Plasma Physics
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Module No. # 01
Lecture No. # 27
Auxiliary Heating and Current Drive in Tokamak

Today I would like to discuss auxiliary heating and current drive in Tokamak. Probably, this will be our last talk on Tokamak.

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Today, we will discuss, we will begin rather with the overview of Tokamak operation that we discussed in some length last time. We will go over to radio frequency current drive in Tokamak, radio frequency heating in Tokamak. Then, neutral beam heating in a Tokamak and finally, I would like to give you a perspective on international thermonuclear experimental reactor called heater which is being built in France.

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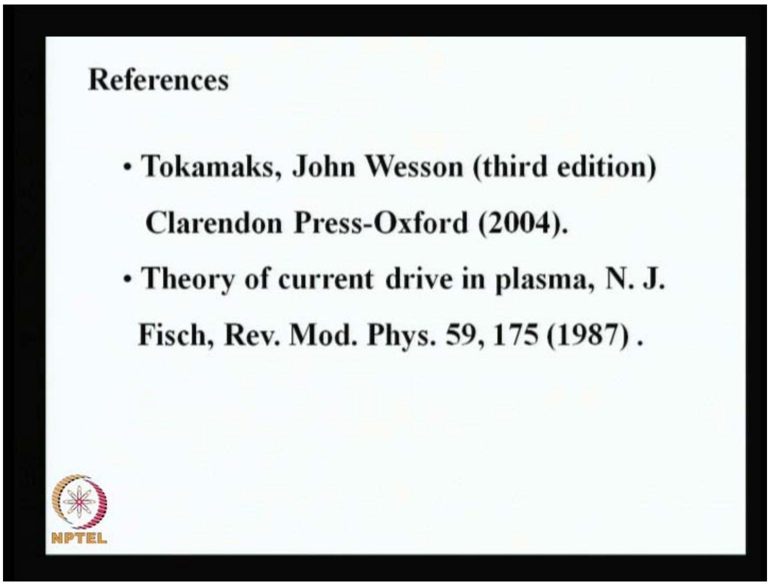

Well, these will be the references for today's presentation.

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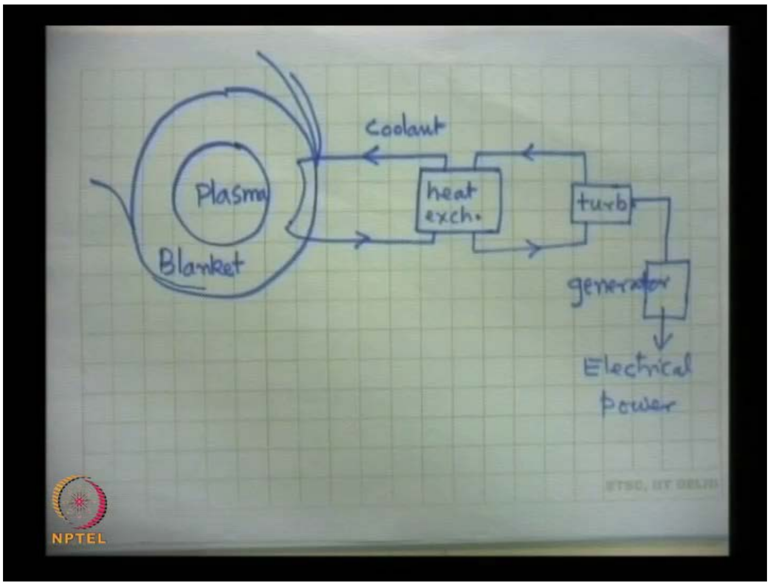

Let me begin with an overview of Tokamak operation. Tokamak well the cross section of a Tokamak I can simply build like this make like this and this would have a plasma in the center. So this is a plasma here and obviously this is something system is going like this and this is blanket. So in the plasma which was deuterium tritium mix when the thermal diffusion reactions produce neutrons and alpha particles you would be aiming at observing the alpha particles within the plasma to sustain the burn.

Whereas, the neutrons cannot be observed and they will be moving out of the plasma; so this will be primarily a lithium blanket and that will absorb the neutrons and get heated. So, this becomes like a heat reservoir and some coolant will transfer heat from here into what we call as the heat exchanger. In this, there will be a coolant which will be coming bringing here and connecting taking heat from here into here; so, this is a coolant and this is, we call heat exchanger. Well, this has to be coupled to a turbine because, this heat energy has to be converted into mechanical energy so we would like to connect this to a turbine and that will be so this is turbine and this will be connected to a generator so this is generator that will convert the mechanical energy into electrical energy, this is electrical power.

Our physics has been primarily focused on the plasma; how to confine the plasma; how to heat it to a required temperature of 10 KeV and how to drive a current that is essential for confinement to the plasma.

So, always keep this in view that we have to sustain a burn by alpha particles. We have to confine the plasma by a mix of a toroidal magnetic field and a poloidal magnetic field. So, the system is going to have, is going to require a current typically of the order of several mega amperes. Now, how can we do this by using waves or particles launched from outside?

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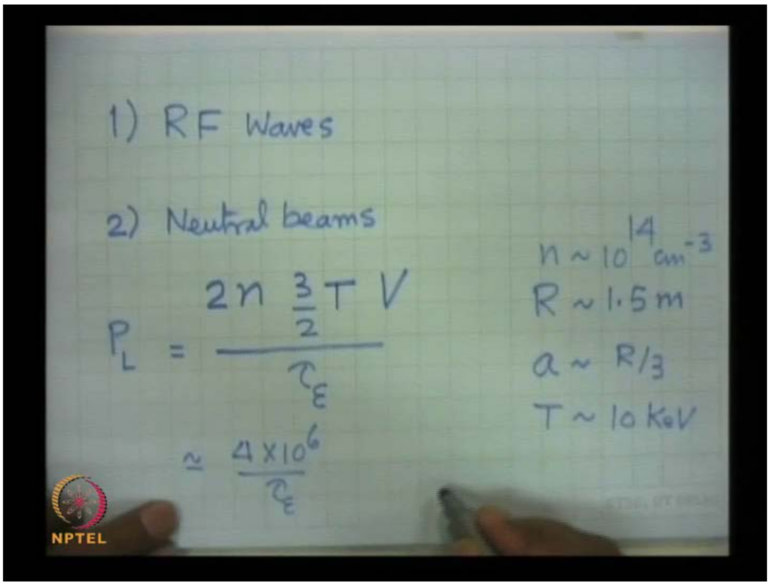

If you want to do this well, this is really done in two ways one by radio frequency waves they can drive a current in the plasma and they can also provide additional heating because, yesterday we learnt that ohmic heating can heat the particles up to a temperature of about 1 or 2 degree 2 KeV; but, the goal is 10 KeV. So, additional heating is required this can be provided by radio frequency waves or by neutral beams. Neutral particle beams are required because charged particles cannot penetrate the Tokamak as they will have to cross the lines of force to reach the center of a Tokamak of plasma. Charged particles will experience a lorentz force and they will not penetrate hence neutral beams have to be launched into the system if at all particles have to be launch from outside.

