Nuclear Physics Fundamentals and Application

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Lecture -39
Thermonuclear fusion reactors

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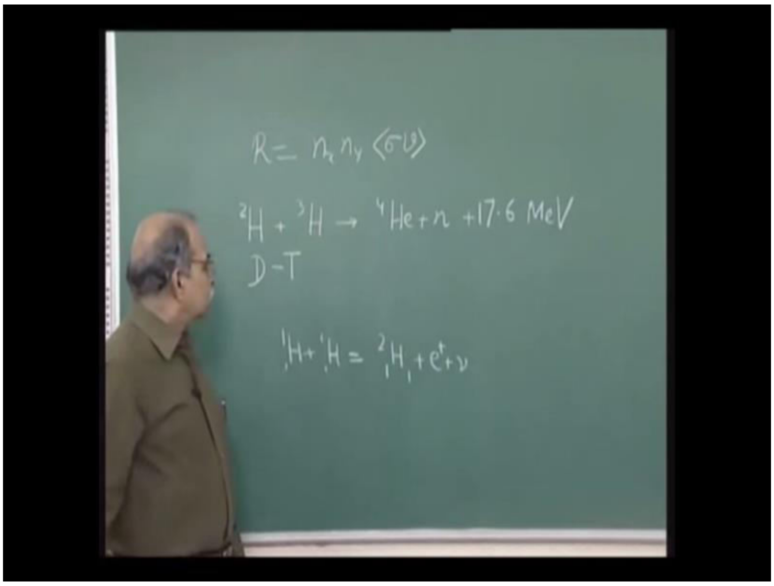

So, in the previous lecture I talked about the reaction rates and the reaction rate is R. If you write n x n y and sigma v average value of that n x n y are the concentrations number of nuclei of x of y per unit volume and sigma is the cross section for that particular reaction in those particular conditions, and v is the relative speed between the two interacting nuclei, and this we saw that the sigma v itself is a function of v and since the velocities are distributed according to Maxwell Boltzmann distribution in the plasma.

So, you have to integrate over all varieties of velocities involved and we saw that only a small part contributes in this integration, because when you do integration using this Maxwell Boltzmann probability distribution for relative velocities. This distribution itself if you write in terms of energy, you get two terms one dominated by this distribution of velocities, another dominated by the barrier penetration probability and then one rises with temperature with a velocity, and one falls with velocity, and the product is contributed only by a small range in these relative velocities, and then we can integrate and get this sigma v.

We also saw that as temperature increases in the beginning this whole thing increases and therefore, the reaction rate increases but, if one goes to very high temperatures which are not very relevant for fusion reactors then but, in principle it is there that this thing may come down. Now that reaction rate can be calculated for any given concentration of x plus y at a given temperature one can look at different possible constituents which can be used in a fusion reactor. And turns out that for making a fusion reactor the most attractive proposition is what you called d t reaction deuteron and a triton this going 4 H e plus n d t.

So, this is D and this is D T reaction, This has the best promise, if you look for low z materials, the first one is 1 H proton, it has its own difficulties will talk about that later the most prominent difficulty with that proton is 1 H plus 1 H. So, you have 2 protons here about 2 protons do not combined to diproton you do not have Di-proton in nature Di-proton is not a stable component. So, it has to be 2 H 1. So, that means 1 proton has to be converted into a neutron and hence this e plus and nu and proton going to neutron and positron and neutrino this is governed by what we called weak interactions and that interaction is really very weak.

So, in the nuclear time scales when the 2 protons are close to each other trying to fuse in that short time itself, this week interaction reaction has to take place this beta decay has to take place and then the total probabilities extremely small. So, this is not at all a good choice then D is one possibility and D T is another possibility. So, on many different accounts this D T seems to be much better making this helium and neutron and it releases some 17.6 M e V of energy. So, and this 17.6 M e V of energy it shared by these two in the center of mass frame if we look at this constituent particles here. In the center of mass frame total momentum is 0. So, here also the total momentum should be 0.

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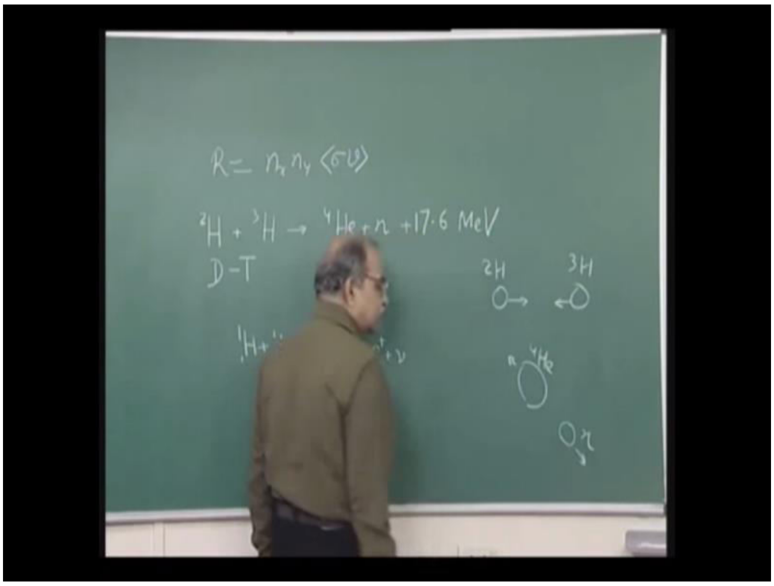

And therefore, if this 2 H and 3 H, if they come towards each other in the center of mass frame and finally, make this helium and neutron this helium and neutrons must go in opposite directions. So, this is 4 H e going in this way and neutron going this way and you can make calculations the momentum should be 0 and therefore, the velocity should be in the inverse mass ratio of.

