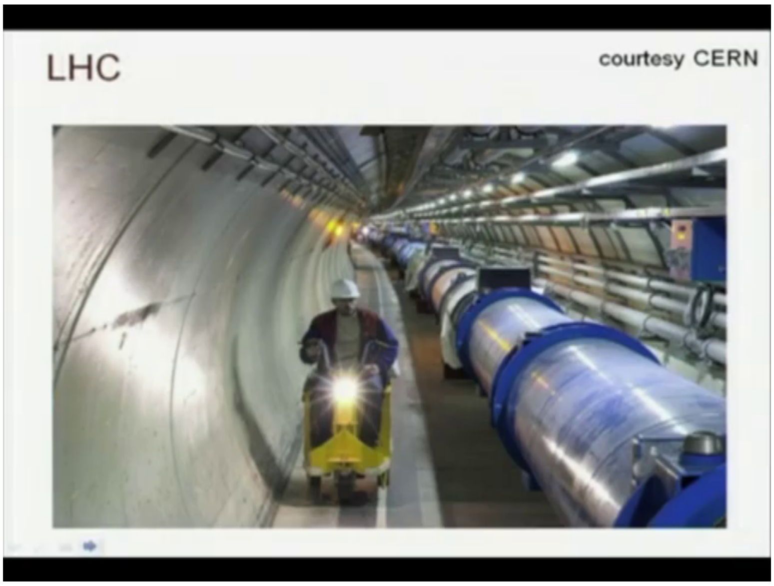

This is the inside the tunnel, if you think that just to give a feel of that although how big it is and then how it looks in. So, this is an actual photograph taken from CERN. So, this is basically (Refer Time: 30:52) that we are seeing this now.

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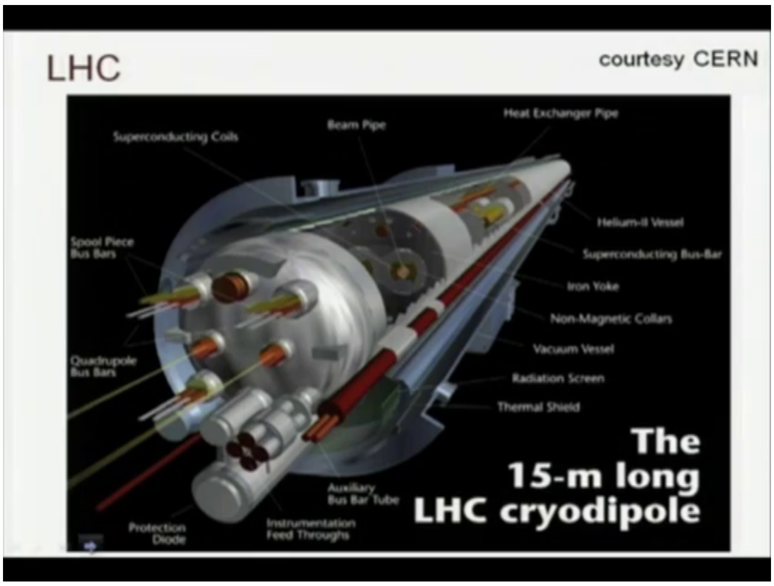

And the magnetic field is provided through what are called dipole magnets ok. So, there are many it is not that there is a continuous magnetic field is not applied all along the 27 kilometer ring. But its provided through a dipole magnet arrangements, each of this is a 15 meter long what they call the cryodipole, cryogenically cooled and all those things there are a lot of technology that is needed there and you can see here various parts of this and some of these are technical details, but some of them you can identify. So, there is a place where it is actually marked as a beam pipe and that is where the particle beams will be beam particle will be accelerated through. So, that beam pipe is very small when the renderer structure otherwise is needed to make the magnetic field there and then cooling system etcetera and the electronics to guide and to control etcetera.

And there is another thing which we are not discussed, but to focus this beams keep them in small focused ring you need to have additional setup usually one of the ways to do it is to actually apply what is called a quadrupole magnetic field which can be arranged. So, that the partprotons are confined in a small region and kept focused there. And then for you know that I mean we already said that there is a proton proton collider machine and then therefore, you have actually two beams passing through the same dipole. So, you will see actually two beam spots actually, the yellow things that is coming up in down towards the regions and that they are the beams. We will see a schematic the other here.

