Jet and Rocket Propulsion
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Lecture - 40

Welcome back. So, we are in the last lecture of this course. So, in the last lecture, we have been discussing... We have discussed the electric propulsion systems; electric rocket propulsion we have been discussing. In the last lecture, we discussed electrostatic propulsion system.

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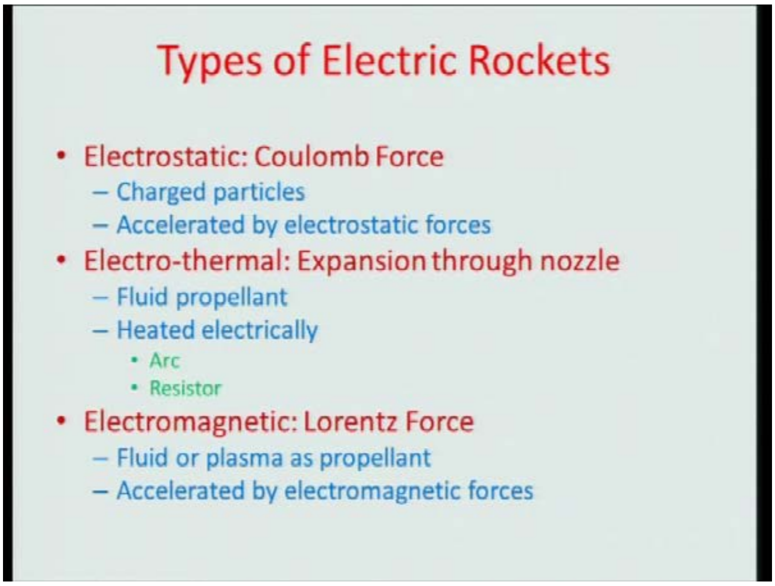

Now, last lecture, I have discussed there are three type of primary electric propulsion systems, electrostatic, electro-thermal and electromagnetic. We have already discussed the electrostatic propulsion system, which operates by Coulomb force. Today what we are going to discuss are the other two variety, that is, electro-thermal and electromagnetic propulsion system. Electro-thermal propulsion system – first let us take them up. In this system, an electric heating is used. Primarily, the principle operation is that, we heat the propellant using electric power, and then accelerate this heated propellant through a nozzle to produce thrust. So, there is an expansion through a nozzle.

So, among all these three, this comes close to rocket propulsion, because we actually use a converging-diverging nozzle to produce the thrust. And then the electromagnetic forces is a Lorentz force, which is created because of the interaction of the electric field and the magnetic field and that accelerates the plasma, which is the propellant by the electromagnetic force accelerates that plasma.

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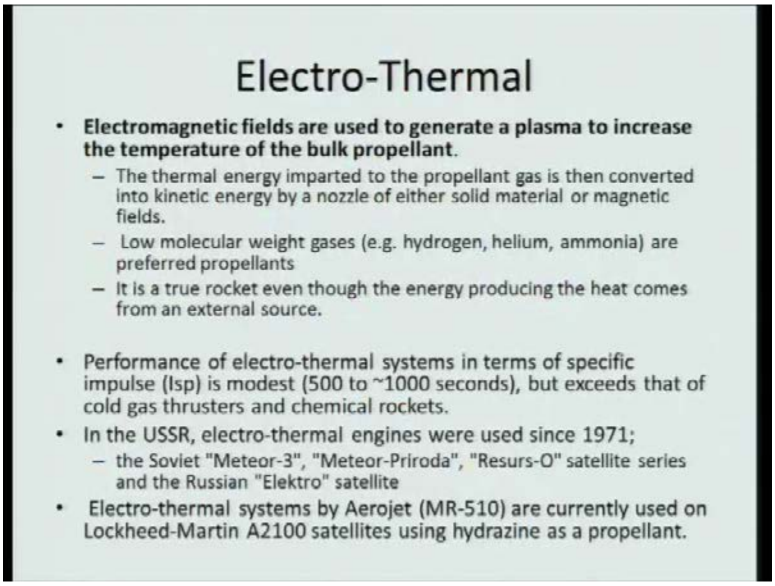

