Plasma Physics

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Module No. # 01

Lecture No. # 41

Laser Interaction with Plasmas Embedded with Clusters

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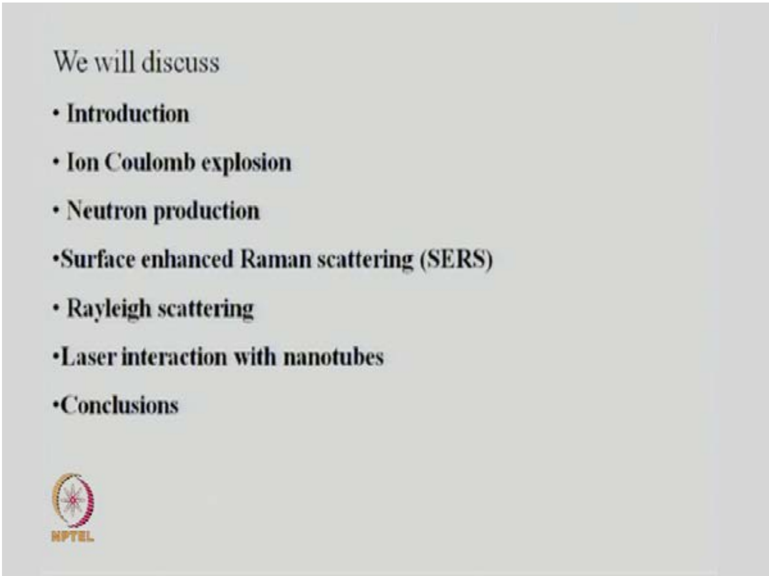

Today, we will discuss laser interaction with plasmas embedded with clusters. We will discuss after making some introductory remarks, the process of ion coulomb explosion of clusters, then why we produce neutrons and then, I will discuss surface enhanced Raman scattering and then Rayleigh scattering and laser interaction with carbon nanotubes. And then, value I will make some concluding remarks.

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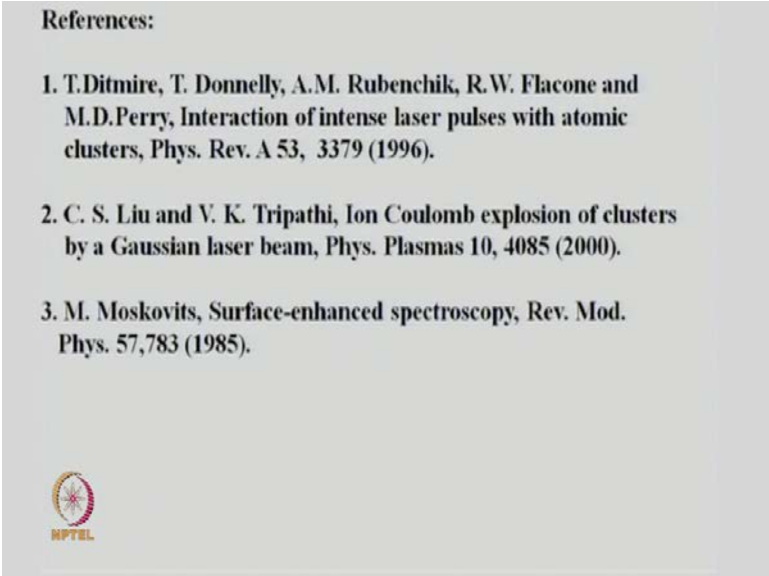

The references for today's presentation are; there is a classic paper by T Ditmire who was the first person to demonstrate ion coulomb explosion of clusters and production of neutrons in his land mark paper in 1996. than Then, we did some theoretical work on this by with professor Liu and myself. And this is published ion in the physics of plasmas in 2000. And I will also like to refer to a very classic paper on surface-enhanced Raman scattering by Moskovits published in reviews of modern physics in 1985.

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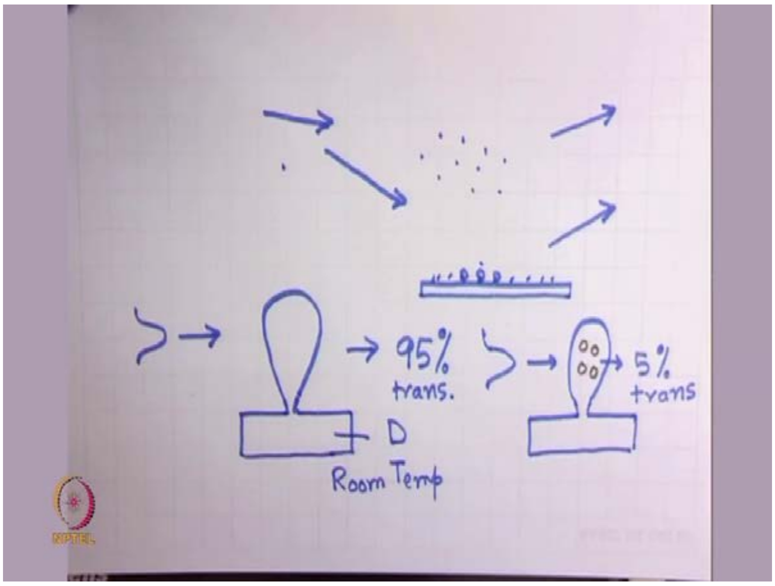

Well, let me mention two experiments that motivated lot of interest. One was conducted more than two decades ago. What was done was that, there was a chamber in which some gas was filled and these get gas molecules were spread all over. And some experiments were conducted by shining laser light on the gas to observe Raman spectrum. So, people were wanted to see Raman scattered light, incident light and this is Raman scattered light, they wanted to see. But the signal was very feeble, very very feeble. Accidentally, they found that if the light is somehow directed towards a silver plate with a rough surface. So, there is some roughness over the surface.

And then, when the laser light was incident on this; then the Raman scatter signal got amplified or enhanced by a million times. This was a very spectacle observation that what happen, what does the roughness of the silver surface do, to enhance the Raman scattering process by a million times.

