Rocket Propulsion

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Lecture No # 34

Principles of Electrostatic and Electromagnetic Rockets

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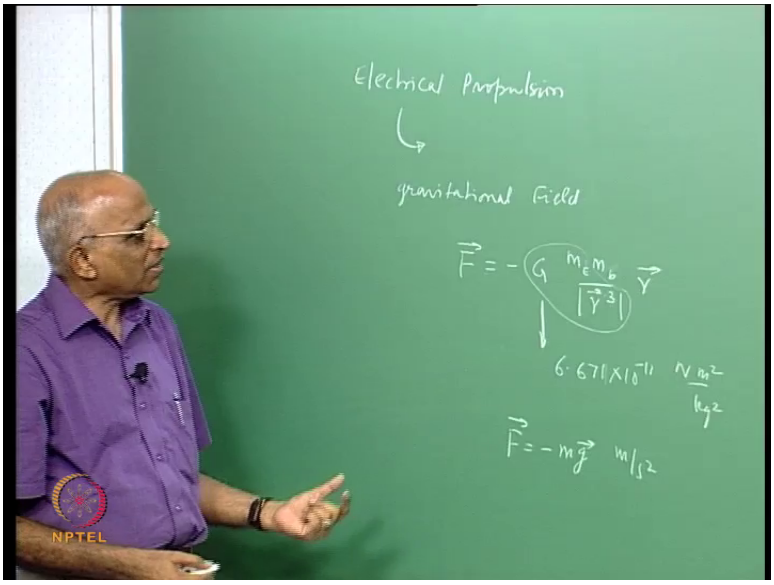

We will start with electrical propulsion today. We had said that propulsion means to push forward and we saw different forms of propulsion essentially dealing with chemical propulsion and inert gas propulsion. When we use electrical power for pushing, we say electrical propulsion, because propulsion we said comes from the Greek word 'propellerie' meaning pushing forward and we use electrical energy for pushing.

Let us be clear how to push using electricity. We talked in terms of gravitational field. We said planets are moving in their orbits in space and Newton observed the similarity between the free fall of the planets and the falling of an apple from a tree and formulated the universal law for gravitational forces, and the force $F = -G \times m_1 \times m_2 / r^2$. If we want put in terms of direction, since force is a vector, we have vector **r** in the numerator and r^3 in the denominator.

This was the universal law for gravitational forces and the gravitational constant G was 6.671×10^{-11}, and the units were Nm^2/kg^2. Why are talking in terms of what is gravitational field? When a mass such as a satellite is up in space or may be on the surface of the Earth, a field due to the heavy mass of the Earth attracts it. For the mass of the body on the surface of the Earth, we substituted the radius of the earth to denote this distance r, and we got the value of force F =– mg, and this 'g' is what we called as a gravitation field of the Earth. Force, as said earlier, is a vector and the vector comes from the direction of this field. Therefore, you see there is field, a vector field, which attracts a body and gives weight to the mass of the body. In other words when force is measured in Newton, mass is kilogram, and the gravitational field of the Earth denoted by g was in m/s^2 and therefore it is loosely talked as acceleration due to gravity. But there is no acceleration, it just a field due to a heavy mass.

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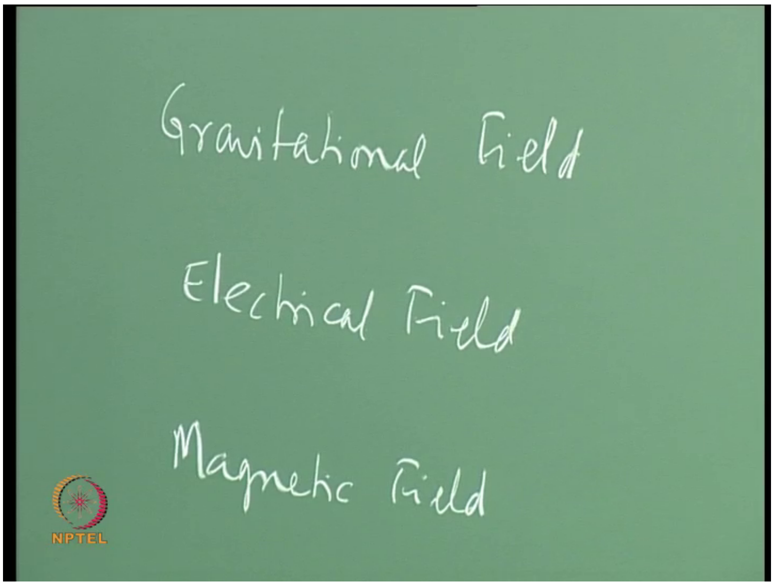

Therefore, just like we talk in terms of a gravitational field, can we think in terms of other fields, especially coming from electricity and magnetism. We can talk in terms of may be an electrical field just the same way we talk of the gravitational field. We can talk in terms of a magnetic field. Are there any other fields we can think of? Maybe we should spend some time on this for there are other forces such as Casmir forces, some other forces associated with 0 Kelvin – so called dark matter in space capable of pushing and doing some work.

What are the electric and magnetic fields? Maybe we have to review it in some way. Since most of us are in mechanical and aerospace engineering and our basics in electrical engineering is somewhat rusty, I thought let us a go ahead and look at the electrical fields and their units. Let us try to see what an electrical field could be, what a magnetic field could be. Whether we could use it in some way to push a rocket. That is what I will be doing in this class, and while doing so, in the same way that we derived the characteristics required of chemical propellants, like a low molecular mass and high temperature, we will try to determine the characteristics of propellants required for electrical propulsion.

Can we first list some requirements to push something using electrical and magnetic field and take quick look at the forces. Let us say, we talk of me as a body and say I am electrically neutral. May be you rub me very hard, remove some electrons from the surface my body, I become positively charged.

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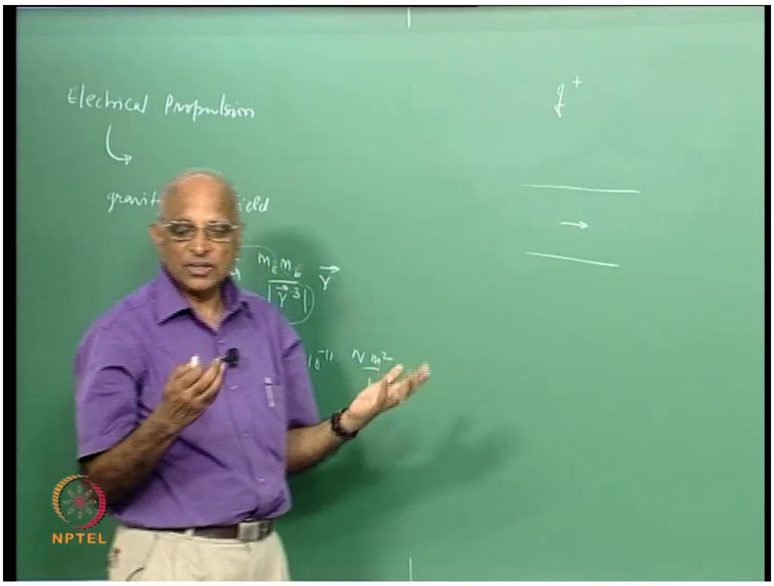

I get a charge q, which I say is positive. In fact we must remember what happens whenever we have a charge. Let us consider through the following example. I have a tube containing, let us say oxygen gas. Very dry oxygen gas is pumped at high velocity through a particular tube. The oxygen molecule is electrically neutral. In the process of the gas rubbing against the wall, some electrons are sheared off from the oxygen; may be by their rubbing action on the wall. We could even ionize, or we could obtain some charge for the oxygen. And it is quite possible that this surface, the wall, could also become charged from the electron as it is transported into oxygen. We could get a spark between the charged bodies of the wall and the gas. This is something, which we have to keep in mind. We also know in a dry climate, if you wear the nylon shirt and you remove it, sometimes it gets charged by the rubbing and some sparking occurs. So also an electrically neutral body or any substance could be charged.

