Introduction to Atmospheric and Space Sciences
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Lecture – 48
Plasma Parameters and Debye's Sheilding

Hello dear students. So, today we will talk about a very important topic in Plasma physics which has to deal with the basic understanding of plasma or how it behaves in the presence of external fields such as an electric field. How does the collective behaviour of plasma comes into picture when it is subjected to an external electric field for example, let us say this topic is called as Debye Shielding.

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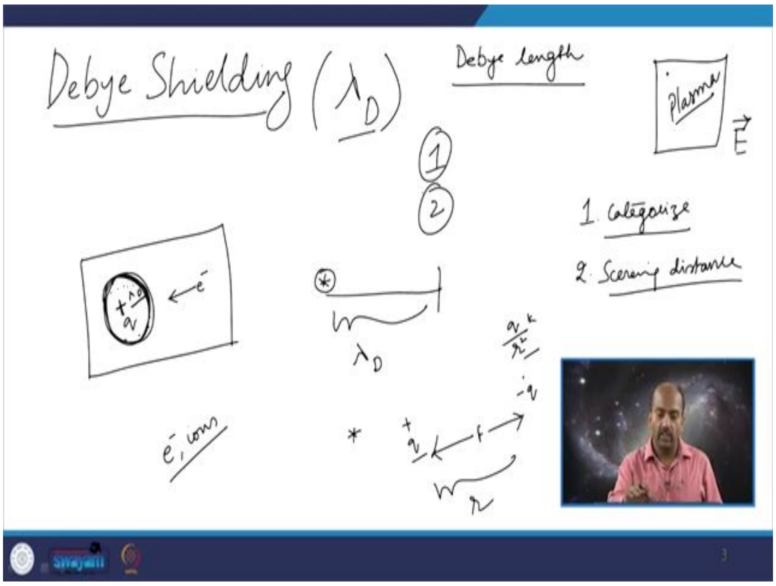

So, Debye shielding or we derive we will derive in this class an expression for lambda D this is called as the Debye length. So, what is Debye's shielding? Now, before I go into the details or take up examples to illustrate what is Debye shielding plasma has the ability to shield electric fields. Let us say for example, if you take an enclosure and if you have a plasma, this plasma has the ability to shield electric field let us say if you apply an electric field. The plasma behaves in such a way that this electric field that is applied from the external is shielded.

So, the effect of electric field will not be felt at some point in the plasma. So, the plasma makes sure that the electric field is shielded let us say for example. So, the Debye's length is the most important and the fundamental length scale in plasma physics.

So, this is Debye's length is very important in categorizing plasma let us say So, whether to call an ideal gas or a collection or charged particles existence in a gas to be a plasma or not in this let us say Debye's length gives you an idea whether something can be called as plasma or it can just be called as a gas.

So, this categorization is very important to understand and Debye's length helps us to categorize plasma as any different types of plasmas. So, it describes the screening distance; this is describes the screening distance beyond which charges are unaware of other charges inside the Debye's length. So, you consider a particular length dimension.

So, let us say you put a charge here. So, this is the maximum length up to which the charge influence can be felt. Generally in electromagnetic theory what we do is if we have a charge the coulombic attraction force or repulsive force can be felt to a very large distance the force magnitude can be very very small, but it is never 0; it is never absolute 0. That means, that if you have an isolated let us say positive test charge, its influence in terms of another charge that is kept somewhere let us say minus q.

There will always be a nonzero magnitude of force which exists between these two charges no matter how far they are separated. So, whatever may be the distance that of separation there will always be some amount of force that will be held, but in plasma physics what we deal is that Debye's length describes let us say if you start to understand this in terms of electric field; the electric field that is exerted by this positive charge is just q by r square times k let us say.

This is electric field that is experienced at any distance. So, as the distance goes very large it drops 1 by r square. So, its a very fast decay no matter what the electric field will always be there, but in plasma what happens is that if you have a charge that is held in plasma. Theplasma will behave as if it will confine the influence of this charge up to a certain point after which the rest of the plasma the remaining plasma will not be coming under the influence of this charge or will not realize that there is a charge that is present at some point in the plasma.

So, a charge in the plasma will attract opposite charges and repel like charges to the point that its electric field is screened by the charges it has attracted. So, that particles outside this influence are unaware of the existence of this particular charge; that means, if you take an enclosure or this enclosure example is easy because you can have things in your understanding in a simple way.