So, the major part of the kinetic energy will be taken away by this neutron and this smaller part will be taken away by this alpha particle here. So, that is how the energy will be distributed now the main problem comes that to do all these things the temperature needed will be somewhere 10 to the power 8 Kelvin or. So, at those temperatures when these particles in the plasma you also have electrons remember. So, you have electrons and the nuclei. So, these particles move with velocities and then they scatter from each other because of the coulomb interactions general and the accelerations produced in these charged particles could be very large and specially for electrons, because the mass of electron is small.

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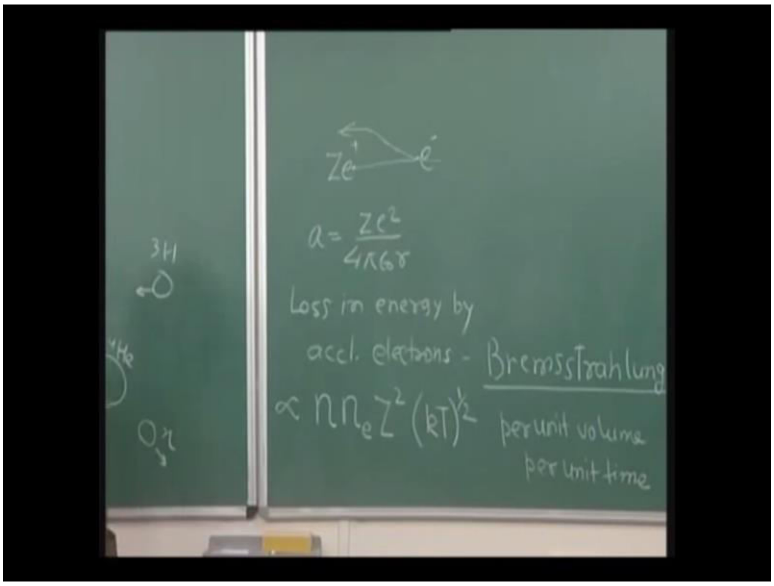

Once the acceleration is there these charged particles emit radiation and that is a loss of energy from that system the energy is radiated in terms of whatever x rays or any wavelength of gamma rays and the. So, this Loss in energy by this accelerated electrons. I am saying the positive charges also accelerated but, since heavy the acceleration is small and therefore, this radiation loss is also small. So, most of the radiation loss is coming because of the electrons. So, this is known as what we call Bremsstrahlung radiation.

So, energy is coming out and one can make calculations the electromagnetic waves those equations are there radiation from accelerated charge and one can work out how much will be the total loss because of this. So, it will be proportional to the concentration of the positive ions, it will be proportional to the concentration of the electrons, it will be proportional to Z square, and then it will be proportional to the relative speed. So, k T half proportional to these, this is loss in energy because of this Bremsstrahlung per unit volume, and per unit time alright.

So, when you confine plasma of these positive charges x and y which are going to fuse and create this energy create energy means remember is the rest mass energy which is going down. So, energy is not created in that sense but, yes usable energy that energy is being produced and energy is being lost here. So, the first condition should be that the rate at which the energy is produced should be larger than the rate at which this radiation is emitted and this is the reaction rate. This is number of fusion reactions taking place per unit volume per unit time in each reaction. If the energy emitted is capital Q.

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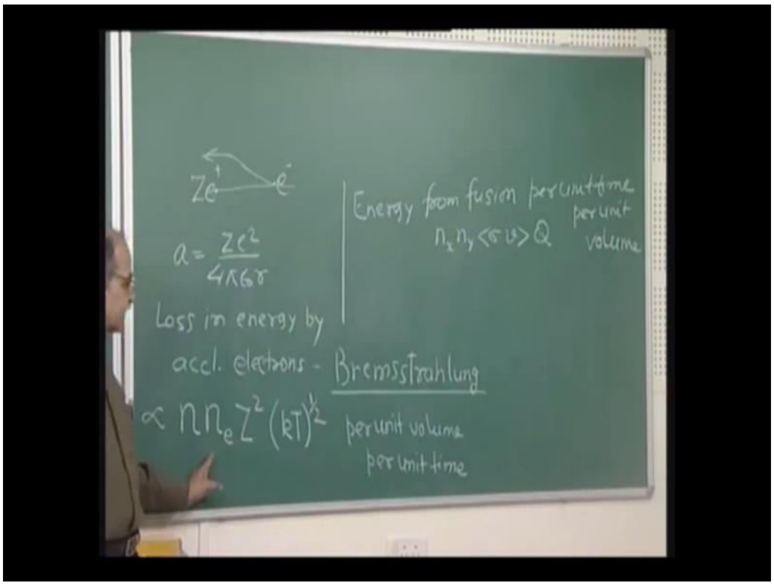

Then, the energy that is being produced per unit volume per unit time energy from fusion per unit volume per unit time, that will be that reaction rate n x n y sigma v and then Q. This is the number of fusion reactions taking place per unit volume per unit time and from each reaction Q amount of energy is coming out. So, this is the energy which is generated in this fusion reaction in that plasma per unit volume per unit time. So, per unit time per unit volume and that should be larger than this loss that is occurring because of this Bremsstrahlung.

All these things are now we can we have the equations one can calculate the energy which is produced per unit volume per unit time, the energy which is radiated. So, when all these calculations are done for D reaction deuteron reaction and deuteron triton reaction D T reaction. Then the result I will be showing on your screen.