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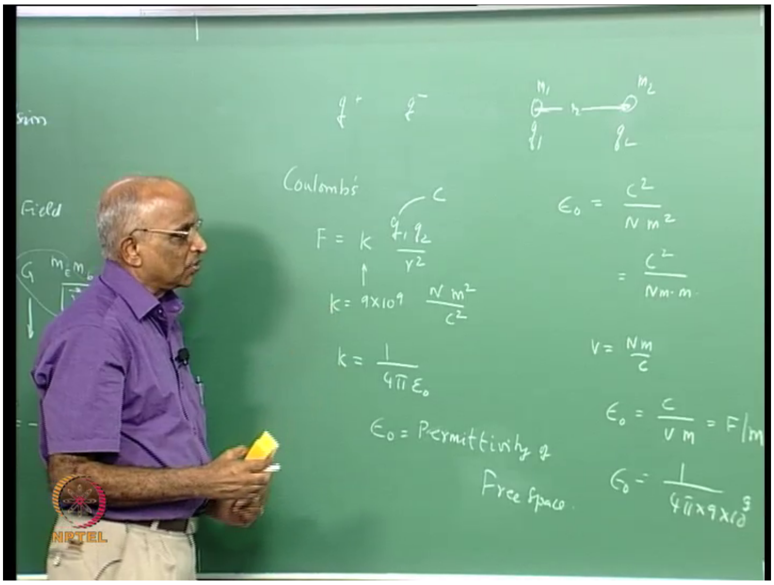

And if we remove electrons from a neutral body, well it becomes positively charged; if we donate electrons, or remove positive charge, it becomes negatively charged. There are some laws that govern the forces between charged bodies, and all of us have studied this in physics, in our high school days. Let us start with Coulomb's law.

Coulomb's law is very similar to the law of gravitational field, or the universal law for gravitational forces. Coulomb's law states that the force between two charged bodies is equal to a constant into the product of the two charges divided by distance square ($F = K\times q_1\times q_2/r^2$) . This was formulated by Coulomb and bears his name and it is possible to derive this law from first principles. Let us try to get some feel for this law. We say if you do a series of experiments, or if you derive it, the value of constant K works out to be 9×10^9.

And now we should have some units for charge. The unit for charge is Coulomb C, and therefore what we say is two like charges say q_1 Coulomb and q_2 Coulomb will repel each other, unlike charges attract each other, therefore we will not put a sign over here, other than say force is in Newton and r is in meter. The unit of K is Nm^2/C^2. The law tells us the attraction between or repulsion between two charges of q_1 Coulombs and q_2 Coulombs placed at a distance r from each other. This is very clear and this is what we studied as Coulombs law.

But we are more interested in the force; therefore we look at this expression in slightly different way. The physicists express this constant K in terms of the medium or the space which can permit the body to hold a charge viz., the permittivity of free space denoted by $\varepsilon_{0.}$ They express K as $1/ 4\varepsilon_0$.

All what we are saying is that we have a constant K in the Coulombs law. The constant K is expressed in terms of another constant ε_0 , where ε_0 is defined as permittivity of free space i.e., for vacuum of space. What is it ε? ε denotes the ability of the space to retain the charge on the two bodies. Let us have a mass m_1 of charge q_1 and another mass m_2 having charge charge q_2. They are separated by distance r. We are talking of the ability of the space between them to hold these charges. This is the permittivity of the space between these bodies. That means the space permits the charge and it is this permittivity of free space, which is denoted by ε_0.

We need to find the units of this epsilon. It must be inverse of K, because it is 1/K that since the constant π does not have is units. Therefore, the unit of permittivity of free space should be C^2/Nm^2. And let us express the units more physically. Coulombs is charge, Newton meter is work done. Therefore, we can also write it as $C^2/(Nm\times m)$. And Newton meter is the work which is done, coulombs is charge, and how do we define potential difference. Work done in taking unit charge, from a lower potential to higher potential; that is the work done in taking unit charge from one potential to other, therefore, I can voltage V as equal to work done in taking unit charge or as Nm/C.

And therefore, I can write the units of ε_0, the permittivity of free space, as equal to $C/(V\times m)$. The unit comes out to be Coulomb per volt meter (C/Vm). However, charge by potential is the capacitance Farad, and the unit reduces to farads divided by meter (F/m). Therefore, what is it we see; the force between charges is given in terms of the permittivity of free space; that is the ability of the space to hold the charge, in terms of ε_0

in F/m, and product of the two charges divided by r squared. Let us summarize it on this side of the board.

We defined permittivity of free space as Farads per meter. And this the value of permittivity of free space $\varepsilon_0 = 1/(4\pi\times 9\times 10^9)$ F/m. And it is equal to 8.852×10^{-12} F/m. But this is for free space viz., vacuum and if we have a space such air, atmosphere with some moisture, or some other medium, etc., the permittivity ε would be different.

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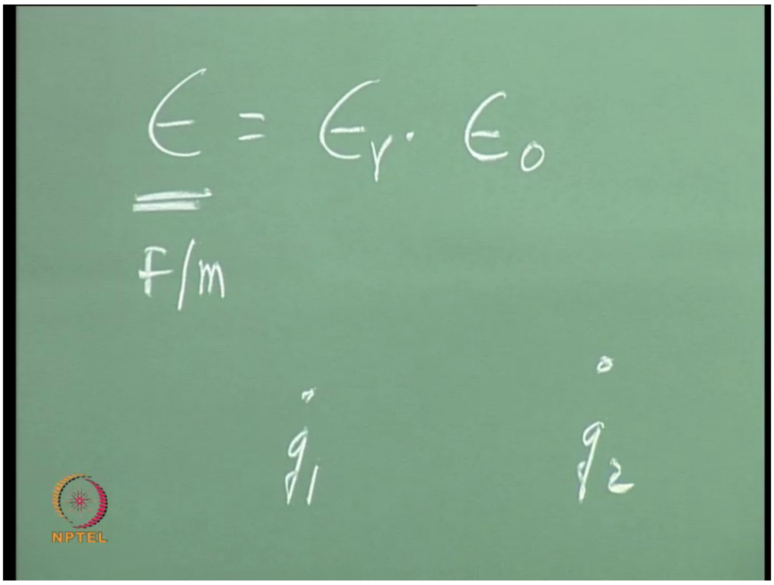

We say the permittivity of the particular space is equal to the relative permittivity $\varepsilon_r \times \varepsilon_0$. The value of permittivity of a medium ε is in F/m, for any medium between two charges q_1 and q_2 C. We will keep this in our mind, because when we do a problem in the ambient we need to use the correct value of permittivity. In vacuum we use the permittivity of free space; in medium for which we have some other value, we multiply it by the relative permittivity ε_r. This is just a number; by how much more or less does the medium permit the holding of charge compared to the permittivity of free space.

