Plasma Physics and Applications

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Week 01

Lecture 01: Introduction to Plasma

Hello dear students. I welcome you all to this NPTEL course on Plasma Physics and Application. Plasma physics is highly interdisciplinary in nature and has a wide spread of applications across the areas of science and technology. So, in today's class we will try to understand the basic definition of plasma and how plasma is different from any other state of matter and what are the potential applications and areas of research which use plasma as a main entity. So, when you want to understand plasma, the first thing is plasma is generally considered as the fourth state of matter. So, what is a state of matter? State of matter is basically the state in which you see visible matter.

It can be in the form of a solid condensed form where all the particles or the atoms or molecules are tightly arranged in a systematic way or a liquid in which they are loosely bound they are moving randomly in all directions or a gas. So, if you go from solid to liquid to gas what you see is the order of arrangement decreases as you go from solid to liquid and liquid to gas. So, solid is highly structured and gas is very weakly bound atoms or molecules in a container or something. Now these are the major states of matter that we are very familiar with and in our perception we know that solid is the most abundant state of matter around us because solid state is visible to the naked eye and most of the things that we perceive around us are generally solids.

Now the fourth state of matter which is like apart from solid liquid and gas is called as plasma or plasma is generally referred to as the fourth state of matter. Now how do we produce plasma or for that matter how do we produce solid liquid or gas if you can tightly bind atoms together in a very small inter atomic distance then you will get what is called as a solid something like that. Now if you want to think of plasma, plasma is not very different from a gas for that matter plasma is also a gas but plasma is an ionized gas where electrons and ions are present in addition to neutral atoms. So, how do we produce plasma? If you take a material or a substance like solid which is at very low temperatures you will find it to be existing in the state of solid for example ice when you heat it by applying temperature by increasing temperature you will get water or liquid

form where the ice will melt and it will form in the state of water or liquid. If you heat it even further you will be giving enough energy for the atoms and molecules to evaporate and form into what is called as the gas state.

So, what you are seeing is as you are increasing the temperature of the surroundings of the matter the matter is there is a phase transition from solid to liquid to liquid to gas. So similarly if you go on increasing the temperature to very high values what will happen is these atoms will get ionized if there is enough energy that is given to the outermost electrons they will come out of the orbits and as a result there will be free electrons in the system and to compensate these free electrons you have equal number of ions or as a result of ions coming out an atom becomes ionized and forms a positive ion. So, this state of matter requires extremely large temperatures to be applied on a gas and also results in the form of many number of free electrons and equal number of ions per say. Now where do you see this plasma state to be existing? Plasma can be found in the sun or stars, electric arcs, lightning, neon signs all these are the places where plasma state is existing in its let us say high energy state. But what is the question that we are trying to answer? Plasma is of course the basic state of matter which is not so abundant when we see around us the most abundant state of matter that we see around us is solid in nature or for that matter gas.

But plasma is the fourth state and if you want to produce plasma the easiest way to produce plasma is to increase the temperature which will make atoms to lose electrons and result in the formation of electrons and ions. So, one thing is very clear at this instant itself is that plasma state contains charged particles. So, if you look at the historical perspective of plasma physics or the origin of plasma, plasma is named after the Greek word plasma. So what they used to think the philosopher used to believe that everything is made up of solid, liquid, gas and fire. So, they used to think that all the material all the matter that you see is basically made up of these four elements solid, liquid, gas and fire.

So they had this assumption and now in today's context even after all this development we know for a fact now that fiery is actually plasma. And generally this also the plasma is also known or you must have heard about plasma in a different context in a totally different context where plasma is referred to liquid or transparent substance in the blood. So, if you take blood the picture shows here 45% of the blood is nearly the red blood cells RBC and 1% is a white blood cell or platelets and 55% of the material or the matter or the fluid which is called as blood is called as plasma. So, what is plasma in this case? In this case it is a transparent medium which is carrying all of these things together from one place to another place. So, this is a watery substance which has salts, minerals and proteins.

So, this is a transparent substance by the way liquid or transparent substance in the blood. So, blood plasma carries the RBC red blood cells minerals across the body. Now the point that I am trying to make here is the plasma in blood is basically the carrier which transports the RBC, the minerals, the proteins and everything from one point to another point. So, this is the carrier which is going from one place to another place. When Laimwehr in 1927 described an ionized gas as plasma drawing an analogy that the fluid which is having electrified nature, this electrified fluid carries electrons and ions from one place to another place.

Now this is more important because just like the watery substance in blood carries all the RBC and everything from one place to another place, the plasma or the electrified fluid carries electrons and ions from one place to another place. So, this substance is being referred to as plasma. Now this is very important for you to understand plasma by name has its resemblance to another substance which is blood plasma but this blood plasma is actually what gave the hint of carrying electric charges like electrons and ions from one place to another place. So, what exactly is plasma? Plasma is the fourth state of matter and as a matter of fact most importantly plasma is the most fundamental state of matter. What does it mean? It means when you call something as the most fundamental it means everything else is supposed to have come out of that particular state of matter.