Let us say you have a test charge plus q. What is plasma? Plasma is already electrons and ions in large numbers let us say or in sufficiently large numbers. Now, generally when you have a electric charge which is let us say positive in this case , it attracts the negative charges. Naturally where are this negative charges coming from? This negative charges are coming from the plasma itself. So, since the plasma has a collection of negative and positive charges the moment you keep a positive charge it will attract other negative charges.

Because of the coulombic attraction forces as a result of which this negative charges that I have been attracted, will try to nullify the effect of this isolated positive charge. To an extent they will form a sphere or cloud of charges such that any charge, any negative charge let us say at this point will not feel the influence of this positive charge.

That means its not electrically attract its not attracted, there is no coulombic attraction force despite there is this two are opposite in nature, these two are in reasonable distances of separation, but still the plasma has been able to create a cloud of oppositely charged particles around this test charge. Such that charges outside this sphere will not be influenced or will not be attracted to this charge.

Now, this distance this length dimension over which this positive charges influence can be felt is generally called as the Debye's length. I will come again. So, Debye's length defines the fundamental length characteristic of the plasma up to which an influence of particular charge can be felt beyond this lambda D or beyond this Debye's length the influence of this charge will not be felt. This is kind of not opposite this is kind of a difference that you see generally in comparison to the coulombic attraction forces or repulsive forces.

Now, what else? So, this can be seen that plasma shields out the electric field that is applied to it this can also be seen in another direction; that means, if you apply an electric field to the plasma, the entire plasma will not feel it. Plasma will try to shield the field such that its the electric fields influence will remain only up to a certain extent in the plasma. The remaining plasma will not field or will not come under the influence of this particular electric field that you have applied.

Now, let us say what we will do is we will take up two examples let us say example number 1 and example number 2, to illustrate the importance of Debye shielding. I mean this examples will lead us to the understanding of the mathematics that is behind the Debye shielding let us say; let us say the way we consider the example number 1.

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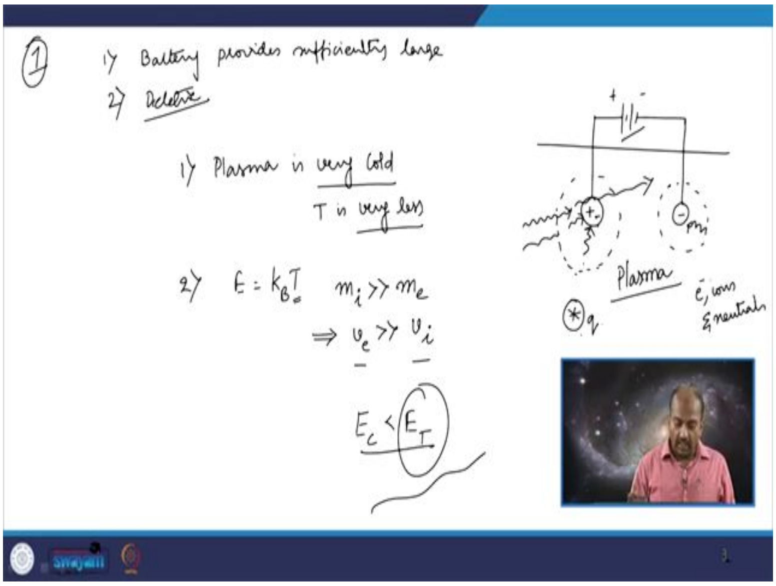

So, let us say we try to put up an electric field inside a plasma, let us say we have a plasma we suspend two electrodes like this and we apply a moderately high potential between these two electrodes. So, what will happen this is the positive terminal this is the negative terminal.

So, this plasma here. So, here what you have taken is you have taken plasma and in the plasma you are trying to create an electric field you are trying to by polarizing it you will try to create an electric field inside the plasma all of this is to be achieved by putting two electrodes and supplying a potential.

Now, what would happen let us say. So, you have what are the constituents of the plasma. Plasma will generally constitute electrons, ions and neutrals; neutrals which which does not have any charge, electrons are negatively charged, ions are positively charged. So, what is the natural course of action when you put a potential in the plasma? What will happen is electrons will be attracted to the positive electrode, ions will be attracted to the negative electrode naturally.