Today, we will discuss the efficacy or effectiveness of these two systems radio frequency waves; well, are primarily electromagnetic waves that are launched from outside and once they reach into the plasma they can mode convert themselves into electrostatic waves some of the waves can mode convert themselves into electrostatic waves for which magnetic field is very weak but, the electro field is primarily in the direction of k vector of the wave but, those wave waves can effectively heat the particles we shall learn some aspect of that process.

But before that, let have some estimate what kind of powers are required in a Tokamak. We are going to have particles with electron and ion based is equal to 2 n; n is the density of electrons and n is also the density of ions deuterium tritium ions. So, 2 n is the total number of particles and each particle is going to have 3 by 2 into T where T is the temperature of the particles as the kinetic energy of each space of each particle.

So, this is the total energy density in the plasma. if I multiply this with the volume of the plasma then, this quantity is the total thermal energy contained in electrons and ions in the plasma and if this is lost in a time of the order of energy confinement time tau E then, this is the power lost in the system from the system per second. So, this is to be replenished this to be provided by the R F or by the neutral beams.

Once the ohmic heating is removed this is the power that has the R F is to provide if I put typical parameters like R of the order of 1.5 meter major radius minor radius of Tokamak around R by 3 like aspect ratio is 1 third then this quantity turns out to be typically if I put the numbers and T temperature is equal to 10 KeV density around 10 to the power 14 per centimeter cube. Then, this number turns out to be around 4 into 10 to 6 upon tau E if this is in seconds then this is in watt. So, you require if I take tau E around 1 second then you require this about 4 megawatt for heater kind of Tokamak where the volume is much larger one should envisage powers typically of the order of 100 megawatt.

So, we are targeting particles particle beams or neutral beams or radio frequency waves with powers of the order of 100 megawatt. So, powers that we are requiring is 100 megawatt; now, if we are using neutral beams then the power.

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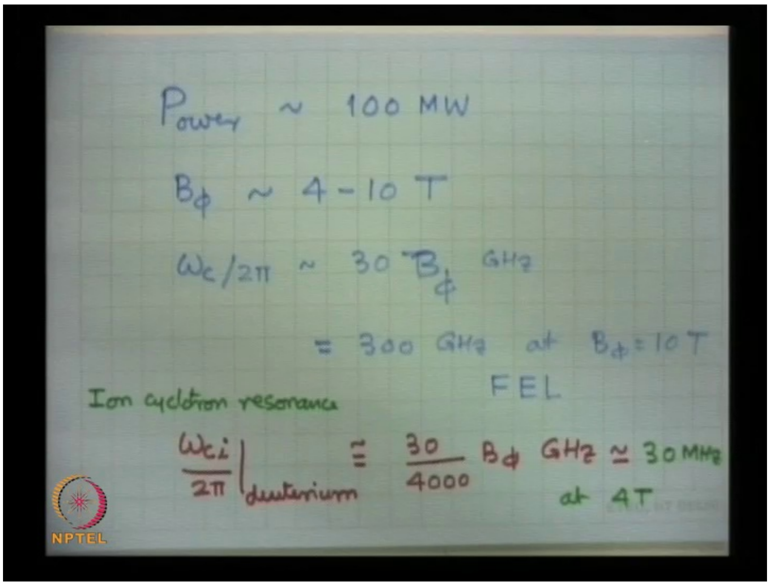

Power required is typically in the domain of 10 to the 100 megawatt radio frequency sources of such high power exist in the microwave range they also exist in the millimeter wave range and they also exist at lower frequencies so this part is we are comfortable at least as the with the availability of powers.

Now let me typically mention that these plasmas have magnetic field B phi and B p B p is a smaller poloidal magnetic field is a smaller and B phi is in the range like 4 to 10 tesla so total magnetic field in the system is around this and this corresponds to a electron cyclotron frequency omega c upon 2 pi so that it becomes in hertz around 30 T in gigahertz if I choose sorry, at 1 tesla sorry, let me put this B phi 30 B phi.

So, if I choose the magnetic field in the Tokamak as 1 tesla this will be 30 gigahertz if I choose like 4 tesla then this will be 120 gigahertz. 120 gigahertz is in millimeter wave of about one fourth centimeter wave length. Conventional Clive stones, magnetrons, do not operate at the xi frequencies even travelling wave it does not operate so one has to go for gyrotron. If you want to go to 10 tesla Tokamak, Tokamak with 10 tesla magnetic field then this will be 300. So, this is equal to 300 gigahertz at B phi is equal to 10 tesla which is a very high frequency like 0.3 giga terahertz and a device that can produce power radio frequency power at the psi frequency is primarily free electron laser. But, if you are operating a Tokamak at 4 tesla magnetic field and if you want to use electron cyclotron resonance or waves of frequency close to electron cyclotron frequency then, one should aim at frequencies around 120 gigahertz some gyrotrons can operate that those frequencies and the efficiency of gyrotron is also quite high. So, I think we have reasonable reasonably efficient sources of power at electron cyclotron resonance frequency.

However, if you are interested in heating the ions via ion cyclotron resonance then, the ion cyclotron frequency, there are two kinds of ions in Tokamak deuterium tritium. Suppose, I want for deuterium then this quantity would be mass ratio times is smaller so this will be mass ratio is typically 4000 as compare to proton electron mass so this becomes 30 upon 4000 B phi so if am having a Tokamak with 10 tesla magnetic field this will be 300 upon and this is in gigahertz.