Now... So, today, first we will discuss the electro-thermal propulsion systems. So, electro-thermal. Here the electromagnetic fields are used to generate a plasma to increase the temperature of the bulk propellant. So, electromagnetic field or the electric field is not for accelerating, but for heating. The primary objective of the electric power is to heat the bulk propellant to high temperature. Now, the thermal energy is imparted to the propellant gas, is then converted into kinetic energy by a nozzle of either solid material or magnetic field. Now, magnetic field can also be used to create a virtual converging-diverging pattern. Now, a low molecular weight gas – typically it is a hydrogen, helium or ammonia are preferred propellant. It is a true rocket even though the energy producing the heat comes from a electric external source, is not the chemical energy, but an electrical energy.

Performance of electro-thermal systems in terms of specific impulse is modest compared to other electric propulsion system. They fall in the range of 500 to 1000 seconds, which is essentially between the chemical rockets and the other electric propulsion systems. And we can see that, but they are almost double than that the cold gas thrusters or the chemical rockets can provide. In the USSR, the electro-thermal energies were used since

1971 – the Soviet Meteor-3 or Meteor-Priroda or Resurs-O satellite series and the Russian Electro satellite. All of them used these electro-thermal engines. Electro-thermal system by Aerojet are currently being used on Lockheed-Martin A2100 satellites, which uses hydrogen as a propellant. So, this is the basic background of electro-thermal systems.

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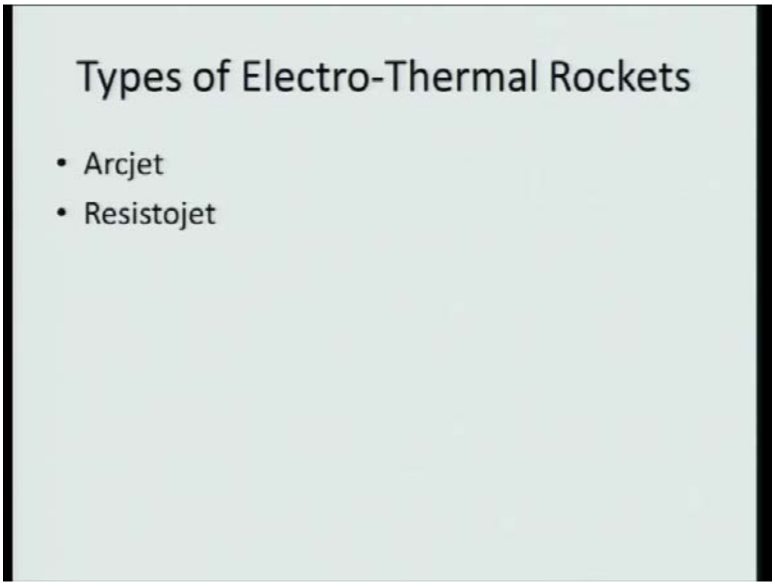

There are typically two types of electro-thermal rockets: one is an arcjet thruster and second is a resistojet thrusters.

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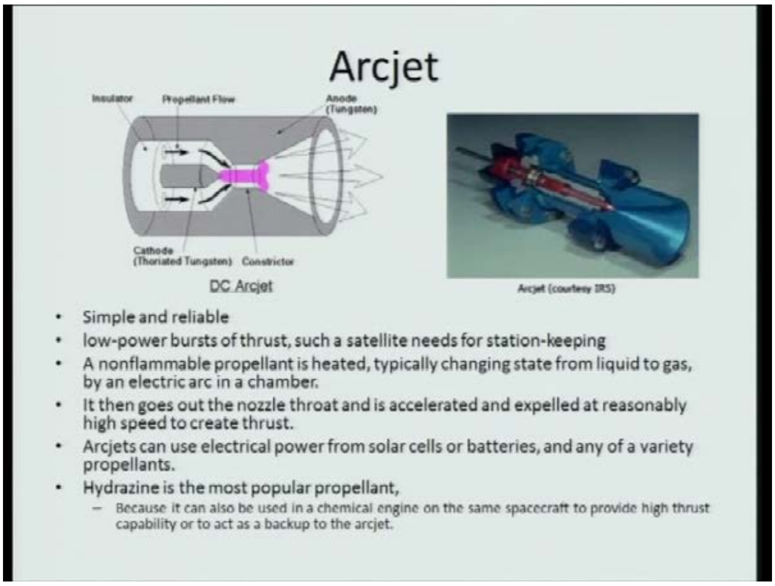

