Introduction to Astrophysical Fluids
Prof. Supratik Banerjee
Department of Physics
Indian Institute of Technology, Kanpur

Lecture - 42
Introduction to plasmas

Hello, and welcome to another session of Introduction to Astrophysical Fluids. In this session, we will discuss the concept of Plasma. Basically, it will be an introductory session. I somehow assume that you know either very few about plasma or maybe nothing about plasma. So, I will start by giving a very basic knowledge of plasma and then I will try to cover several aspects, which are relevant for our course.

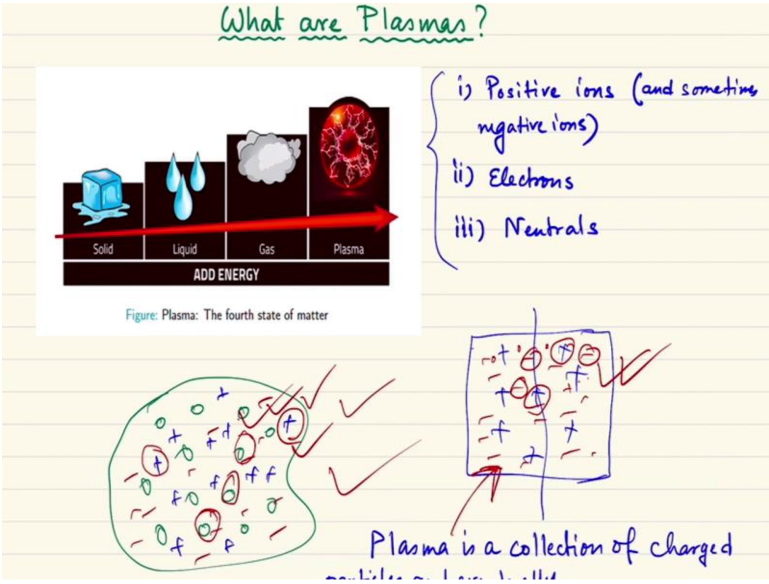
So, it is true that almost I mean 70 percent of the course which is done till now, we have only discussed about neutral hydrodynamic fluids. And we discussed various astrophysical phenomena just using neutral fluids.

Although in some cases we said that the consideration of the plasma aspect and at least the magnetic field is very necessary, but we have not treated, I mean anything other than neutral fluid till now. Now, in reality, as we know that almost all the astrophysical media belongs to the class plasma.

Then the natural question, of course, comes that what is a plasma, how can we characterize a plasma, how can a plasma be sufficient or be useful in explaining several astrophysical phenomena, and can we derive the same type of fluid equations for plasma.

So, can we also have the same type of properties as we have discussed for normal fluids, can we also have this type of fluid properties in case of a plasma fluid, that we will try to discuss in this course. But specifically in this lecture I will mainly give you a very basic introductory view of plasma.

(Refer Slide Time: 02:43)



So, the first question which comes to our mind is what is a plasma? And of course, the first thing which comes to our mind from our general knowledge is that plasma is nothing, but the fourth state of matter.

So, when we were in high schools, suddenly maybe during some quiz competition or some TV program of general knowledge or by some science teacher, we came to know that well besides solid, liquid, and gas, there exists another state of matter which is plasma.

Now, this is very true and even at this level we will not change any, I mean we will not really change this concept. This concept is completely right, that is plasma is exactly the fourth state of matter. But this is not something very much mysterious because from my personal experience I saw that whenever we are talking about like solids, liquids, and gas, people are very energetic in discussing.

Once I just enter in the plasma, they say well oh my God this is something, oh it is too much its enigmatic, it is mysterious. So, the first comment is that plasma is not a mysterious thing. It is a very interesting thing. If you know classical mechanics and electrodynamics then you will you can gain sufficient knowledge about normal or usual plasma.

So, as you can see in this picture that solid to liquid to gas to plasma is just a transformation which is classified by an increase in the energy. So, if you give some energy, for example, if you heat a solid it will melt, if you further heat the liquid it will vaporize. Now, when you further continue heating this gas what happens?