So this will be typically of the order of a 10 tesla may be let me call it 4 tesla. At 4 tesla this will be 4 will cancel out with this 4 and this will be 30 divided by 1000. So, 3 by 100 3 by 100 gigahertz; so this will be 30 megahertz I guess at 4 tesla magnetic field I think. If I put B phi is equal to 4 4 will cancel out 1 0 will cancel out. So, this becomes 3 upon 100 gigahertz or 30 megahertz which is right so then, you should be aiming for ion cyclotron resonance ion cyclotron resonance. If you want to choose the radiation frequency close to ion cyclotron frequency then you require a radio frequency wave of frequency about 30 mega hertz.

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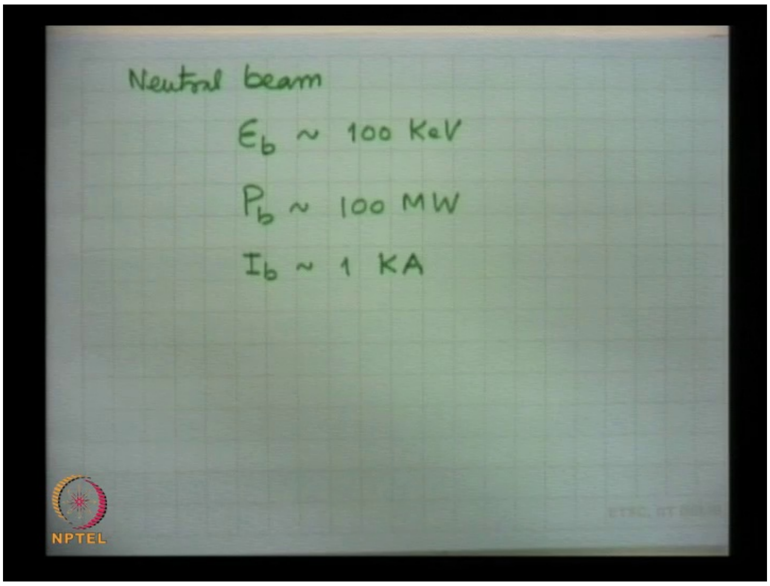

One can also choose alpha waves whose frequencies are smaller than this frequency. Now, as far as neutral beams are concerned, neutral beams typically have beam energy E b of the order of 100 kilo electron volt. Normally, people produce deuterium beams or hydrogen beams ions neutralized deuterium typically and the beam energies are around 100 KeV or less 80 90 KeV; something like that is the kind of beam energy.

If you want to produce beam power of the order of 100 megawatt then the beam current you can estimate this will be about a kilo ampere typically because, it is the product of these two that gives the power. So, we are really talking about neutral beams of very large currents.

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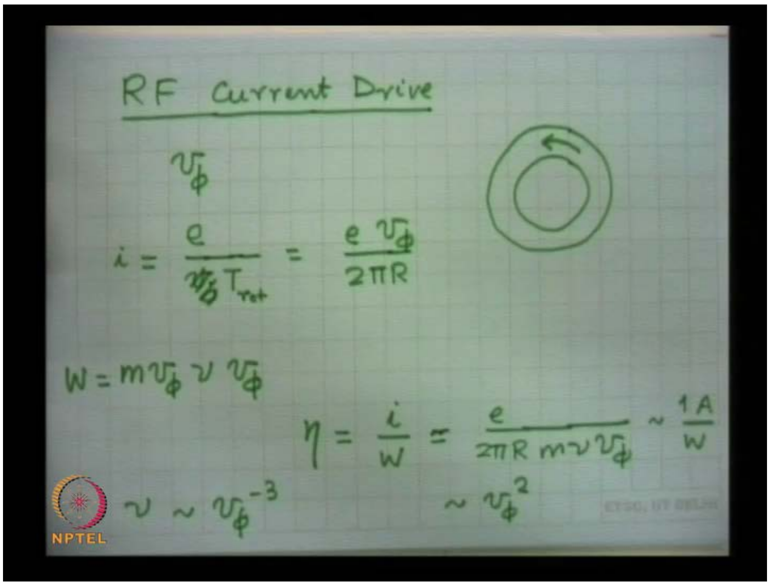

Now, before I go into the neutral beam heating, let me talk something about the current drive by using R F in the plasma R F current drive. Yesterday, I mentioned to you that in a Tokamak I you want to drive a toroidal current. Then, it will be preferred if the current is carried by energetic particles the particles which gyrate, which rotate with the velocity v phi in the toroidal direction; this is called toroidal direction then a particle of charge e magnitude wise and moving with velocity v phi.

Well, not v phi rather covering one circle in time T will produce so much current in the system, a charge particle of charge e if it is rotating making one circle complete in time T. so, this I called as rotation time T r rotation period then and this can be written as typically e upon 2 pi R upon v phi because, the time it takes to go round once is equal to the distance as to cover divided by the velocity along the line of force; so, typically this is the quantity.

So, current is proportional to velocity and these electrons suffer collisions and I mentioned the sp collisional drag was m v phi is the momentum which is lost in one collision and if there are nu collisions per second, so much is the momentum lost by these particles via collisions and this is the kind of momentum should be supplied to the electron per second. Means, so much force must act on the particle and the distance travelled by the particle per second is v phi. So, this is the kind of energy lost by the agency that is providing momentum to particle.

So, this is the work done; this is the current drive by single particle and this is the energy given to single particle per second. If I derive the 2, divided the 2 in the efficiency of current drive which is the current divided by the energy lost. This is equal to divide the two and you get this is equal to e upon 2 pi R R is the major radius of the Tokamak into m nu into v phi. Since, nu goes as v phi to the power minus 3; hence, this efficiency of current drive goes as v phi square hence its always preferable to have current driven by the fast electrons and typical values that you can achieve by this if the current is driven by 100 KeV electrons. Then, this efficiency can be of the order of 1 ampere per watt which is very reasonable thing that has been achieved also.

So, if you want to drive a 100 say 10 mega ampere current then you require 10 megawatt R F power. This is what I want to convey here if the energy is the positive in fast electrons. So, that is something to be kept in view and if you look at the distribution function of electrons in a Tokamak.