First, let us look at an arcjet thrusters. As the name suggests, in the arcjet thrusters, the heating is provided by the electrical arc. So, if the electric arc has to be produced, again we need to have a cathode and anode; and like a welding machine, an arc can be produced; we provide high enough potential difference between the two; and electric arc can be produced between the anode and cathode; that is the principle. So, here is the schematic picture of an arcjet thruster. Of course, this needs to be insulated. As we can see that, the propellant is coming from here into this gap, the centre one is the cathode, which is typically made of thoriated tungsten, and then we have a converging area; and this is the anode. Anode is tungsten. So, high voltage is applied between the cathode and anode; because of that, an electric arc is created here. And then the propellant, which as I have just mentioned is some light weight gas – passes through this electric arc. And because of the high temperature that is produced by this electric arc, it gets accelerated and goes to supersonic speed; and then it goes through a diverging nozzle creating a very high supersonic speed; and then it goes out.

As you can see here, this is the schematic of an object thruster. So, these devices are simple and reliable; low-power bursts of thrust can be produced, such a satellite needs for station-keeping, it can be produced by these thrusters. Typically, a nonflammable propellant is heated. So, you do not have flame. Typically, the changing... We can use... If you are using hydrogen, which is typically a liquid; then that gets gasified when it goes through this arc. So, it converts into gas. So, there is a... This is typically change of state from liquid to gas by an electric arc in a chamber; and then the gas goes out of the nozzle throat, is accelerated or expelled at reasonably high speed to create the thrust.

Arcjet can use electric power from solar cells or batteries also, and any variety of propellant can be used. At present, hydrogen is the most popular propellant, because it can be used in chemical engine also in the same aircraft. So, if you are carrying say this device for station-keeping or for say in a retrorocket or a ((Refer Slide Time: 06:00)) rocket. The same propellant system can be taken; hydrogen can be used from that, because hydrogen is also a chemical propellant. So, that is why, this is typically used to provide high thrust capability or to act as a back up to the object also. Sometime chemical rockets are also used as backup to the arcjet thrusters.

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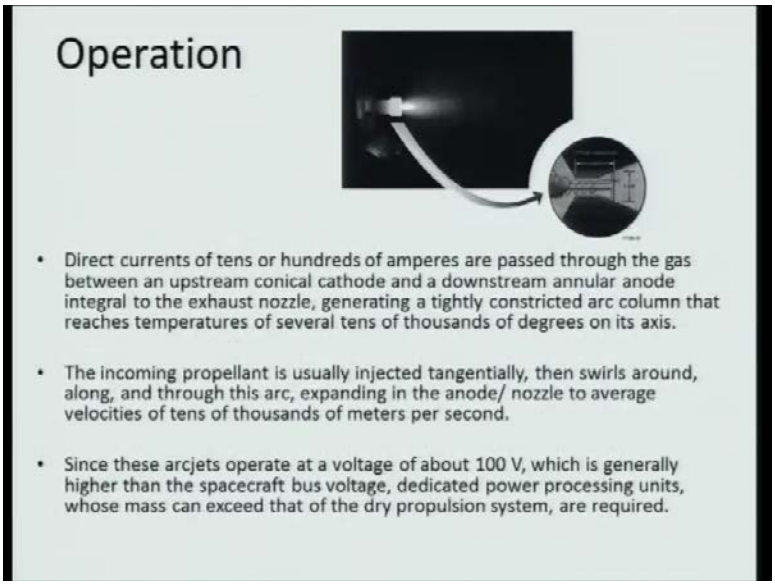

