Plasma Physics

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IGNOU

Module No. # 01

Lecture No. # 39

Diffusion in Magnetized Plasmas

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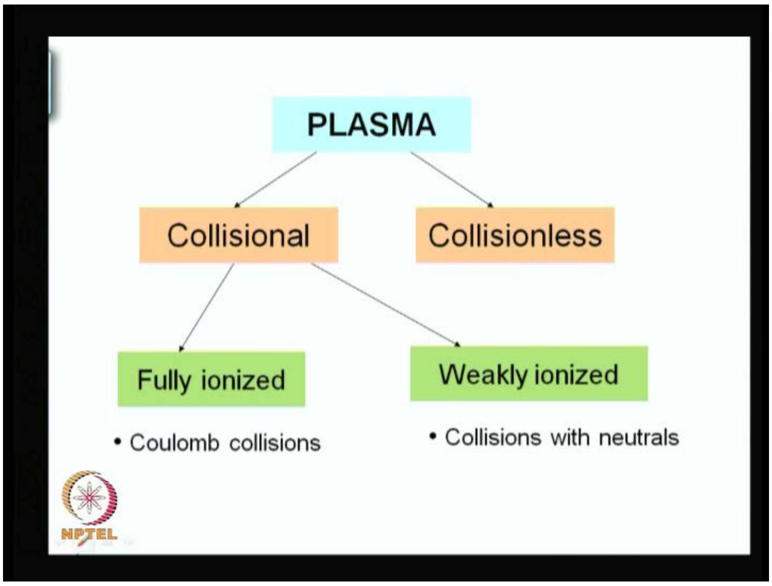

Today's lecture, lecture 39 is about diffusion in magnetized plasmas. If you recall the previous lecture 38 you will remember that we have taken up the case of collisional plasmas, and we have discussed weakly ionized plasmas but, without magnetic fields.

So, we have seen the effect of collisions in weakly un-magnetized plasmas, where the problem was stated like this, that we had considered the collision of charged particles with neutral atoms, there was a dense gas of neutral atoms in which the charged particles exhibited a random walk process.

Today, we are going to take up weakly ionized plasma once again but, now it is a magnetized plasma and if you remember last time, we had not discussed fully ionized plasmas. This time we will also take up fully ionized magnetized plasmas and describe the effect of coulomb collisions, and find an expression for the diffusion coefficient, which we have already defined in the last lecture.

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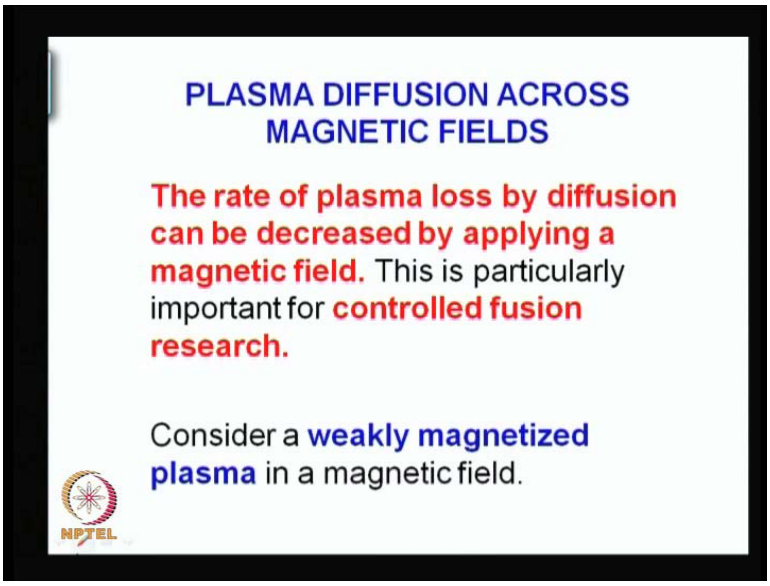

So, we will study plasma diffusion across magnetic fields and why is it important? It is very important a problem in controlled fusion research, it has been found that the rate of plasma loss by diffusion can be decreased by applying a magnetic field. Today we are going to see how this is done.

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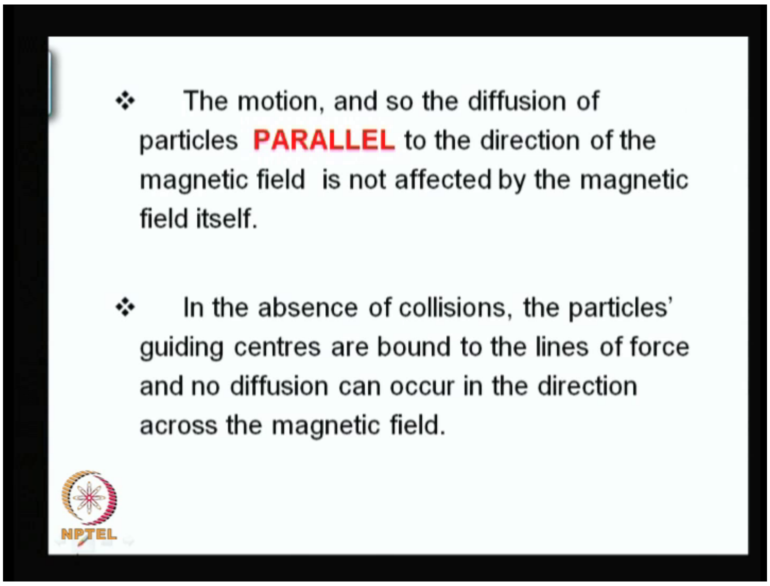

Let us first take up the case of a weakly ionized plasma, a weakly magnetized plasma. So, the weakly ionized plasma is in a magnetic field, qualitatively you know that, because of the magnetic field there is the V cross B force on the charge particles in the plasma.

So, we can say that the motion and therefore, the diffusion of the particles parallel to the direction of the magnetic field is not affected by the magnetic field, because the V cross B force is zero when V is parallel to B. In the absence of collisions the particles move in circles in the magnetic field and the in a helical path in the magnetic field, and the guiding centers are bound to the lines of force.

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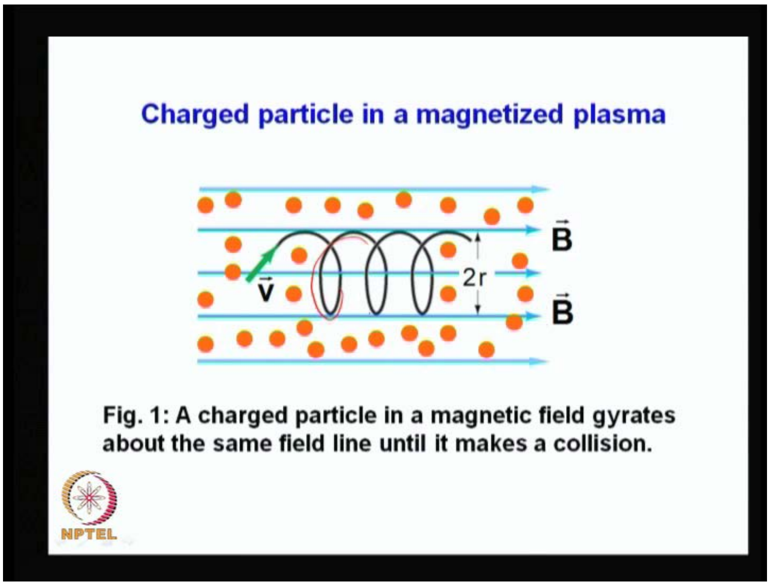

So, no diffusion occurs in the direction perpendicular to the magnetic field across the magnetic field, it is a situation like this figure. Here I show you charged particles in magnetized plasma, a single charged particle motion in a magnetic field, it is following a helical path, it is bound with the line of force in the magnetic field, the path of the plasma, path of the electron or a charged particle here.

This helix or the helical path is the path of the charged particle, it gyrates about the same field line until it makes a collision, this is the coalitional problem that we are taking up. So, a charged particle will gyl/gyrate gyrate about the same field line till it makes a collision and what happens when it makes a collision?

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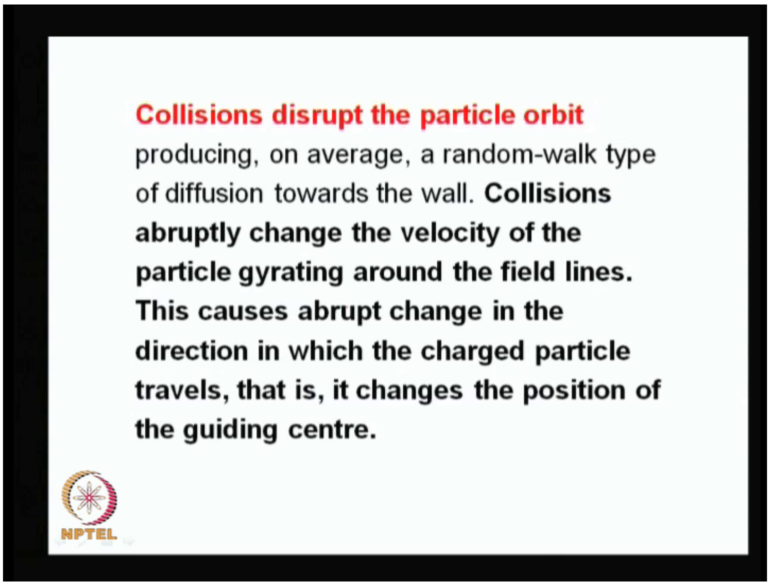

The orbit of the particle is disrupted and a random-walk, we can again take it as a random walk type of diffusion. So, what happens is collisions abruptly change the velocity of the particle gyrating around the field line.

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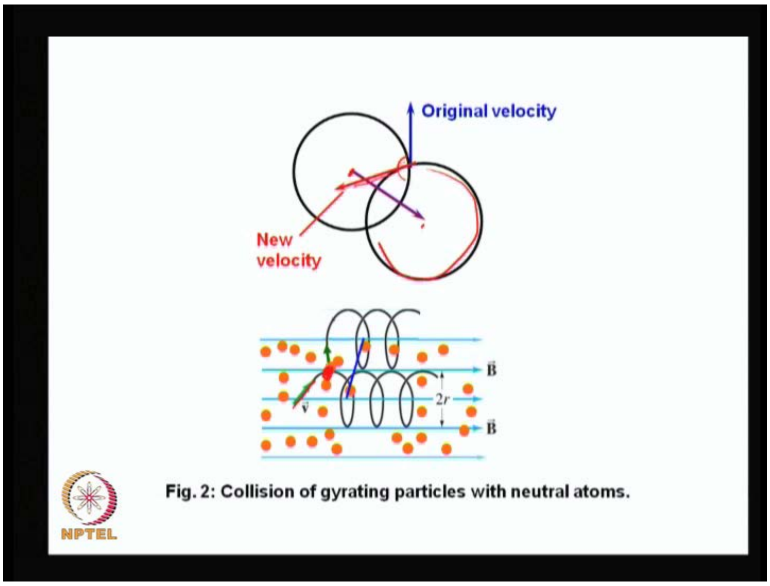

Fig. 2: Collision of gyrating particles with neutral atoms.

So, the direction in which the particle moves is changed and therefore, the position of the guiding center is also changed, you can understand this better from this figure. Here, there is a particle gyrating in around field line and let us say the first figure shows you when you are looking at the particle in a transverse direction.

So, you you see a circle and you see the original velocity, at this point at this point the particle collides with another charged particle so, the velocity changes direction this is the direction of the new velocity the red arrow.

And therefore, the guiding center shifts, this is then the new path around which the particle gyrates, the new circle, this circle and the guiding center shifts from this point to this point. If you look at it from a distance then the lower figure shows you what is happening, here is the original path of the charged particle, it is gyrating about a field line.

Now, look at this particle in the plasma. Say the electron while gyrating about the field line collides with this particular particle, what happens? The direction of its velocity changes, and now it gyrates about a different field line and the guiding center shifts so, the charged particle has moved across the B field, because of the collision. This is how particles diffuse in a collisional plasma in the presence of a magnetic field.