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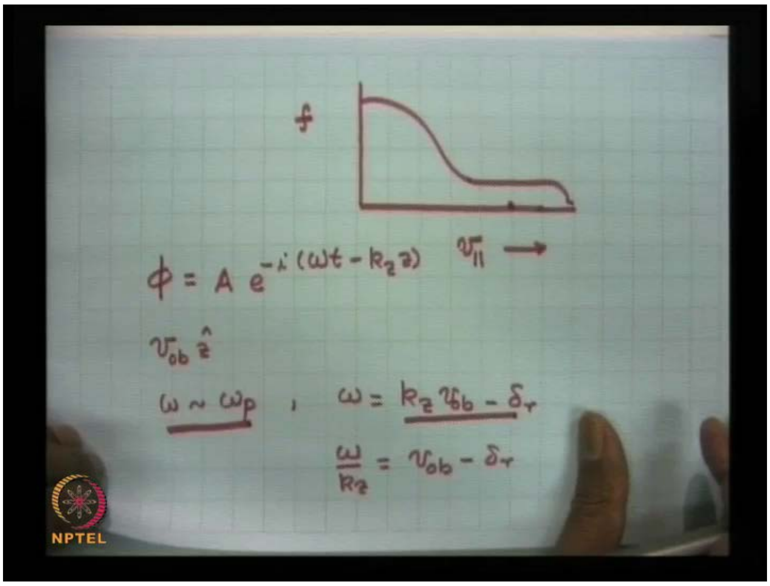

Let me plot here f versus v phi v phi normally we call in plasmas v parallel because, this is parallel to the phi direction or azimuthal magnetic field direction, the distribution function if it is a Maxwellian it will be like this. However, in Tokamak the distribution function has a longer tail and these are the high velocity particles that they carry that carry effective with the current and what you want is that the radio frequency wave that you want to launch from outside should deposits its momentum and energy on particle which are here means it should resonantly interact with particles with large v parallel.

Now, when we were doing the when we were discussing the two steam instability we mentioned that if there is a wave plasma wave and plasma wave we consider of this form phi is equal to some amplitude A e to the power minus i omega t minus k z z and we consider the propagation of an electron beam of with velocity v 0 b also in the z direction. Then, we found that the wave can be driven unstable if omega is close to omega p which is the natural frequency of plasma oscillation or plasma wave and also when omega is simultaneously equal to k z v 0 b or slightly bigger than this more slightly bigger rather slightly less than this minus we called as some delta r slightly less than this.

The reason was that when the phase velocity of the omega by k z was is equal to v 0 b minus a small quantity then, the electron deposits energy on the wave in the other case when omega by k z which is the phase velocity of the wave is more than v 0 b. in that case, reverse happens means energy goes from the wave to the particle sorry sorry sorry yeah.

Instability occurs when the wave amplitude grows and beam has to move faster than the wave. So, what you really require that for resonant interaction this condition should be satisfied and wave frequency should be close to some normal eigen frequency in the system normal frequency of any electrostatic wave in the system in a unmagnetized plasma. There are only three kinds of waves (( )) wave, ion acoustic wave and electromagnetic wave is a transverse wave which cannot be driven unstable by an electron beam. So, it is only the there are only two electrostatic waves; one is a high frequency electrostatic wave called plasma wave or linear wave and the ion acoustic wave is a low frequency wave whose frequency is less than the ion plasma frequency. So, you have very limited choice however a Tokamak there is a magnetic field.

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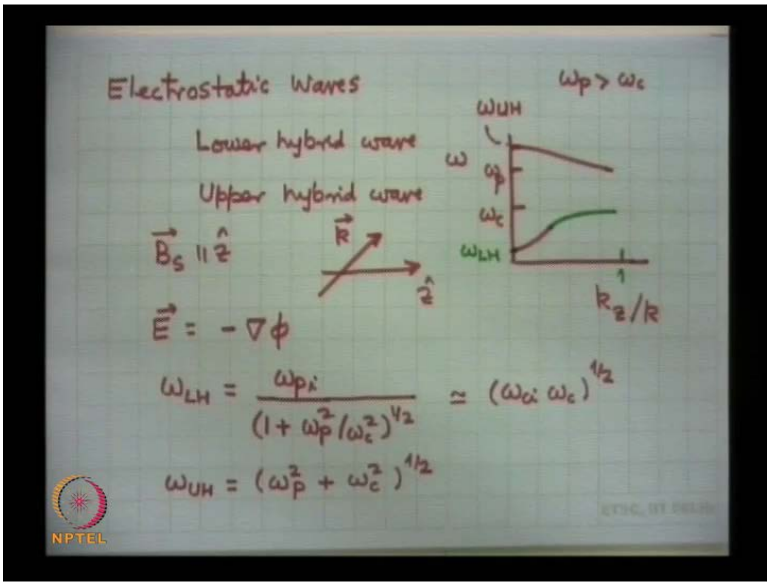

Magnetic field allows a much larger verity of electrostatic waves in the plasma and there is some beauty in that. Let me mention something; first of all, the linear wave breaks into two branches one is called lower hybrid wave and upper hybrid wave. Lower hybrid wave has an interesting property; if I choose a plasma of plasma frequency greater than cyclotron frequency and plot the frequency of this mode lower hybrid wave as a function of say k. well, if I consider a plasma in which there is a magnetic field in the z direction static magnetic field. So, suppose this is the direction of a static magnetic field and my wave is going at some angle so this is the k vectors of wave it is a electro static wave whose electric field I express as minus gradient of some potential phi.

Suppose, this moves some angle so this I choose as my z axis the direction of static magnetic field and wave travels at some angle. So, if you plot k z by k of this wave this is suppose omega p somewhere this is suppose omega c; somewhere this wave when k z is 0 has a very low frequency and the frequency becomes large when k z becomes 0 sorry opposite I am sorry; I made a mistake omega c is large here I think let me remove this portion is not at k z equal to 0. These waves have a frequency well k z equal to 0 means k is parallel to perpendicular direction and this is all right and this goes from here to this then this is unity here.

So, there is a frequency here which is called lower hybrid frequency omega L H and the upper hybrid wave if I plot dispersion relation here and we shall do it someday then it varies between two frequencies ranges it is starts from somewhere called upper hybrid frequency and goes like this. This is the frequency called upper hybrid frequency omega U H now these quantities omega L H and omega U H are simply symbols omega L H is symbolically written for this quantity called ion plasma frequency divided by 1 plus omega p square by omega c square to the power half where omega p i is called as the ion plasma frequency omega p is the electron plasma frequency and omega c is the electron cyclotron frequency.