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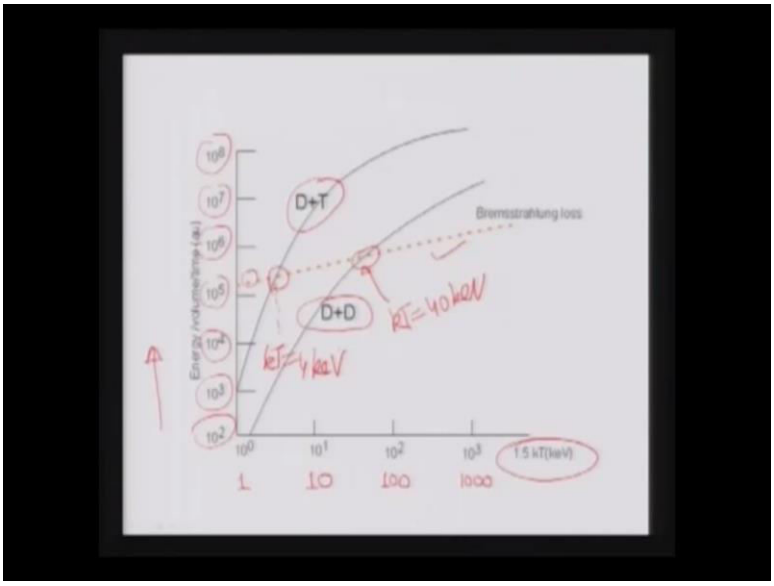

So, here you see on the screen we have on the x axis side horizontal side it is the k T 1.5 k t here, this is as a function of temperature we are plotting and this is a log scale. So, this is 10 to the power 0, this is 10 to the power 1, 10 k e v, this is 100 k e V, this is 1000 k e V and. so on. These are all in k e V's on this side we have two quantities plotted one is the rate at which energy is being produced in fusion and that is for D plus T. It is this black curve here and for D plus D, it is this black curve here.

So, at these energies 10 k e V around these energies, we have D plus T is for a given concentration, it is larger than D plus D that is one thing and the loss bremss trahlung loss that is plotted here in this dotted line and a this access y axis is also in log. So, it is energy per unit volume per unit time again it is 10 to the power 2 here, and 10 to the power 3 here 4th is a log scale. And on this log scale this is linear this Bremsstrahlung loss is almost linear.

In this log scale and now you can see that for low energies, the loss is larger, lower temperatures, The loss is larger and the production is small and this is the crossover time alright this corresponds to something like k T is equal to 4 k e V. So, k T is equal to 4 k e V here this loss and the production will match with each other, and for D-D crosses at this point deuteron deuteron reaction it crosses at this point and this is something like 40 k e V. k T is equal to 40 kilo electron volts here. k T is approximately 4 kilo electron volts. So, that is how you have to choose the operating temperature at least it has to be larger than this, loss there are many other things. So, it not only should be larger but, should be much much larger than that.

So, that is the one consideration the temperature has to be large enough. So, that the production of energy exceeds far exceeds the loss because of this Bremsstrahlung. And Z square is there. So, D and D T Z is 1 z, 1 Z 2 both are 1 but, if you go for higher heavier element fusion than this, loss is also going to be very high. Another justification why 1 should go for the low Z materials coulomb barrier is low. This loss is low and so on. Now, suppose the plasma is confined at temperature high enough so that, this loss due to this Bremsstrahlung radiation is small as compared to the energy that is being produced but, to take the plasma to that temperature it has to be heated in whatever fashion. So, energy has to be given from outside how much is that energy and how much is the fusion energy that we obtain from that heating normally.

What happens at these high temperatures confining it in a small volume for a long period? It is very difficult some plasma particles will leak through that confined volume one. And if they leak through they will hit the walls of the container and the container will be heated and the plasma will be cooled. So, generally this confinement to maintain that high concentration generally it is done in a pulsed way for presently it is of the order of a one second or.

So, for a small time interval the high concentration are maintained and after that the concentration goes down and then next cycle goes in, and for the next cycle again it has to be heated. So, the heat that we are the energy that, we are giving to heat up this plasma to those high temperatures has to be compared with the total energy output in that confinements time. So, if that concentration is maintained for say one second in one second how much fusion energy we have gotten from system and to heat up? How much energy we had given to it? So that can be estimated.

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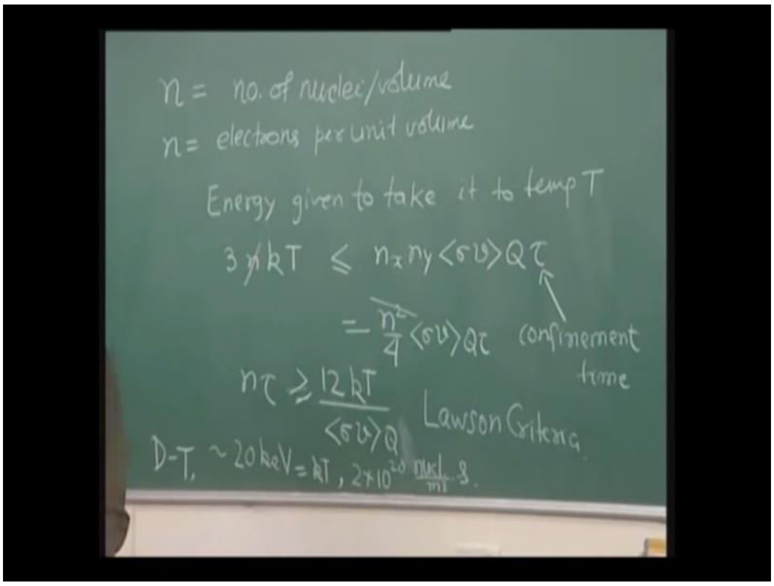

So, suppose n represents the total nuclei concentrations number of nuclei per unit volume, total nuclei x and y both. So, if n represents this and if it is hydrogen isotope deuterium is this tritium. Then the electron you have one electron. So, if n number of nuclei is there you will also have n electrons per unit volume, and if the temperature rise is capital T, then the energy which is given to take it to temperature T will be three-second n k T for the nuclei three-second, n k T for the electron. So, that will be 3 n k T if you take the mixture deuterium and this tritium 50. So, the concentration of x is n by two concentration of y is n by two.