Let me just demonstrate this again to you, this is the path of the original particle, now it collides as it is moving along this path, it collides with the particle here in the plasma and acquires a different velocity in a different direction. So, its starts gyrating in a different path though in the same direction along a different line of force, and its guide the guiding center shifts so, there is a shift, there is a diffusion of the particles across the magnetic field.

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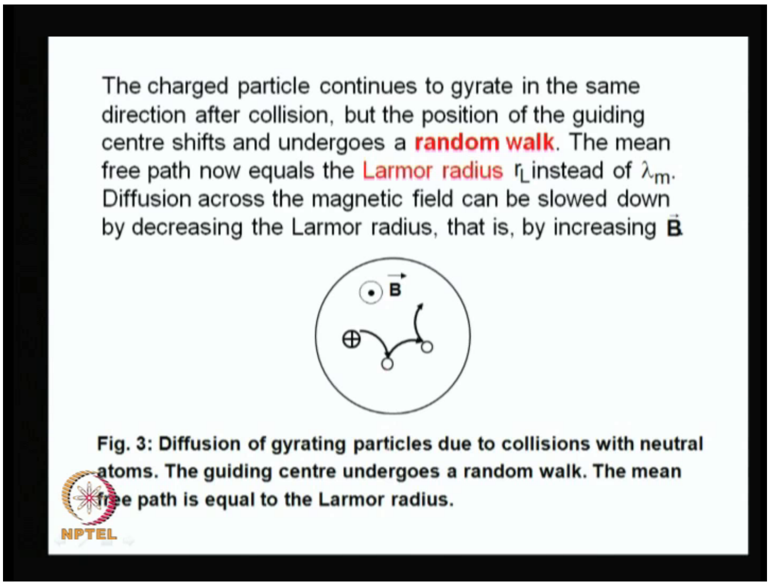

So, this is how diffusion takes place in a magnetized plasma, the charged particle continues to gyrate in the same direction after collision, as you have seen in the previous graphic but, the position of the guiding center shifts, and the guiding center undergoes a random walk.

But the mean free path now is equal to the larmor radius instead of the lambda m, earlier it was the charged particle that was undergoing a random walk, in a magnetized plasma it is the guiding center which undergoes a random walk, and the step length is the larmor radius. Now, diffusion across the magnetic field can be slow down by decreasing the larmor radius that is, by increasing the magnetic field.

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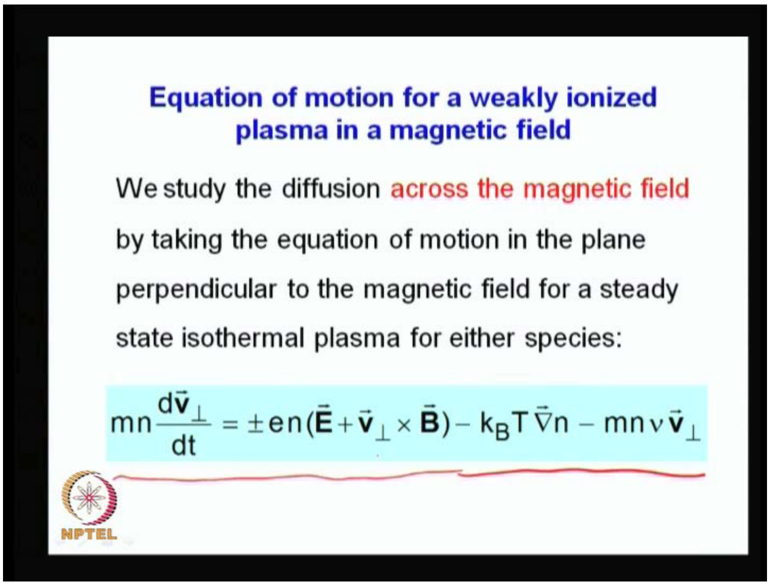

So, we have to find out the the diffusion coefficient for a weakly ionized plasma in a magnetic field, for the diffusion of particles in a weakly ionized plasma placed in a magnetic field.

As usual, we will start with the equation of motion since, the motion in the direction parallel to the magnetic field is absent, there is no motion in the direction in which V is parallel to B therefore, we will study the diffusion in a direction perpendicular to the magnetic field, across the magnetic field writing the equation of motion in a plane perpendicular to the magnetic field.

Once again, we take the study state isothermal plasma and write down the equation of motion, it is written here m n D v perp upon D t is equal to plus minus e n E plus V perp cross B minus K B T grad n, the density gradient minus m n nu v perp the momentum loss.

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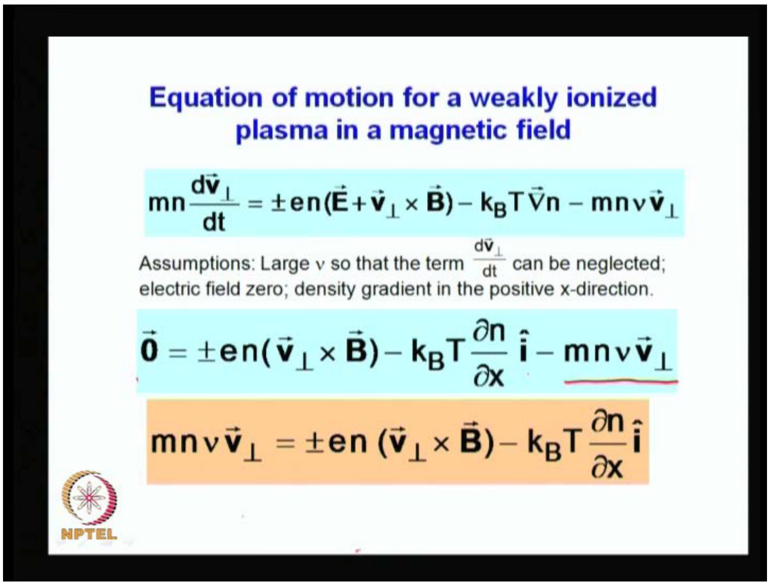

So, this is the equation of motion for the perpendicular component of the velocity. Once again, we solve it under certain assumptions, the way we did for un-magnetized plasmas we take the collision frequency to be large so that, in comparison to this term, the term D v perp upon D t can be neglected, for simplicity we take the electric field to be zero and the density gradient in the positive x x direction you will see that the results arrived are at the same are the same, but the algebra becomes pretty simple.

So, let us see what this equation of motion, reduces to under these assumptions. The term on the left hand side is zero and we have also put the electric field equal to zero. So, we are left with three terms now the V perp cross B, the density gradient which is parallel to the x axis, and the momentum last term. From here we can write down an expression for V perp by taking the last term to the left hand side, we are left with the two terms V perp cross B and the density gradient in the x direction on the right hand side.

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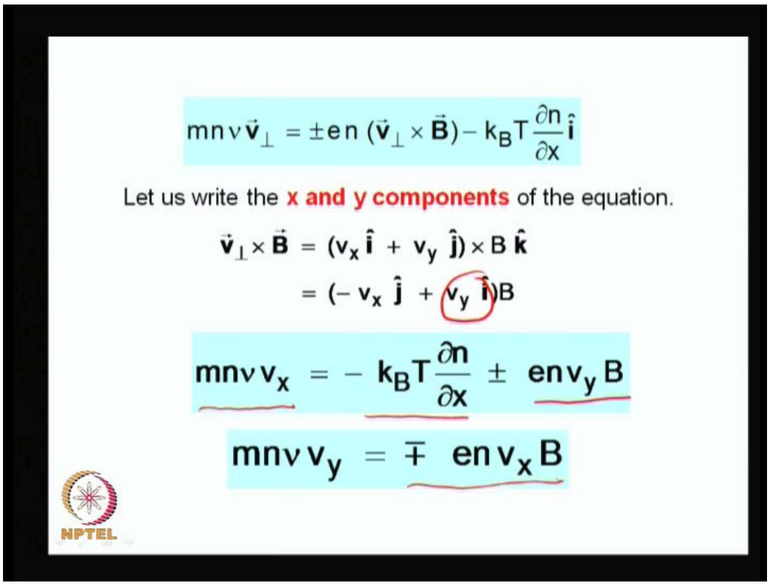

Once again we fallow the same process and divide the entire equation by m n nu, but this time the v perpendicular has two components x and y components so, we write the x and y components of the equation.

Now here, we have a cross product V perp cross B, which you know very well is minus V x j cap plus V y i cap B, if you apply the definition of the cross product then, you can simply write the equation of motion for the V x and V y components. You just take the x component of V perp and the x component of V cross B term and you get this, the density gradient term is already there, and you get this term from the x component of V cross B term. This is the x component the V y i cap similarly, the y component you do not have in the density gradient.

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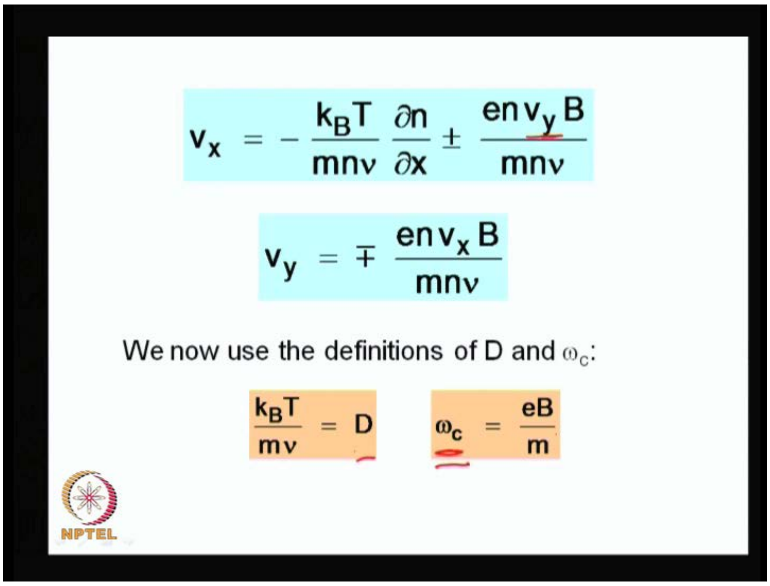

So, you are left with only one term, divide by m n nu you get expressions for V x and V y, what is the difference between these two expressions?

From the earlier case, these are now coupled equations you have V y in the equation for V x and V x in the equation for V y so, how do you solve this? You have to get an expression for V perp and you have to write the equation, continuity equation.

So, what do you do? You just, before getting into the algebra we will also make use of the fact that, D the diffusion coefficient is K B T upon m nu and we will use the definition of omega c equal to e B upon m, and write V x and V y in terms of D and omega c.

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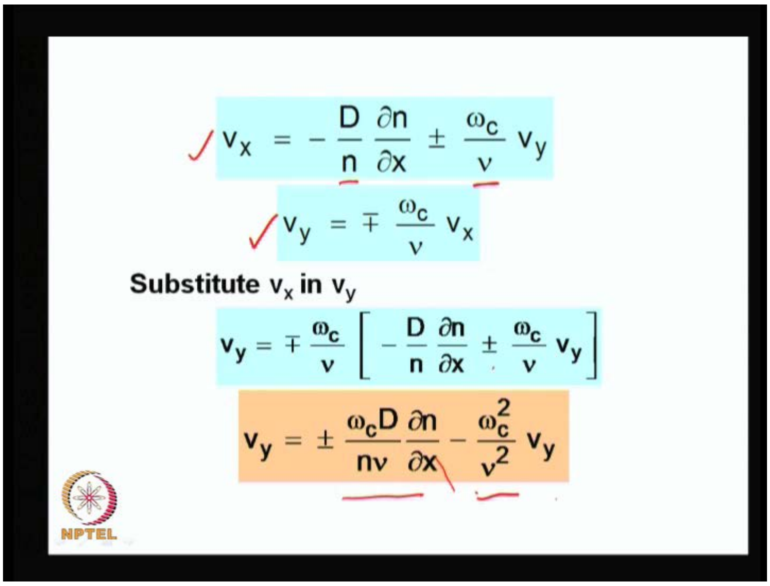

So, in terms of D and omega c obviously you can see that the expressions are much simpler. Now, we substitute V x in V y V x from this equation in V y in V y, V x from here in V y. What do we get? It is a matter of algebra, we have set V y is equal to minus plus omega c upon nu V x so, you substitute V x here is minus so, minus plus and this is minus this becomes plus minus omega c D upon n nu, del n upon del x minus omega c square upon nu square V y.