So, this is how an arcjet operates. As you can see, there is a schematic here, which is scaled up. The propellant is sent through a swirler actually. So, it swirls here as you can see here; it swirls through this. So, a long time, it will spend within that; and then the direct current of tens or hundreds of amperes are passed through the gas between the upstream conical cathode as is shown here – the cathode and the anode; a very high current will be passed, and this gas is swirling in through this passage. So, then generating a highly constricted arc column that reaches temperatures of several of tens and thousands of degrees, because of the electric arc that is produced within that. And that high temperature will heat up this gas; and anyway increase the residence time of this gas by allowing it to swirl around. So, it is spending lot of time and then it gets heated up; goes to very high temperature.

So, as I mentioned here that, an incoming propellant is usually injected tangentially. This then swirl around; and through this arc, it swirls expanding in the anode, which is also the nozzle. As we have mentioned, the anode is also the nozzle to average velocities of tens of thousands of meter per second. So, the exit velocity is very high. Since this arcjet operate on a voltage of above 100 volt, which is generally higher than the spacecraft bus voltage, dedicated power processing units are required. And then that requires an additional mass. So, 100 volt DC power supply is required; let me put it this way. So, additional mass; mass of that can be actually more than the mass of the thruster itself. So, this is what an arcjet is.

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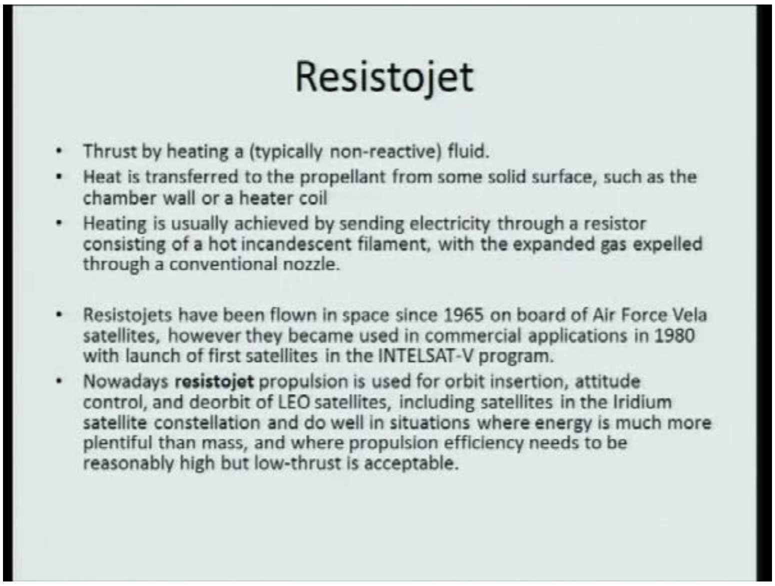

Next, let us talk about a resistojet. What is a resistojet again? Is an electrical heater. An electrical heater is used to heat up the fuel; that is what the resistojet is. So, here thrust is produced by heating a fluid – typically a non-reactive fluid. Heat is transferred to the propellant from some solid surface such as the chamber wall or a heater coil. So, heating is usually achieved by sending electricity through a resistor. So, a simple electric coil heating, nothing else. And because of this heating, it essentially the propellant, the fuel that is used gets converted into gases taking beyond its boiling temperature; then that gas is expelled through a conventional nozzle; that is what a resistojet is. They have been flown in space since 1965 on board of Air Force Vela satellites; however, they became used in commercial applications in 1980 with the launch of first satellite of INTELSAT-five program

Nowadays, resistojet propulsion is used for orbit insertion, attitude control or deorbit of low earth orbit satellites including satellites in the Iridium satellite constellation. And they do well in situations where energy is much more plentiful than mass, and where propulsion efficiency needs to be reasonably high, but low thrust is acceptable. So, propulsion efficiency of the systems are rarely high.