So, in a plasma where omega p is much bigger than omega c i can ignore this one and this quantity then takes becomes equal to omega c i and omega c under root where omega c i is the ion cyclotron frequency and omega c is the electron cyclotron frequency so this the hybrid between the two frequencies. Whereas, upper hybrid frequency omega U H is equal to omega p square plus omega c square under root so this is higher than omega p and omega c both.

So, the plasma wave which has a frequency in equal plasma equal to omega p splits into two different waves with very different frequencies. Actually, this is a new mode that appears well the dispersion relation. Probably, we can derive this later; we have to discuss these waves in detail in some separate lectures. But, for today's purpose I would like to emphasis that a plasma supports a much larger number of waves. These two waves I simply mentioned because they are related to or similar to electron plasma wave or linear wave. But, then at lower frequencies you get a new verity of waves called ion cyclotron waves ion busting waves we also get electron busting waves and so on so plasma has a ( ) magnetized plasma, is very rich in wave phenomena and any of these waves can be employed for plasma heating. Now, let me mention what are the basic requisite for resonant wave particle interaction, we already got a clue that a beam moving with a such a velocity that the frequency of the wave as seen by the particle is nearly 0.

Then, we say that the particle is in phase synchronism with the wave and it can very effectively exchange energy with the wave. So, the main requirement has been that find a frequency that some moving particles in the system either electrons or ions they see the wave to be some sort of a electro static wave or effective frequency is 0.

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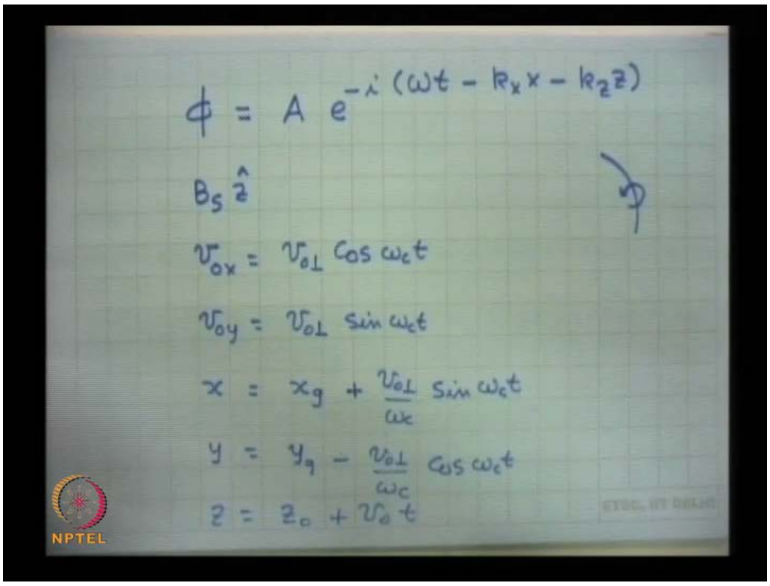

Now, let me consider a wave in the plasma electrostatic wave in the plasma with amplitude a exponential minus i omega t minus k x x minus k z z.

Suppose, I create a wave in the plasma via mode conversion from an electromagnetic wave launched from outside in the plasma it has become a this kind of wave. Now, if the system has electrons which are gyrating about the lines of force because, there is magnetic field is here. So, the electrons are gyrating about the lines of force; they are going like this and we had solved for the equation for electrons in a straight line geometry when the lines of force are straight we found that if the system has magnetic field along z axis. Then, the particle trajectories were something like this particle velocity was 0 th order velocity was v 0 x is equal to v 0 perp cos omega c t where omega c is the electron cyclotron frequency. V 0 y was v 0 perp sin omega c t x was guiding center coordinate plus v 0 perp upon omega c sin omega c t y was y g minus v 0 perp upon omega c cos omega c t and z was equal to some constant plus v 0 into t so this is representation of particle trajectories particle coordinates when there was no wave now these particles when they see a wave obviously if the and suppose the wave amplitude is very low then we say that x will be modified y will be modified z will be modified velocities will be modified is just a little.

But, primarily the x coordinate of the particle because its changing with time originally and consequently the field or potential of the wave as seen by this electron will have x as a function of time put this x in here put this y in here there is no y here so do not have to use this but, put this z here then we will find that there is a time dependence not only coming through frequency through this omega t term it comes through here as well as here. So, effective frequency of the wave is no longer omega; it is modified because of dependence of x and z on time let me use these two in here.

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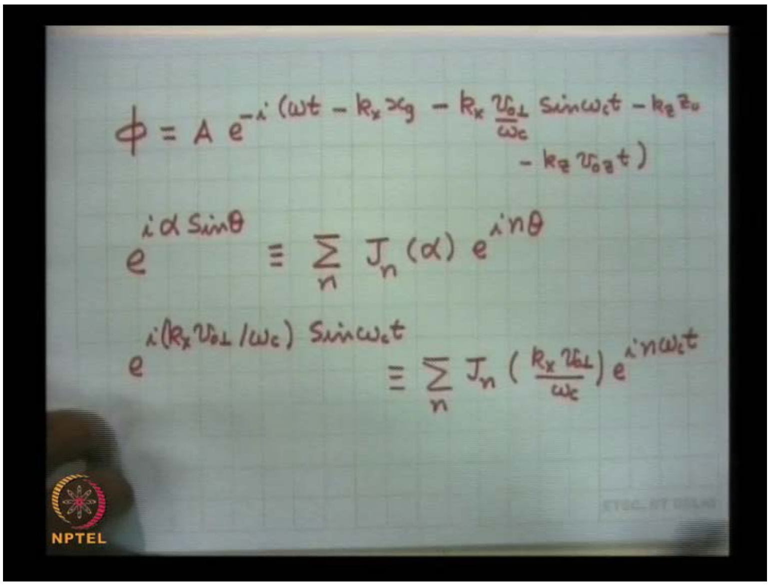

The problem would come that when I substitute this say, here let us see what do I get my phi becomes the potential of the wave as seen by a moving particle. The gyrating particle rather becomes a exponential minus i omega t remains as such now this k x x term becomes minus k x into x g then there is a term here minus k x v 0 perp upon omega c into sin omega c t. then, this is k z then z 0 minus k z v 0 z into t these are all in exponents exponential.