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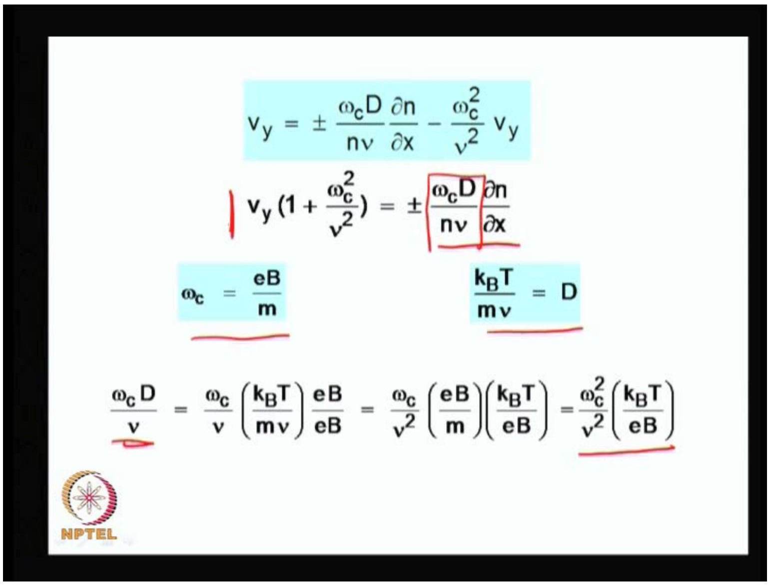

So, this equation you have V y alone and the density gradient now, you take this term to the left side, minus omega square upon nu square V y and you get V y equal to V y multiplied by 1 plus omega c square upon nu square equal to plus minus omega c D upon n nu delta n y delta x.

Once again, we use the definitions omega c and D and we write this term omega c D upon nu here, the coefficient of the density gradient, do some simple algebra substitute for D, multiply and divide by e B so, we can express this as omega c square upon nu square K B T upon e B, this is also that the final expressions look simpler and elegant.

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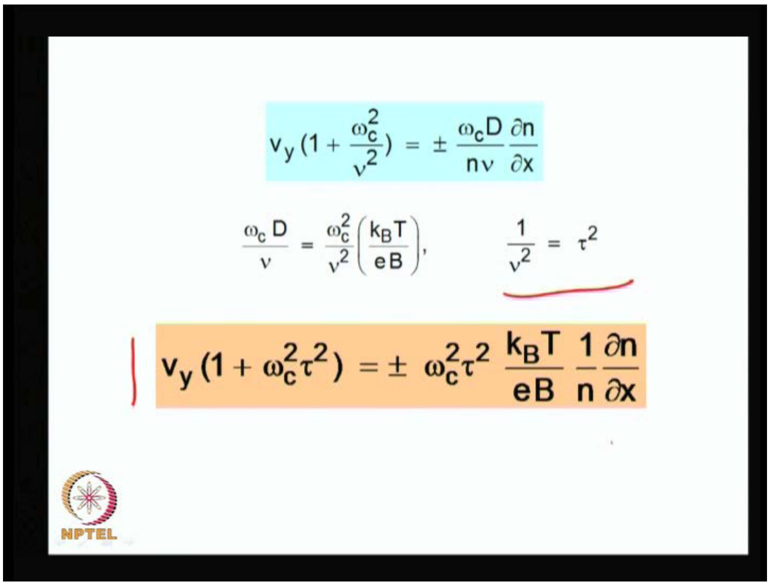

So, we rewrite this equation for V y as V y 1 plus omega c square, tau square, which is nothing but, 1 upon nu square this is what we have used. And omega c D upon nu as K B T upon e B, omega c square upon nu square 1 upon nu square we have written as tau square.

So, we get an equation for V y, which does not contain V x, it is a result in terms of the density gradient. We divide the expression by 1 plus omega c square tau square and we get an expression for V y.

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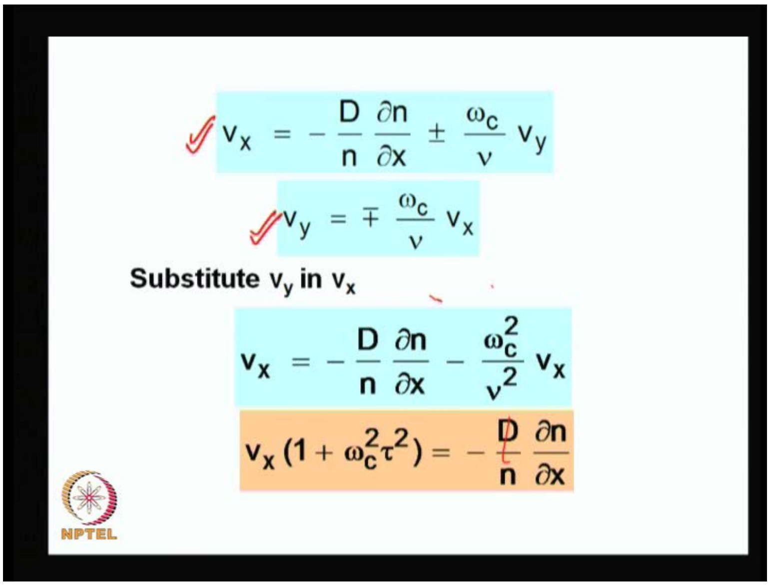

Similarly, by substituting V y in V x here, this now in this V y is equal to minus plus omega c upon nu V x into the expression for V x, we can again derive an expression for just V x the way we have done for V y, V x 1 plus omega c square tau square is equal to minus D upon n del n upon del x.

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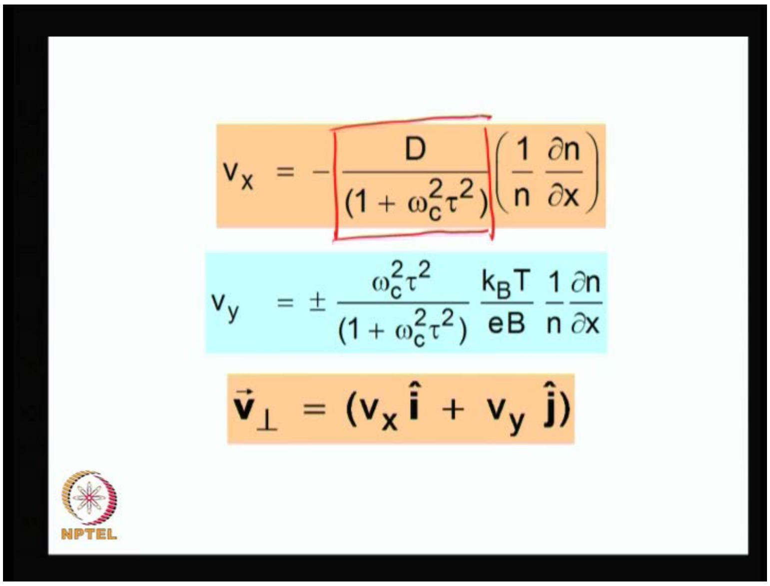

So, we get two equations for V x and V y, which are now uncoupled and they are now given in terms of the density gradient, this is what we had done for un-magnetized plasmas also. We have a term D upon 1 plus omega c square tau square here. Now, we have to write an expression for the perpendicular velocity vector, which is again reconstituted by adding up the x and y vector components.

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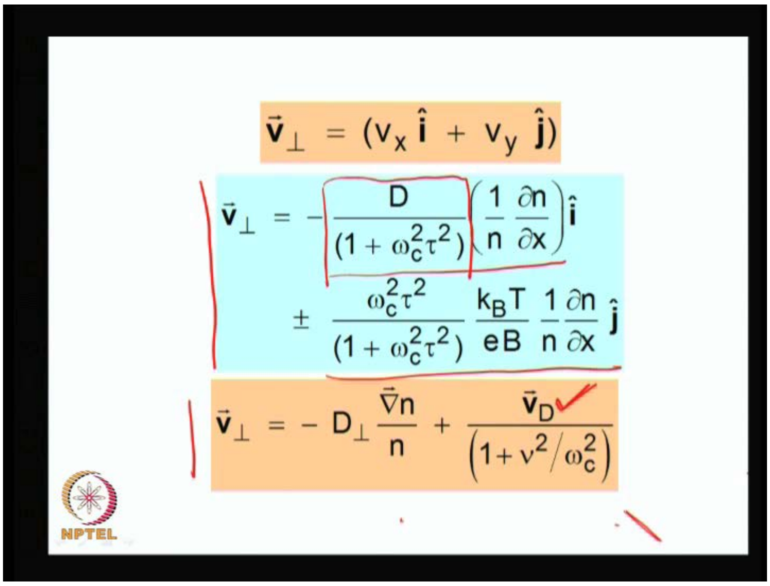

So, although the expression looks a bit involved you will find that, this is simply the V x term, this is the V y term and we define a new quantity called D perp here, and another quantity v D here so, that the expression for v perp becomes simple. It becomes minus D perp, grad n upon n, grad n is simply in the x direction so, del n upon del x can be written as grad n plus another term V D upon 1 plus nu square upon omega c square, this is what we have defined to write the second term in a simple expression, this is what we have defined D perp equal to D upon 1 plus omega c square tau square and v D equal to plus minus K B T upon e B, 1 upon n del n upon del x j cap.

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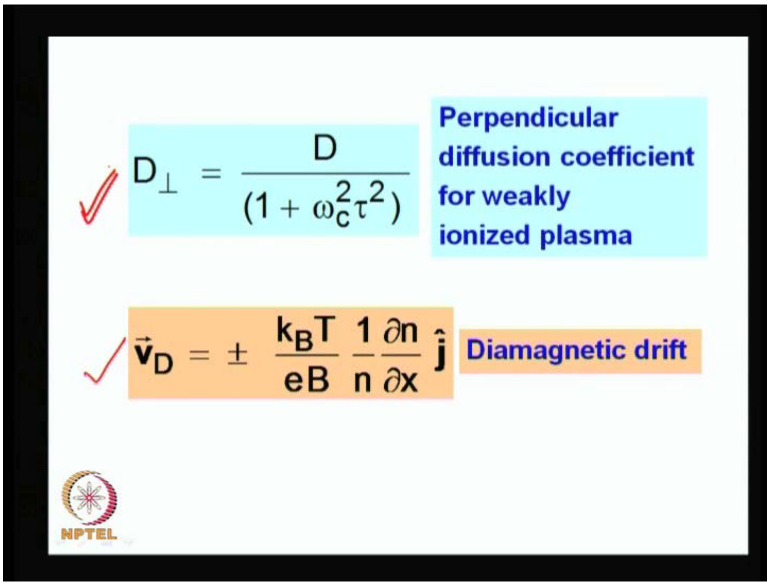

So, this particular term except for this the frequency dependent term can be written as V D, and if you divide this whole thing by omega c square t tau square you can write the expression as 1 upon, 1 plus nu square upon omega c square.

So, the D perp is the perpendicular diffusion coefficient for weakly ionized plasmas, and what is this term V D, that we have defined. It is actually a diamagnetic drift term, write now we are not going into the diamagnetic drifts across a magnetized plasmas, we will be concentrating on the diffusion coefficients.

So, we have found a diffusion coefficient for magnetized, weakly ionized plasmas as D upon 1 plus omega c square tau square, you can see that it depends on the collision frequency, because you have tau here or 1 upon nu square and also on omega c square.