The Raman spectrum was the characteristic not of silver, it was the characteristic of the molecules of the gas that was filled in the chamber. So, people believed that there is gas roughness is equivalent to some sort of particles over which these gas molecules were absorbed Adsorbed. And Raman scattering was taking place from these absorbed adsorbed molecules on these some sorts of roughness means like clusters. So, this was one observation that motivated lot of interest. And second experiment was conducted a decade later or more than a decade later by Determiner and that experiment were like this:

That, if you take a chamber rather a vessel containing a high pressure gas and have a nozzle here, a very small thin nozzle here, then, when the gas gets out it forms a plume, sort of a plume here. This sort of a plume irritated to the gas by means of a laser of this sort. This was the interesting distribution of the laser laser was traveling in this direction. What was observed that, when the gas was filled in this chamber; deuterium gas was filled, in the deuterium gas was filled at room temperature and with a high pressure then, roughly 95 percent of laser energy got transmitted and no spectacular observation was made.

However, when the temperature of this was lowered to liquid nitrogen temperature and then this was found that, nearly 95 percent of laser light was observed absorbed and only 5 percent was transmitted. So, this was when room temperature or high temperature and at a low temperature the same experiment demonstrated; if you have a nozzle here the room was like this, laser light was coming like this and only 5 percent transmission was there. Besides the laser which was transmitted, they found a huge flux of neutrons produced. So, these two observations I consider to be ground braking observations. One was the enhancement in Raman scattering by a million times by the reference on the silver surface. And second was the generation of neutrons and very strong absorption of laser by a gas jet or gas jet plume if the gas was kept at a low temperature.

What was then detected was; that this gas was qualitatively different than the gas jet here and the difference was that this contained clusters. And this is the presence of clusters that made this experiment qualitatively different than this experiment. And the size of the clusters was typically about 50 Armstrong radius. So, now, I would like to examine what physical effect a cluster will would do on the laser coupling with plasma.

Well, in this case, laser will when travels through a gas, whether with clusters or without clusters, it ionizes the gas if the intensity is large enough. And the process of ionization is called tunnel ionization.

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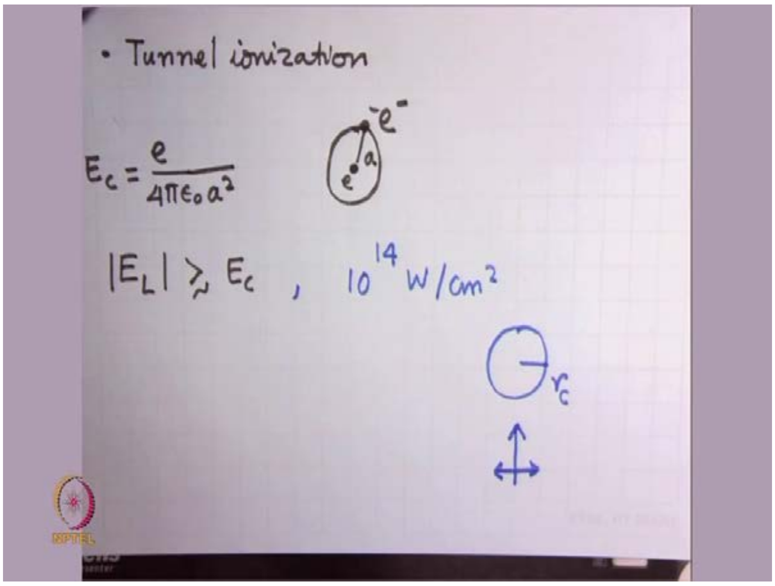

Let me illuminate the processes. The is the first process is that the tunnel ionization of the gas. This occurs when? Because in a gas you are having nuclear atoms with the nucleus in the middle and electron going round. This this is nucleus, this is electron

So, electrons always fields feels a coulomb force due to the nucleus. Whenever the coulomb field, which is equal to e upon if charge of the nucleus is plus e, this electron is minus e then, e upon 4 pi epsilon 0, the distance from here to here suppose a, then a square this is called coulomb field. So, when an electron revolves around the nucleus at a radius a, bit it experiences an electric field of this order due to the nucleus. And, if you can have a laser with laser field strength greater than of the order of E c then, this electron can be released instantaneously out of this atom and the atom get ionized and this process is called tunnel ionization.

(( )) wrote a pioneering paper on this and that explains the processes with clarity. Now this condition is satisfied typically at intensities of the order of ten to the power fourteen watt per centimeter square. So, whenever the laser intensity exceeds this number then, laser can cause instantaneously or very rapid ionization via tunneling. And if you are having a system with clusters in which there are many atoms. So, if I have a cluster of radius r c, suppose r c is the radius of the cluster; when the laser shines on this cluster this is my laser coming in here, with this is my direction of electric field and as if the intensity of laser is chosen higher than ten to fourteen watt per centimeter square; then this laser can also cause tunnel ionization all the atoms inside the cluster and converts it into a plasma ball. So, deuterium ions are left by themselves as ions, but, they are in the ocean of free electrons of sum same density. So, you are having two overlapping spears spheres; the ionic spear sphere and an electrons spear sphere. But, the electrons do not belong to a particular atom; they belong to the entire spear or cluster.

Now, let us consider what will happen when the laser sees a fully ionized plasma ball. I think in order to understand the physics on this process; well physically what would happen is like this:

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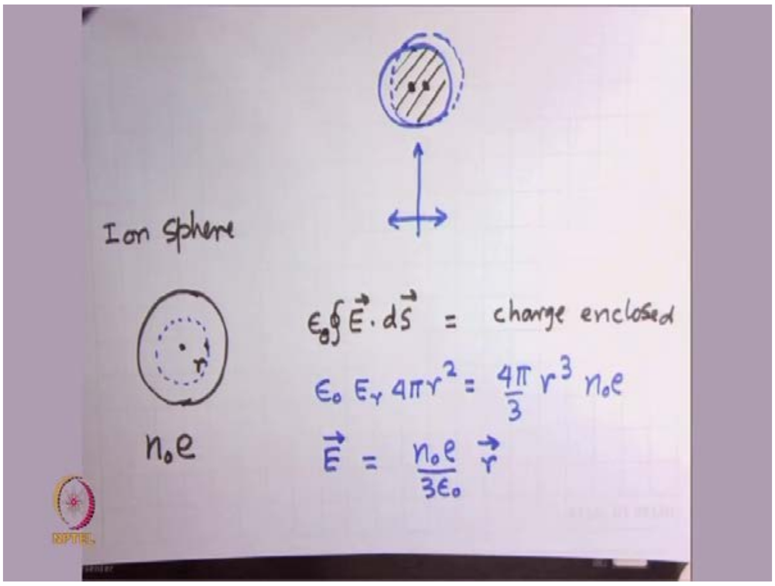

Let Like, when the electron in the ionic spear sphere, they see the electric field of the laser, laser is coming like this, is the electric field. Ions are very heavy. They will not respond to the electric force due to the laser. But, the electron could cloud will oscillate. It will move. It may move something like this. It may move away from here. It can get shifted. So, what will happen that, there is an overlapping region where the ions and electrons both exist in this region.