In this case plasma is the most fundamental state of matter which means all the other states of matter are actually coming out from that particular state of matter. So technically an ionized gas consisting of ions and approximately equal number of electrons resulting in no net charge is generally referred to as plasma. You see this is very important it is consisting of ions and approximately equal number of electrons. What does it mean? So, total number of ions is equal to total number of electrons. What does it mean? So, total positive charge is equal to negative charge.

So, as a whole you have neutrality established. So is the gas having any charge? It does not have any charge as such. It is electrically neutral but it is made up of charged particles electrons and ions. As a consequence if you subject this gas to electric and magnetic fields it will get deflected or it will show some effects but whereas you consider a neutral gas in which there are only neutral atoms or molecules this gas will not show any effect of the electric or magnetic fields. So, this is the defining characteristic of plasma where plasma is also a gas an ionized gas but not exactly a neutral gas.

So, where do we find plasma? So in the last slide we have seen that you can easily

produce plasma by heating a state of matter to extremely large temperatures. So, these extremely large temperatures are basically facilitating the removal of electron from the outermost orbits and creating ions. So, you can find plasma typically under two different situations. One very high temperature or very low pressures. So, it is easy to find plasma in low pressure situations where for example upper atmosphere of planets.

So, as we know the pressure or the number of atoms per unit volume decreases exponentially as you go from the surface towards the higher altitudes. What it means is that the pressure inside this small unit volume is decreasing exponentially. So, at very high altitudes you will find very little number of atoms or molecules per unit area or per unit volume for example. And fluorescent lamps we know how fluorescent lamps operate very low pressures are created inside and that is a mechanism by which we make fluorescent lamps. And at the same time like I said plasma can also be found at very high temperatures.

Where do we find very high temperatures? Let us say in stars inside or on the surface or inside fusion reactors. We know what are nuclear reactors and how energy is produced and if the energy is produced by what are the orders of magnitude of the temperature that can exist inside the reactor. So, these temperatures are sufficient to produce plasmas. So, if you want to produce plasma you can either increase the temperature to very high values and subject a state of matter or you can create very low pressures and you can pass electric fields wherein under this very low pressures the ionization will take place. So, the ideal conditions are low pressure and very high temperature.

So, what is the relevance of plasma being referred to as the fourth state of matter? So, like I said plasma state is the most fundamental of all the states of matter. So, all the remaining states of matter are different phases or different forms of this fundamental state. So, plasma should actually be referred to as the first state of matter. Why? Because all the states arise from plasma and most importantly in the known universe that we know or we can see. Plasma is the most abundant form wherein 99.

9 percent of the matter exists in plasma state. So, in totality the entire universe is made up of plasma. It is not liquid, it is not gas, it is not solid, it is plasma. And we seem to be living in a very miniscule percentage wherein we do not find plasmas that easily around us naturally. We create plasma, we create this fluorescent lamps and everything but these are manmade.

So, the point is 99.9 percent of the visible universe is made up of plasma and we seem to be living in a place which is very small in percentage in which plasma does not occur naturally. You have to create plasma. So, fourth state of matter it does not end here.

There are other very interesting states of matter like for example there are fifth state of matter, there are sixth state of matter. So, these states of matter exist under a very peculiar conditions of temperature, pressure, density etc.

But what are those? Fifth state of matter is called as the Bose Einstein condensate. So, we know when at very low temperatures it is possible to populate a single quantum state with many number of particles with infinite number of particles. So, that particular state of matter is called as the Bose Einstein condensate. So, what are the bosons? You can find bosons to be the entities in this condensate and sixth state of matter is the Fermi gas. And there are other exotic and unusual states of matter that we generally do not overcome in day to day life.

But they can exist based on the prevailing conditions of temperature, pressure, density and many other choices of these parameters. For example, matter inside a high pressure white dwarf or a neutron star, we do not know the state of matter that can exist and it can definitely be a state of matter which is not familiar to us or not very well understood by us. The fact is plasma is now referred to as the fourth state of matter but ideally plasma should be referred as the first state of matter and it seems to be the most fundamental state of matter. Let us talk about why plasma is different or how plasma is different? The characteristics of plasma make it very different from other states of matter. For example, the way plasma behaves makes it very difficult to say that it is just a gas.

So, the characteristics of plasma make it very different from other states of matter. So, plasma is made up of electrically charged particles. Plasma is made up of electrically charged particles. What are those? Let us say electron ion, let us say ion can be a single positive ion or anything and because of the presence of electric charges like electrons and ions, it can be strongly influenced by the electromagnetic fields. So, this is what makes plasma as different.

So, you take a magnet, you keep it in neutral gas, nothing happens. You take a magnet, you keep it in plasma, many things happen. This differential behaviour of a gas to electric or magnetic fields is the fundamental nature of the plasma. The behaviour does not resemble with any other state of matter. As a result of this, we have large number of applications which are devised using this characteristic of plasma which is an ability to be influenced by the electromagnetic fields.