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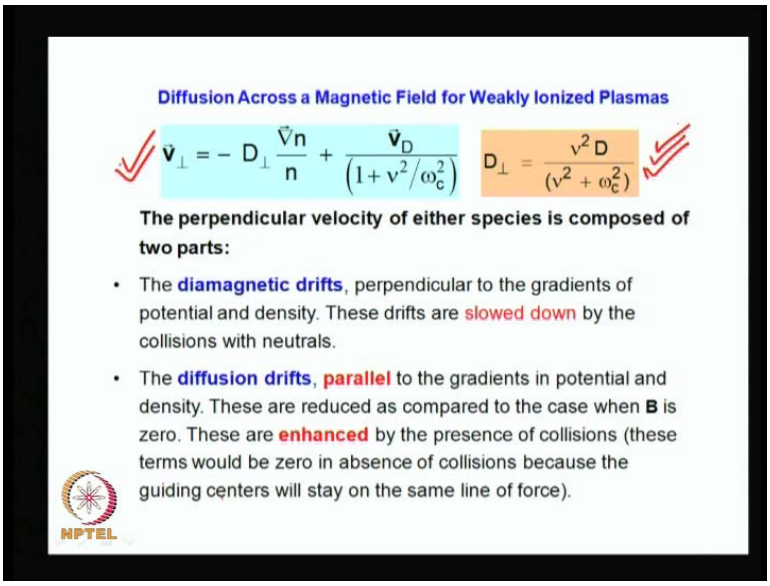

So, let me summarize this discussion on diffusion across a magnetic field for weakly ionized pro/plasma plasma, we have derived an expression for the perpendicular velocity term.

We have found that, there is an extra term due to the diamagnetic drift, write now we do not pay any attention to that, and we have defined the perpendicular diffusion coefficient

The diamagnetic drifts are perpendicular to the gradients of potential and density, and these are slowdown by collisions with neutral atoms, because there you have the collision frequency. The diffusion drifts on the other hand are parallel to the gradients in density, the diffusion drifts are parallel to the density gradients these are in the direction of the density gradient, and these are reduced as compare to the case when B is zero, when you have B you have a term omega c here so, the diffusion drift is reduced.

However, the presence of collisions enhances this phenomenon of diffusion, because we can see that, this term would be zero if the collisions were absent, you have nu square D upon nu square plus omega c squares. So, if nu was zero, D perp would be zero there would be no diffusion across the magnetic field, this is in the direction of the density gradient it is reduced as compare to the case when the magnetic field is zero, and these are enhanced by the presence of collision, the diffusion processes enhanced. So, this in a nutshell is diffusion across a magnetic field for a weakly ionized plasma.

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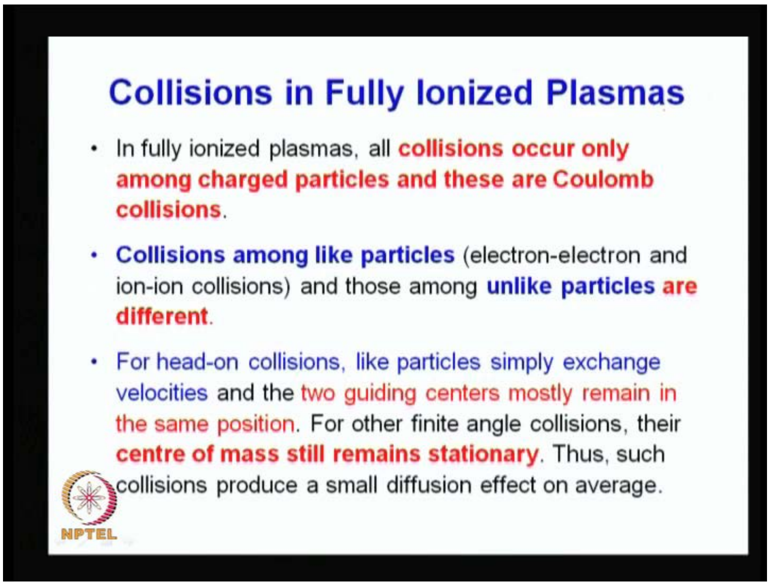

Now, we come to the case of collisions in fully ionized plasmas, in fully ionized plasmas all collisions occur only among charge particles, in weakly ionized plasmas you will remember the collisions were between charged particles and neutral atoms now, the collisions are between charged particles and these are the coulomb collisions or the Rutherford scattering that I have shown you last time.

Now, if we want, if we look at the collisions between charged particles, there is a difference between, collisions between, like particles and collisions between unlike particles, for example, if it is an electron, electron collision or an ion, ion collision the masses are about the same, what happens is simply that the velocities get exchanged and the guide, and the center of mass of the system remains just where it was, the guiding centers mostly remain in the same position.

So, for our calculations we can neglect this, there is no diffusion as such for or very small diffusion for like particles collisions, particularly for head-on collisions you can remember for, you can go back to your college physics and you can see that the two particles of equal mass just exchange their velocities.

And for other finite angle collisions, the center of mass of the system remains stationary and so on, an average such collisions produce small diffusions, which we can neglect.

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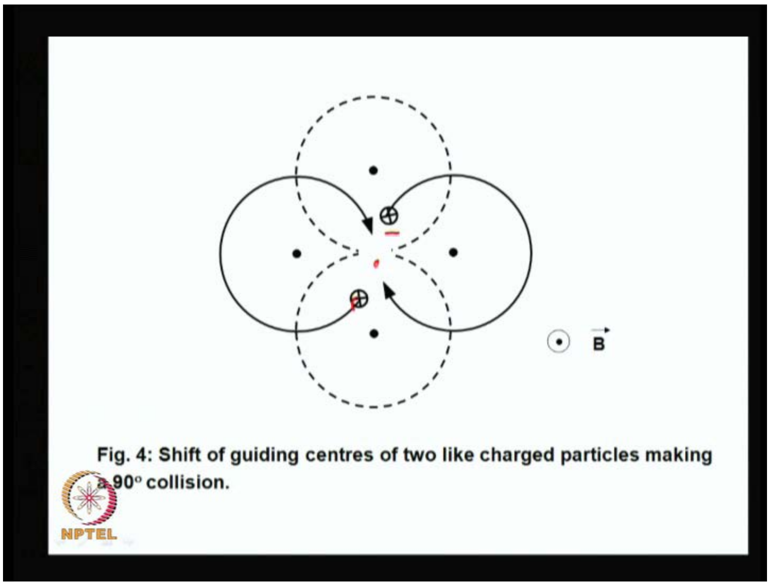

This is the figure which shows the collision of like particles, this is one particle and this is the other particle, they are gyrating, they collide and their paths shift in a manner that, the center of mass remains the same it is stationary, it is a 90 degree collision between the particles.

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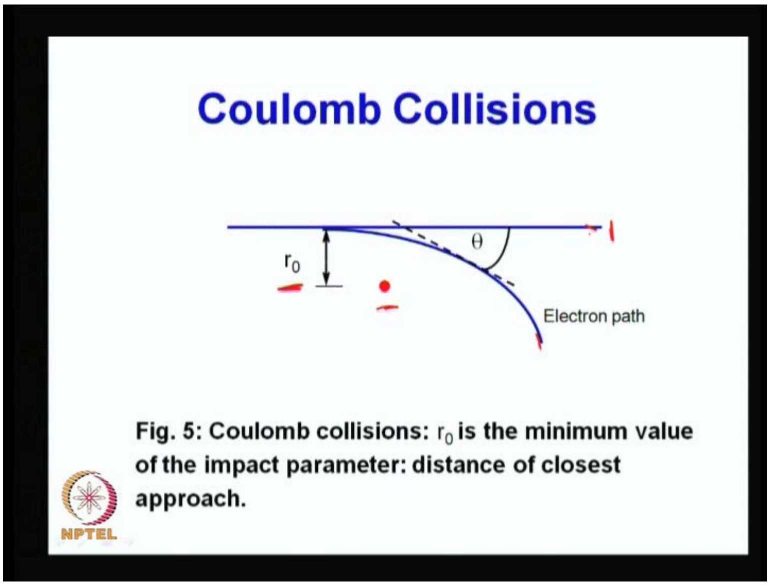

Now, what is of interest here in the diffusion phenomena, is the collision of unlike particles, collision of electrons with ions or ions with electrons in the plasma fluid. And here we take records to coulomb collision and coulomb collisional cross section.

What happens in a coulomb collision is that, a charged particle, as a charged particle approaches an ion, it undergoes scattering and follows a hyperbolic path, if we go back again to our college physics, we can find out the path of charged particles scattering. In this figure, we have shown the collision at the distance of closest approach, this distance r 0 here is the impact parameter, it is the minimum value of the impact parameter. So, it is called the distance of closest approach and this is the electron path the solid line, this is the original path of the electron this, horizontal line and it gets deflected in the collision, because of the presence of the ion.

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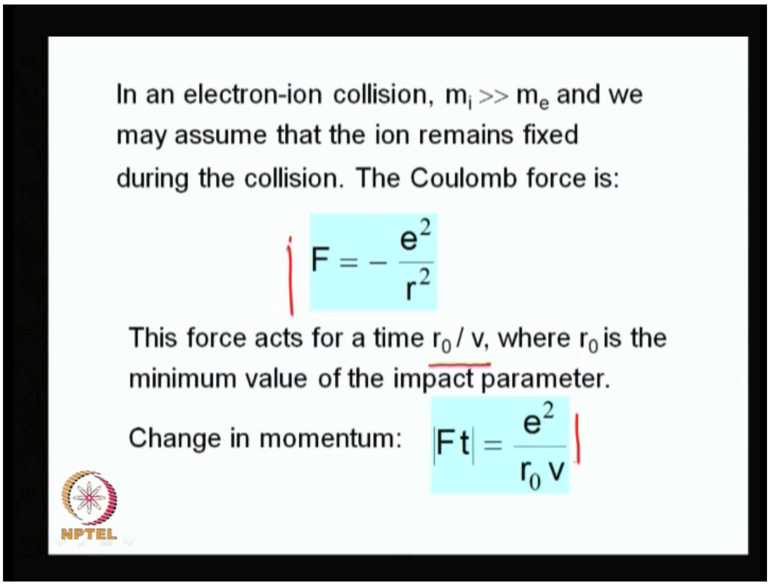

Now, in an electron ion collision, the mass of the ion is much larger than the mass of the electrons so that, we can assume that the center of mass is at the ion and at the ion and the ion remains almost fixed during the collision.

The coulomb force is simply between the two, if we do not take the atomic number into account, to keep things simple we can write the coulomb force as F equal to minus e square upon r square. If the velocity is V then and the distance of closet approaches r 0 then, this force acts for a time r 0 upon V.

So, the change in momentum is just the average force multiplied by the time so, you multiply e square upon r square, by r 0 upon V, we can put r equal to r 0 there so, this is the change in momentum e square upon r 0 V.

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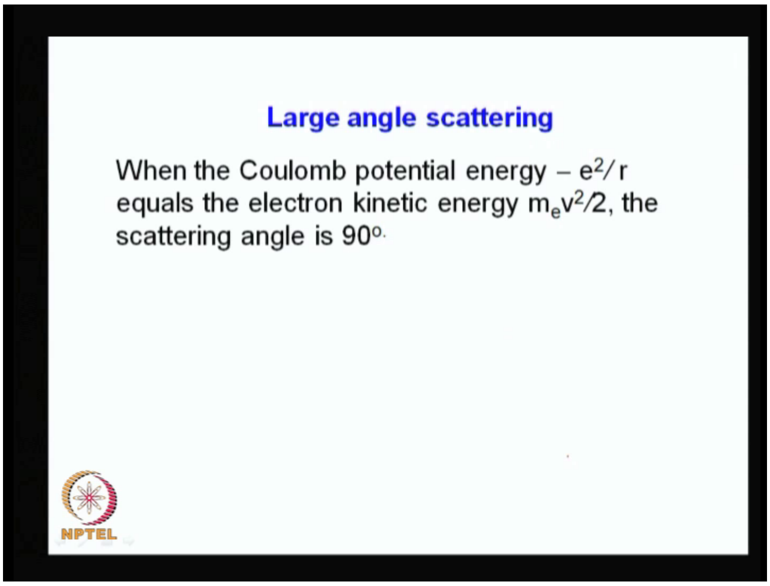

And we are right now discussing large angle scattering, when the coulomb potential energy is equal to the kinetic energy of the electron, this scattering angle is ninety degrees and at those scattering angles the change in the momentum is of the order of momentum itself.