But, we were interested in something else, not really in permittivity though permittivity is basic parameter. Whenever we talk of free space, whenever we talk of may be attraction due to charge, we must keep in mind that the constant in the force equation is $[1/(4\pi\varepsilon_0)] \times q_1 \times q_2$ /distance r^2. The only reason why we tell this is repeatedly because when we use Coulombs law, as force $F = \text{constant} \times q_1 \times q_2 / r^2$ and the constant must comes from the value of the permittivity of the medium. Let us now see if we can get something like a field are an equivalent of it coming from the expression of Coulombs law.

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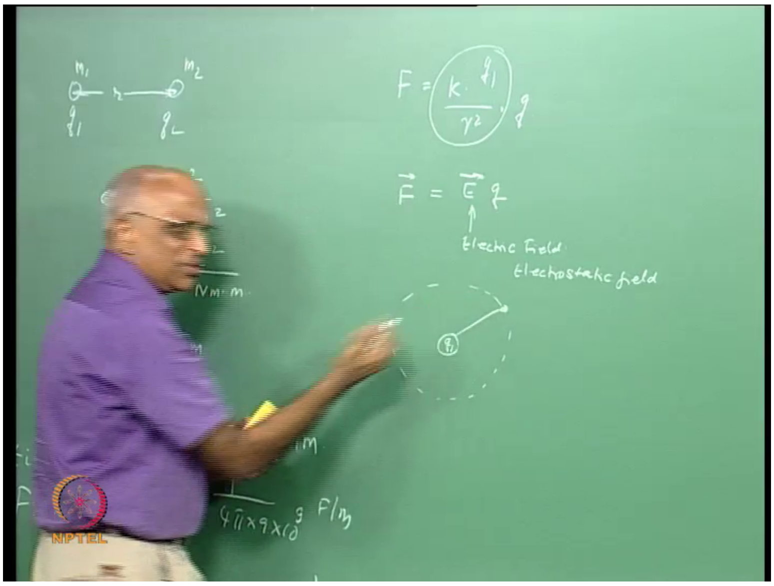

We said Force is equal to constant K into q_1 by r^2 into q_2. Suppose we were to put a charge q in an electrical field; we have still not defined an electrical field. I have a charged mass q_1 available in a medium and at a distance r from it. We now introduce this charge q. Well! The charge q experiences a force. It tells me that something like a field is available when the charge q is placed due to the effect of q_1. Had I put a unit charge instead of charge q, it would have experienced a force q_1/r^2. If we were to denote it by E, then E × q is the force experienced by charge q at this point due to q_1. In other words, if we have a charge q_1 and at a distance r from it, we have the effect of this on charge q to produce a force on q equal to E into q. We want to express the effect of charge q_1 at a distance r. We can very well call it as the field due to q_1 and denote it by E.

And since force is vector, field is vector, and this is what we called as an electric field. Strictly, it should be called as electro static field, because all what we are saying is we have a charge q_1, the reference charge and at a distance r away from it, we have another charge and want to determine the force that this charge experiences. I know the force is equal to the charge placed × q_1/r^2, which we call as an electrical field. The charge introduced at a distance r away, experiences a force but is at rest. This charge is not in motion. It is therefore actually an electro static field. The charge is not dynamic, it is not moving. If this charge is held stationary at the given point, the field E attracts or repels it, either towards it or pushes it away, depending on the sign of the field with a force equal to the value of q what you have into the value of the field E.

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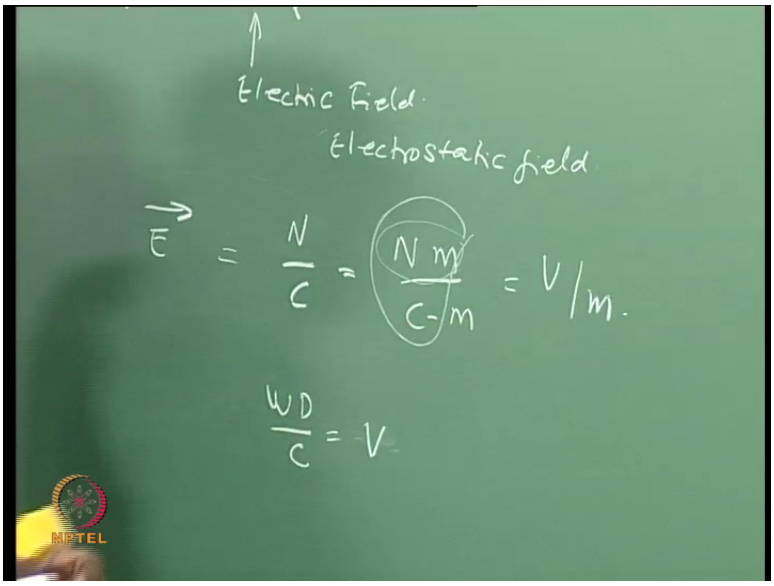

What is going to be the unit of the electrical field E. Analogous to what we had for the gravitational field ‘g’; for ‘g’ we said the unit is equal to m/s^2, what is going to be unit for E, the electrical field? We can write it in terms of Newton/Coulomb. And instead of Newton/Coulomb, let me multiply the numerator and denominator by meter. It becomes Newton into meter divided by Coulombs into meter. I find Newton meter is work done by a charge of C coulombs, therefore, a work done per unit charge is potential difference or voltage; that means work done for taking unit charge Newton meter per coulombs, is equal to the work done per unit charge and is voltage V. The unit for the electric field therefore becomes volts per meter (V/m). Therefore, the unit of the electrostatic field is strictly Newton per coulomb, which can be written as Newton meter per coulomb meter, which is Volts per meter.

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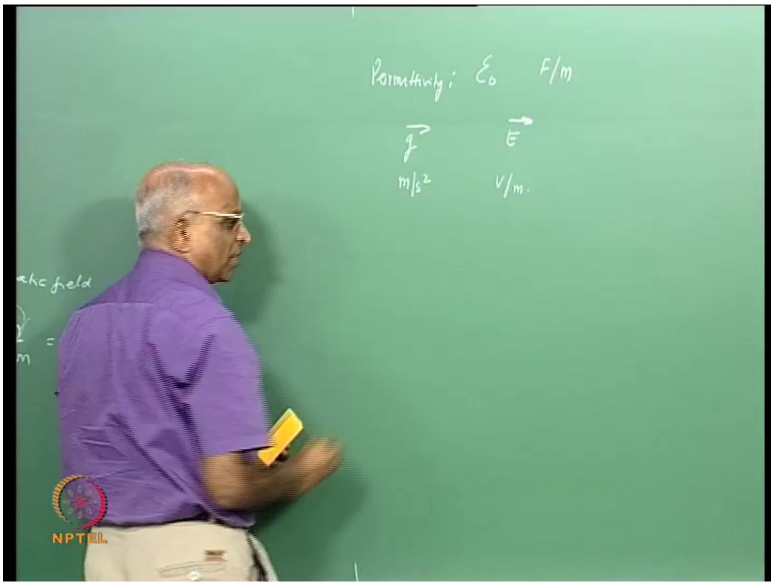

And therefore, I say that the electrostatic field E is written in terms of Volts per meter, just like the gravitational field g is written in terms of meter per second square.