Well, the gas molecules or atoms will now get ionized and the gas which was previously just an ensemble of neutral molecules and neutral particles will now be a collection of some positive charges and some negative charges that means, the ions and the electrons.

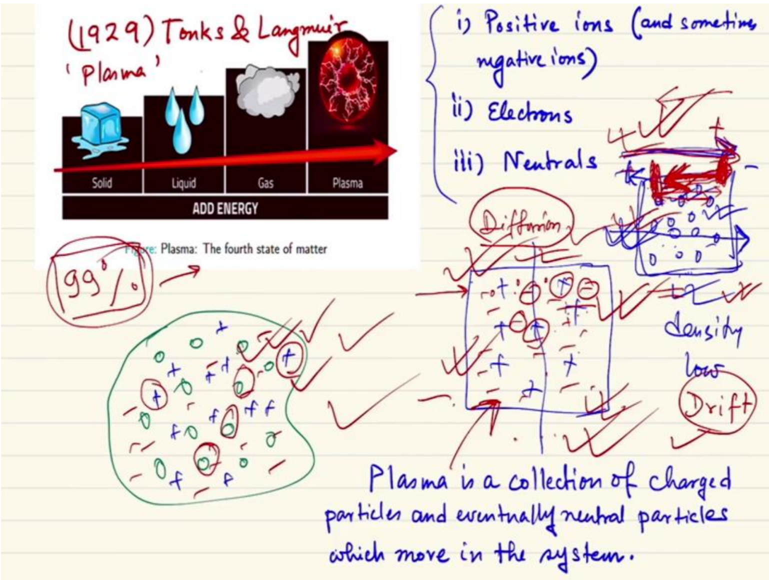
This is the very common case of a plasma there can be a bit more complicated plasma which can also contain, more than one type of positive ion, more than one type of negative ions. So, a general plasma can contain one or more type of positive ions, electrons maybe some negative ions, and also do not forget that a plasma is almost never 100 percent ionized. So, there should always be some neutral particles intact.

So, a plasma as a whole is the gas which contains three type of particles, 1 is positive ions or negative ions, I mean not or, but sometimes and sometimes negative ions, number 2 is electrons, number 3 neutrals. So, you can simply understand that a plasma is a collection of all this.

Now, in various cases, under various circumstances you will see that for the sake of simplicity people just consider a plasma which is fully ionized and just is a collection of only positive and negative ions. But this is not the real case, although for some analytical convenience we do that.

Now, try to understand that you have heated, the system gets ionized. So, the system now has a lot of energy. So, when the system was just neutral gas type of thing, so with respect to that state now the system has much more energy. So, a part of this energy is used as the ionization energy of this molecules, energy of ionization. Now, the rest of the energy the kinetic energy of these charged particles.

(Refer Slide Time: 08:52)



So, a plasma is a collection of charged particles and eventually neutral particles, which move in the system, right. Now, you can easily understand that when this system was simply just an ensemble of neutral molecules or atoms, then if you just put an electric field then, my question is that would that be affected?

Well, the answer is yes, but at least what happens that there can be some polarization in this molecules or atoms. But that depends on the particles of course. Now, in general the system is not ionized, but let us say that you are making the gas very dilute. So, you are making the gas very rarified.

The density is very low, and you are not heating the system, but you apply a very strong electric field. In this condition, it is much more probable to get an ionization of the system just by using the electric field, and this is what done during the discharge in the laboratories, in the discharge tubes. Then, we just make a very dilute gas at very low pressure, and then we just apply some electric field over there.

Now, once the electric field is applied like this and this particle let us say is ionized in some plus and minus, so this minus will be attracted towards this and the plus will be attracted towards this, right. So, due to this electric field there should be a current. So, as you can easily see that the original electric field was this and so the plus charges will be accumulating here and the negative charges will be accumulating here.

So, as a result in this plasma there can be a current from plus to minus, right. So, this current will be actually opposing the original electric field. Now, whenever we are talking about this type of system we have to also remember or rather keep in mind that whenever we are talking about giving the energy.

So, basically here the electric field is giving the energy for the ionization, here the thermal energy. So, when electric field is applied and some ionization is just caused by this. Then you see after the ionization the charged particles they have very well directed motion, they know where to go.