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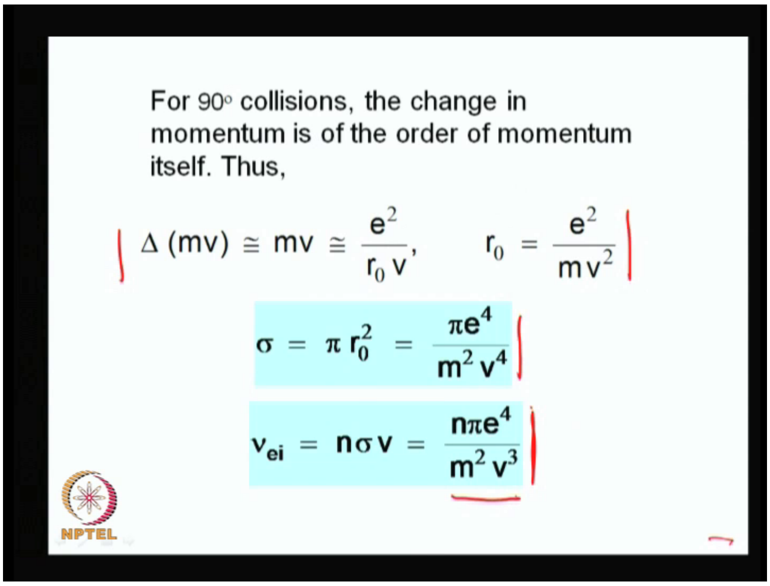

So, we have an equation which gives us the change in momentum as e square upon r 0 v, from where we get an expression for the impact parameter as r 0 equal to e square upon m v square.

And once again using the classical total collisional cross section as pi r 0 square, we simply put r 0 square here we get the collisional cross section as pi e raise power 4 upon m square v 4 and therefore, the collisional frequency is simply n sigma v, we have defined it earlier and this is equal to n pi e raise power 4 upon m square v cube so, we have our collision parameters.

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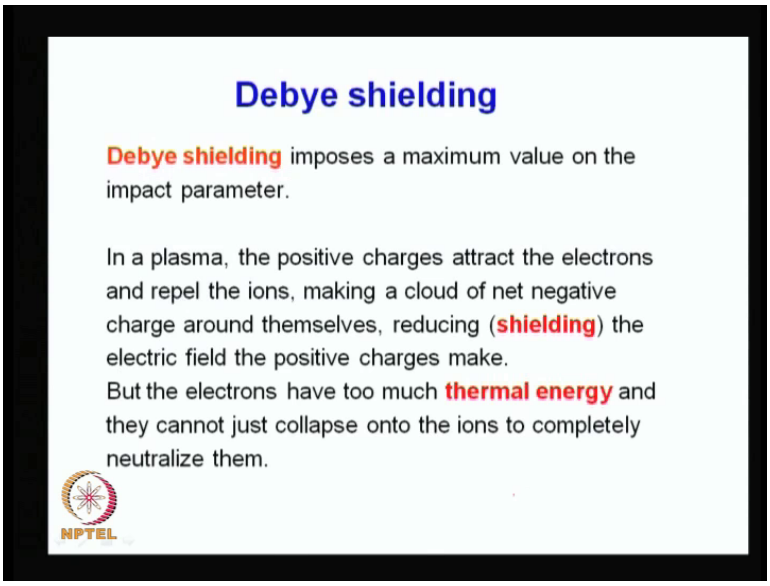

Now, there is something which we need to discuss here is Debye shielding which you have studied earlier in these lectures. Debye shielding imposes a maximum value on the impact parameter, as you know in a plasma, the positive charges attract the electrons and ripple the ions and so a net negative charge accumulates around the positive charges, thus producing or shielding the electric field due to the positive charges, on the other hand electrons also have thermal energy.

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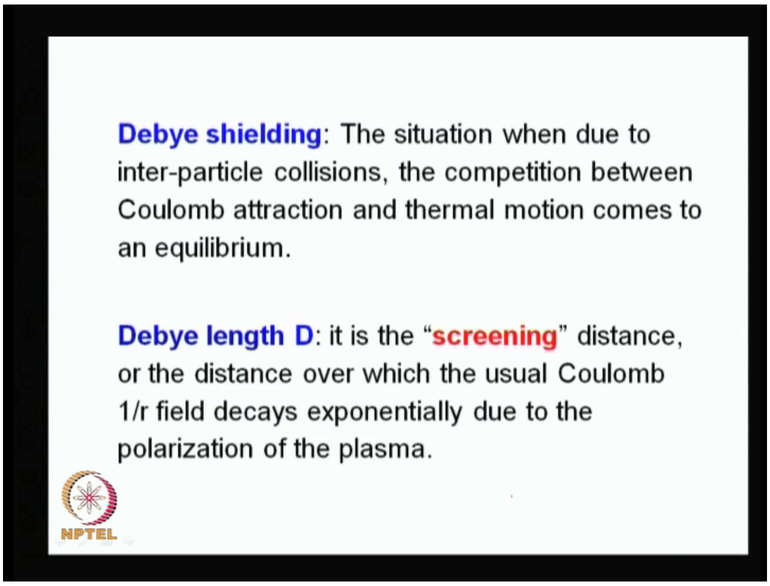

So they cannot just collapse on to the ions so, there is an equilibrium which is established between the attraction, force of attraction of the ion on the electron and, because of the collision, due to collisions, because of the movement of electrons away.

So, due to inter particle collisions, coulomb attraction and thermal motion comes into equilibrium and the field of the plasma is shielded from any external fields, this is the Debye shielding. You also studied the parameter Debye length, which is the screening distance over which the coulomb field decays exponentially.

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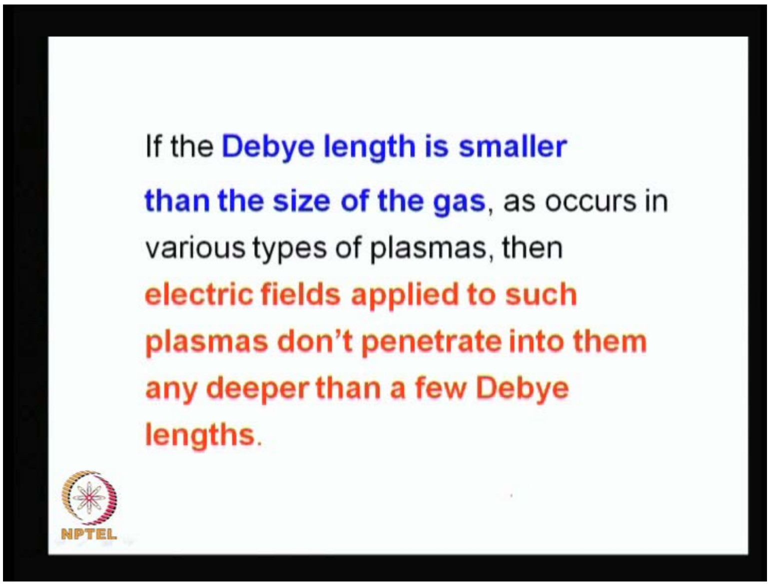

So, beyond the Debye length the coulomb field of the charged particle falls very fast and so, within the plasma electric fields applied to the plasmas beyond a few Debye lengths do not matter, the plasma is shielded so the upper limit of the impact parameter then becomes equal to the Debye length.

So, we are considering a collision between r 0 and the Debye length lambda D, and we have seen the parameters for ninety degrees collisions for small angle, so the b maximum impact parameter is simply the Debye length.

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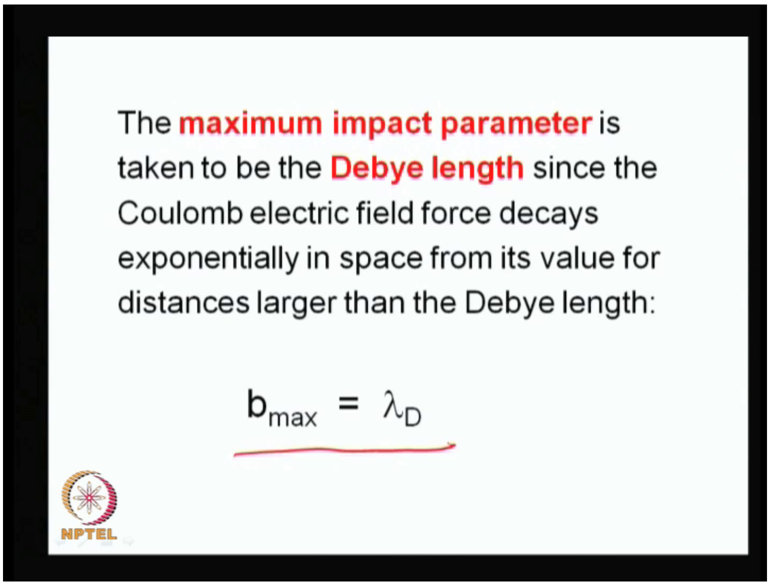

We have already written the collision frequency for 90 degrees or large angle scattering for the small angle scattering effects, a small correction which is called as spitzer correction needs to added.

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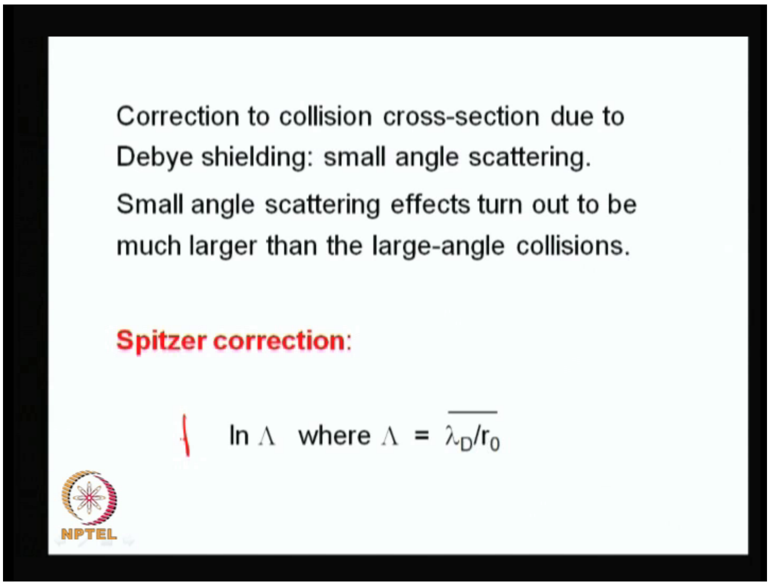

And we will not going to the calculations, because these are pretty involved, with this we can now once again try and derive the coefficient of diffusion in a fully ionized plasma.

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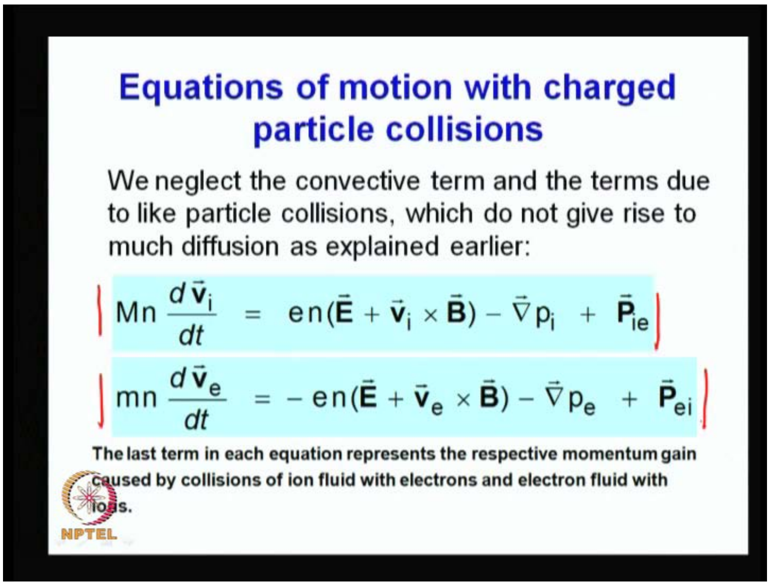

Once again, we write the equations for both this species, m n d v i upon d t is equal to e n E plus V i cross B minus grad p i plus P i e and similarly, the equation for the electrons. The last term in these equations p i e and P e i are the momentum terms, momentum gain caused by collisions of ions with electrons and electrons with ions. Once again, we will be making certain simplifications and we will study steady state and isothermal plasmas.