So, the charged electrodes will start attracting the opposite charges, almost instantaneously when you switch on the circuit almost instantaneously a cloud of ions will be surrounding the negative electrodes. So, this negative electrode will be surrounded by a cloud of positively charged ions and this positive electrode will be surrounded by a cloud of negatively charged electrons this happens almost instantaneously.

Now, the electrons and ions what they can do is see you are applying the potential by a certain amount of strength let us say, what can happen is this electrons which are attracted to the positive electrode can stick to the electrode itself and they can neutralize the potential, they can neutralize the effective charge. Let us say if it take 100 electrons, so be it 100 electrons will stick to the electron and eventually you have equal and opposite charges they will recombine.

What is the net potential, what is the net charge that you see? Net charge that you will see will be 0. So, similarly electrons ions can also stick to this electrode and as a result of this the net charge may become 0, but we do not want to have such a possibility. That means, our objective is to understand how the Debye's shielding will or Debye's length dimension comes into the picture to understand the fundamental characteristic of the plasma.

So, this Debye's length depends at some point of time depends on how many charges are present and what is let us say if you apply certain potential, does the Debye's length change with respect to the potential that you have applied? Does it change with respect to the amount of charge carriers that are present per unit volume inside the plasma? Does it also depend on the temperature that the plasma is existing at? Let us say.

So, these three are the main thing. So, what I want to do is let us say by applying some potential I want to see I want to electrify plasma I want the induced electric field into the plasma. How do I do that? I can create charge separation with charge separation happens electric field is created from one charge polarity to other polarity that is the natural way of creating an electric field.

Now, I do not want this recombination to happen at a very fast pace and if the recombination happens the net effective charge at the positive electrode will be 0 and the net effective charge at the negative electrode will also be 0. So, I want to avoid such a possibility. So, to avoid such a possibility I can do two things to. So, we can assume that the battery that is providing this is sufficiently large. So, to avoid the possibility of recombination and losing the entire setup what I can do is the battery is supplies sufficiently large potential difference.

Battery provides sufficiently large potential difference. Then the second method that I can avoid this recombination is that I can wrap these electrodes with dielectric material which will not allow the recombination to happen.

So, as a result my objective is achieved that it will be suspended in this plasma and it will keep on attracting so this may eventually will not happen as such, but what is most likely to happen let us say now the plasma is very cold let us say if the plasma is very cold, now another possibility. Now, that you have avoided recombination and you have avoided the possibility that the entire positive electrode has sufficiently attracted electrons and these electrons are stuck to the electrode and the net charge at this terminal is 0.

So, to we have avoided such a possibility. Now, once that is done let us say the plasma very cold; that means, temperature are T is very less, let us say the temperature is very less, what does it mean? If the temperature is very less the mean molecular energy or the amount of energy that the particle for example, the electron or the ion will also be less.

That means the speed at which this particles will travel will also be less. So, if the temperature is being very very low let us say the random thermal motions will cease to exist. So, there may not be any combination as such. So, there would be just as many charges in the cloud to shield the positive charge.

So, eventually the idea is let us say if you have sufficiently large number of electrons in this region. So, any particle let us say this star should ideally be a particle with the charge will not be is able to see this positive charge that is the idea this shielding is what I am talking about. There would be just as many charges in the cloud shielding would be perfect and there would not be any electric field outside the cloud. So, outside this cloud there would not be an electric field.

So, this charge will not be able to see the influence of this electrode. Now, otherwise let us say when the temperature is very less this is the possibility that it can happen otherwise if the temperature is not very less or if the temperature is finite. Then the idea of temperature gives away the energy let us say energy can be a measure of temperature is a measure of energy is k B T.

So, if there is temperature the amount of energy that are associated for a particle at this temperature is k B T. Now, here the most important thing is the mass of ions is very very large in comparison to the mass of electrons. So, it is natural to expect that the velocity of the electron will be very very large when compared to the velocity of the ion. So, what does it mean? So, there is the possibility that electrons and ions may not be able to deposit their energy, but those electrons and ions will make it cloud around the electrodes for which the coulomb force overcomes the thermal energy of the particle.

What it means is that electrons and ions they have sufficiently large velocities by the virtue of its temperature or the ambient temperature of the plasma. As a result what you may expect is that electron indeed wants to recombine, but the thermal motion of the electron, if it exceeds the coulombic attraction of the between the electron and the electrode positive electrode if the coulombic attraction falls short of in terms of short in front if let us say the thermal energy the electron will simply overshoot the electron.