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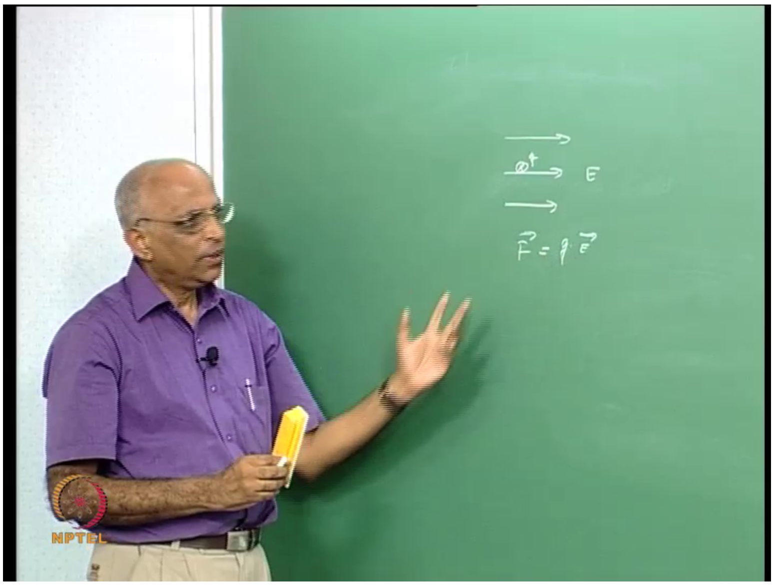

Therefore to characterize an electrical field, we note that if I were to put a charge q in it, this charge will experience of force equal to q × E in the direction of field. This is what constitutes an electrical field.

Therefore what are things we have said so far? Whenever we talk in terms of electric charges, we talk of permittivity of the space, which is in F/m. The force is Newton and the field, electrical field is in V/m. But, in addition to the electrical field, you also know in the environment of the Earth we have a magnetic field. How do I define a magnetic field? I think that this also must be fairly well understood along with the units.

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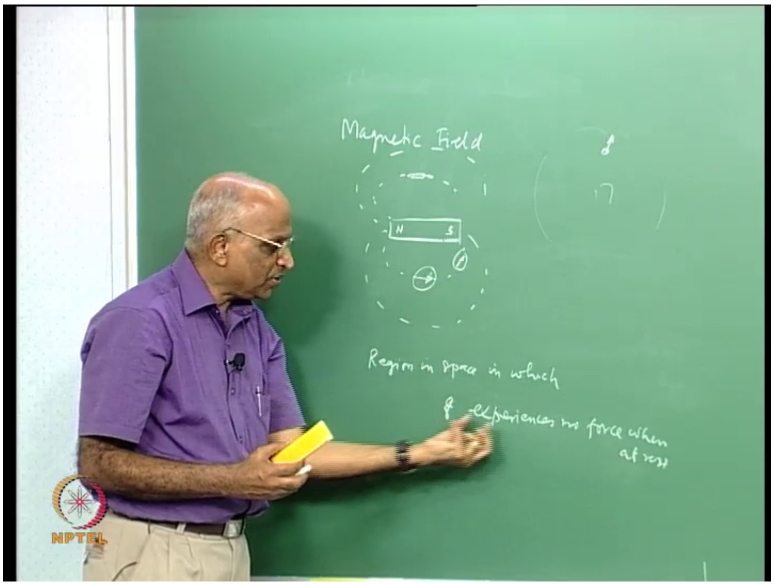

How do I define a magnetic field? In what way is it different from an electric field? Any guesses on that. See all of us have studied this, but may be several years ago. How would you define a magnetic field?

A magnet is associated with a field, which we called as magnetic field. We did experiments by spraying iron filings around a magnet. All of us also know that on the Earth, there is something like a magnetic field available. There must be something like a field that produces a force, a field should have units, a field could be a vector, because there is some change in direction taking place. We have done this experiment. Supposing we put a dipole here; a magnet with a north south direction and it creates a field. We place a small magnet it aligns along a given direction due to the field. Like I put a compass over here. Compass needle always points in a given direction because of Earth's magnetic field. The needle aligns itself along the field.

How do we then define the magnetic field, in contrast to the electrical field, which we just talked of. Like for instance, again it could be a region in space. Any region, may be anywhere. Suppose we have a magnetic field here. If I were to put a charge here. There is no change and the charge does not experience any force. But were the charge going to move in the particular magnetic field, it experiences a force. That means in a region in space, in which let say a charge q experiences no force, when at rest. If I were to put a charge here, well it does not experience any force. However, if the charge were moving, then it experiences of force. In this case the field is known as a magnetic field.

Therefore, a magnetic field is defined as a region in space wherein if we were to put a charge and the charge experiences no force; however, if that charge were to move in the field and it experiences a force, the field is known as a magnetic field. The only way a charge at rest can experience a force is when it is placed in an electric field.

Let write to understand it a little more through an equation, because that makes it much simpler.

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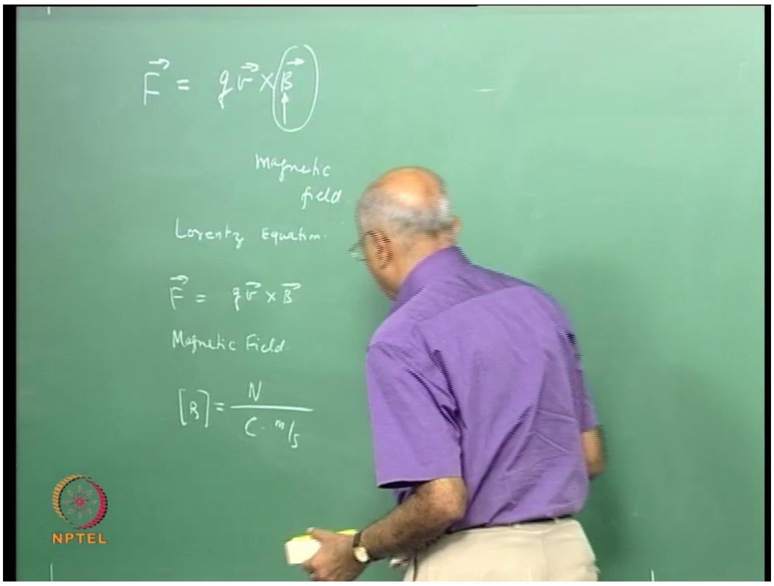

We have something like a force in a field, and this force comes when the charge q moves with a certain velocity. And the direction of force is normal, to the direction of motion of the charge and also normal to the direction of the magnetic field. B denotes the magnetic field. In other words if we have a magnetic field along the board, and if were to move the charge in a particular direction, we have a force which is coming either out of the board or inside the board; rather we say that the curl of this vector along the field and the vector along the motion of the charge, curl of these two vectors. We have the vector cross product over here, and this is what is known as a magnetic field. The particular equation, which defines the force in a magnetic field, due to motion of charge in it, is also known as Lorentz equation $\mathbf{F} = .q\mathbf{V} \times \mathbf{B}$

Just like, we have the Coulomb's equation for electro static force, we have a force, which comes when a charge is moving in a magnetic field. We get a force as a vector product of charge q and velocity V with field B. Therefore, what should be the unit of magnetic field? How do we say the earth has so much of magnetic field?