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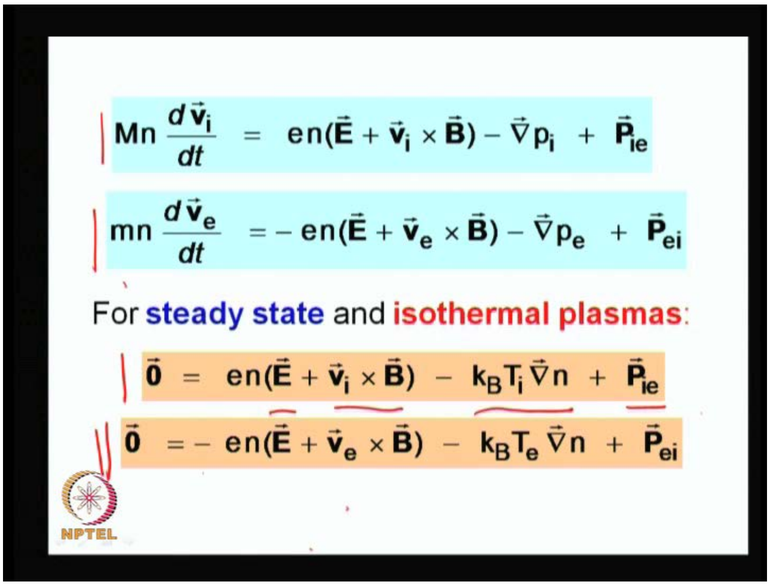

So, the term on the left hand side then becomes zero and for isothermal plasmas, we can write the pressure gradient in terms of the density gradient so, the equations are somewhat simplified.

We have e n E plus v i cross B minus K B T I grad n plus P i e equal to 0, and in the same way we can write the equation for the electron with v i replace by v e, T i by t e and P i e become instead of P i e we write P e i.

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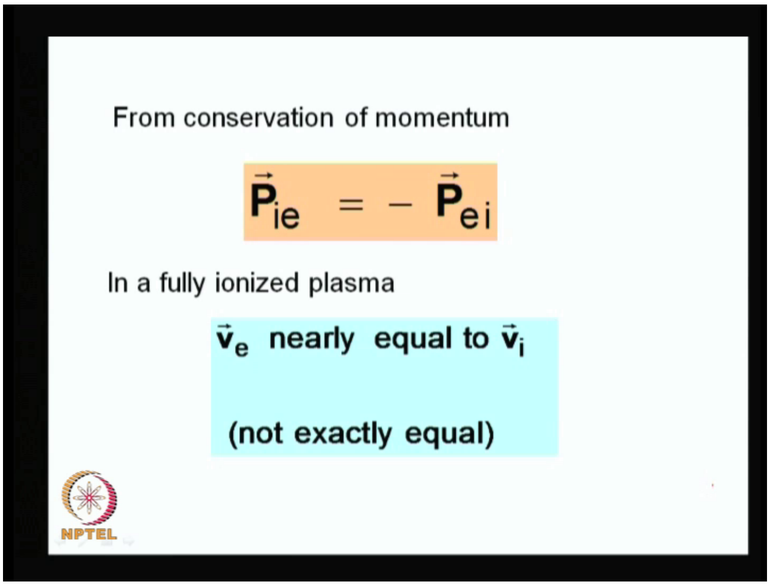

From conservation of momentum P i e is simply minus P e i and in a fully ionized plasma v e nearly equals v i, it is not exactly equal you will see the implications, if you remember p is m n v nu i.

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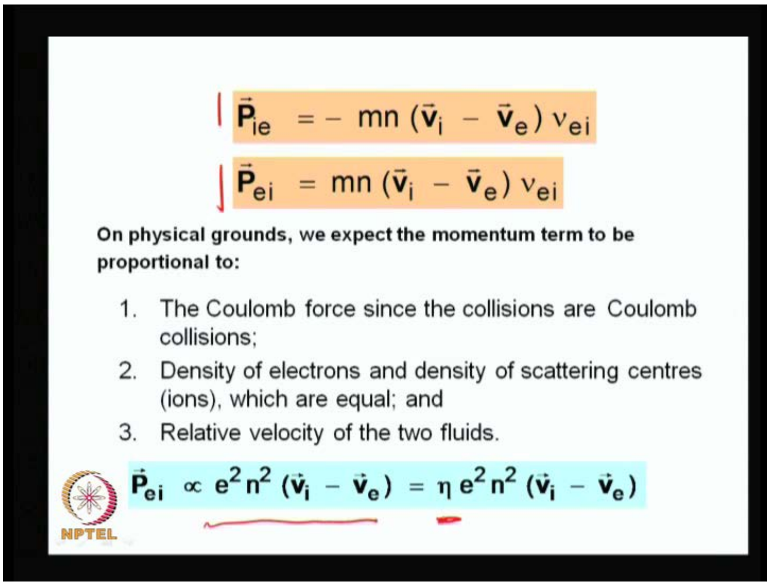

So, in terms of the velocities you have P i e minus m n multiplied by v i minus v e nu e i P e i is minus P i e so, you write that expression.

Now, on physical grounds we expect the momentum term to be proportional to three factors, the coulomb force; since the coulomb collisions are coulomb collisions, density of electrons; density of scattering centers which are equal and relative velocity of the two fluids.

So, P e i lets take P e i is proportional to e square n square and the difference of velocities here, we replace the proportionality constant by eta here.

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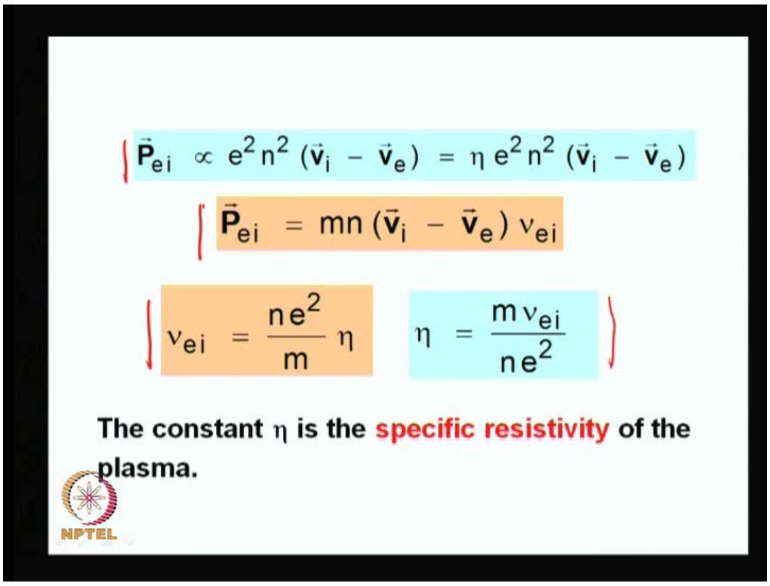

So, we write P e i as m n v i minus v e nu e I, and we have on physical grounds an expression for P e i in terms of eta, and if we compare the two we get nu e i in terms of eta or eta in terms of the collision frequency.

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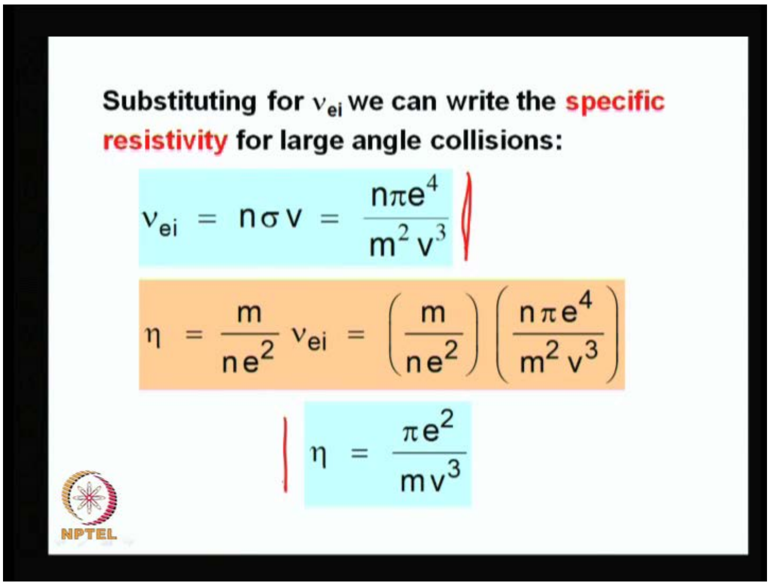

What is this constant eta? We can see that it is nothing but, this specific resistivity of the plasma. How it is so? Let me explain very quickly but, before that there is one expression for eta, which we can also write by substituting for the expression of the collision frequency in terms of the mass, and the charge, and the velocity we get an expression for eta equal to pi e square upon m v cube.

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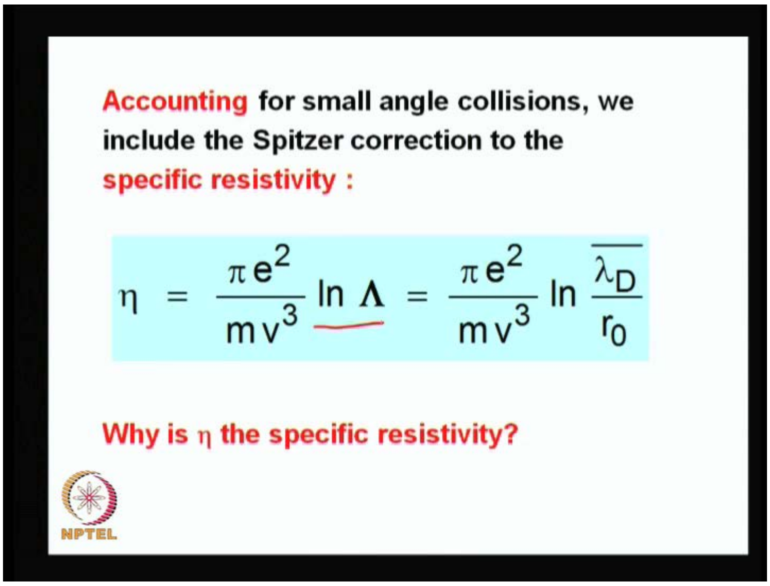

And if we account for the small angle collisions, we have to multiply by a factor log lambda which is the spitzer correction again, lets come back quickly to the point why we call eta as the specific resistivity.

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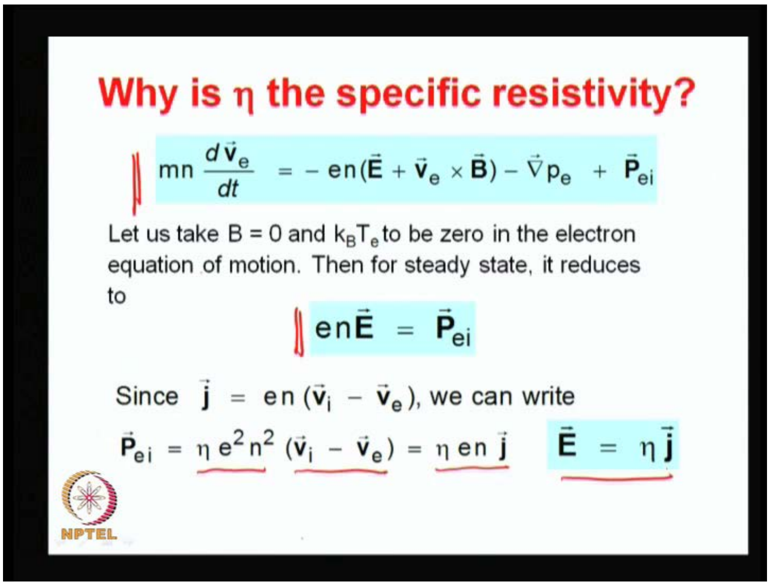

If you go back to the equation of motion and put p is equal to 0 and K B T e equal to 0 in this equation of motion for electrons, for steady state you get a simple expression e and E equal to P e i. And since j is e n v i minus v e, we can write P e i is equal to eta e square n square v i minus v e equal to eta e n j, from where we get E is equal to eta j. This is nothing but, the ohm's law.