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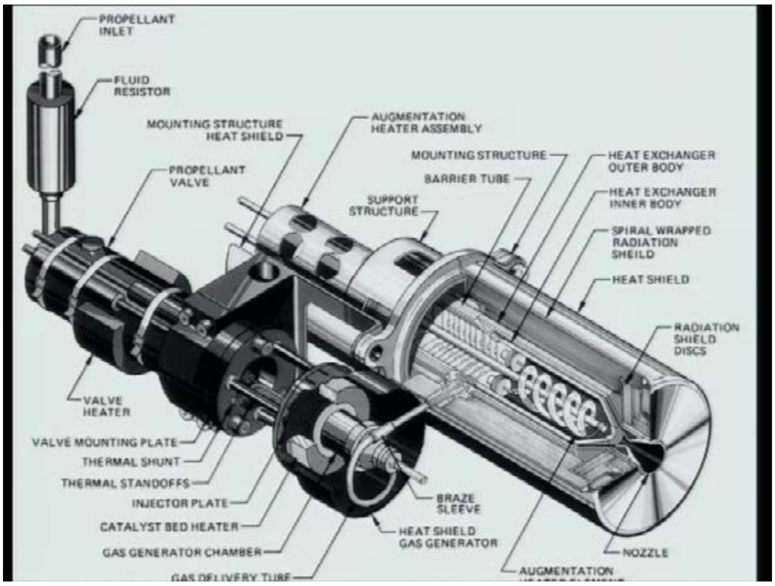

So, here is a schematic of a resistojet. Here the propellant comes in – the fuel resistor propellant comes in, propellant is passing through these tubes; there is a wall heater here, which will heat it; then the valve mounting plates; there is a thermal shunt, thermal standoffs, injector plate; the propellant is injected here; there is a catalyst bed heater. After going through all these, the propellant is heated enough to get converted into gas. Then, this gas is again taken here; then it is further heated in this coil. So, the gas is... So, there is a braze sleeve; there is a heat shield gas generator; braze shield – the gas is going here, passing through these coils.

It gets further heated, further heated, further heated; there is a heat exchanger essentially. Then, after this is delivered here, there is a nozzle – converging-diverging nozzle. Going through these so many heaters, a small amount of gas is passed through, it gets heated to a very high temperature; and then that is essentially exhausted through the converging-diverging nozzle. That is the principle of a resistojet, nothing else. These devices are very small and compact; only thing is that, lot of insulation is required, because so much of heating is taking place; they can be heated up to 1000 degree Celsius.

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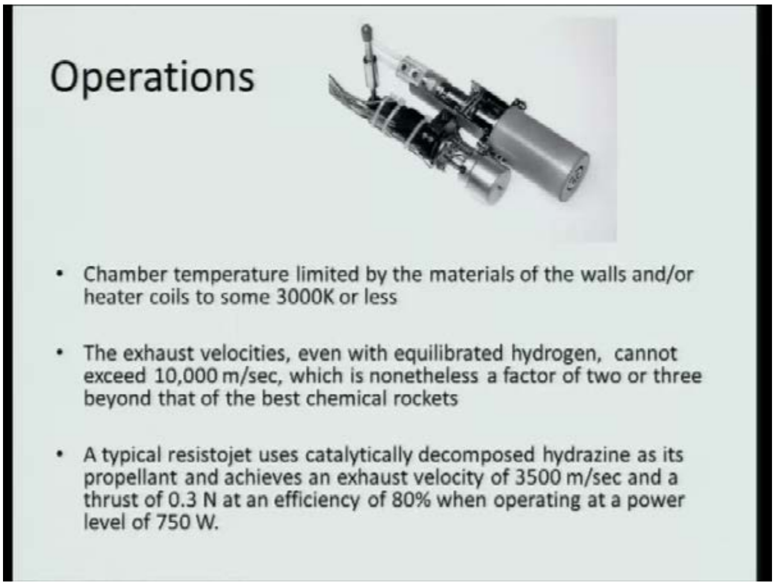