But if the system is ionized just by using thermal energy, then the system does not know where to go after ionization. So, it is a random process because thermal energy does not care, right. It just leads to random motion. So, this type of motion which is led by the thermal energy leads to random motion and is called a diffusion type of motion, and will be led by the concentration gradient.

So, whenever you have the dominance of thermal energy, then what happens? The particles will move from a region of higher concentration or higher density to a region of lower density, as simple as that. So, that is somehow you can say as the rough symbolic direction for the thermal energy.

But for electric field this is even simpler, the particles will exactly move to the opposite of the external electric field, right. That is why, so, external electric field is just like that and the positive particles are going in this direction.

So, after some time, there will be a concentration and these positive particles will create a current which will be in the opposite direction, right. So, that is something also to understand that, and of course, whenever some electric field is applied, after ionization the positive particles will follow the electric field there is no problem for that.

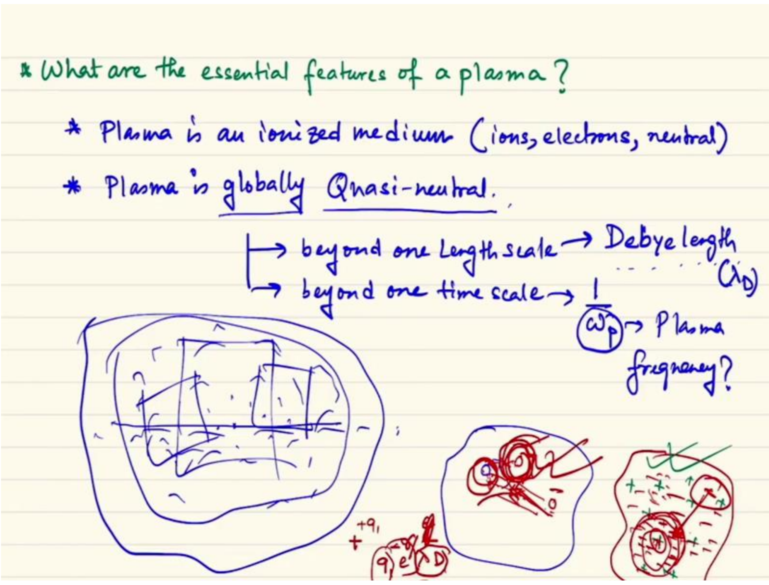
So, they will follow the electric field and the negative particle will just move to the opposite of the electric field. But once they are accumulated here then only inside the plasma or the system you will have a current, which will counter-pose or which will oppose the external electric field.

So, this type of directive motion under an electric field is known as drift motion. So, in a plasma always we can see there is a competition between drift motion versus diffusion motion. Now, just a bit of history, so that you can also have the idea that how important plasma is.

So, first of all 99 percent of the whole known matter, not only in the astrophysical domain, but the whole known matter the 99 percent of that is plasma. Now, the plasma was introduced for the first time in the year 1929 by Tonks and Langmuir. So, these two persons for the first time they use the word plasma.

Now, we have defined the formal definition of plasma. I mean we have discussed the formal definition of plasma, and we have also seen that depending on the energy, which is creating the plasma we can have either diffusion or drift type of motion, but in a practical case you can have both and then there will be a competition between drift and diffusion.

(Refer Slide Time: 17:52)



So, now, the next question is simply that what are the essential features of a plasma? So, as I just said that plasma is an ionized medium, right. So, we all agree that plasma is not a neutral medium, it is ionized medium, but it can contain ions, electrons. Ions, means in the very complicated case it can also contain negative ions as well and neutral.

Now, second thing is that plasma is globally Quasi-neutral. Now, there are two points one is globally, one is Quasi-neutral. What is the meaning of that? So, first of all globally simply means that the Quasi-neutral properties or Quasi-neutrality is not a property which is true at every point in a plasma. So, you can simply now see the plasma as a kinetic ensemble, but not like kinetic ensemble of neutral gas molecules, but a kinetic ensemble of charged particles, ions and electrons, you can simply see that.