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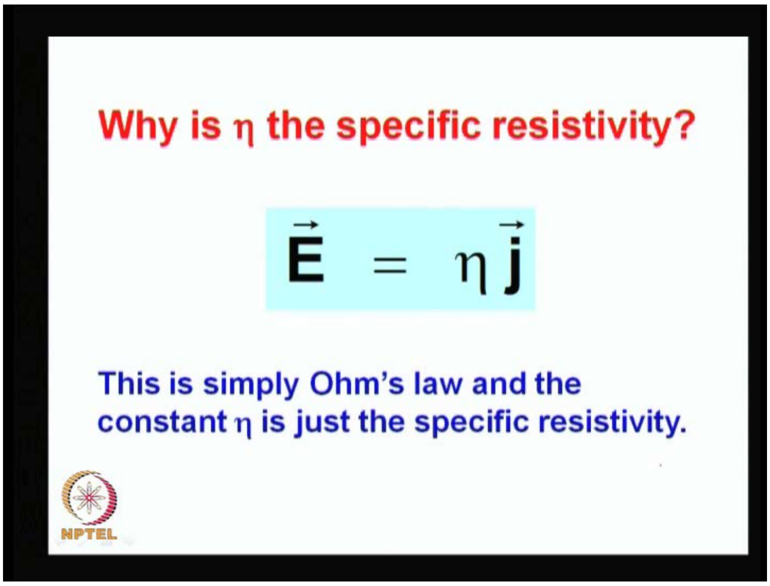

And so eta is nothing but, the specific resistivity, with this we can now make a calculation for the diffusion coefficient for fully ionized plasma in terms of the specific resistivity. We write the equations of motion, for steady state isothermal plasmas, for electrons let us say we get this particular equation, we have the electric field term the V cross B the density gradient and the momentum terms.

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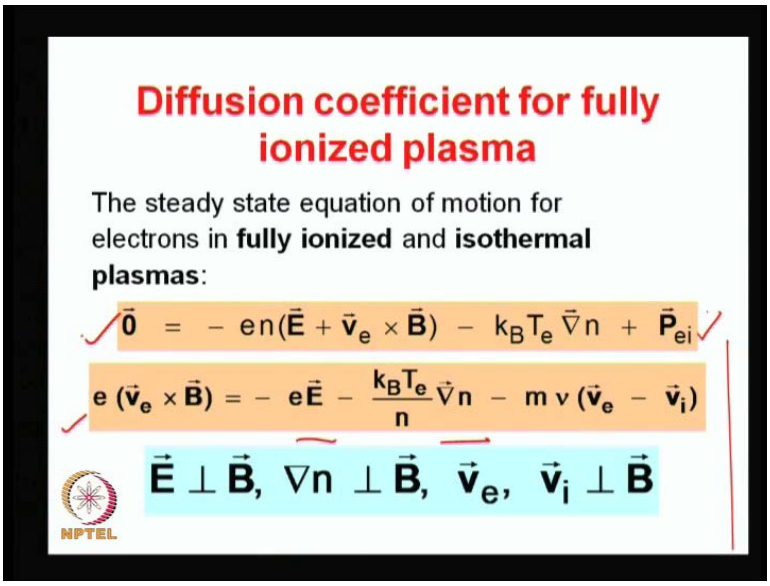

We do a simple algebra and we write E V e cross B, in terms of e gradient n and substitute for P e i here, P e i. We say that E is perpendicular to b, the density gradient is perpendicular to B and the electron and ion velocities are perpendicular to B.

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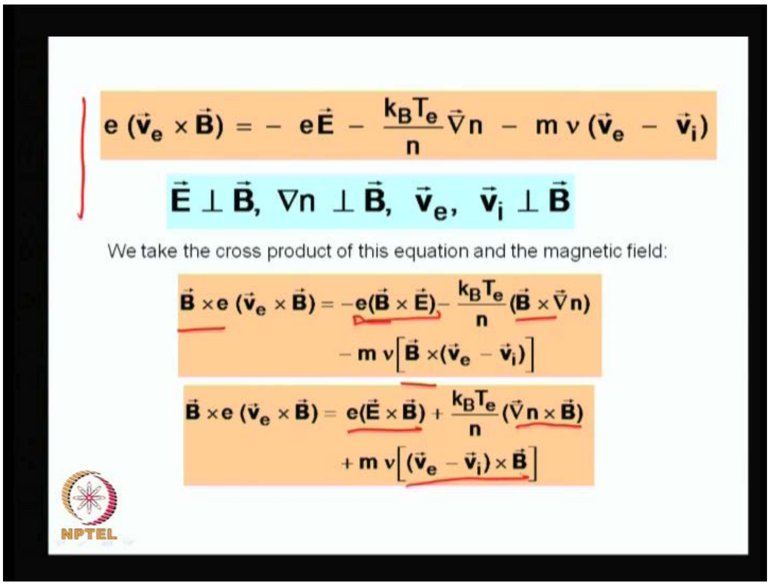

Under these assumptions I have written down the equations again for ready reference, under these assumptions we write the equation and take the cross product of this equation and the magnetic field from the left, B cross e, v e cross B and from the left you have this, you have this, and you have this, in all three terms you take the cross product of b from the left.

So, on the right hand side minus e B e, B cross e is simply e, e cross B similarly, we observe this minus sign in the second term by interchanging the cross product, and in the third term too so, we interchange the vectors in the cross product and now we have to calculate the vector triple product.

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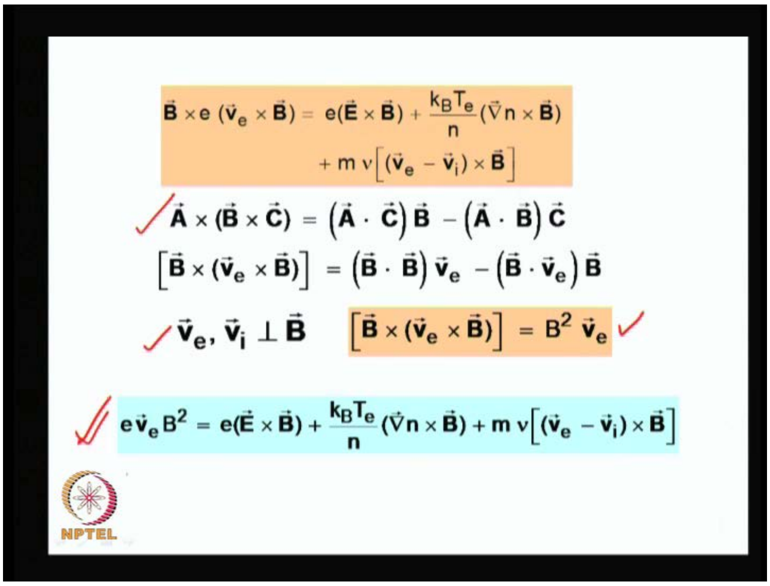

From yours college physics you know that A cross, B cross, C is A dot C B, minus A dot B C so, you can apply that result, and what do you get under the condition that v e and v i are perpendicular to B, you get the triple product simply as B square v e write, it is a simple expression. Substitute that in the original equation you get a simple expression on the left hand side, the right hand side remains the same.

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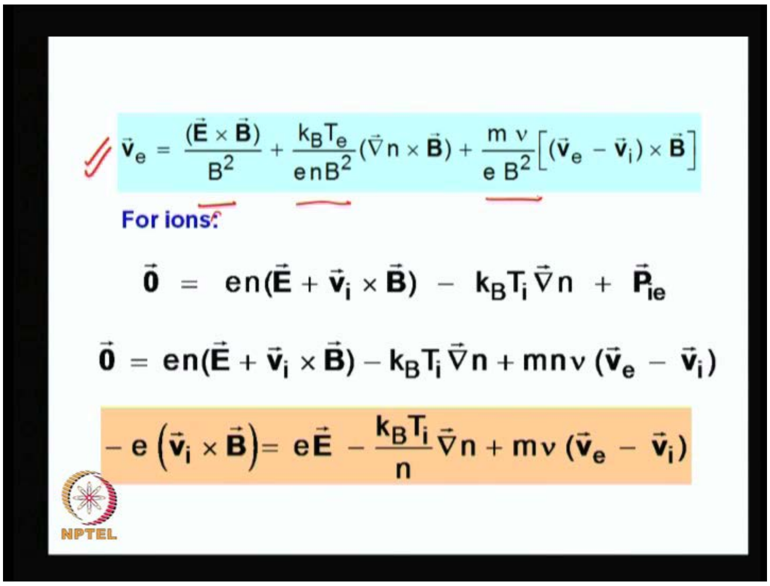

You divide then by e B square the entire equation so, you get this equation in which you have divided the previous equation by e B square so, e and E cancelled out in the first term, and here you have e B square in the denominator.

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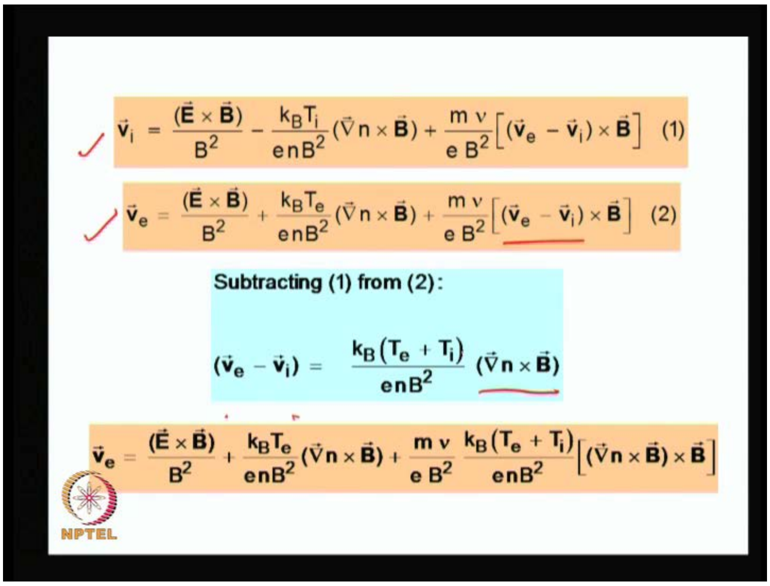

This is simple algebra, you can repeat the same procedure for ions and write an expression for the ion velocity in terms of E cross B gradient, and the momentum terms. These are the two terms for electron velocity and ion velocity, in these you have an expression for v e minus v i so, we have to still do some more algebra, what we do is we subtract v i from v e and we get an expression for v e minus v i in terms of grad n cross B, which we substitute again in these two equations.

So, we get v e, all other terms remaining the same the last term has another vector triple product del n cross B, cross B, you use the same method to simplify the last term but, the triple product is this time different, it is a cross B then cross c, which is a different product apply this and you get a simple answer del n cross B, cross B is equal to minus del n B square.