We have take the values; we say F is in Newton, q is in coulombs, velocity v is in meter per second. The unit of B should therefore be: Newton per coulomb divided by meter per second. How can we express it or simplify it or and put it in a way which is easy for us to understand and interpret. N/(C m/s).

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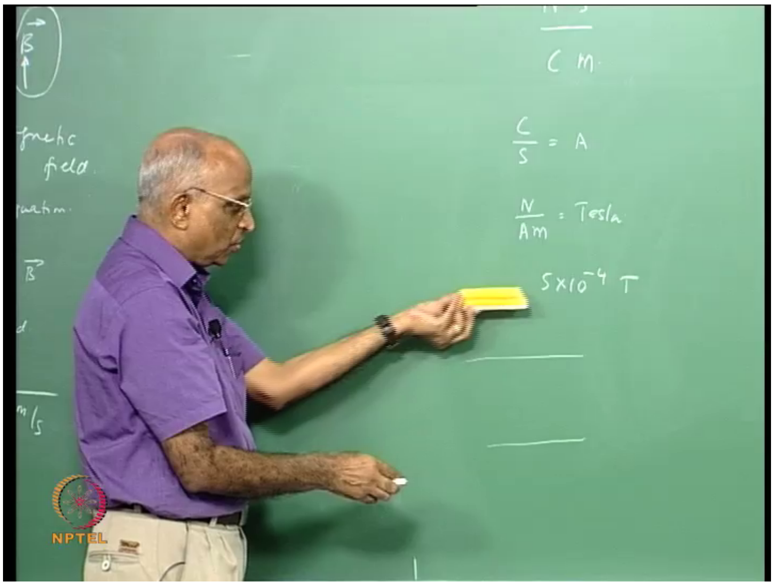

Let us write it as N s / C m. We find that C is charge, s is time, C/t is charge per unit time that is current ampere A, and how is ampere defined? A = dC/dt or ampere is the current viz., charge per unit time, and therefore we can write the unit of B as Newton per ampere meter. Newton per ampere meter (N/(Am) is called as Tesla T. Therefore, the unit for the magnetic field B is N/(Am), which is known as Tesla. Well the magnetic field is expressed in terms of Tesla, which is Newton per ampere meter. I think we should get units to be clear, because we want to determine the forces.

I do not mind if we use unit like Newton per ampere meter. But we must get a feel for these numbers. What is the value of the magnetic field on the surface of Earth? It is 5×10^{-4} Tesla. We talk of may be magnetically levitated trains. We say yes we have trains which are magnetically levitated using magnetic field. You have very strong magnetic field of order of the few Tesla for the levitation. We say the Earth's magnetic field of the order of 5×10^{-4} Tesla is weak.

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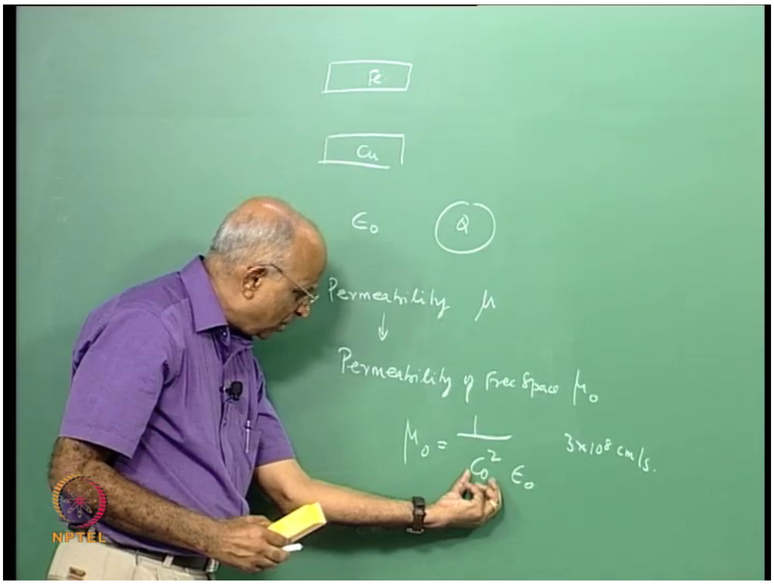

We know that a piece of iron gets magnetized easily. A piece of copper does not get magnetized like what iron gets magnetized. Therefore, just like I have permittivity of free space, can we define a quantity, some quantity that will consider the magnetic effect; rather we say a substance is more prone to getting magnetized. We call this as permeability. What is permeability? Let me repeat again. The ability of a body to get magnetized in a magnetic field; iron gets easily be magnetized, air does not get easily magnetized. We call this property as permeability and it is denoted by μ.

And permeability of free space, is denoted by μ_0, and using basic physics, it can be shown, that μ_0 = permittivity of free space ε_0 / (velocity of light in vacuum $C_0)^2$, because electrical and magnetic fields are related in some way. It comes through this relation, the velocity of light in vacuum, which you know is equal to 3×10^8 m/s. And we have already calculated the value of permittivity of free space; we can calculate the permeability of free space. And for the permeability for any substance, we define the relative permeability of μ in the same way as I define the relative permittivity of a medium.

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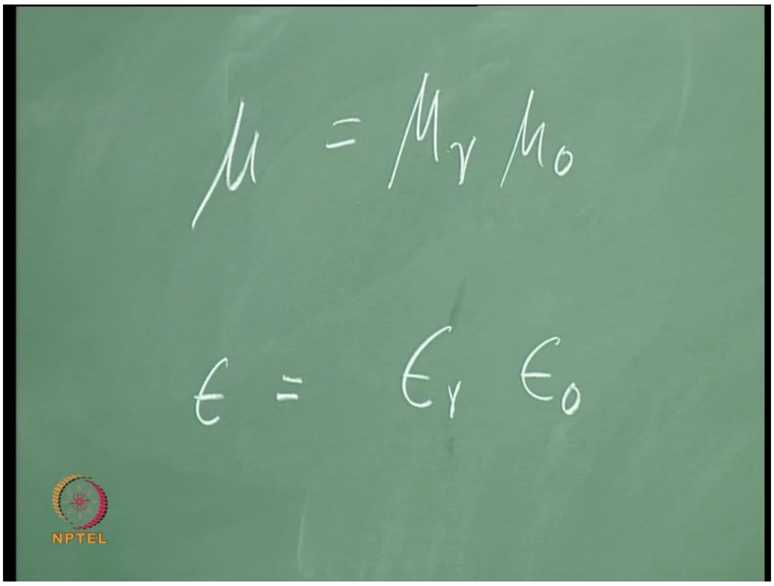

And we say $\mu_r \times \mu_0$ = permeability of the body μ, just like we say permittivity of a medium is relative permittivity into permittivity of free space. Therefore, we can get the value of permeability of free space.

We already determined the permittivity of free space. We calculated this as $1/4\times9\times10^9$. We can therefore get the value of permeability of free space. The velocity of light in vacuum is 3×10^8 m/s. Therefore, what will be the value and units of permeability?