Now, it will simply overshoot I mean it will not be able to come and touch the electrode as such. So, there is a possibility the electrons and ions may not be able to deposit the charge. So, this is very crucial I mean where is the coulombic energy in balance with the energy due to thermal motions if the coulombic can I mean if it is very very less. So, the thermal motions will take over and electron will just move of course, it will come under the influence of this charge, but it should not be able to stay forever or it will not be able to stick to the positive ion, positive charge center.

So, what is the role of coulombic force ,coulombic force can make them stay in the cloud, but not get them stuck because of the random thermal motions. So, it will always overshoot the electrodes. So, the electrons and ions at the edge of these clouds where the electric field is weak; obviously, at the edge of these clouds where the electric field is weak electrons and ions have enough thermal energy to escape from the electrostatic potential which is at the edge of this cloud.

If you want to achieve. So, at the edge of this cloud electrons and ions have sufficiently large amount of energy to exceed or to overcome the coulombic attraction force that is provided by the electrode.

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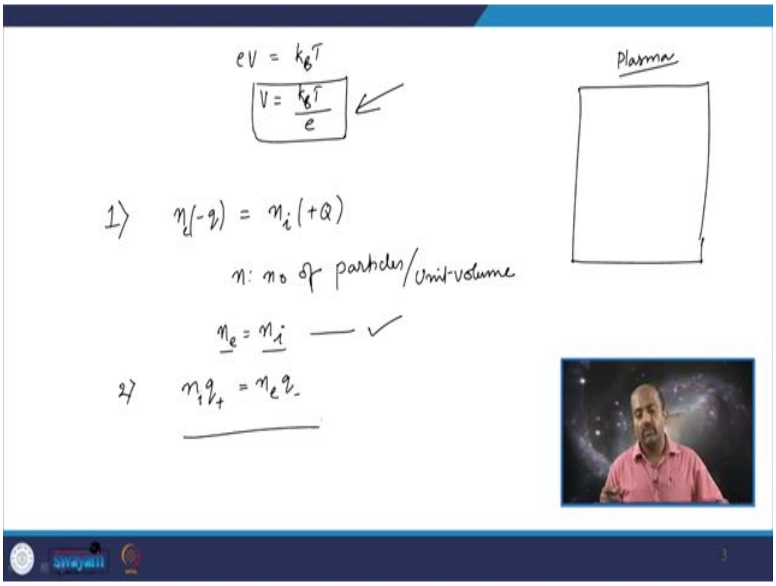

In that cases we will simply write e V which is by the virtue of the potential that is created is equals to k B T; that means, the potential that is existing is roughly of the order of k B T by e.

Electric potential

$$V = \frac{k_B T}{e}$$

What is this potential, where is this potential coming from? So, this potential is of the order of. So, potentials, so this is the at the edge of the cloud. So, potentials of the order of k B T by e can leak into the plasma. So, potentials of the order of V can leak into the plasma and cause finite electric field to exist beyond the shielding cloud. So, shielding cloud is the maximum or are the farthest shielding cloud the dimension of shielding cloud the outer dimension of shielding cloud is the farthest point up to which an electric field can penetrate into the plasma.

But at the edges of this shielding cloud the coulombic attraction force is not sufficient to hold the charged particle; that means the coulombic potential will leak into the plasma if this is of the order of this.

So, now, let us say this is one example where you have tried to create electric field in by the means of applying two electrodes oppositely charged electrodes let us say. Now, the second example could be let us say we consider an isolated plasma. Let us say the plasma is neutral in the sense the number of negatively charged just charged particles is equal to the number of let us say n e is equal to n i; n i indicates the total amount .

So, n is number of particles per unit volume so; that means, how many number of particles exist per unit volume. So, this plasma has equal number of particles. So, let us say n e is equals to n i in addition to this, so we have considered a plasma such as the one that is confined within this box.

Now, what are the characteristics of this plasma? It is such that the total number of electrons is equal to the total number of ions. In addition to this the total number of the total positive charge let us say n i q plus is equals to n e number of electrons and q minus. So, generally if you think of ions with a single positive charge this condition itself is sufficient to say that there is equal amounts of positive and negative charges.