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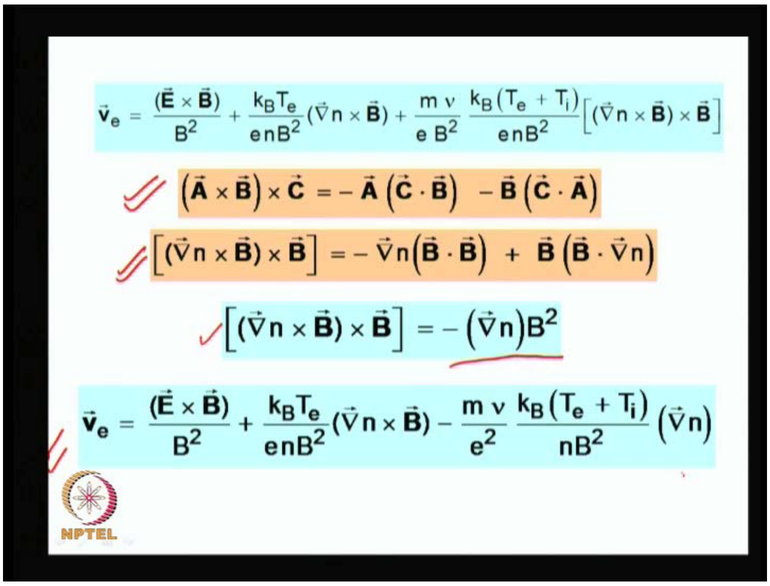

So, v e becomes, just substitute this term in the third term on the right hand side you get an expression for v e, all other terms are the same. Having found v e, we substitute it in the continuity equation the way we did earlier, and simplify del dot n v.

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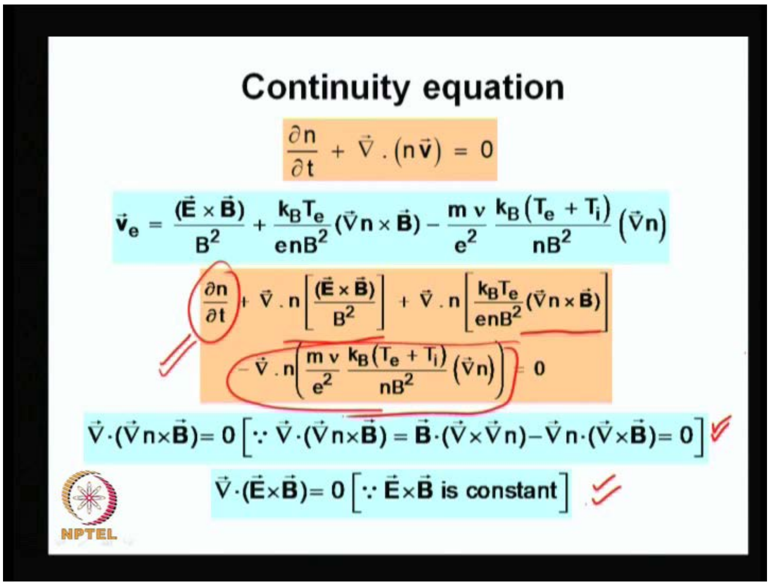

This is the equation when we substitute v e, here you will know from the vector identities that del dot del n cross B is 0. I have shown you the vector identity del dot E cross B is also 0 since, E cross B is constant so, this term is 0 and this term is 0, and we are left with two terms here on the right hand side.

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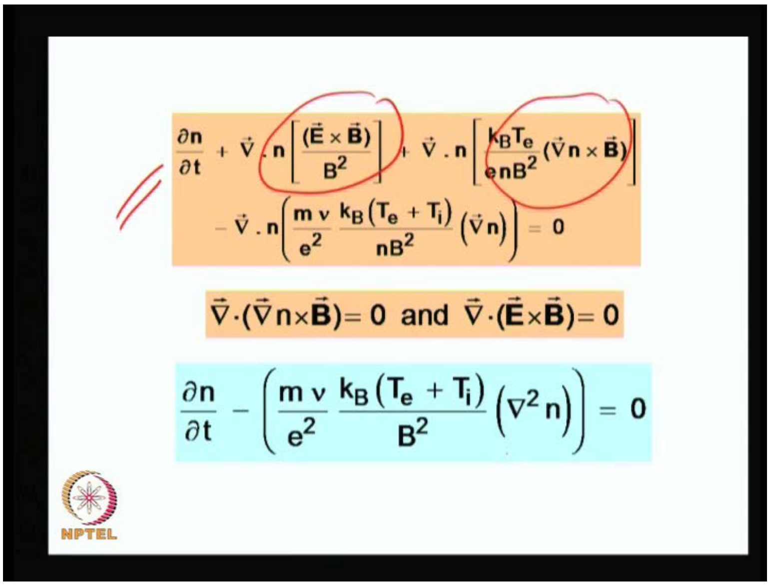

We are left with two terms, I have repeated this expression, in this huge expression two terms are zero this term and this term so, we we are left with two terms one of which gives us the coefficient of del square n, and that is nothing as you know but, the diffusion coefficient, this is nothing but, the perpendicular diffusion coefficient.

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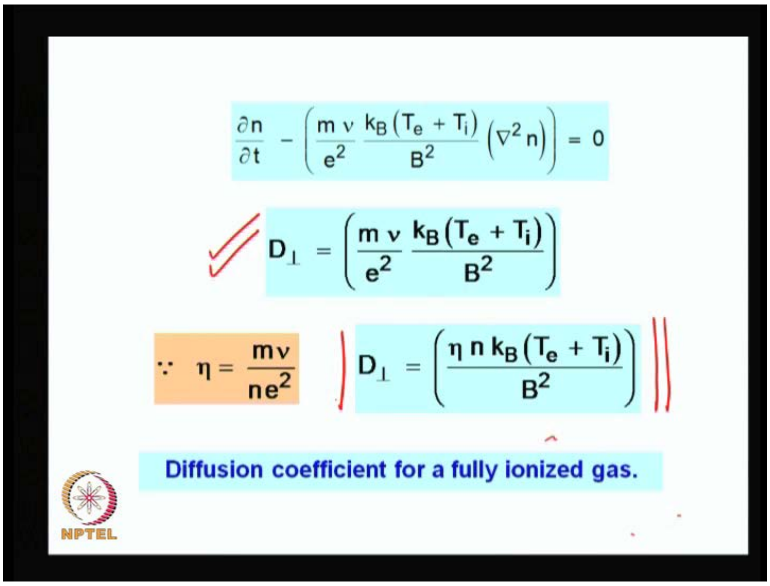

And since eta is m nu upon n e square, we can write this diffusion coefficient in terms of eta as eta n K B, T e plus T i upon B square this is the perpendicular diffusion coefficient for a fully ionized gas.

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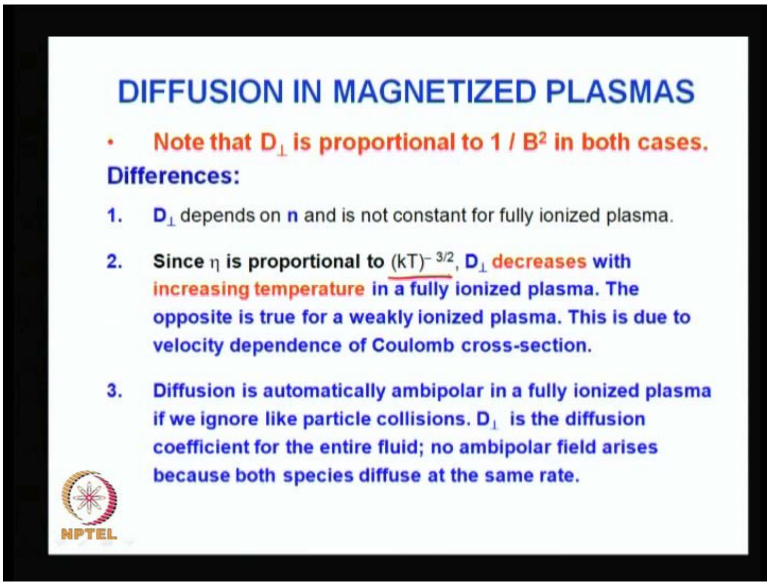

So, we have been able to derive an expression for the perpendicular diffusion coefficient in fully ionized plasmas and weakly ionized plasmas in the presence of magnetic fields.

What, we let us compare quickly the D perps in both cases you will note that, they are proportional to 1 upon B square so, as you increase the magnetic field diffusion across the field is reduced. However, the difference is that for a fully ionized plasma D perp is not constant, it depends on the density. Moreover, the specific resistivity is proportional to k t raise power minus three half so, D perp in a fully ionized plasma decreases as the temperature increases and the opposite is true for the weakly ionized plasmas, this occurs because of the velocity dependence of coulomb cross section.

The third difference is that, diffusion is automatically ambipolar in a fully ionized plasma if we ignore like particle collisions, it is the diffusion coefficient for the entire fluid, no ambipolar field arises, because both species diffuse at the same rate so, these are the differences between diffusion in a weakly ionized magnetized plasma and a fully ionized magnetized plasma.

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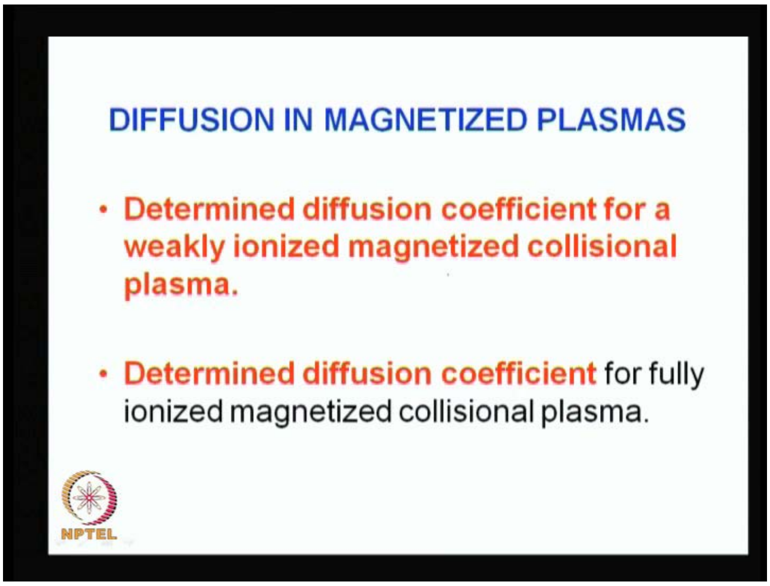

For the sake of interest, I would like to show you graphic, showing the theoretically determined perpendicular diffusion coefficient D perp, this is D perp on a logarithmic scale. This is the classical diffusion, which is the expected diffusion we are taking a logarithmic scale and showing D perp versus collision frequency.

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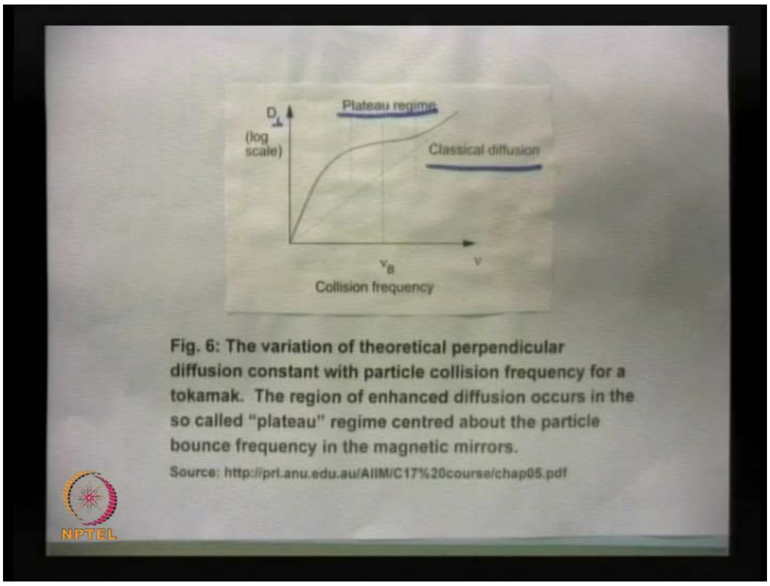

There is an enhanced diffusion in this so called plateau regime, it is a, it is an experimentally observed situation and it is still an area of active research for explaining this particular diffusion phenomena, which appears in a tokamak in controlled thermo nuclear fusion.

So, with this we come to an end of the discussion today on diffusion in magnetized plasmas. In this particular lecture, we have determined the diffusion coefficient for a weakly ionized plasma, in a magnetic field the plasma is also collisional so, we have taken into account the effect of collisions in a weakly ionized plasma in a magnetic field then, we have also determined the diffusion coefficient for fully ionized magnetized collisional plasma. So, this is all for today, thank you very much.