As we will see that after certain conditions plasma can also be treated as a fluid, but for the time being we just see as a kinetic ensemble. So, at every single point or I mean if you just take a local neighborhood of any plasma particle in a plasma then the question is that in this neighborhood whether the total charge density is 0 or not. The answer is not necessarily.

But if you take sufficiently bigger volume, so then you can have actually globally Quasi-neutrality. That means if you now take a sufficient amount of bulk of this material and then you just measure the charge neutrality, the charge neutrality will be almost 0. It is not exactly 0, but almost 0.

So, that is why this word Quasi comes in. So, globally simply means that you have to take into account like some considerable amount of material or considerable volume.

For example, if you just take this volume and then you calculate the total number of ions inside it and electrons inside it and then you just add them together just to check the charge neutrality and charge density, you will see that should be very near close to 0. So, that is the meaning of globally Quasi-neutral.

Now, this globally Quasi-neutrals simply means that we have to define a length scale and a time scale beyond which the Quasi-neutrality is defined. So, for plasma this is exactly the case that is globally means beyond one length scale and also beyond one time scale. Now, this length scale is known as the Debye length, we denote by λ_D and the time scale is known by $\frac{1}{\omega_p}$, where ω_p is the plasma frequency.

Now, you can ask me what is plasma frequency? That we will discuss in a few minutes. But before that just to understand that what is happening, for example, if you have one length scale let us say this, and then if you just take particles within this length scale let us say if you take any volume, well, you cannot expect charge neutrality.

But if you take a volume of the order or larger than this scale then you can simply expect that there will be a very negligibly small charge density. Now, this length scale is known as

Debye length. Now, the Debye length is conceptually introduced in other way that whenever in a plasma, now you go to this original picture this is quite useful.

Now, in a plasma when you have this type of charge particle like this, then it is true that at the first loop you can have this idea that maybe this plus will be recombined with this minus or this plus can also recombine with this, this plus can go to this. But is it really as simple as that?

What happens? Let us say if your system just contains one positive ion and one negative ion, and then of course, the only force which is acting between them is the coulombic attraction force, right. But if the force is hindered by another negative ion let us say, then what happens? These and these will act by a stronger coulombic attraction force because this is closer to this, and this one will be a bit further.

Then what happens? When this will try to come to this particle after just coming the neighborhood of this particle, besides experiencing the attractive force due to this it will also experience actually, it will experience from the beginning.

But what I am saying that when it comes to the neighborhood of this particle then it is experiencing attractive force due to this towards this particle, but at the same time it is also experiencing repulsive force due to this particle. So, attractive force towards this particle repulsive force towards this particle.

So, that is why after coming to this, this particle actually may deviate or I mean I do not know like may deviate like this. So, what we actually assume that this coming from this point to this point will be very simple. Now, in the presence of this third particle is no longer that simple, and this situation becomes worse if your system is like having let us say, some positive ions and in practice the positive ions are bulky.

So, they are not protons, they are ions, and negative species, they are the electrons they are very light, so they can move anywhere they want and finally, you can always see that usually around every single positive ion you can have a cloud of negative ions.

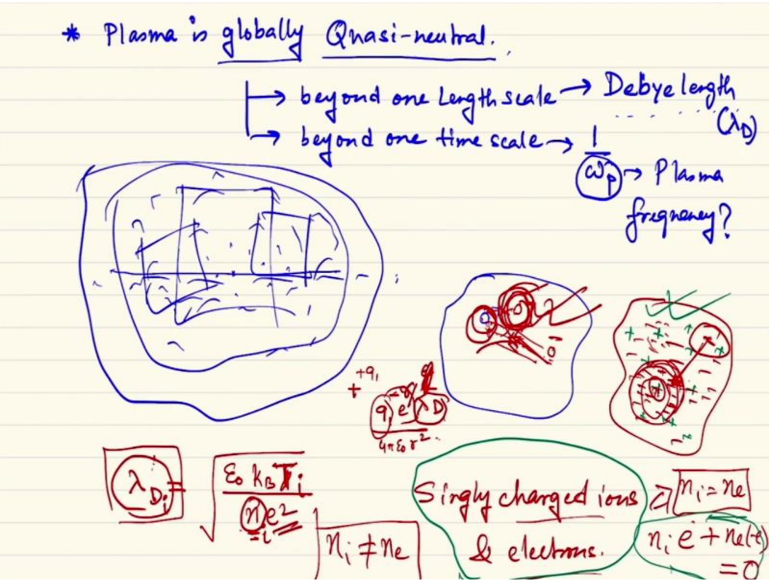
So, a positive ion is surrounded by a number of negative ions. So, it is actually screened by the group of these electrons. Now, let us say one electron which is coming towards this position, before it could have been attracted by this plus directly, but now due to this cloud, when this particle is now here it will be repelled because of the repelling force.