So, how much fusion energy we produce in that confinement's time say tau. So, the energy which is produced per unit volume per unit time is n x, n y alright let me write n x, n y and then sigma v and into Q this is the energy produced per unit volume per unit time multiplied by tau this is the confinement time . So, this fusion reaction in one pulse goes for this time tau. So, this is the total energy that has been produced per unit volume and here is the total energy, that we had initially given to heat up the this thing and this should be at least equal to this should be larger the energy which we produce from the fusion should be larger than whatever energy input we have given to heat up. The plasma we are neglecting the Bremsstrahlung radiation, assuming that the temperature is high enough. So that part can be neglected.

Now if you put n x equal to n by 2, n y is equal to n by 2 this side will be n square by 4 remember n this we are taking as the total concentration of x and y. So, total concentration is of nuclei is n and half for deuteron and the D n T. So, this is n by 2 this is n by 2. So, n Square by 4 sigma v Q tau. So, if we take the equality sign that is the threshold minimum that has to be maintained then you can write n tau you can take here this side and let this n cancels with this square here, and n tau you can then written on this side everything else you can transfer to other side. So, this should be equal to 12, 4 into 3, 12 k T here and then that divided by sigma v and Q and tau is there we have already written here.

So, it should be greater than this alright it should be greater than equal to this is the famous Lawson criteria. So, the concentration and the confinement time that, this product should exceed this quantity, one can calculate it also depends on temperature and it has a minimum as certain temperature for D T reaction, for this quantity minimum at around say 20 K e v K T is equal to 20 K e v. So, this is the temperature in fusion community temperature is described in terms of K T and in the units of kilo electron volts.

So, at this is minimum and it is around say 2 to the power 10 to the power 20. So, what unit's nuclei per meter cube and second. So, the reactor design should be such that the concentration into this confinement time should exceed this number. So, that the energy output that we get is more than what energy we are giving. So, these are some of the design considerations. Now the next topic is this whole fusion idea started sometimes in 1950's. So, it is almost more than 60 years that people had conceived people have thought of it people has started working on it. Mid 50's there were already some experiments going on to do. This fusion the 60 years down the line we are still not having a nuclear fusion reactor.

So, where are the problems? So, the problems are that one is this the main problem is confinement main problem is for confinement this high temperature plasma 10 to the power 8 Kelvin or. So, at high temperature plasma has to be confined in a small volume to get this large concentration n and no material boundary can be used to confine that gas because no material boundary will sustain this. So, it has to be done in some other way and the most widely pursued root is magnetic confinement. What is magnetic confinement? Suppose you have some container.

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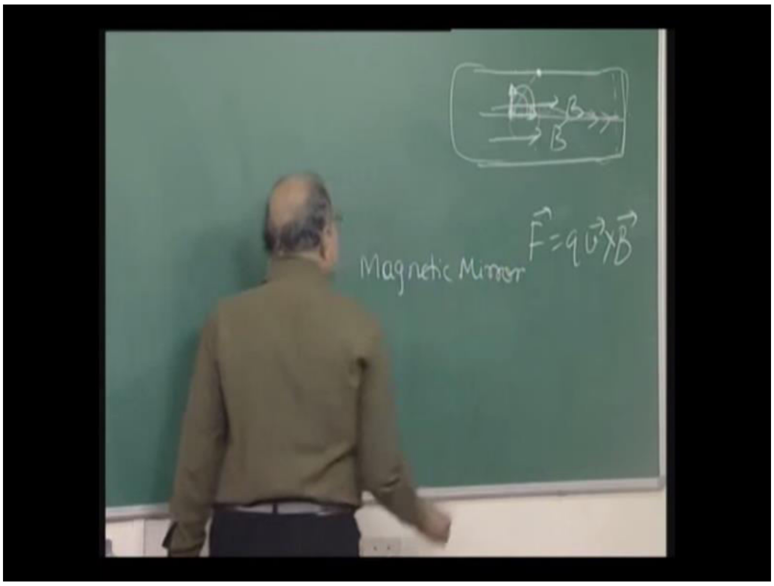

So, you have a container and you have some gas molecules and which are going in random directions with random speeds. So, the molecules will go and strike here. So, if you take this kind of says imagine this kind of cylindrical thing then the particles which are going this way. They will go this way of course, you will have some boundary here also is not an infinite thing, it is not a infinite tunnel but, let us look at this the component of velocity in this direction this component will take the particle to hit this wall. So, the particle will go somewhere and hit here now if I apply a magnetic field in this direction? What happens the velocity component in the direction of magnetic field? Does not change but, if there is a component of velocity perpendicular to it goes around that magnetic field.