But there are some some regions, some electrons are additionally electrons are moved out and some electrons are deficiency here. So, this is a distorted overlap. The large part of the two spears spheres are overlapping. And we will show quickly that, the electric field produced by the charge separation when then the electrons center of electron charges somewhere here and ion space charge center is here and they are shifted by a distance delta then, there is an electric field produced in this region and that pulls back the electrons. So, the basic thing is that in a spear sphere, a spherical ball, when the electrons are displaced, they are they experience a restoration force. And that is the key to understand the two processes that I just mentioned.

Now, in order to derive an expression for the electric field in overlap region; let me consider step by step. So, consider an ion sphere first. I will consider an ion sphere of density n 0 ions per centimeter cube. So, charge density is n 0 e where, e is the electronic charge magnitude.

So, this is the charge per unit volume of the sphere. Forget the electronic sphere for a moment. This is the center of this sphere. And I want to find out the electric field at a distance r from the center of the sphere. So, what I do, I use gauss divergence theorem which says that e dot d s into epsilon 0, this is called total outward normal flux. Epsilon 0 into e epsilon 0 is the free space permittivity. Epsilon 0 e is the displacement vector dot d s is the total flux linked with the close surface is equal to charge enclosed in neither surface.

So, now consider a Gaussian surface of radius r, r is the distance at which I want to find the electric field due to this charge sphere. So, I consider a spherical Gaussian surface and calculate this quantity by symmetry. The electric field is in the radial direction. So, this is E r and photo surface area would be 4 pi r square. So, this becomes epsilon 0 E r four pi r square is equal to charge enclosed would be volume of the sphere which is four pi by three into r cube into n 0 e.

So, when the point of observation lies inside this sphere then, the charge enclosed is given by this and what you get here is, E r is equal to n 0 e upon 3 epsilon 0. And I will denote this by the vector sign and the radial direction. So, this is the electric field seen at a distance r from the center of a sphere. This is due to a single sphere, ionosphere. But, when we have a displaced electronic sphere also, the center of the electronic sphere is suppose, at a distance delta. I have moved this by distance delta this is the ionosphere center. So, the electronic sphere suppose I have shifted by distance delta, then what will happen?

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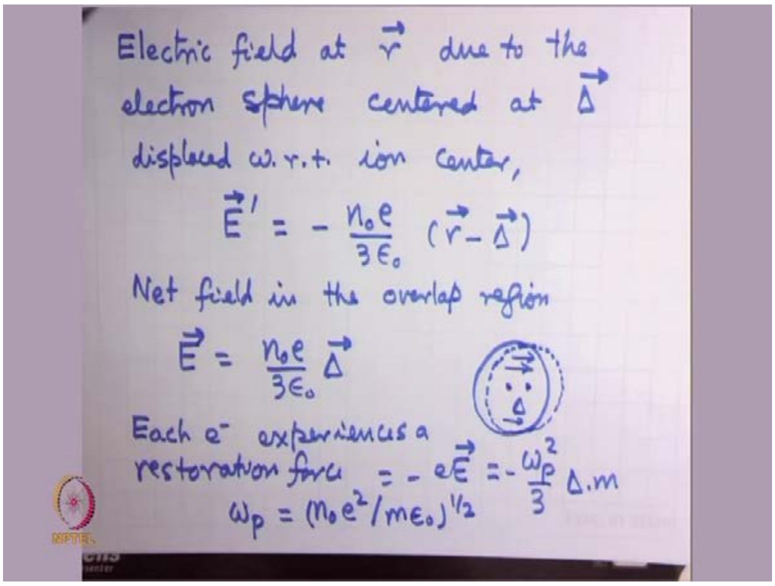

The electric field at the position of observation, at r due to the electrons sphere centered at delta distance away from the ion center displaced with respect to, ion center then how much this would be? I will call this as e dash. That would be equal to charge is negative. So, minus n 0 e by 3 epsilon 0. And the position of the point of observation from the center this sphere would be I minus delta.

So, the ion field I got. Earlier electron field I got. Now at add the two fields in the overlap region. So, the net field in the overlap region would be e is equal to n 0 e upon three epsilon 0; delta, which is a constant. Let me draw a picture. I have a ionosphere. Then, I have a displaced electronic sphere, the center of the electron charge is here, the center of the positive charge is here, the distance here is delta. So, we find that the electric field is in the direction of electron displacement is in this direction and its uniform.

Now, what is the force on the electron? Electric field if you multiplied by the charge of the electron then, the electron will experience a force. Every electron will experience a force. So, each electron experiences a force. A restoration force is equal to minus e E. So, multiply this quantity by minus e and this turns out to be equal to omega p square by three deltas. Because I am defining omega p, the plasma frequency as before n 0 e square upon m epsilon zero. So, multiply m also here delta into m this to the power half. So, there is a restoration force experienced by every electron. Now, let me write down the equation of motion for an electron inside the electron sphere in the presence of the laser field.

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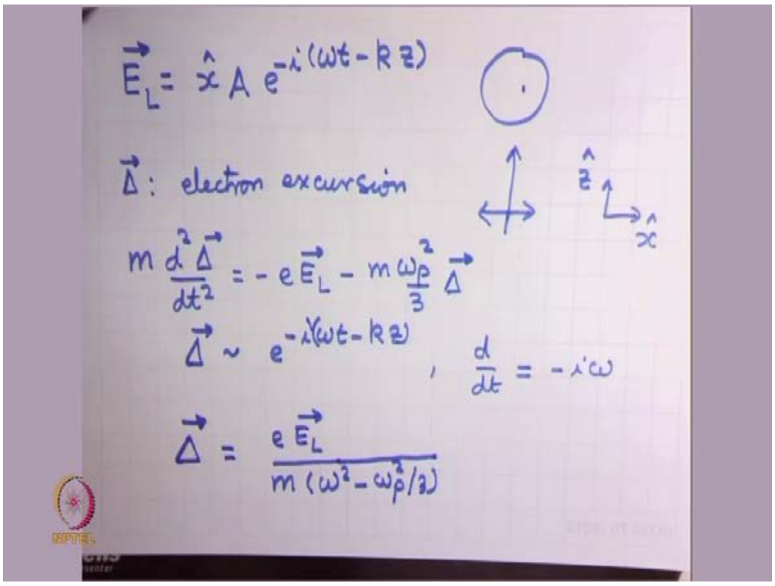

So, I want to examine the response of the cluster to a laser field like this. So, let me take laser field like this. Suppose, this is polarization polarized in the x direction. This is my x direction, this may be z direction. And which would of the laser is suppose a exponential minus I omega t minus k z this is the field of the laser.