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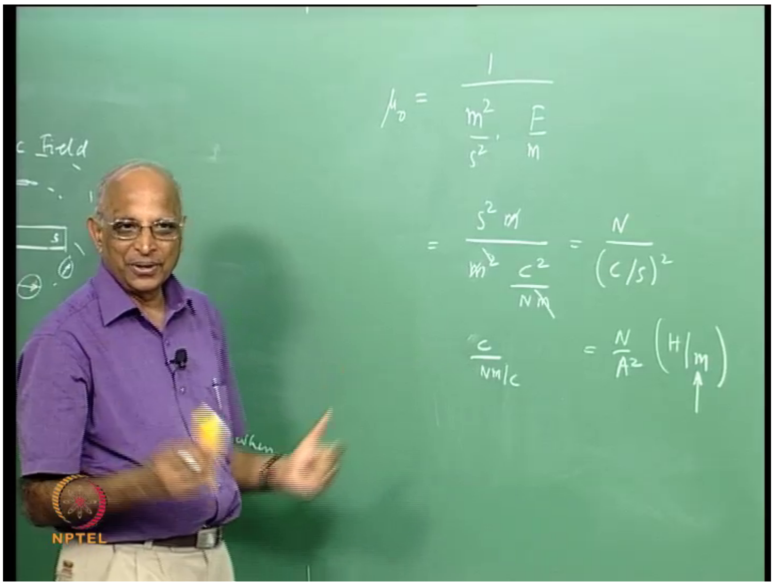

The units of μ_0 = 1/ [C_0^2 in m^2/s^2 × F/m]. And now I simplify this, I bring second square on top, meter over here, meter square over here. And we get $s^2/(Fm)$ Farad is the charge in C per unit voltage V (C/V). And what is V? V is the work done Nm/C.

We found Farad is equal to charge by voltage, voltage is equal to work done per unit charge, and therefore the unit of Farad should be C^2/Nm. The unit of B is therefore s^2N /C^2 or N/$(C/s)^2$ or N/A^2. The unit of permeability is N/A^2. This is also denoted as Henry per meter.

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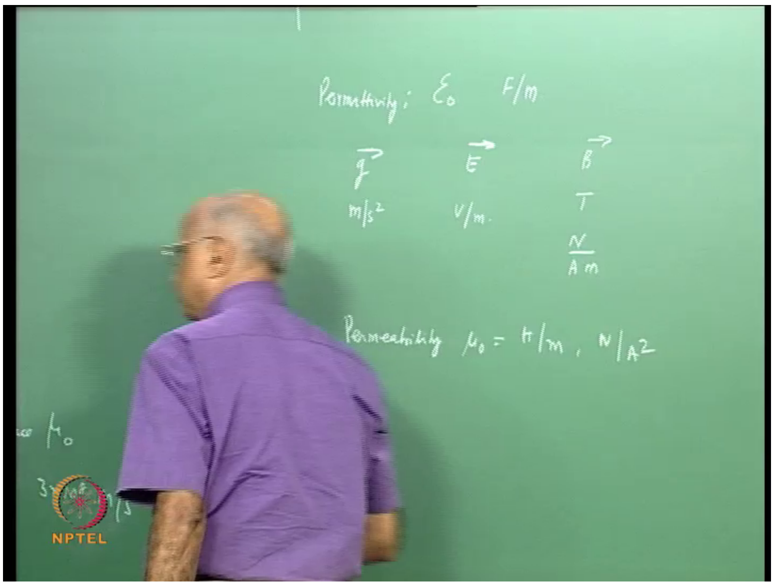

And therefore, now I add the units of permeability. Permeability of free space, which is written as μ_0 has units of Henry per meter, or rather it is also equal to Newton per Ampere^2. I hope we are clear about whatever we have learnt so far and it will be possible for us to find the force or the thrust using electrostatics and magnetics.

We also talk in terms of induced field say an induced magnetic field. We talked about magnetic field produced by magnets. What is the difference?

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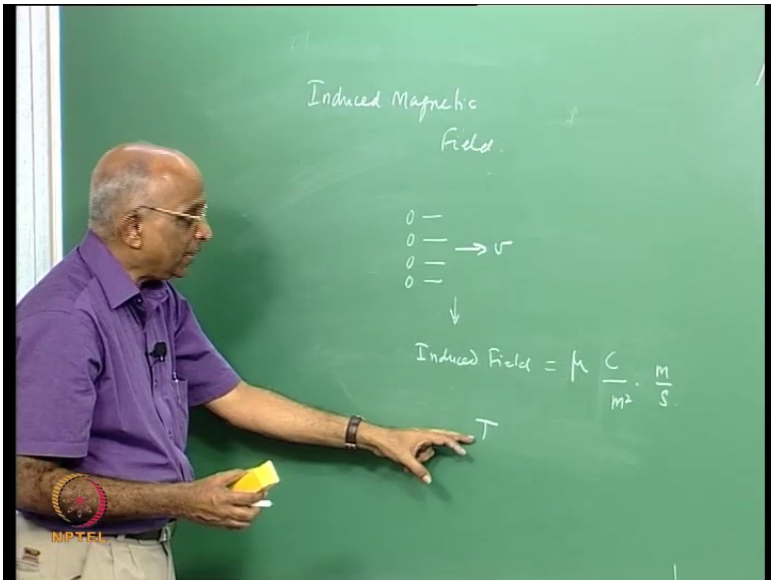

Whenever you have charge, let us say charge so many Coulomb per unit area moving with some velocity V, that means we have a charge which is moving with some velocity, then it is possible that this producers a particular field, which is call as an induced magnetic field. It is denoted by H and we will see what is the unit of this induced field H. All what we are saying is, it is not necessary that only a magnet can produce a magnetic field. It also possible that the motion of charges can produce a field, which we say as induced field – an electromagnetic field. And an induced field is defined as, we have to talk in terms of permeability × something like the motion of charge say electrons, let us say coulombs of charge, which is moving per unit area into velocity: charge Coulombs per unit area in meter square, moving with a velocity meter per second ($C/m^2 \times m/s$).

Now if you see the unit of this it will again come to permeability × ($C/m^2 \times m/s$) = $N/A^2 \times (C/s) \times m = N/Am$ viz., the unit of Tesla. Therefore whether the field is induced by magnetic field or by charges, which are moving per unit area at a velocity, the field in

Tesla. Therefore, the field due to the magnetic field or due to induced field, can be describe in terms of Tesla or N/Am.

With this background, we get into the problem of how to determine the electric and magnetic forces for propulsion. We say analogous to the gravitational field 'g', we can also have electrical field E, whose unit is V/m and a magnetic field Tesla, the unit of Tesla being N/(Am) Newton per ampere per meter.