What you can do? Combine this t term with this t term but, this is a term which is little complicated because in the exponential your getting sin omega c t but, there is a identity called vessel function identity that, whenever you have a term like this I alpha sin theta this you can always write as a sum over integer n which goes from minus infinity to plus infinity vessel function of order n and argument alpha exponential of i n theta.

So what you get here this term is getting exponential of I k x v 0 perp upon omega c into sin omega c t. This will be how much this is like alpha and this is like theta, this becomes summation over n J n of k x v 0 perp upon omega c exponential of i n omega c t means this term is equivalent to many terms having their frequencies time dependence at multiples of cyclotron frequency 1 omega c, 2 omega c, 3 omega c, etcetera and n can take negative integer values.

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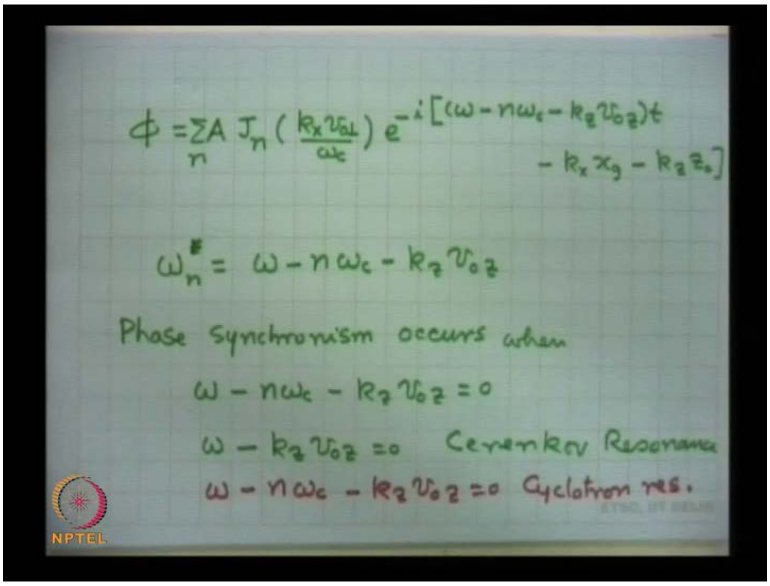

Also, when I substitute this expansion in here then expression for phi becomes your phi turns out to be equal to A or rather summation over n many terms A J n of argument k x v 0 perp upon omega c and the frequencies turn out to be exponential minus i omega minus n omega c minus k z v 0 z into t and minus k x x g minus k z z 0. This is the kind of expression we get for phi. My main point was that a wave of frequency omega when viewed by a gyrating and moving electron the frequency is no longer omega. But, it is omega dash or omega n rather I will call omega n which becomes omega minus n omega c minus k z v 0 z.

If you can choose your particle velocity v 0 z and n in such a way that this becomes a 0 then, we say that for the particle the wave field will appear like a d c field and so phase synchronism will occur. Synchronism occurs means the particle will all the electron will always see the field as a d c field when omega n is 0 so omega minus n omega c minus k z v 0 z is equal to 0 obviously for all n this cannot be satisfied simultaneously for some particles moving in some velocity v 0 z this will be satisfied for some specific value of n.

When this is satisfied for n equal to 0 case then we call this resonance cerenkov resonance this is called cerenkov resonance and when this is satisfied for n equal to 1 then we call this cyclotron resonance omega minus n omega c minus k z v 0 z is equal to 0 we called it cyclotron resonance.

Important thing of the magnetic field, please note, when there was no magnetic field this was missing. So, magnetic field opens up a new possibility of several resonances corresponding to different values of n. however, these resonance are significant only when the argument of the vessel function is significant. So, v 0 perp is what in a thermalized plasma Maxwellian plasma electrons and gyrating different electrons are gyrating with different velocities so, me typical average velocity I can take to be like thermal velocity.

So whenever k x v thermal upon omega c is comparable to one not too small if it is too small then only n equal to 0 term survives other terms are not important so what you require is that this should be significantly comparable to unity or bigger when this is comparable to n then this is very substantial. So, if the, if I want this equation to be satisfied for n th harmonic cyclotron harmonic then, I must choose those waves for which k x v 0 v thermal upon omega c is comparable to n if possible.

You can achieve this condition for ion cyclotron ions also and consequently those waves for which this condition is satisfied for ions. They can directly heat the ions and which is what ion cyclotron waves or ion hybrid waves do. So, this is an important thing that we should keep in our head that if you want to derive current then, you are expecting to rather you want the energy to be deposited into on the electrons and hence this kind of conditions should be satisfied on electrons because, this condition will be satisfied with electrons of lower velocity. This will be satisfied on electrons of larger velocity so this is a more preferred condition.

However, people have employed this condition as well. So, depending on at what value of k z the wave is launched the interesting thing is that you can preferentially deposit your energy only on those electrons for which this condition is satisfied. If there is a spread in velocity distribution of electrons then only those electrons will be satisfying this condition for which the velocity v 0 z is omega by k z and if I choose my lower hybrid wave for instance with omega by k z around half c by 2 half the right velocity then v 0 z will be like c by 2. Those electrons with v 0 z equal to c by 2 will be absorbing the lower hybrid wave preferentially and hence, they are the ones that are needed for current drive.