But the distance z is very tiny when you go from one end of the cluster to another end and hence this term is not really significant. So, in order to find the electron response we solve the equation of motion for the electrons inside this electronic sphere and every electron is displaced by distance delta.

So, delta I will call as the electron excursion. Which will be in the x direction anyway and the equation would be m into d two delta by d t square is equal to the laser force which is minus e E L and plus the restoration force which is minus m omega p square by three into delta. This equation can be solved easily because, electric field goes in time as exponential minus I omega t. So, in the quasi steady state, delta should also behave in the same manner with time and you can take delta to vary as exponential of minus I omega t minus k z also.

So, replace d d t by minus i omega and that gives me delta. The displacement or excursion of the electron from the nucleus of the ion or rather ion electron sphere with respect to the ionosphere is equal to e E L upon m omega square minus omega p square by three. This is a beauty here that, this quantity, this expression as a resonance in denominator. At omega equal to omega p by root three, the excursion would be very large. So, if you choose a cluster whose plasma frequency was such that, omega p is equal to root three omegas where omega is the frequency of the laser then, the electron cloud will oscillate with very large amplitude. This is very important thing. Now, if I calculate the electric field due to the space charge in the overlap region let me using this value of delta how much is this let us see.

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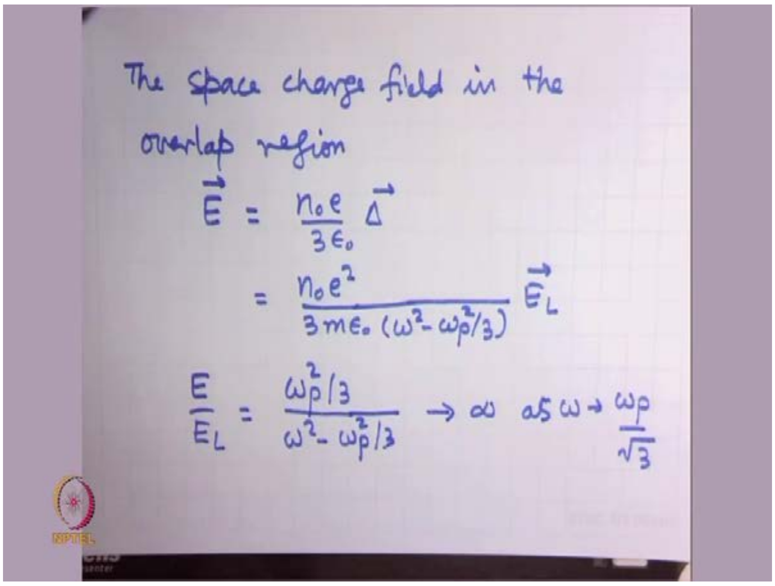

Please, that is the way of revealing thing. The space charge field that I just calculated in the overlap region where the two spheres overlap; e is equal to it was, let me just write down n 0 e upon three epsilon 0 into delta. And put the value of delta that I just evaluated. It turns out to be n 0 e square upon three m epsilon 0 multiplied by omega square minus omega p square by three into electric field of the laser. So, if you compare the amplitude of the electric field of the space charge that is been induced by the laser field, this turns out to be much bigger than this in the neighborhood of this resonance.

So, e upon E L is equal to this quantity is omega p square by three divided by omega square minus omega p square by three. And this goes to infinity as omega approaches omega p upon root three. This frequency omega p by root three is called plasma on resonance frequency. So, laser field if it can do any effect on charged particles then inside a cluster, the effective field that has been induced by this laser is resonant be enhanced by this factor. And this is primarily the basis for surface enhanced Raman scattering by million times. And we shall discuss that.

This is primarily the physics where the resonance that arises due to space charge oscillations of the electron oscillation with respect to ionosphere that gives rise to this resonance. And this resonant field enhancement manifests to self in the form of surface enhanced Raman's scattering. We shall discuss that. But, before I go to discuss this surface enhance Raman scattering let us see what will happen to the cluster.

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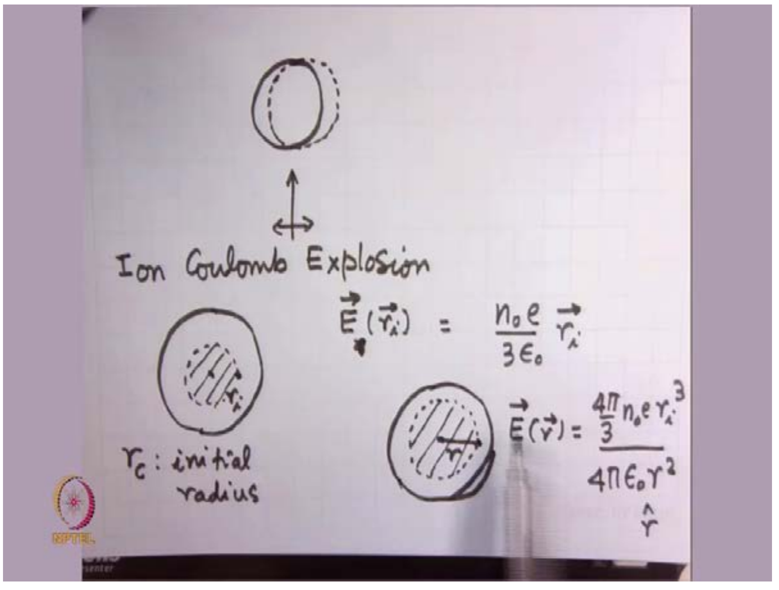

When the laser intensity is significantly large, your electron cloud is really moving out and back in fourth and if you choose very large intensity of the laser then, the electron cloud can completely move out of this. So, for a very significant part of the laser period the ionosphere is rendered un-neutralized because electrons are not there. So, it becomes positively charged sphere and this will undergo what we call as the coulomb explosion. Well, if the intensities are in the intermediate range that, the electron cloud is partly overlapping with the ionosphere moving out significantly, but, not completely in that case one should develop a model where, the electrons and ions electro ns neutralize partially the space charge of ions, but, not completely.