That is why this particle maybe in practice would never reach this in the neighborhood of this particle. So, then with respect to this electron the ion is simply screened, and these the characteristic distance of the screen is known as the Debye length.

So, there are some analytical theories by which you can have some definitions of Debye length. So, simply just by saying that in general if there is a positive ion and the negative ion the coulombic force is like, if this has a charge q_1 and this has e, so it will be $\frac{q_1 e}{4\pi\varepsilon_0 r^2}$.

But if this particle is positive charge is screened by a number of electrons, then with respect to another electron which is coming from far, it will see the effective charge not q, but $qe^{-\frac{r}{\lambda_D}}$ and this λ_D is the Debye length.

(Refer Slide Time: 31:37)



Now, in general for Debye length, we have some expression and for a plasma whose temperature is T, of course, this is a kinetic ensemble I told you we can assume that. So, it can have a kinetic temperature. So, λ_D is nothing, but $\sqrt{\frac{\varepsilon_0 k_B T}{ne^2}}$, where ε_0 is the free space permittivity, k_B Boltzmann constant, T temperature of the plasma, n is the number density of the species.

So, just to tell you when I say that T is the temperature of plasma this is a wrong statement, this is actually the temperature of the species. So, λ_D is corresponding to a species. For example, here when we are talking about the λ_D, it was the λ_D of the ions. Now, the same type of thing can happen for electrons.

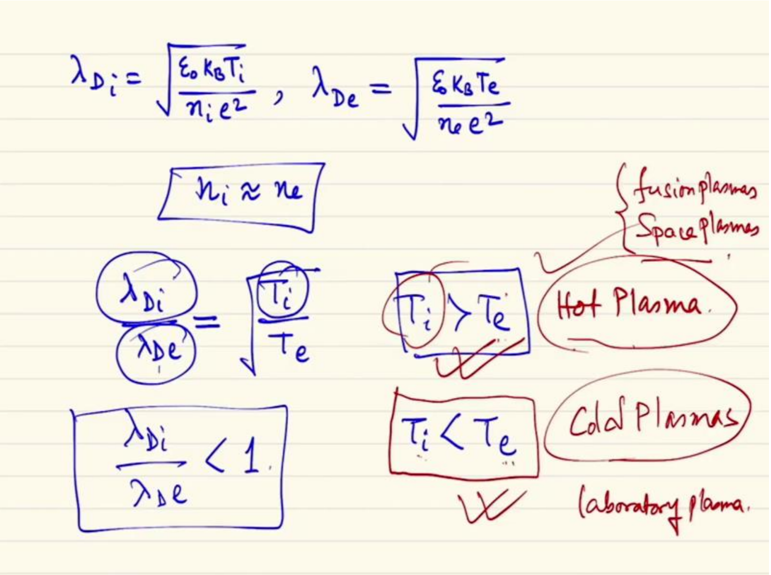
So, when you have a large collection of plus and an electron can also be surrounded by very slowly moving ions positive ions, then some positively moving ion would also feel although they do not move much, but anyways if they move at all, then they can also see some screening effect, and thereby defining an equivalent λ_D for the electrons as well. So, n is the number density of the species.

For example, here for the ions, in general write λ_{Di}, T_i, n_i. So, we are talking in general in terms of the singly charged ions and electrons. So, charge is plus or minus e. So, e^2 that will not change and n is the number density of the ions.