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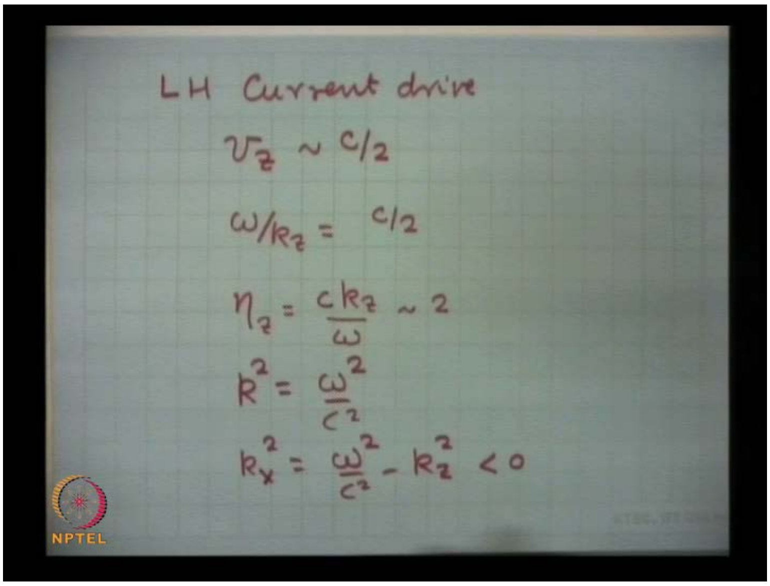

So, for lower hybrid current drive what we require is v z of the order of c by 2, which is something electrons like 100 KeV electrons. For this you will require omega by k z equal to c by 2 and this corresponds to eta z or eta parallel that we call as which is defined as c k z upon omega. This should be around 2; there is a serious matter in free space if you launch a wave then, k z suddenly is less than omega by c any component of k cannot be more than that. But, if you have this kind of situation then other component of k x will like k x will be imaginary because, k square and free space is equal to omega square by c square. So, this is k x square plus k z square if I write then this requires k x square is equal to omega square by c square minus k z square and that will be less than 0 because k z is too big. How will you create this kind of wave this is normally done by using a phased antenna array?

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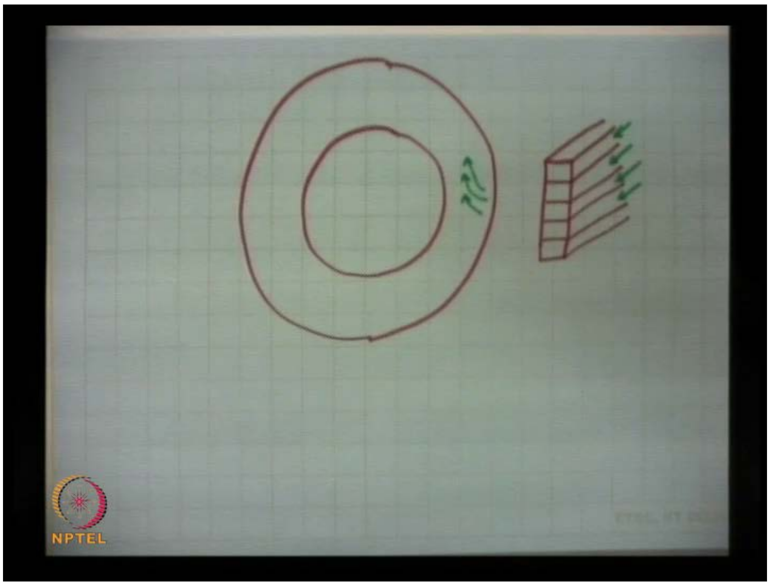

So, if you have a Tokamak like this in which you want to drive a current then you have a wave guide array here wave guide array here which is essentially not a single wave guide array of many wave guides this this this this these wave guides are travelled like this.

In the successive wave guides, you are launching waves in every wave guide wave is coming but, they are in not in the same phase. So, this wave coming in this wave guide will have one phase the wave coning in the second wave guide will have different phase the one in the third one at a different phase and so on. So, by properly phasing these wave guides you can make your wave that is launched here to travel in a particular direction like this, the wave is evanescent from the except to the wave guide to the plasma but, right when it enters into the plasma it becomes a propagating mode and this can heat the plasma. I think details of this scheme we will discuss when once we have discussed the electrostatic waves in plasmas, magnetize plasmas and that we should do later.

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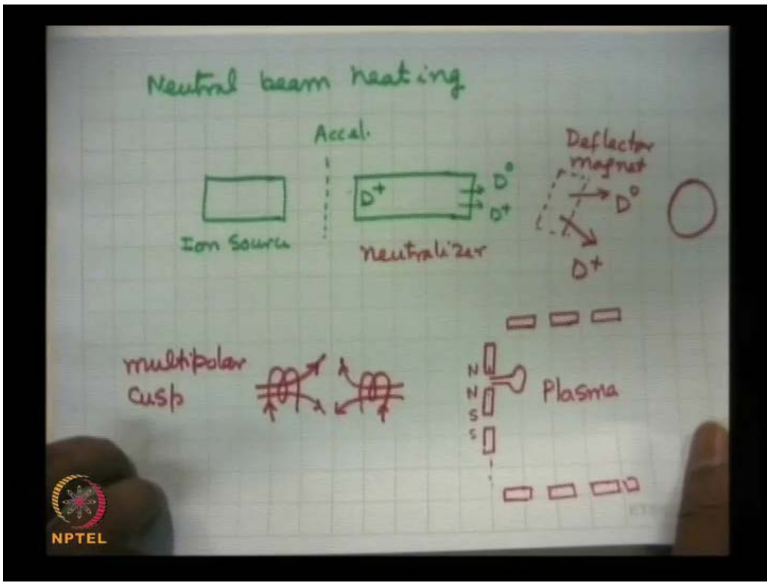

I will keep this discussion to a later stage but, let me now mention about neutral beam heating for, neutral beam heating usually one employs deuterium beams and the system is something like this. you have an ion source here; this is ion source or deuterium source and there is some accelerator here a negative grid with large potential difference so that the ions are pulled with the large velocity and then this is a charge exchanger or neutralizer in which deuterium ions enter here from this ion source. Deuterium ions are pulled; this is the accelerator and these ( ) are then actually neutralized. So, from here you get two kinds of particles. One of them are neutral deuterium atoms and then some deuterium ions are also residual ions are there. So, you pass this mixture through a magnetic field which I will designate like this is called deflector magnet deflector magnet and that will make the D 0 uncharged deuterium atoms to travel like this. so, D 0 goes like this and then they hit the plasma here.

So, plasma is somewhere, Tokamak plasma is somewhere there; whereas, the ionized deuterium or deuterium ions will be deflected out. This is called neutralizer or charge exchanger and the ion source has a very typical structure; it is called a multipolar cusp. Let me tell you what is a cusp if you have a coil magnetic field coil like this which carries current in one direction and you have another field coil that has current in the opposite direction. Then, the lines of force here will be like this; they will be diverging and from here they will be in the opposite direction so the lines of force are like these; this is called a magnetic cusp.