So, this behaviour does not resemble anything that we know with the other states of matter. So, in most of the matter in the visible universe, we are not talking about the dark matter. So, in the visible universe 99.9% of the state of matter is called as plasma or is said to be existing in plasma state.

So, it is important 99.9% of the visible universe. So, we can conveniently or safely say that the entire universe is filled with plasma, flows across the universe guided by the electromagnetic fields which are existing in the space. So, plasma just is flowing everywhere, it is there everywhere. With what densities you ask? That depends. But plasma to varied densities, let us say you take one particle per cubic kilometre or you take millions of particle per cubic centimetre, it depends on where you are looking at but we can safely say that the entire universe is filled with plasma or entire universe is filled with charged particles, electrons and ions.

And the movement of this plasma is guided by the electromagnetic fields that are there in the universe. So, plasma exists widely in fire, lightning, ionosphere, polar aurora. So, these are places that you can associate earth. Stars, solar wind, interplanetary medium, accretion disks, nebula, lamps, neon signs, ozone generator, fusion energy, electric arc, laser material interaction, all these places you can find plasma. So, all these things, let us say fire, lightning, ionosphere, all these are related to earth, of course, laser material interaction, all these places related to earth, the other are beyond the earth in space or in related to astrophysical entities.

Now one thing is very clear at this point of time, what is it? Plasma is nothing but an ionized gas. So, how do we differentiate plasma with a gas? So, depending on these four properties, we can say what is plasma and what is a gas? Property number one is conductivity. What is conductivity? Conductivity is the ability of a material to allow the passage of current. To what extent it allows decides the magnitude of conductivity. There are some substances which are highly conductive in nature.

So, if you try to pass some current, current is nothing but the movement of electrons from one point to another point. There are some substances in this universe which conduct the electricity excellently and there are some substances which will not conduct the electricity at all, the current at all. So, conductivity of a gas is very low, is typically an insulator. If you want to pass current, you have to think of a dielectric breakdown, where in despite having very large values of resistivity under high potential difference, the currents can pass from one point to another point but that is an exception. So, the point is gases are very weak, very bad conductors of electricity and they are generally referred to as insulator.

But plasma nearly at the same densities can be a very good conductor of electricity. You do not need to think of the dielectric breakdown at all. Species usually one, what are the species? The neutral species, it can be anything but the electric nature of these species is neutral in nature. So, it is not ion, it is not electron. In plasma, the species are

actually two, there can be electrons and there can be ions.

So, I say that there are at least two. Apart from electron and ion, you can also have neutrals. It is not necessary to say that plasma should invariably contain only electrons and ions, not necessary. It can contain electrons, ions as well as neutral atoms, molecules. Distribution, what is distribution? In this context, if you are familiar, if you have studied any undergraduate course in physics, the distribution is a very well known or very well heard of word. So, what distribution is if you have, let us say 10 to the power of 26 atoms or molecules and if you give energy or even if you do not give energy, if you try to see how these atoms or molecules velocities are there, I mean how these they are distributed.

When you want to define itself, you have to use the distribution again in the definition itself. If you want to see how the energies or velocities are organized across all molecules, for example, it is not practical to say that all the 10 to the power of 26 atoms or molecules will have highest velocities. No, they will not. At the same time, I cannot say that all of them will have low velocities. What will so happen that there will be some molecules which will have highest velocities, there will be some molecules which will have average velocities, there will be some molecules which will have very low velocities like that.

So, the way these energies are differing across this 10 to the power of 26 atoms or molecules is referred to as distribution. So generally, what you will find is you will find a distribution like this, wherein neither that low energies nor the high energies are very well populated. You will not find maximum number of electrons to be existing in this state or in this state, you will have maximum number of particles to be existing in this interval. So, this is one sort of distribution, there can be many other types of distribution. Distribution generally tells you how the particles energies are spread across the full spectrum.

The gas generally follows what is called as the Maxwellian distribution function, but plasma is not Maxwellian, it is generally usually non-Maxwellian. It is a very profound difference that the gas by nature follows the Maxwell distribution and plasma although it is a gas at the same temperatures, it will be non-Maxwellian. Interaction is binary, what does it mean? Interaction is always like with the nearest particle. You have an atom, how does it interact? It interacts with other atom, what is the means by which this force of attraction or force being transferred is basically the gravitational force or Van der Waals force depending on the situation.

But it is a very short range interaction. So, as you go away, the interaction will cease to

exist or will decay very fast. But interaction plasma is fundamentally different when you compare it with a gas. So, where plasma demonstrates what is called as a collective behaviour. If you impose any external electric field to the plasma, plasma behaves collectively as a single entity, the entire gas as a single entity behaves to shield this particular electric field and the range of interaction is long range. What does it mean? Plasma interacts over very long distances.

So, we will stop here. We will take the discussion in the next class. Thank you.