If that is the only component that goes in circle otherwise, it goes in a helix this is the simple F is equal to q v B q v cross B. So, it bends if you have magnetic field in this direction and velocity in this direction then it bends, q v cross B. So, if it is positive particle it will go like this. So, instead of hitting this, if the velocity and the magnitude of magnetic field they are proper then before hitting it can make a turn and it can go around this. So, this is the basic very fundamental principle of magnetic confinement that by magnetic field you can bend the charge particles and if it bends then there is chance that it will escape hitting the walls another interesting thing in this is suppose you have a magnetic field because this kind of field will talk stop or is likely to stop or it has some potential to stop this.

These particles to hit these walls but, in this direction it is going and somewhere here, there must be a wall if it is a container there must be a wall. So, in this direction also it has to be stopped. It is not allowed to hit this it should not be allowed to hit this wall also I give you another configuration, which is known as magnetic mirror.

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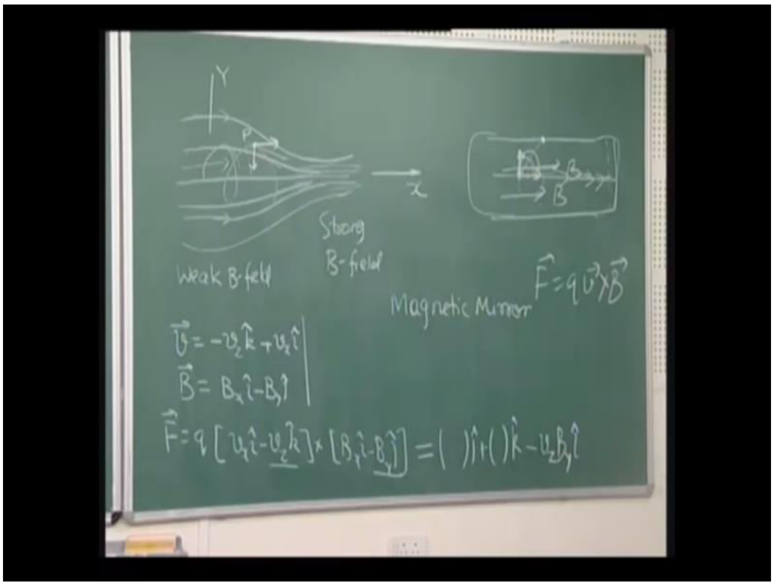

Suppose you have a magnetic field which is non uniform and here the field is strong here the field is weak. So, if you draw field lines here the field lines are widely separated here the field lines are more congested. So, that means the fields must be field lines must be go like this. So, you have larger field here strong field strong B field and here you have weak B field and suppose you have a particular which is circling this magnetic field and at the same time moving towards this direction towards right.

So, a particle is there which is circling it and then is going towards right. So, it has a velocity suppose let me take this as the x axis, this as the y axis and this particle is going like this. Suppose the particle is here, it is going into the board has as well as it is drifting towards right. So, velocity you can write as this x, y and z. So, minus say v z k cap this is the velocity component that is perpendicular to this x direction. So, it is going like this. So, this z component here and then there is a component in this direction is going ahead also, this component will be plus v x I cap and the magnetic field has this field lines are bending the magnetic field also has a component in this direction and in this direction. These are the directions of the magnetic field. So, it has a component here. So, b is equal to this is some B x in I cap direction this and then minus B y j cap direction. So, if you calculate q v cross B the force is q v cross B. So, q then v x I cap minus v z k cap and cross product with b x I cap and minus b y J cap. Now look at the various terms, this I cap terms cross product with I cap terms gives me 0 this I cap cross product with J cap gives me k cap. So, there is a force in k cap direction. So, that component will change.

Now here k cross I is J cap. So, there is a force in minus J cap direction. So, that is a. So, there is a force this is the centripetal forces circling. So, there should be a force towards the center of the circle. So, that minus J cap will be there and that last term look at that last cross term here, so minus and minus. So, it is these two minus makes it plus but, then you have k cap cross J cap which is minus I cap.

So, this will be something in J cap direction, something in k cap direction and I cap direction I am interested to write it explicitly it is v z B y v z and minus I cap. So, v z here I am talking of these two terms, this is going to give me a product in I cap direction this combinations. So, v z b y and then k cap cross J cap is minus I cap. So, you have a force in negative x direction, the particle is coming in positive x direction and there is a force which is in negative x direction so, it decelerates. This is strong magnetic field stronger magnetic field here is pushing the particle back that is how it is acting like a mirror. So, this third dimension also can be managed with magnetic field so that it is confined in this side also.

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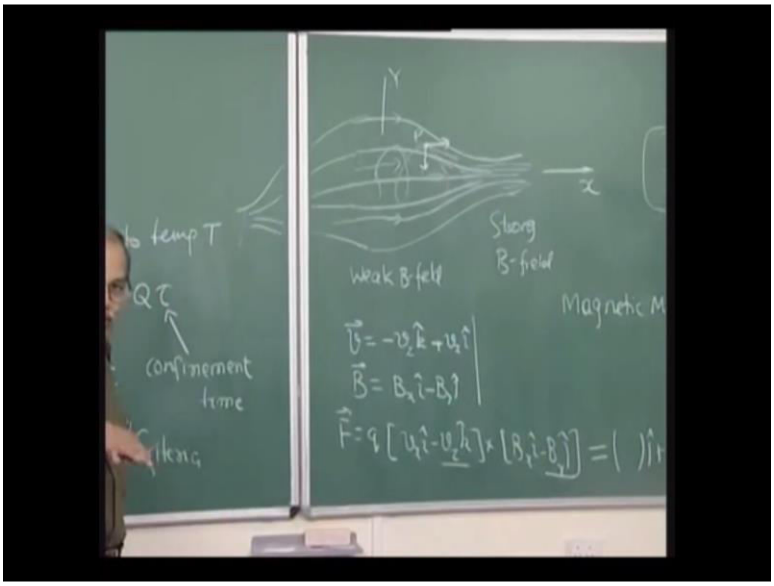

You can have similar structure magnetic field. If the magnetic field is strong on this side also it is some kind of a magnetic bottle. So, particle is if proper field magnitudes are there this particle which is coming towards x axis will be pushed back and once it reaches here and tries to go towards this stronger field, once again it will decelerated and will be reflected from this strong field region. So, these are some of the simple designs only to say to show that magnetic properly designed magnetic fields can contain charged particles in a volume of course, the things are very complex because of this very high temperatures random velocities, random directions speeds large and so on.