Magnetic field is quite small in this region; large all around. So, this is called a simple magnetic cusp and what kind of ion source you have? you have a large number of permanent magnets with north and south pole opposite to each other; so you have this structure here you have many these bar magnets with opposite polarities like, if this is north here then this is also north here; this is north here this is also north here. This is south here; then, this is also south here and so on. So, place time in such a fashion many in such magnets.

Then the magnetic field that they produce in this region is called multipolar cusp b field and hot wire cathodes are mounted in between these regions. So, they produce hot wire cathodes are they like these. You have to mount them in between these two; this a hot wire cathode comes in here. So, you pass a current through this wire and then the electrons are emitted and that gets ionized. So, a plasma is formed here and from the plasma this deuterium plasma you form here and deuterium ions are pulled and then you get this beam; so this is a schematic of this.

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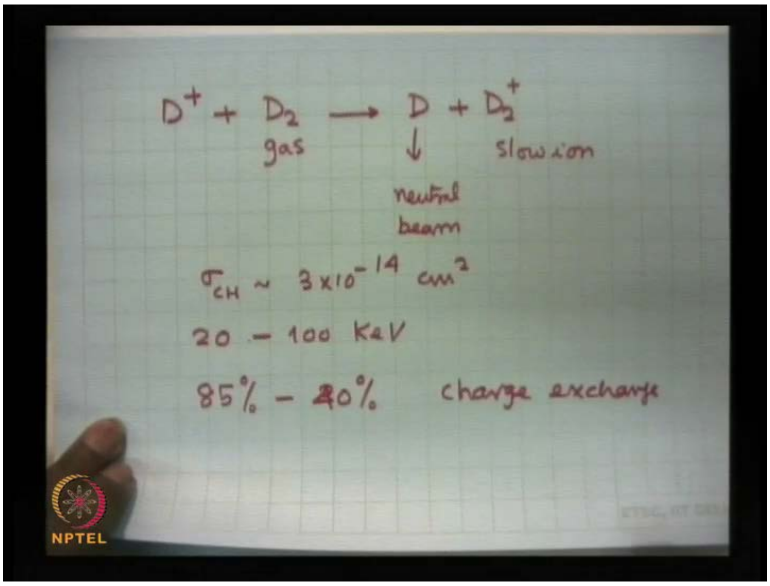

Now, the physics is rather simple. First of all, the neutralizer what does it do in a neutralizer the deuterium ions collide with deuterium gas molecules and they undergo exchange collisions. So, this produces deuterium without any charge plus D 2 ion is created like that. This is slow ion because the molecule was slow; only the electron has been transferred from deuterium molecule to deuterium ion. So, this is energetic particle this is the required neural beam this forms actually neutral beam and the typical charge exchange cross section is around three into 10 to the power minus 14 centimeter square and roughly.

Well, this is actually sensitive to energy this is the probably the maximum value I am saying that if you are having energy in the energy range, deuterium ions in the energy range 20 to 100 KeV. Then, you get 85 percent ions getting neutralized when they merge. Otherwise, when the energy is increased then this reduces to above 40 percent charge exchange. This is the efficiency of charge exchange 85 percent ions will get neutralized if the energy around this. But, the typical energy is required for Tokamak neutral beam heating are around 100 KeV. So, I would say that roughly half the ions get neutralized so you get a neutral beam.

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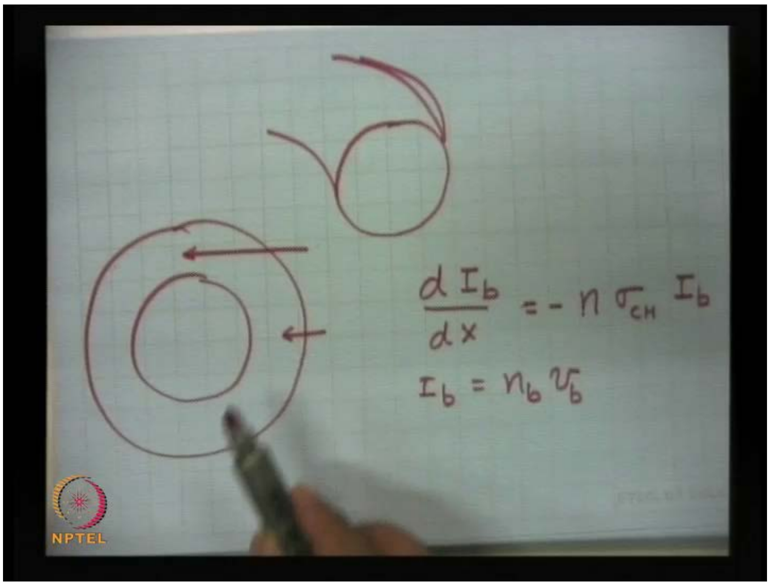

Now, these ions when they enter into the Tokamak plasma you have a Tokamak somewhere here. This is the cross section of a Tokamak sorry, Tokamak is like this. This is the torus this is a cross section of a Tokamak. You can launch neutral beam either tangentially actually let me just draw a another picture here this is important cross sectional wise you see from the bottom the Tokamak will look like this.

What you can do if you launch your neutral beam here? It will have a long distance to travel. You can launch this neutral beam through here or you can launch your neutral beam through here. If you are launching neutral beam like this then it has only very small distance to travel. Obviously, this also quite large but, this has a much larger distance so it is preferable to launch your neutral beam through here and in this the neutral beam as you travels it will loses its energy and if neutral beam current I define I b then as it travels in this direction let me call the direction as x some direction x then this is equal to minus the density of neutral beams into charge exchange collision cross section into beam current I b. I am defining a quantity which is the product of beam density multiplied by beam velocity this n is the density of ions so the neutral beam as it travels will lose its energy and typically in a distance of about 30 centimeters it loses complete energy so the neutralize the neutral beam that you launch you can cross plasma can cross the magnetic field and reach the main body of the plasma and then it gets totally ionized and then it is can deposit primarily its energy on the ions; so this is a very important scheme of plasma heating.

I think all supplementary heating schemes will employ neutral beam whether it is a heater certainly is in (( )) using neutral beam heating and other devices also. All experimental Tokamaks are large sized. Tokamaks are employing neutral beams for heating and I think I will stop at this stage; thank you.