Anyway, let me first consider the case where, for the ideally if I remove the electrons of the sphere how the ions will respond. When it has been a classic problem in fusion research that if you want to produce thermonuclear fusion in lab then you need to supply energy of the laser to the ions. And ions are very heavy. So, whenever you have plasma the electrons oscillate more vigorously than the ions and energy is taken by the electrons and ion energy is very tiny. So, people have always being worrying that what is could be the efficient way to transfer energy from laser to the ions which are heavier than electrons by several orders magnitude, mass.

Now, let us consider an ionosphere. So, I am I am not talking about the ion coulomb explosion. Consider an ionosphere. Forget the electron for a moment. This is the center of the ionosphere. Ions have to ripple each other and I want to estimate how much energy they will gain. A radius of the ionosphere is r c, initial radius of the ionosphere.

Now, consider an ion placed at a distance r i from the center of the ionosphere. I want to find out how much electric field this ion will, how much the force this electron will experience. Now, just I calculated that. If this is a fully ionized sphere of charged density n 0 I n 0 e and the electric field at position r i which will be the radial direction, this is equal to, I just calculated and this was equal to n 0 e upon three epsilon 0 into r i this is the electric field that we will we produced well this is the radial direction. So, I do not really have to write this. Otherwise, put a vector sign here. Forget this r here.

So, the electric field produced by the space charge of this ionosphere at position r i is so much. When this sphere expands, one thing you may note, that every ion, this ion will experience a force which is proportional to this electric field charge, this field times they the charge Now, the ions which are at a larger value of i, are I they will explicit bigger force. So, when this sphere expands, then the ions which are farther from the center they will move faster and the once which are closer to the center they will move slowly.

As a result there will be no crossing of ions. So, when this has expanded to a bigger size of this form, suppose this is the bigger size it has acquired later on. Then, the ion which was here, it has moved somewhere here, then the charge which was contained in this radius r I, has moved to a distance r, but, the total charge contain will be same. Because the charge that was contained in this inner sphere the same sphere is expanded. So, the charge which was here in this radius has moved to vigorous sphere of radius r. But, the total charge remains the same

So, if I calculate the electric fields seen by this test ion that originated at r i when it has moved to distance r, the electric field by is the same ion at position r would be. So, total charge in this sphere is four pi by three into n 0 E r i cube. This is the total charge upon four phi epsilon 0 into r square. And that is in the radial direction. So, this is the electric field seen by the same ion means, as these is this sphere undergoes coulomb explosion, the ion which was starting at position r i the with 0 velocity has, it moves out. It sees a decrease in decreasing electric field because, the distances r increases field will decrease.

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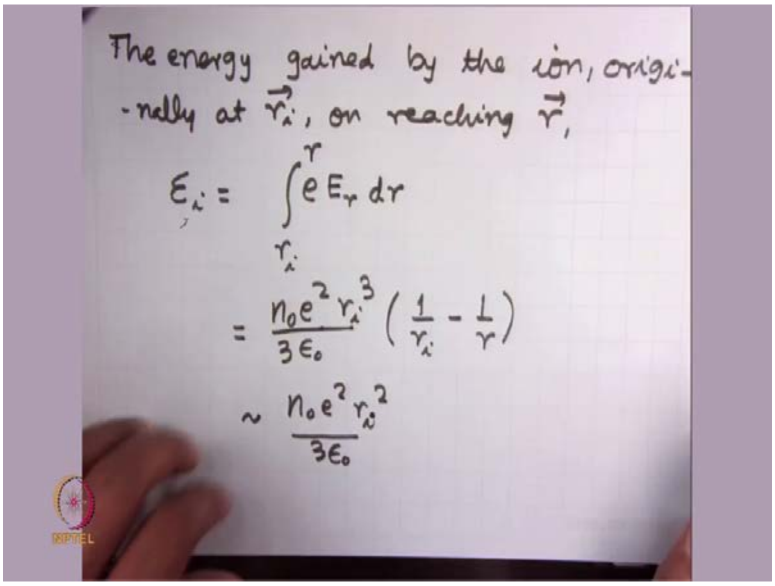

So, if you calculate the work done or energy gained by the ion as it goes from r i to r, the energy gained by the ion originally at r i on reaching distance r . This energy would be E i is equal to the electric force on the ion which is e times E r multiplied by the distance traveled. So, d r if I multiply and integrate from initial position r i to position r, this is the work done.

If you evaluate this quantity, it turns out to be e is here, e is there. So, this becomes n 0 e square upon three epsilon 0 r i cube. And this turns out to be equal to one upon r i minus one upon r. This is the energy gain by the ion. If I choose r i; obviously, it has to be less than r c because the total cluster radius is r c. So, ions are there between 0 and r c. And this r could be may be when the cluster is expanded to a radius of two r c or something. So, this could be smaller than this and hence the typical energy gain will be of this order: N 0 e square r i square upon three epsilon 0 means, the ions that leave from higher value of that at higher distance from the center of the ionosphere, they will gain more energy, their number velocity more. So, E I, the energy gain is a function of distance from the center of the sphere. And if I want to calculate the energy distribution, I will do something like this:

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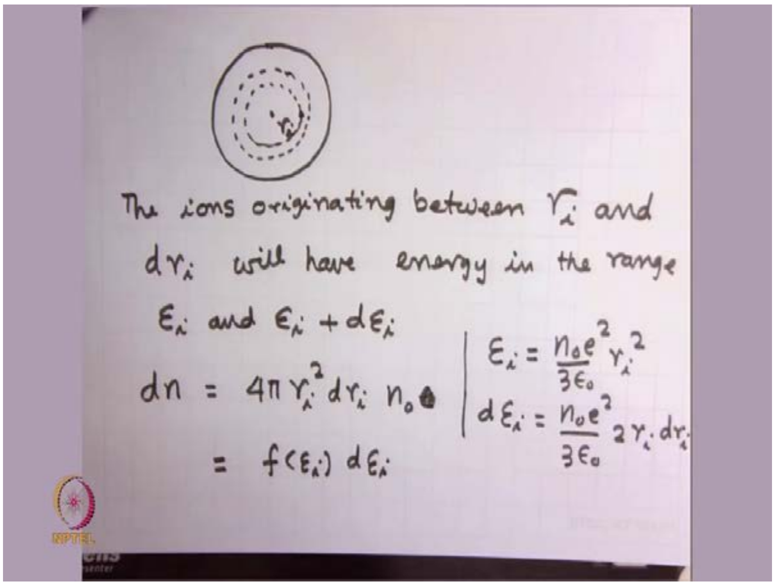

Consider the ionosphere. I am considering an ion which is somewhere at r i and another of group of ions which are lying between r i and r i plus v r i. So, this is my r i distance and this distance between the two concentric sphere is v r i. So, the ions originating between r i and d r i will have energy in the range E i and E i plus d E i. What I am saying here is, what is the number of ions contained in between these two concentric spheres? Let their number be d n. That would be the total volume of this region which is, four pi r i square d r i, this is the volume. And the number of ions per unit volume is n zero.