So, the magnetic fields are to be designed in a very careful manner that is what is being done for the last 70 years 65, 70 years people are designing magnetic field there are other methods also for confinement like inertial confinement, what we call inertial confinement. So, that inertial confinement is another approach which people are working very seriously and this inertial confinement is to start with solid pallet your deuterium and this tritium at D and T that is in the form of a solid pallet.

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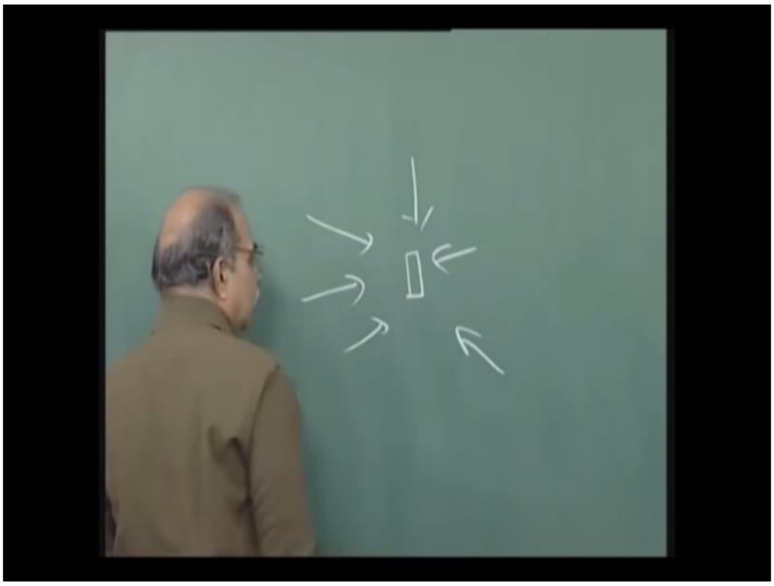

And that solid pallet is hit by from various sides intense energetic particles all or photons. So, let us started with lasers, so from all sides put very high intense lasers on this pallet, and then this pallet gets all that energy, and it evaporates makes plasma there that much of energy goes in. So, the temperature rises and that is how the plasma is created but, there is no confinement acts at it as only because of the pressure, because of the pressure of these beams that it is confined but, once it is evaporated it does expand the pallet does expand but, for whatever time because of this beam from all sides compression that shock waves that hit that shock wave keep going in this material. So, for some time it is confined that plasma is created high temperatures are created and confinement is created. The normally in this particular design the confinement time is say nanoseconds or.

So, in magnetic confinement we are not talking of seconds and minutes and. So, on but, here it is still nanoseconds and the density of course, are quite high because there it is all gases here it is solid compressed by all these things. So, the density is because of that compression is very high and one still reaches the same kinds of n into tau concentration into confinement time which is comparable to what one has in magnetic confinement. So, this is another way on which people have worked very seriously very intensively and again once again there was some a period when this particular inertial confinement results was going low but, now again it is revived and people are thinking this as another possible way.

Coming back to this magnetic confinement a particular design is nineteen sixty eight in soviet rules this design was constructed and there we people found that, this concentration and confinement that was very high as compared to all other kinds of magnetic confinements that was being tried. Since then almost the entire activity has is going on which that particular design which is known as tokomak design.

What is that tokomak design? As I told you here if you have a magnetic field in a particular direction then the particles can go around and in that transverse direction particular fields can be applied to avoid collision with the walls but, then on the longitudinal side there is a problem alright that you have to do some kind of reflection or something but, if this cylindrical thing itself is bent and joint to make some kind of ah motorcycle tube structure, doughnut structure, Taurus structure.

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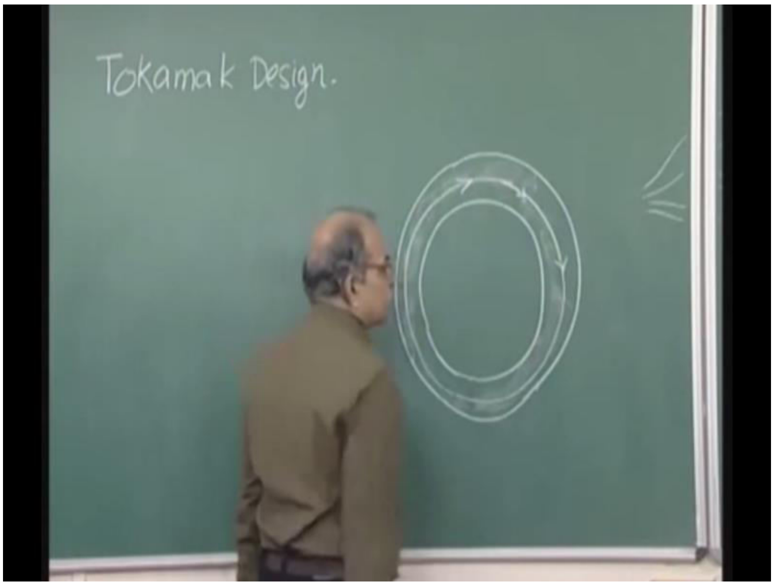

So, the cylinder is bent. So, this is the volume in which you create that plasma at in this volume you try to confine it. So, there are no ends has such. So, that confinement in that direction is automatically taken care of. So, you have cylindrical thing and that whole thing is joint here like tube or Taurus or doughnut of that type and the magnetic field which are needed for confinement are going like this. Just like here. If it is a big cylinder and you are not worried about the end we are only worried about this cylindrical wall then you can create field like this and this field will keep it moving.