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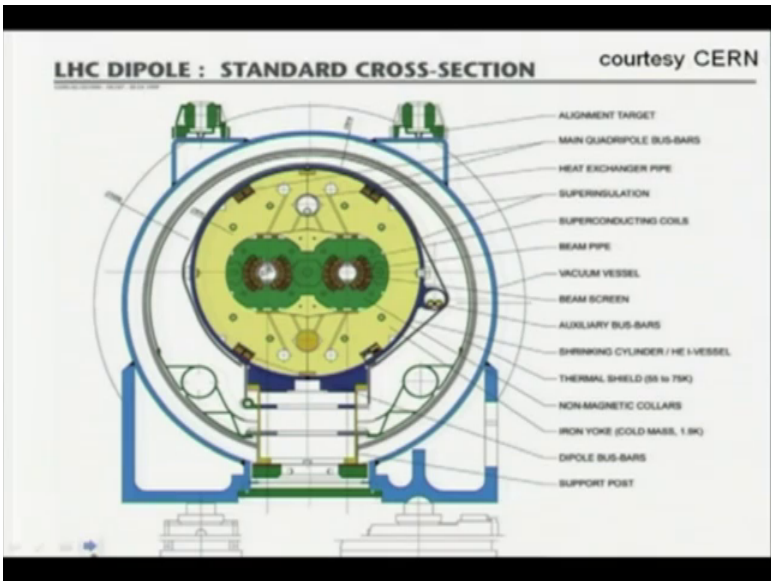

The schematic is the cross section of that the cross section is clear here. So, you see two white spots in the center near towards the center and center of that green annular ring which is actually called the beam pipe right you have seen that. So, there are two of these. So, through one of this protons is one beam of proton will be passing going in one direction and through the other the protons the other beam of proton will be going in the opposite direction and the whole setup is like this a lot of things that you can look at.

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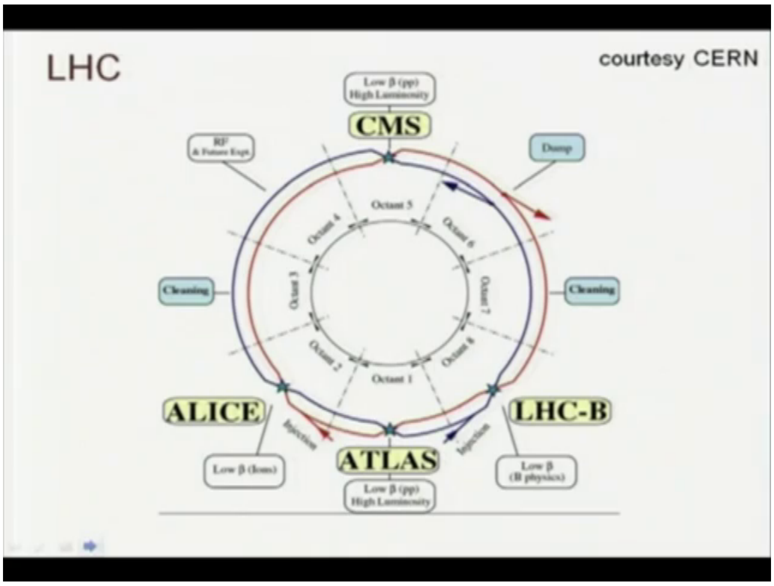

And say when you collide them you have to actually now make special arrangements. So, that these two beams are now bent towards each other and then collided. So, such collisions are made at special points where do you also have made arrangements to detect or understand the product of this collision. There are two major such sites such collision points one is CMS the other is named ATLAS here, and there are two will come to that the same and there are two others ones, one is an ALICE collision point and detector and the other is an LHC, other is called a LHC-B collider or experiment ok. So, these way the blue is one beam of proton the red is another beam of protons and then they are collided at different point, special points which are mentioned in this way.

So, basically to know more about all these things week you can take a look at the source web page website and then go through a lot of, lot more pictures and a lot more information that is available at CERN and including various engineering technologies that are needed and in physics that is going around in the accelerator, accelerator mechanism etcetera.

The other part that we will discuss is what is called the detector. The detectors as I just mentioned need to be kept at the interaction points. So, CMS is actually stands for the detector names compact muon systems and ATLAS is a toroidal LHC apparatus. So, these two are the general purpose experiments detectors which actually are designed to detect anything that is coming out of p-p collisions in LHC experiments.

And there are lots of things that we need to know about the detectors and then we will come to that in the next discussion.