The chamber temperature limited by the material of the wall and or heated coil to some 3000 degree or less. So, that is, essentially without chemical heating, we are producing about 3000 degree kelvin temperature. The exhaust velocity even with equilibrated hydrogen is about 10,000 meter per second, which is essentially factor of two or three beyond the best chemical rockets. Best chemical rockets will give about 5000 – 4800. So, this is double than that. So, specific impulse is higher. And the typical resistojet uses catalytically decomposed hydrogen as its propellant and achieves an exhaust velocity of 3500 meter per second and the thrust of about 0.3 Newton with an efficiency of 80 percent; that is the big number when operate at a power level of 750 watt. 750 watt is very small. So, 750 watt – we are getting that high efficiency. So, that is a good system. With that we conclude our discussion on the electro-thermal propulsion systems.

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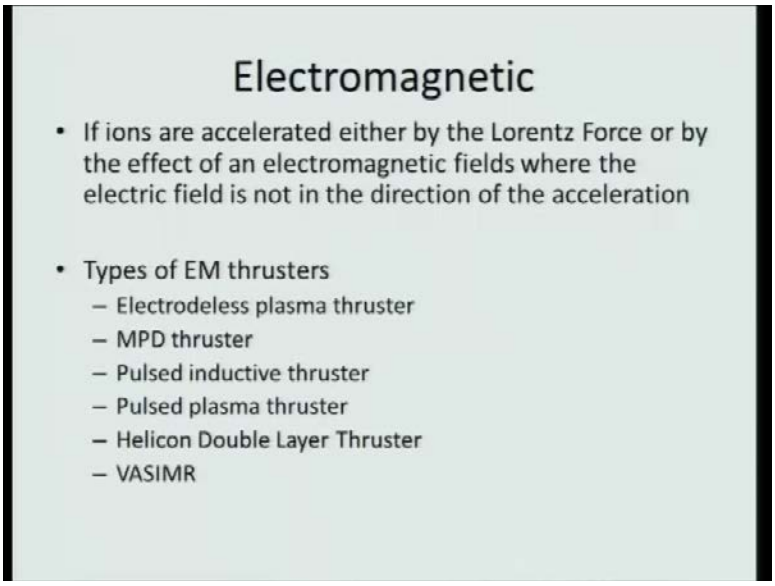

Next, let us talk about electromagnetic propulsion system. As the name suggests, in electromagnetic propulsion system, the acceleration is primarily provided by electromagnetic fields. So, if ions are accelerated either by Lorentz force or by the effect of an electromagnetic field, where the electric field is not in the direction of acceleration, those devices are called electromagnetic propulsion devices. So, electromagnetic propulsion devices – some of the devices are listed here. The electrodeless plasma thrusters, the MPD thrusters; I will discuss which they are pulsed inductive thrusters, pulsed plasma thrusters, helicon double layer thruster and VASIMR, these are the electromagnetic thrusters that are presently in use; I will discuss all of them one at a time.

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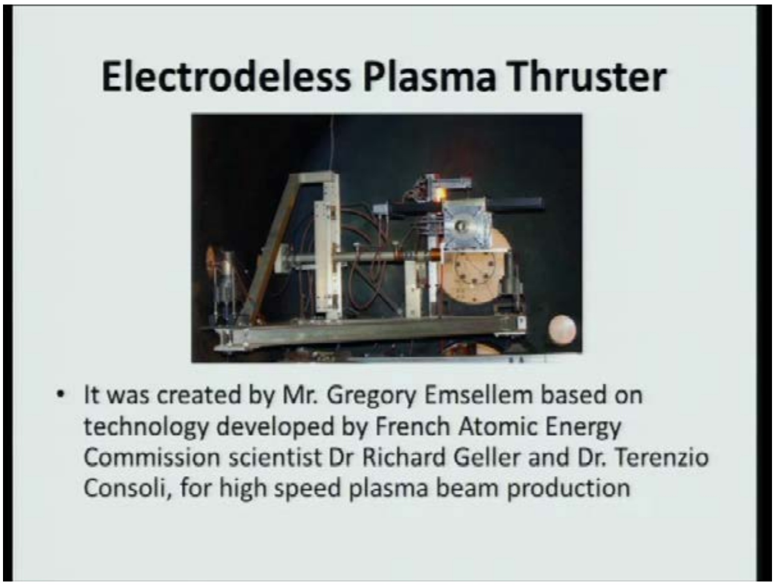