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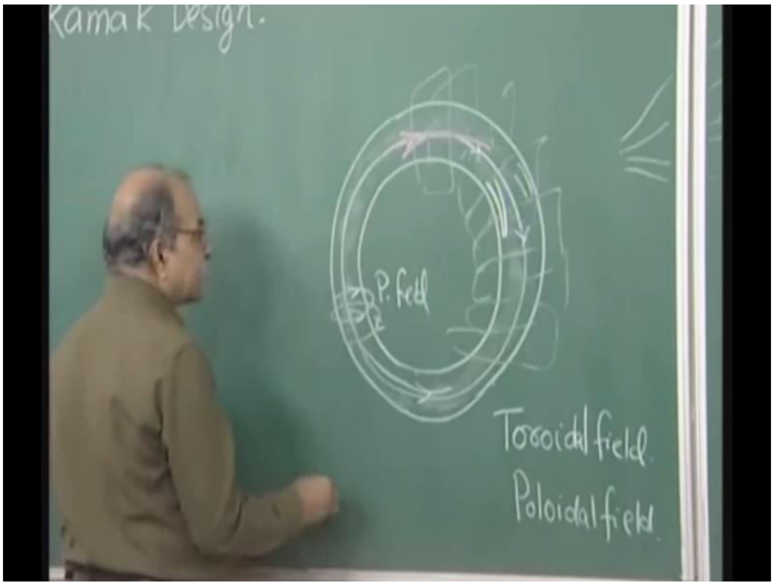

So, similarly, here field of this type and then the plasma will just go around this and will be confined and how to create that field? For that one can put large electromagnets here you can put coils you can put coils around. So, that those coils and pass current and from there the magnetic field can be created but, then in this design there is an inherent problem and that is on the inner side on the inner side the concentrations of this coils will be larger on the outer side it will be smaller because of the radius difference and. So, the field will not be uniform inside this volume the field will be stronger here and the field will be weaker here alright in it if a solenoid a cylindrical solenoid the field is uniform everywhere but, if you have the steroid described and then you put windings there and from there pass a current and produce a magnetic that magnetic field is strong the on the inner side and weaker on the other side and you have seen that stronger magnetic fields tend to push the particles back.

And therefore, this magnetic its magnetic field itself will help these particles to go hit the outer walls on the outer side and therefore, at such more complicated fields are needed. So, what this is known as Toroidal field of course, this is the basic that field very much there toroidal on top of it another field called Poloidal field is added and that field is circling the Taurus like. So, this is the Poloidal field and this type of field can be created by passing a current along this line along the length of this toroid along the length of this doughnut. So, we have a several circles here. So, one circle is for this is the magnetic field, Toroidal magnetic field and then we have another circle here which is say current. So, the combination of these fields properly designed this toroidal field and poloidal field is able to contain the plasma for some reasonable time.

So, this is basic of Tokomak Design and this design is being pursued in India we have in Ahmadabad, Gandhinagar. We have this Indian institute for plasma research where people work on this design the name of that reactor is adhithya where people have studied all these things round the world people have worked on this design. Once it came into light by the soviet scientists in 1968 the current status the current status is that several countries United states, China, India, Japan, South Korea and this Russia the seven European union. These 7 partners have joined hands. It is a big international collaboration almost half the population of the world is represented by these partners and they have now in collaboration building up a machine known as I T E R.

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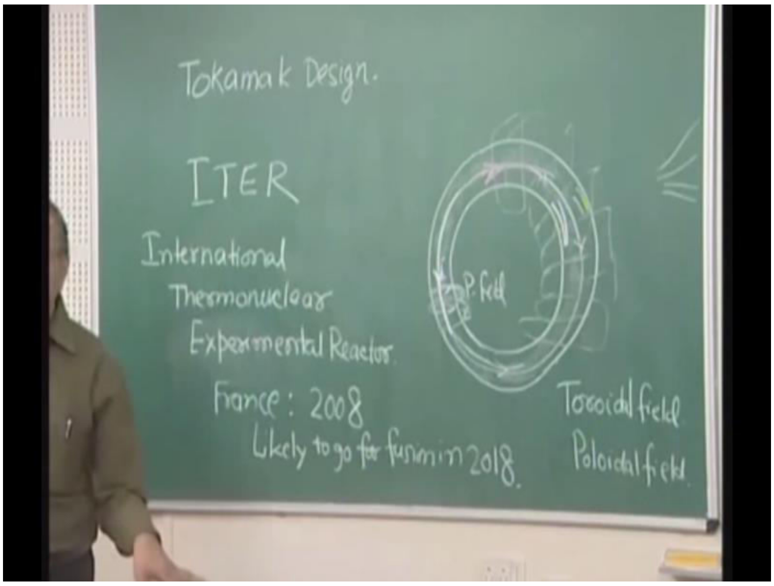

So, International Thermonuclear experimental reactor, so all these partners they are building up different components and this whole thing will be assembled here the status is that it is being constructed in France, the construction that groundwork there and the site started 2008 Likely to go for fusion in 2018. So, the things will start producing fusion power in 2018. So, this is the construction period or the preparation period the partners are doing their job in their places India is also a partner in 2005 India joined this collaboration and that i p r they are working on some kind of this in the currently on the currently operating machines joint this European Taurus J E T.