Now, you see that within the Debye length, the charged neutrality is not valid so that means, n_i is not equal to n_e. Of course, if we are just talking about plus and minus charge then the total charge density at a point will be $n_i(+e) + n_e(-e)$.

So, it will simply be giving you if it is almost equal to 0, then it will simply lead to n_i is equal to n_e. So, for this type of specific systems, the equivalent condition of Quasi-neutrality can be written as n_i is equal to n_e. But the fundamental condition is this, the total charge density is 0 at every point. So, n_i is equal to n_e is no longer true, but at Debye length or beyond Debye length n_i is equal to n_e.

(Refer Slide Time: 35:15)



So, now we can do a very simple thing that what is then the λ_D for ions that is simply $\sqrt{\frac{\varepsilon_0 k_B T_i}{n_i e^2}}$, and what will be the λ_D for the electrons that will be simply $\sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$. Now, let us say we just assume that n_i somehow is very very close to n_e. Then λ_{Di} by λ_{De} will be what? Will simply be $\sqrt{\frac{T_i}{T_e}}$.

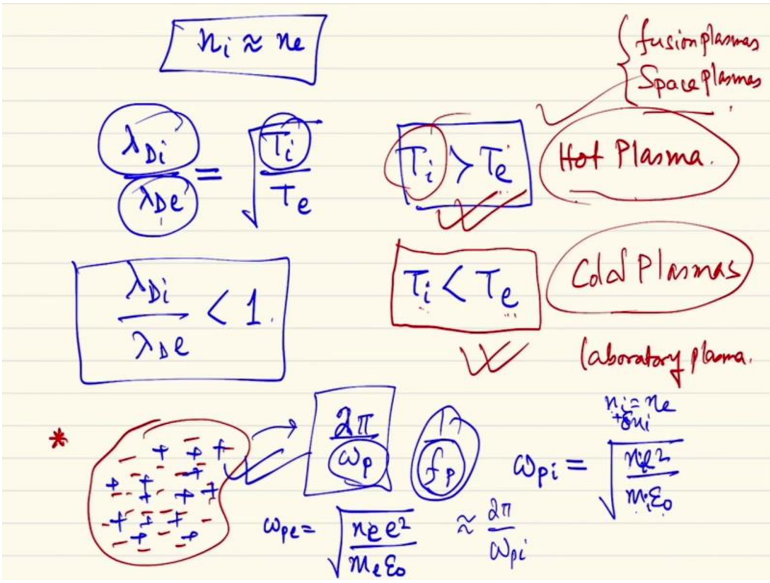
So, if in a plasma the ion temperature is greater than the electron temperature then the ionic Debye length will be greater than the electronic Debye length, right, and if the ionic temperature is less than the electronic temperature then ionic Debye length will be less than the electronic Debye length. This situation is known as hot plasma. I have to write it in red, so that you can see it, hot plasmas.

Mostly the plasmas which are strongly ionized that mean, the degree of ionization is very high, let us say 80 percent or 90 percent, then for those plasma, this type of condition is verified and this is called a hot plasma. A plasma whose degree of ionization is very weak then the electronic temperature is much greater than the ionic temperature which is of the same order or a bit greater than the ambient temperature and that is the case for the cold plasmas.

So, the thumb rule is that, T_e is always hot, I mean the electrons are more or less always hot. But if your ions are hotter than the electrons then you have a hot plasma. If your ions are colder than the electron then this is cold plasma. So, mostly the laboratory plasmas they are the cold plasmas.

For example, our space plasma, they are fusion plasma, they are the examples of hot plasmas. So, like Debye length we have another associated concept, this is the concept of plasma frequency. So, as I just said this Quasi-neutrality is guaranteed beyond one time scale and one length scale.