So, charge contained in this would be this, into e sorry not charge. I want the number of ions only. So, the total number of ions contained in this region will be some much. But, r i and E i are connected, I just wrote down that relation. That energy of the ion is equal to n 0 e square by three epsilon 0 r i square. So, r i, I can write down in terms of E i and d r

i. I can write down in terms of d E i. I can differentiate this d E i is equal to n 0 e square upon three epsilon 0 two r i d r i. So, d r i is related to d E i. You can connect this and what is funny is that, this turns out to be some function of E i into d E i. This coefficient because r i i can write in terms of E i d r i i can write in terms of d e i. So, I can write down this entire coefficient here in terms of E i. This is called the distribution function

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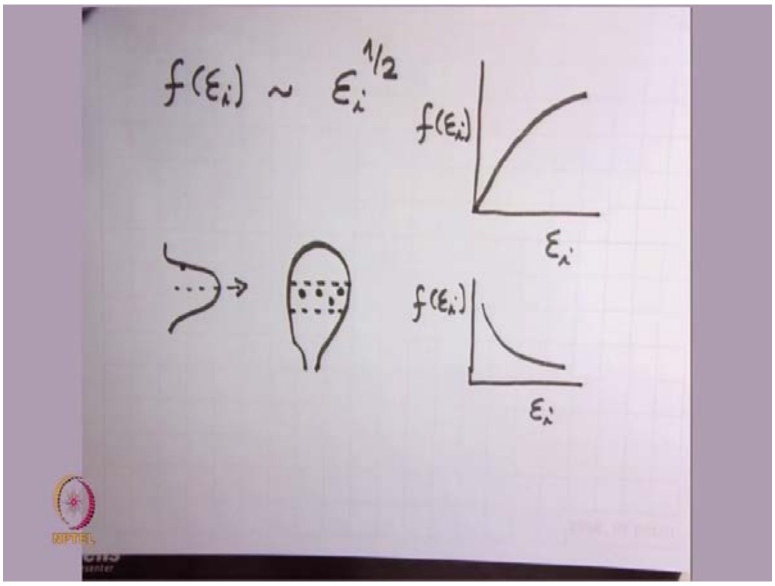

So, this is the energy distribution function of ions and this turns out to be proportional to E i to the power half. So, the interesting part is that, the distribution function turns out to be E i to the power half. One can easily calculate this number. And this quantity if I plot here, then distribution function of ions that are produced from a single cluster if it is hundred percent electron evacuated as a function of E I, this goes like this. This is the distribution function.

Now, consider the illumination of a clustered gas by a Gaussian laser beam. Suppose, I choose a laser beam of this sort and shine this on a plume like this; then this is the region where laser has falling. So, whatever clusters are there those clusters will see the laser field. However, the clusters at the center of the laser or laser axis, this is the laser axis; they will be experiencing a stronger electric field of the laser and hence they will undergo a stronger excursion delta will be large whereas, the clusters which are encountered on the periphery, they will see a smaller laser field and hence the electron evacuation will be less.

So, one should improve the model to take into account the intensity variation of the laser as a function of transverse distance. And when you take that into consideration, the clusters on the laser axis will be fewer in number. But, as you move radically away, the number of clusters available at the shoulders will be larger and larger. So, it turns out that the distribution function if you calculate like this, f i turns out to be it decrease the function of z of E i. For details I would simply refer the readers or the audience to refer to our paper in which we have done this calculation. I have already given the reference in the beginning.

But the interesting part is that this energy could be typically of the order of ten k e v for clusters of radius of the order of fifty to hundred Armstrong. And laser intensity is like ten to fifteen watt per centimeter square. That is the advantage. That is the intensities that are used in laser driven fusion to produce neutrons are three orders of magnitude larger intensities. But, here the intensities are three orders of magnitude less and the protons that you are producing are around ten k e B energy.

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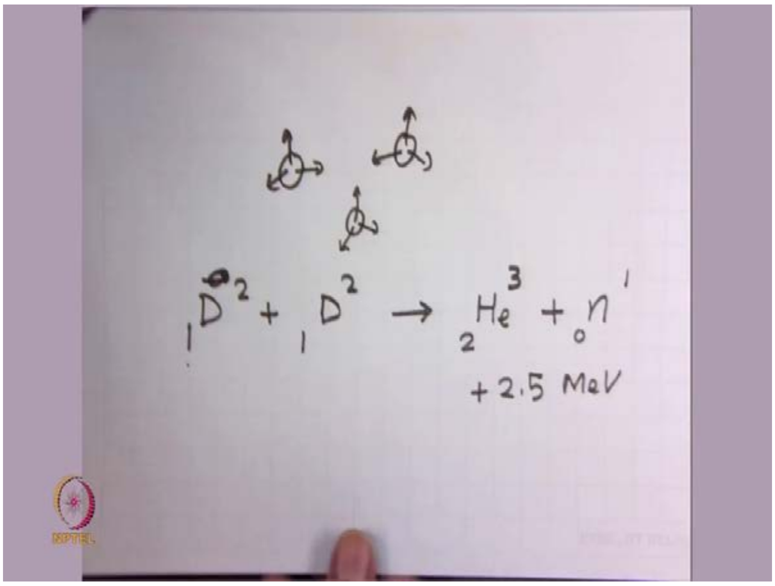

Now, let us see what the consequence of this is. These deuterium ions from clusters collide with each other. So, if there are many clusters, one cluster is here, another cluster is here, they are expanding like this, these are expanding like this, and another cluster is here they are expanding like this. So, they will collide. These deuterium ions will undergo fusion and the reaction is deuterium, sorry one d two plus deuterium. one d two, this is the atomic number atomic weight. It undergoes fusion producing 2 H e 3 helium plus neutron and releasing about two point five m e v energy. So, the energy required for this fusion reaction is 10 25 k e b. But, the energy produced is in m e v and this is how the neutrons are produced.