But there is a possibility that doubly ionized or triply ionized species can exist in that cases the total amount of positive charge equal to the total number of negative charge. So, the total amount of negative charge. So, in that cases, so it is equal in terms of numbers as well as in terms of quantity of charges.

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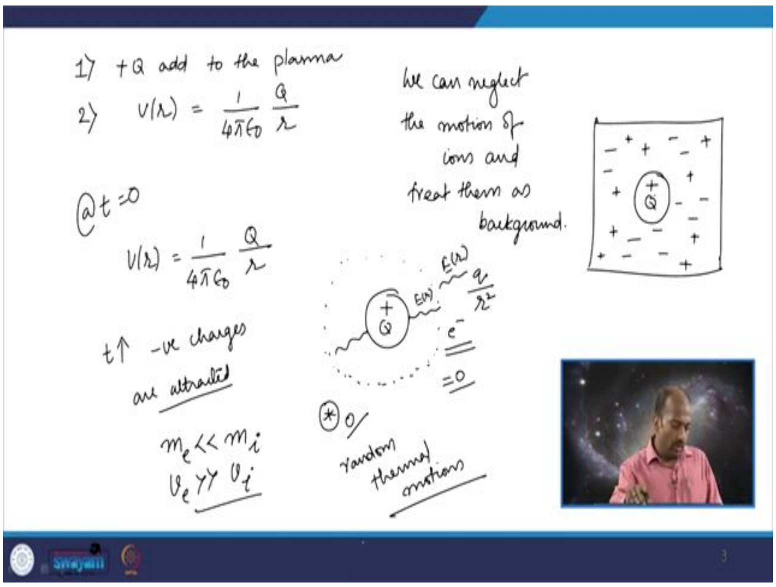

So, we have considered the plasma to be this. So, if this is the case then we will introduce a positive test charge inside the plasma. So, there are plus minus everywhere. So, of course, they are randomly distributed, but overall the charge neutrality exists inside this plasma. Now, let us add. So, the step number 1 is to add positive test charge to the plasma.

So, we keep this positive test charge inside the plasma let us say. Now, when we have this test charge ideally what is the potential that can be felt as a function of distance? So, ideally the potential due to this charge is simply 1 by 4 pi epsilon naught Q by r. So, starting from this point at any point at any radially separated point the potential is always V is equals to 1 by 4 pi epsilon naught Q by r.

So, what is this potential? This is the coulombic potential. Now, the presence of now what happens is in the presence of large number of freely moving charges this situation changes drastically. Now, the presence of large number of charged particles around this charge changes this situation entirely. What is the immediate course of action when you keep a positive test charge? Immediately charges of opposite polarity will be immediately attracted to this chest test charge naturally charges of opposite polarity are attracted. So, that charges of like polarity form a cloud in the vicinity of the test charge, this is important.

So, in the vicinity of this test charge charges of like polarity. So, this is plus Q and charges of like polarity will form a cloud in the vicinity of this test charge. So, these are electrons, these are like charges. So, they will form a cloud in the vicinity of this test charge. So, the charges of opposite polarity are attracted and form a cloud in the near vicinity which tends to neutralize the test charge in some way.

What is the role? So, the total positive charge and the total negative charge will be such that it is neutral I mean the total charge is 0 in this picture. Now, but ideally what is supposed to happen, but this will not happen now, what happens is in between these the random thermal motions of these particles will come into picture, random thermal motions of these electrons will come into picture which will.

So, what is the role? The random motion of the particles will not allow the particles go to the test charge and stick to it. So, naturally the coulombic attraction forces should overtake and as a result the electron should be brought closer to the positive charge and they should be combining and neutralizing. But because of the random thermal motion of electrons this will not happen.

Now if we measure the electric field in the nearest vicinity we would recover a single particle potential, single particle electric field in the nearest vicinity of this test charge it will it will just v Q by r square. But due to the fact that many particles are moving in this vicinity this situation changes rapidly over a period of time. Now, what we want is we want to find out how the field we will be varying or how will field be inside over a long period of time.

What we want to find out is that how will the field vary over a long period of time, let us say how will the field vary here or how will the field vary here as a function of r. So, we want to find out the field that will be inside over a long period of time; that means, we want to see what I am trying to say is electric field due to a charge Q is q by r square anywhere, but if you have particles surrounding this charge, what will be the role of this cloud of oppositely charged particles on this?