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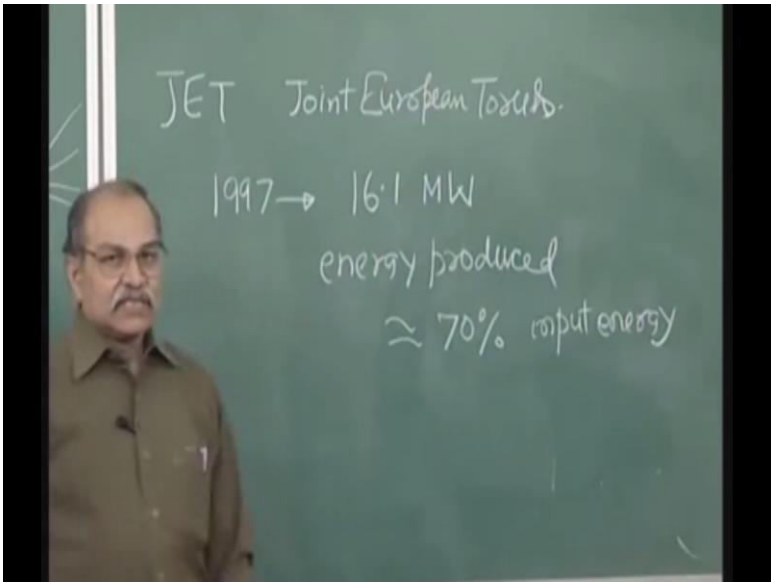

Joint European Taurus working for since, second half of 80s 85 or. So, this is a machine which has says maximum efficiency shown. So, 1997 or. So, it has produced a peak of something like 16.1 megawatt and the energy produced was around 75 70 percent of the input energy given. So, that is the best. So, still the energy being produced by these fusion reactors.

The most advanced types of fusion reactors after 60 years of experience is still not matching with the energy that is needed to heat of the plasma energy that is being input to the machine and this 70 percent 65 7 percent it is taken as a big achievement but, then all these reactors there are many more all these reactors have given a very high level of understanding of this behavior of plasma and controlling the plasma in all those thing. So, finally, the design for I T E R which the scientists have made and which is approved and on which things are going. This is the design if everything works alright. It is the factor that energy output divided by energy input the factor is supposedly it will hit the number 10.

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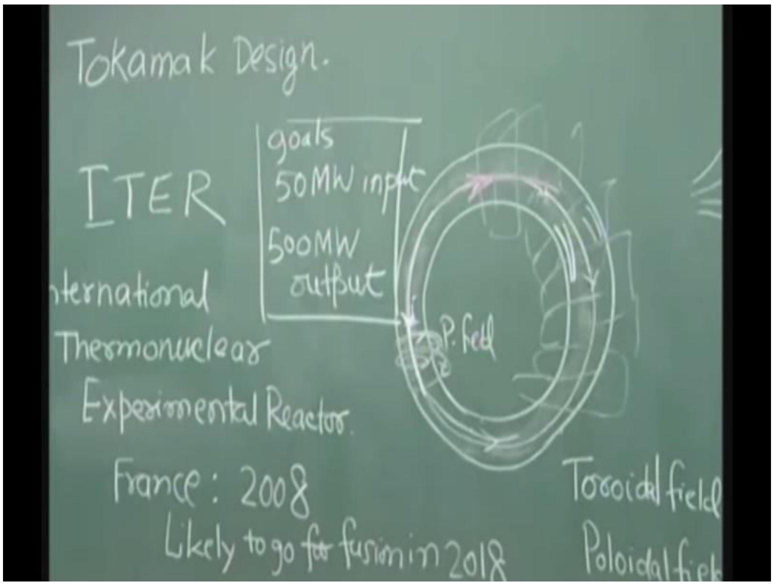

So, this I T E R the goals is that 50 Megawatt input and then 500 Megawatt output so, 10 times. So that is the kind of design have been created to all simulation on all calculation, on the all equations and this and that, it is still experimental reactor International Thermonuclear Experimental Reactor is still not a commercial units to produce electricity.

If everything works out well then the next phase which will starts something 2024 or. So, known as demo, they are it is expected that a prototype commercial fusion reactor will be created and one can expect real output somewhere in 2050 or. So that the current scenario of nuclear fusion reactors but, people are very enthusiastic because the they have come a long way and now the kind of understanding and the controls in the engineering that has been developed through various reactors working in different parts of the world.

This particular design has been made and it is expected that they will succeed in doing that and if it happens like that it will be a big thing for our planet, because this will be a source of energy where the fuel will be abundant where the radioactivity problems will be small and all kinds of ever increasing energy demands can be met. So, that is how it is it is going. So, with that I will close this thermonuclear reactors terrestrial thermonuclear reactors next lecture I will go how fusion takes place in the sun no scientists working there and still the sun is the or the starts are the best nuclear fusion reactors where hydrogen is being converted into helium and fusion energy is being produced for billions and billions of years. So, how that sun works, how the star works little bit of nucleosynthesis little bit of nuclear astrophysics that will be our next chapter.