So, the determine experiment was a demonstration of this reaction taking place. And this is a table top laser that can do this job. So, this appears to be a very efficient chief source of neutron production and this can used for several applications. So, this was one thing that I wanted to mention to you. And second thing is, surface enhanced Raman scattering energy. What is this? How does it manifests in surface enhanced Raman scattering?

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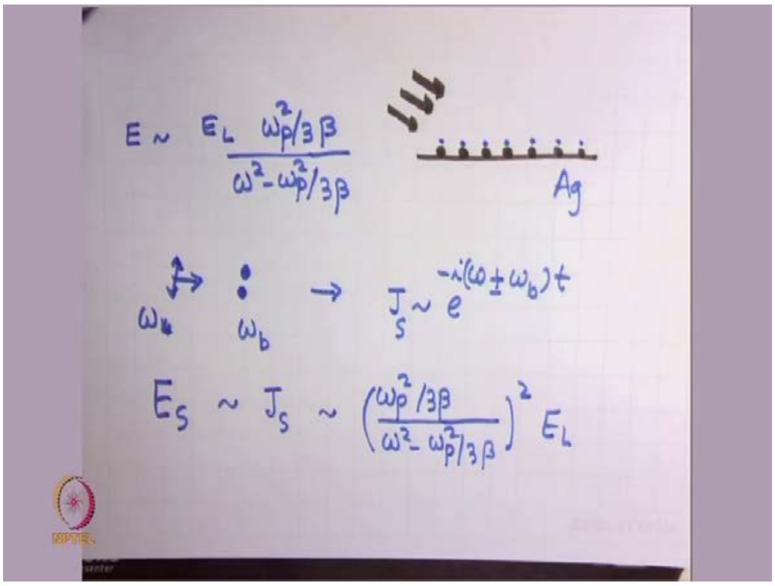

What happens is, if I take a silver plate and suppose, there are some some roughness. You can model the roughness like some silver particles of various shapes. I made the calculation for moment movement of electrons in a spherical particle. People can make or people modeled the motion of electrons in a non spherical particle. But, I, for the sake of physics, I will forget the shape, I will consider the particles these are placed or roughness as particles on the surfaces. Suppose the laser is falling in here. And there are some molecules of air absorbed adsorbed on the surface here. These are the molecules absorbed adsorbed on the surface. I have showing shown them separately. But, they are essentially attached to them. So, these blue dots are essentially the molecules of air absorbed adsorbed there.

When laser light falls on a dust on a particle, on a particle; which is also a silver particle, in that case this field is enhanced by a factor. So, e inside the particle is equal to the laser field that is come out from there. Multiply the enhancement factor which was omega p square by three upon omega square minus omega p square by three. What has been seen that, if these particles are not a spherical they are spherical then these three is multiplied by a quantity called beta. And this beta depends on the shape. So, for certain particles beta is like unity for others it could be more than one.

And this resonance condition can be certainly satisfied for some of the particles. So, when you are shining visible light, laser light on this rough surface of silver, this is silver, then these particles will see an enhancement of field by this factor. Beta is a typical shape factor that depends on the shape of the particle. So, now the molecules that are sitting on top of these particles, they will not see the laser field because that is too feeble. But, they will see the field due to the space charge this e field which is, order of the magnitude bigger.

So, the scattered field will be enhanced by this factor. Now, how the Raman scattering take place. Let us understand this problem. In Raman scattering consider for instance, chlorine molecule. Chlorine molecule will have two chlorine atoms which are vibrating with respect to each other then, laser light comes in these oscillating molecules also experience a oscillating electric field of the laser. Suppose there are oscillating with vibration frequency omega B, the laser frequency is omega l or omega, simple omega. So, what happens that the non-linear current that is induced here has a frequency omega plus omega B and omega minus omega b.

So, the laser field on when impinged on vibrating molecule of chlorine for instance, it will induce a current on this system which will go as at frequency exponential of omega plus minus omega B I times into t. And this gives rise to the field. Now what is happening that, these oscillatory dipoles, oscillatory atoms or molecules absorbed adsorbed on these particles, they induce a field. If they were in free space, they will induce a small electric field. But, that induce field is also enhanced by the particles here because particles are there.

So, what is happening? It is a two way enhancement that the incident laser field as seen by the electrons of the clusters or the particle is enhanced by this factor. And in this presence of this field when the molecules oscillate, the oscillatory motion produces some equivalent current and that induces a field which is enhanced further by this similar factor. This is double enhancement of the field. So, scattered field is enhanced by this square of this factor. And hence, the intensities enhanced by square of the field. So, it is a fourth order of magnitude four to the power four enhancements. And that becomes very huge.

So, the Raman's carryover signal e scattered, goes as this is induced current, which goes as J s, which is enhanced by this factor omega p square by three beta upon omega square minus omega p square by three beta to the power two into the laser field. This is the great advantage. So, though all molecules all particles may not be having same value of beta. So, resonance will not be seen by everyone. But, even if one percent particle see or a few few percent particles see then, this resonance then the field enhancement is very very large. That is a great thing.

So, this is the basis of surface enhance Raman scattering. If you really look into the literature that, now we understand this physics with this great simplicity and with clarity. But, in seventies when this was demonstrated for the first time, people developed well sorts of very fancy and very lengthy calculations. But I thing think, now we understand it very simply, in terms of the plasma on resonance. This is the plasma on resonance.

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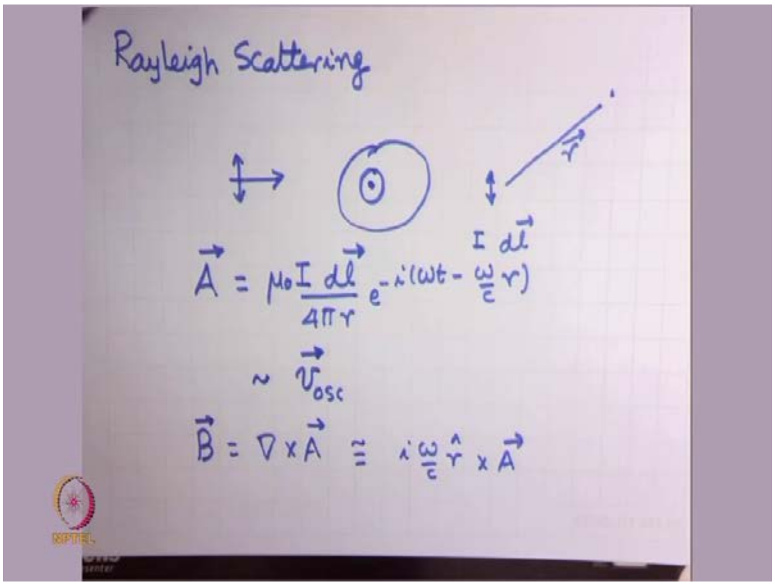

I think now, I would like to tell you something about the nanotubes. I think before I go to nanotubes, I should mention something about the Rayleigh scattering. Our colleague have has developed a theory for Rayleigh scattering. We have done this calculation, but, let me let you what is the physics.