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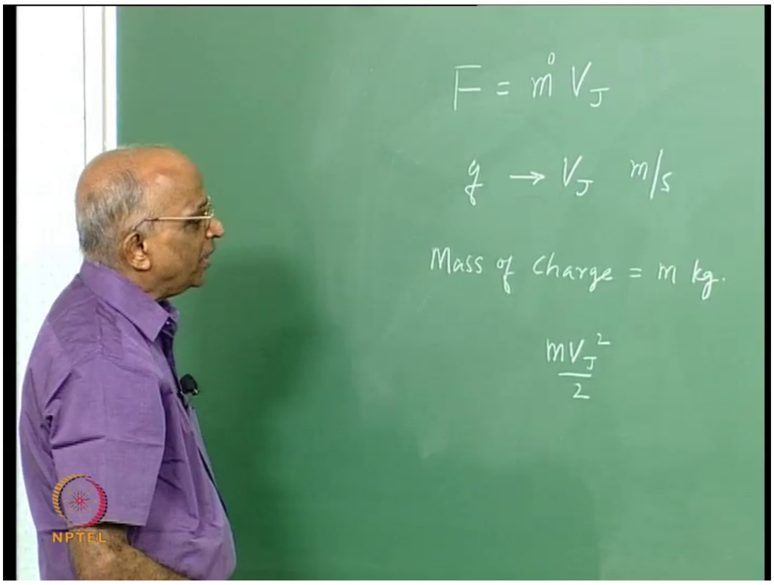

And how can I use the electrical field E, the magnetic field B, and this induced field H due to the electrical charges or the motion of the electrical charges to generate a particular force. Therefore, can we go to the next step? This is a brief review, of what we must know, relating to the fields and also, something relating to permittivity and permeability. Permeability is something which induces magnetic properties in the medium; that means we say it is something, which induces a magnetic field in a medium. Permittivity is something which holds or which can contain charge in the medium.

Force is equal to $m°V_J$. Now all what I am trying to say, we have a charge q, it could be positive are negative charge. If it could be accelerated to get a velocity V_J meter per second, and if the mass of this charge m kg, can we get the force or thrust? The kinetic energy is equal to the m × V_J^2 / 2. We would like to relate this value, to the electrical field and determine the force.

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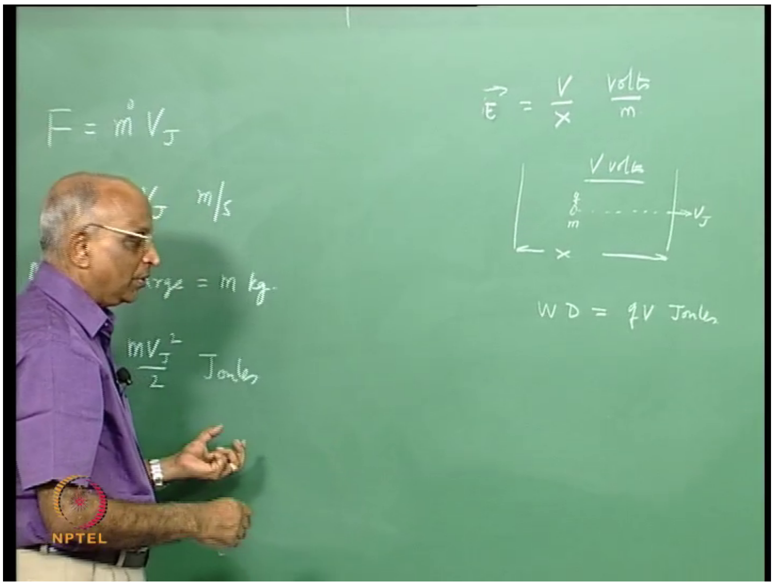

We defined the electrical field E as volts per meter, If we have particular distance over which the charge accelerates and let us denote it by X. The potential difference, which is doing work and accelerating the unit charge is let say V volts. Then I can write the electrical field E is equal to V volts divided by X is so much volts per meter is the electrical field. In this electrical field, if we put a charge of mass m and accelerate the charge of mass m, the charge being q, we should be able to accelerate it to V_J. I am interested in find a relation between the electrical field and the kinetic energy, which I am supplying to the particular charge of mass m. How did we define volts V; as the work to be done to carry a unit charge, through a potential difference of V.

The work is done by the charge of mass m having a charge q, which is being accelerated by the electrical field, and the electrical field is V/X. Now what is the work, which is done by the electrical field? We have work done by the electrical field for the charge of q through a potential difference of V. The work done is therefore q × V so many Joules. The energy the body gains or the work done on the charge is m × V_J^2 / 2. We equate these two expressions, to be able to determine the value of V_J.

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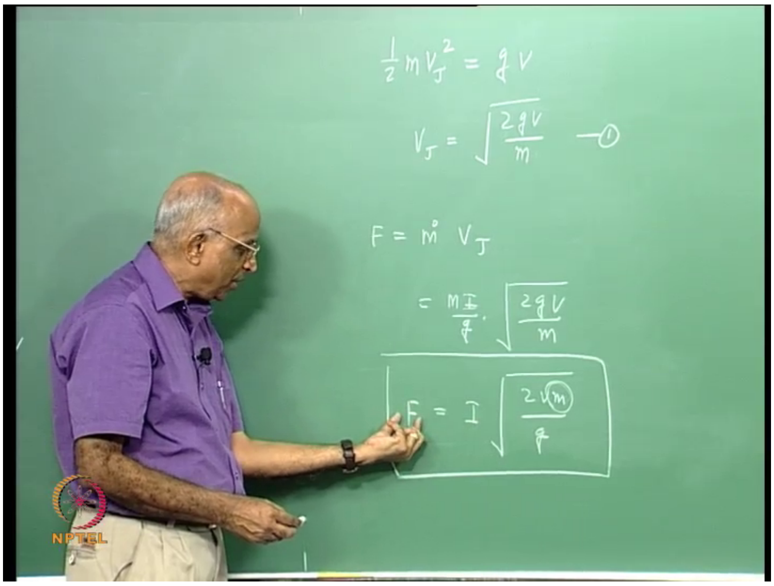

Let us put it together. We get $m \times V_J^2 /2 = q \times V$, or rather we get a value of $V_J = \sqrt{2qV/m}$, which we say is equation 1. And what was my equation for the thrust F. $F = m^\circ V_J$ and we can write $m^\circ = m \times I/q \times V_J$ which is equal to $\sqrt{2qV/m}$. This becomes equal to I, I take it outside, m comes on top, q comes at the bottom into under root. Further, I get q comes in the denominator, into 2 V into m is equal to the thrust. Therefore thrust $F = I\sqrt{2Vm/q}$. This is the thrust what I get by moving a charge in an electric field in a medium.

What type of propellant or charge would be able to do this type of job well. We need for any meaningful value of thrust, the mass of the propellant must be large. Otherwise, if we have a very small mass and we could get a high V_J velocity, but ultimately the thrust is going to be very small. Therefore, the requirement of my propellant, which has the charge to generate a force using an electric field, is that its mass should be significant. I need a large value of current I, and the charge for given mass should not be very high.

Let us look at some properties of the propellant what we would require, just like we said for the propellant used in chemical propulsion, we should have low molecular mass and it should be at high temperature.