So, ideally if there are enough number of negative charges in this cloud electric field at this point will be 0 right and electric field inside this need not be coulombic because we have an electron cloud. So, we have to find out I mean how will it look like let us say. So, what we will do is we will allow sufficient amount of time to pass by and we will try to find an expression for the electric field as a function of distance inside the cloud over a long period of time.

So, we will allow enough amount of time to pass by. So, we want to find out the electric field that is inside over a long period of time; that means, we want to find out averaged field over sufficiently long period of time. Now, let us consider at t is equals to 0, the potential as a function of distance v is equals to v of r is equals to 1 by 4 pi epsilon naught q by r.

Let us say we have the test charge being indicated as this, so we will write as Q by r. So, what is this? This is the potential the moment you keep the charge inside the plasma you suspend the charge inside the plasma this is at t is equal to 0 as the time progresses. So, as t increases the negative charges; the negative charges are attracted and in addition to this you have the mass of electrons which is very very small in comparison to the mass of ions.

And the velocity of electrons thus becomes very very large in comparison to the velocity of ions. So, as a result of this velocity of ions becoming very very small when comparing to the velocity of electrons we can neglect; we can neglect the motion of ions and treat them in treat them as background.

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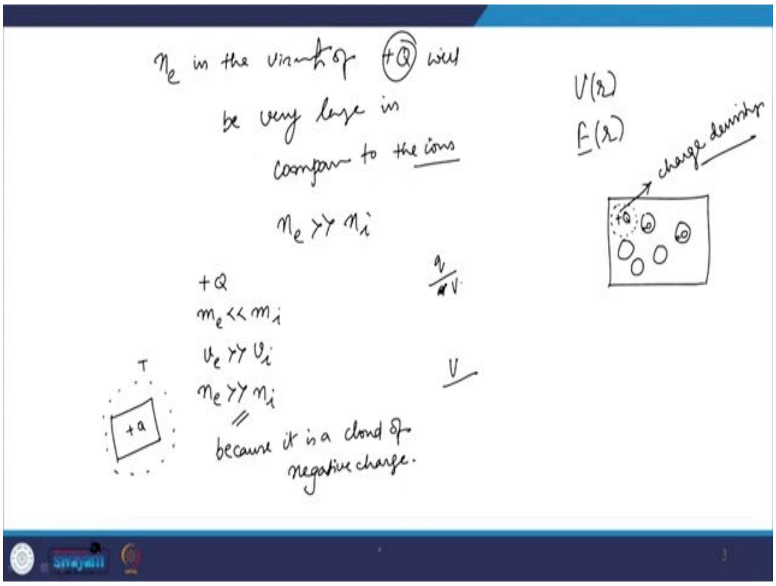

Now, what I after a sufficient amount of time has passed, what will happen? What will, the most likely thing that will happen is the number of electrons in the vicinity of this positive test charge will be very large in comparison to the ions. So, as the time passes.

Now, let us say if you consider this inclusion that number of electrons will be very very large when comparison to the number of ions. So, the consequences were do how did we arrive at this point? Since you have suspended a positive test charge plus Q the electron mass is very very less in comparison to the ion mass as a result at the same value of temperature, see the temperature is same for electrons and ions.

So, that the velocity of electrons will be very very large when compared to the velocity of ions. As a result within this limited space surrounding the positive charge or near the cloud within this limited space not the entire, within this limited space we can say that the number of electrons are very very large in comparison to the number of ions. Because it is a cloud of negative charges, not the positive charges .

Now, what is our objective? Our objective is to find the potential for or let us say electric field as a function of distance. Now, so what we have realized so far is that due to this attraction forces the number of electrons are very very large in comparison number of ions. So, effectively there is a charge density which is let us say charge per unit volume let us say per unit volume. Now, previously there was no there was no concept of charge density because there were charges.

So, we have taken the plasma to be equal in numbers of positive and negative charges. So, wherever you take in whichever the smallest region that you take in each of these regions, we have taken that the total charge in this regions; what is the total charge in these regions? Is 0, the total charge in each of these regions is 0; that means, that in each of these smallest region that you could think of the total positive charge is always balanced by the total negative charge.

But after having introduced an isolated positive test charge we have realized in a very small region there are more number of electrons by a very large proportion in comparison to the total number of ions. So, there is a charge density of negative charges in; so there is a charge density. So, we will try to derive an expression for the potential probably in the next class.