Rayleigh scattering has been known to be responsible for the blue color of the sky or red color of the sky during sun set sun shine. What has been happening is like this: If you take a gas here, bring in electromagnetic radiation; then the gas is made of many of atoms, these made of molecules. But, forget the molecular characters, you just see look at an atom.

Electrons are rotating round the nucleus in each atom. So, when the electrons or electron cloud of an atom sees the electromagnetic wave, these electrons experience an oscillatory electric field of the laser, of the light. And they start oscillating. So, each atom becomes an oscillatory dipole. So, the electron cloud is essentially undergoing oscillation like this and this becomes like a small dipole, it radiates.

And dipole radiation if I calculate the vector potential of a dipole radiator, it turns out to be current in the dipole, into length of a dipole, into mu 0 times. This quantity upon four pi distance r. Suppose, I am finding this oscillatory dipole with equivalent current I of length d l then, at a distance r the vector potential due to this would be this quantity exponential minus I omega by t minus omega by c into r. This is the expression for vector potential at a distance r due to a small dipole.

Now, what is current? If the electron is oscillating, then, ideal I dl is proportional to the oscillatory velocity. So, this quantity is proportional to oscillatory velocity of the electron cloud. And magnetic field that is produced by this radiation field which is equal to curl of a. And curl I can replace by at a far distance by I omega by c like a equivalent k vector and this is the radial direction cross a.

An important thing I wanted to make was, that B is proportional to the magnetic field is proportional to omega. Higher the frequency of the laser, that is impinged, higher the magnetic field of the scattered light. And this will be proportional to v oscillatory. Also if oscillatory velocity is proportional to velocity also omega also, then, this will be omega square dependence. And a scattered power goes as the square of magnetic field. And hence you will get omega four dependence which is the conventional Rayleigh scattering.

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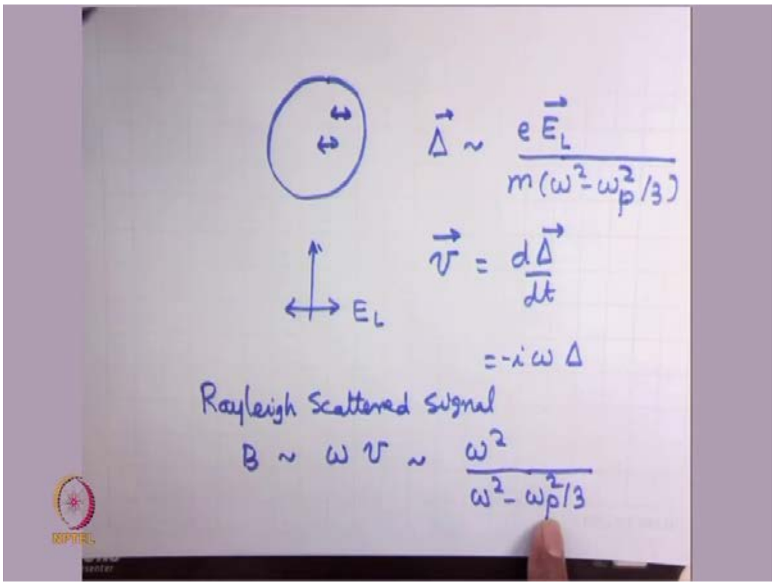

Now, what happens in the case of clusters? When the laser light is impinged on a cluster, you are having a cluster, big cluster which is many electrons. Suppose I am sending my lights from here, this is the electric field of the laser that is impinged on the cluster particle. Size of the cluster is much less than the radius of the electromagnetic wave of the laser wave. Now, the electrons, every electron is oscillating here, like this. And this every electron that oscillates here has an excursion that goes as, e E laser upon m omega square minus omega l square omega p square by three.

So, there is an enhancement in this quantity and how about the velocity of oscillation of this electron cloud which is equal to d delta by delta t, a rate of change of displacement delta. Delta is the displacement. So, this is equal to i omega into delta; if omega is much less than omega p square by three then, obviously, delta will be independent of omega p and v will be proportional to omega.

However a very important thing are occurs when omega is close to omega p by root three that this v is enhanced by this resonance. And hence, the Rayleigh scattered signal is enhanced by this resonance that goes as B field, that goes as omega times v. This velocity, this scales as omega divided by or omega square divided by omega square minus omega p square by three and that is a big advantage.

So, people have seen stimulation in experiments also, orders of magnitude enhancement in Rayleigh scattering when omega is close to omega p by 3 v square by three. One thing must note that, many to even if this resonance is not satisfy satisfied, what Manoj has seen that, if you have a high intensity laser, the cluster expands. When cluster expands, omega p decreases. When omega p decreases, even if initially omega was too small as compare to omega p square by three, but, as cluster expands a situation will arise when omega will become comparable to omega p square by three. At that instance sudden enhancement Rayleigh scattering takes place. So, that is the thing that has been observed. And I think it is a very fantastic observation.

The phenomena that I discussed today have been essentially limited to laser coupling with clusters. A very similar phenomenon takes place when you are dealing with carbon nanotubes. Carbon nanotubes are essentially cylindrical, cylinders of lengths of the order of a few micron, but, size typically of the order of ten, twenty nanometer. So, the physics is very similar. If you shine laser light and t I if our group is doing lot of experiments on this you will see same kind of thing enhancement in ion energy enhancement, in absorption and also be they have observed a strong enhancement in x-ray machine.

I think if time permits, I will discuss some of these effects tomorrow. But, I think this plasma physics at nono nano dimension is getting very attractive, very exciting these days. And I think it will have lot of device applications also. And here we are dealing, we today I talk to you about plasma balls, but, even if the plasma is not created there are already small metal balls like in the case of a c r s surface enhance Raman scattering. I told you that, carbon nano particles wave like behave plasma balls because there are free electrons in them. So, this physics is getting very exciting these days. And I think, we shall we can continue our discussion on that. Thank you very much.