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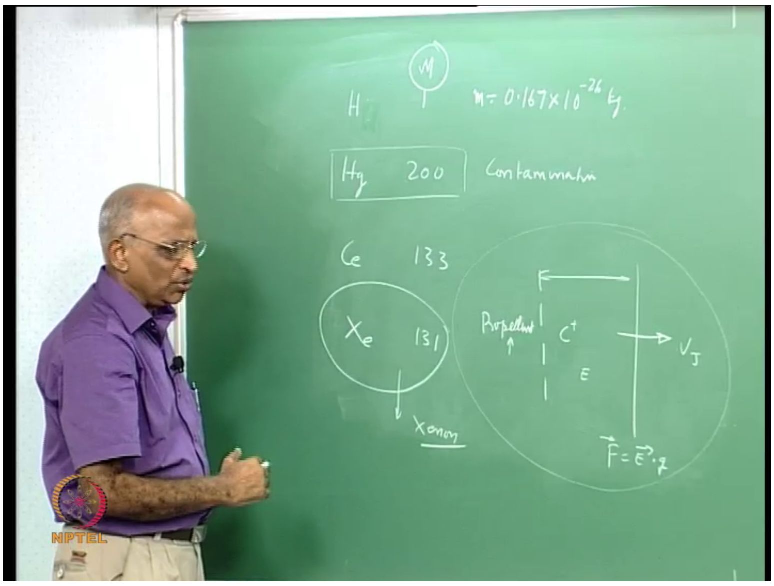

Let us start with the light gas hydrogen. The atomic mass of hydrogen is one. For a heavy substance like mercury, the atomic mass is about 200. I take another substance cesium, I will say why we look at it a little later; the atomic mass is 133. I take an inert gas like xenon; the atomic mass is 131. All what we note is the, with reference to hydrogen as one, mercury atom is 200 times heavier, cesium atom is 133 times heavier, and xenon 131 times heavier. And the mass of hydrogen atom is equal to 0.167×10^{-26} kg. We can calculate the mass of mercury atom which is 200 times more to be something like 0.33×10^{-24} kg. We find that the atomic mass of certain substance like mercury, cesium, xenon are very much higher, and we would like to use such substances in the cases of propulsion using electric fields rather than hydrogen.

Therefore, compared to chemical propulsion, wherein we need a low value of molecular mass of the propellant, we are looking for substances which have higher molecular mass. If we were to use electrical propulsion, which we are yet to describe, we require a propellant, which could be charged and we should look at the heavier substances that can be easily charged. I have to first take a substance, a propellant, and get it charged. Then I have to put a field over here; that means a voltage difference or a potential difference, which will give it a velocity. And choose a value of potential difference such that I get high jet velocity V_J. This is what gives us the electrostatic propulsion. All what we are saying is, that we have a propellant, we have to provide electrical charge to the propellant. We have to acquire the charged propellant in an electric field E, so many volts per centimeter to generate the thrust.

Therefore, we will be better of using heavier substances like mercury, cesium, xenon and all these three have been used earlier in electrical propulsion. Mercury is liquid metal but its vapor contaminates the surfaces of sensors in a spacecraft. Cesium is little reactive even though it can be easily ionized. It is more difficult to use, and the general trend today, is to use xenon, which is a noble gas. Where do we use xenon in real life; maybe we see them in the name board in shops with colorful display.

The preferred propellant is the noble gas xenon. But cesium is also used and in the older electrical propulsion systems, mercury was employed. Cesium is easy to charge as ions.

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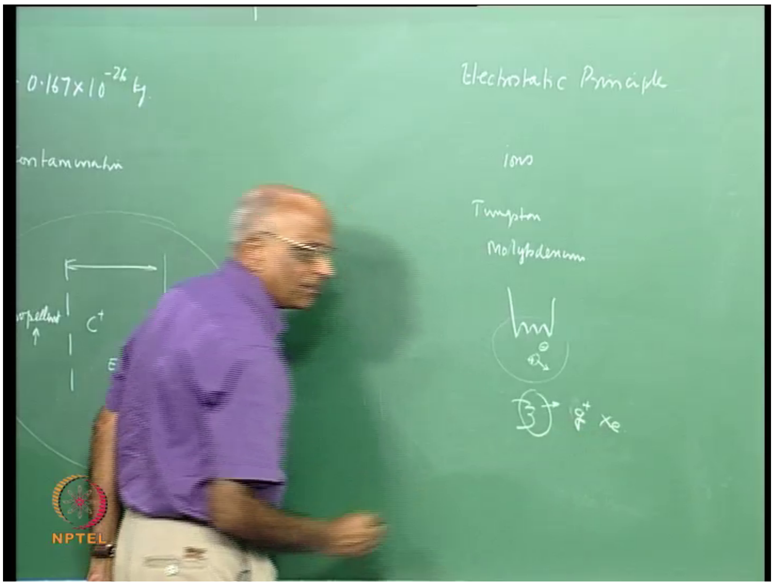

In electrical propulsion, using electro static propulsion or electric field, we generate ions. And how do we generate ions? We have some material like tungsten or molybdenum. When you heat these metals, which have low work function, they emit electrons rather easily. You have this medium, like xenon gas surrounding it, when impacted by electrons, it dislodges an electron on its shell and thus gets positively charged. The xenon gas thus gets positively charged. Therefore, we have tungsten, you put tungsten in medium of xenon are some other propellant, and heat it, it is possible for you to get positively charged propellant.

And this point in time I must also tell you about the mass of the charged propellants. Now should we used proton i.e., should we used positive charges or should we used negative charges. The mass of the proton is about 1850 times the mass of an electron. In other words the protons are very much heavier than an electron, and therefore it is necessary to use the proton, rather than an electron to generate thrust.

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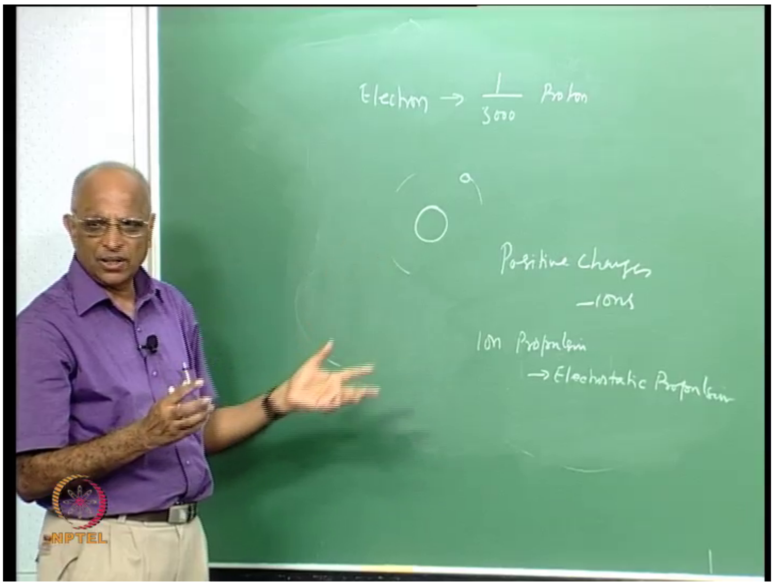

And therefore we talk in terms of ion propulsion, ions being the positively charged propellant, when dealing with electrical fields and electrostatic propulsion. I will continue with this in next class, but all what we did in today's class was that we reviewed the units which we should be used whenever we talk of electrical fields and magnetic fields. Then we derived what must be force in an electro static field. We find for the forces to be significant, the mass of the charge must be large. For the mass of the charge to be the significant, is necessary to use to ions, rather than the negatively charged electrons.

Even in early part of 1900 when the rocket equation was invented by Tsiolkovsky, he talked of high jet velocities using electrical means. But at that time the mobility of electrons was understood with the vacuum tubes and electrons were conjectured for use. But the forces that could be obtained were too very small. Only when we start using ions, namely positive charges, it is possible to get meaningful values of force from it. And we will continue on this with the next class. We will look at the type of system and how to generate the force and we will address the problems involved.