(Refer Slide Time: 38:55)



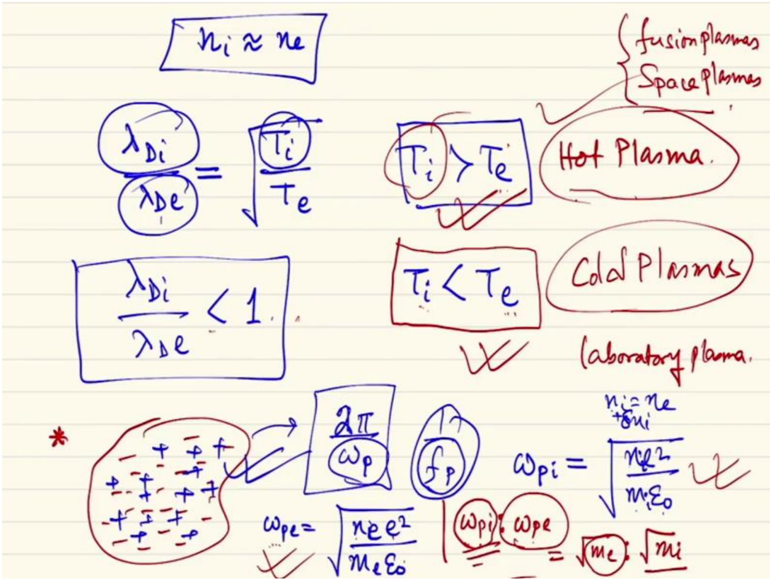
So, now, let us say where the time scale is such that if in a system you have positive ions and negative electrons. I mean not so beautifully like that, but anyways I am making it full of positive and negative species. So, now in general the total positive charge is almost equal to the total negative charge if you take a bulk.

Now, let us say by some artificial way we just perturbed that charge neutrality. Then, the plasma will respond to such a fashion that its Quasi-neutrality will be retained in a time which is $\frac{1}{\omega_p}$. Actually, not $\frac{1}{\omega_p}$, but $\frac{2\pi}{\omega_p}$. $\frac{1}{\omega_p}$ is not the correct way of writing. f_p is known as the plasma frequency.

Although in many literatures you can see ω_p, which is the angular frequency is known as the plasma frequency or it is called the plasma frequency. No problem for that and this ω_p is also defined for every single species. If you just perturb the ion charge from, let us say your original system has n_i is equal to n_e and if you perturb n_i to $n_i + \delta n_i$.

Then the charge neutrality will be established with a time which is of the order almost equal to $\frac{2\pi}{\omega_{pi}}$ where ω_{pi} is nothing, but $\sqrt{\frac{ne^2}{m\varepsilon_0}}$. Once again, e is the charge square, n_i is the number density for the ions, m_i is the mass of one ion, and ε_0 is the free space permittivity. Similarly, ω_{pe} is nothing, but $\sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$.

(Refer Slide Time: 41:54)



Now, if you just want to compare those two, ω_{pi} is to ω_{pe} will be simply equal to again n_i is almost equal to n_e. So, it will be simply equal to $\sqrt{\frac{m_e}{m_i}}$. As mass of one electron is much smaller than the mass of one ion, then the ionic plasma frequency is lower than the electronic plasma frequency.

That means, if you perturb the electronic charge and the ionic charge by the same amount the ion population will take much more time to re-establish its charge neutrality once again. But you see that unlike the Debye length here the ω_{pi} and ω_{pe}, their respective weightage that does not depend on the nature of the plasma whether the plasma is hot or cold, right. That is something very interesting thing.

So, just for your convenience, so, in the exams, we will ask you to calculate this type of quantities. So, we can supply you all the necessary quantities and then you can calculate the plasma frequency, the Debye length, this type of thing. So, this lecture was principally to give you a very short and level zero introduction to the plasmas.

So, in the next lecture, we will discuss the fluid picture of plasma. So, plasma is a vast subject and it can equivalently be treated, I mean it can be treated well not equivalently depending on the situation it can be treated as kinetic ensembles. Sometimes it can be treated such as an ensemble where are individual particle properties are very important.

For example, there is a phenomenon called landau damping, where individual particle effect is very important. You cannot avoid that, and in certain situations, it is only the collective effect which is necessary so, that I will tell you in the next lecture. Some people include collective behavior in the definition or characteristics of plasma. I will come to that in the next lecture, where I will first start by saying the three plasma, I mean standard three plasma criterion.

Thank you very much.