First, let us look at the electrodeless plasma thrusters. It was created by Mister Gregory Emsellem based on technology developed by French atomic energy commission scientist Doctor Richard Geller and Doctor Terenzio Consoli for high speed plasma beam production. So, the initial aim of the French atomic energy scientist, were to produce high speed plasma beam, which was then modified as a plasma thruster.

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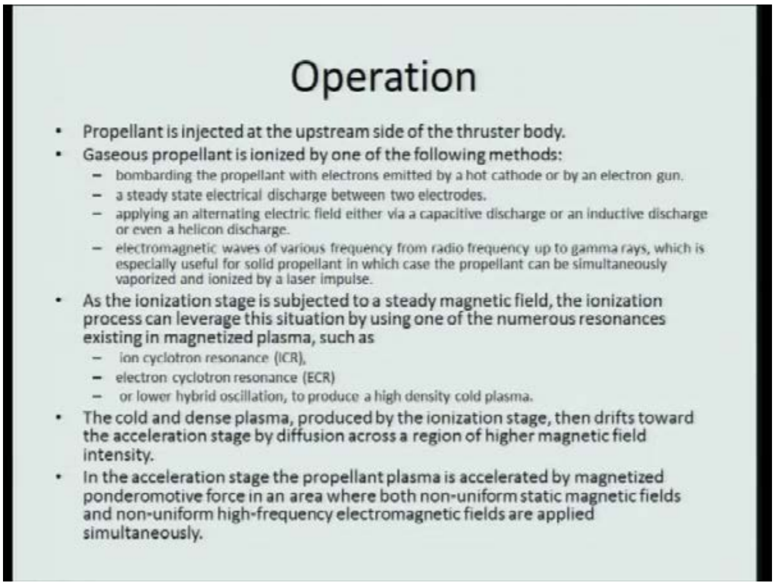

So, here is how it works. Propellant is injected at the upstream side of the thruster body. This gaseous propellant is ionized very similar to ion thrusters, is ionized by one of the following methods. Either they are bombarded with electron, which has been done in the previous case – we have discussed – by a hot cathode or by an electron gun, a steady state electrical discharge between two electrodes; applying an alternative electric field or electromagnetic waves of various frequency – radio frequency. So, this portion is same as the ion thruster that we have discussed. As the ionization stage is subject to a steady magnetic field, the ionization process can leverage this situation by using one of the numerous resonance existing in magnetic plasma. So, this ionization state – we have a magnetic field around it. And that magnetic field and electric field is tuned in such a way that, it creates magnetic resonance. So, the resonance can be ion cyclotron resonance, electron cyclotron resonance or lower hybrid oscillation.

So, the cold and densed... So, here the plasma is not hot. So, cold plasma is produced here – produced by the ionization stage; then drifts towards the acceleration stage by diffusion across region of higher magnetic field intensity. So, essentially, a high magnetic field is produced. So, the magnetic field actually is changing in its intensity from one position to another position. In the acceleration stage, the propellant plasma is accelerated by magnetized ponderomotive force in an area where both non-uniform static magnetic fields and non-uniform high frequency electromagnetic fields are applied simultaneously. So, two fields are applied simultaneously. So, essentially, the difference between this and the ion thruster is – there it was not converted into plasma, just ion; here in the presence of the magnetic field, it gets converted into plasma; then the plasma is accelerated by the electromagnetic field. So, that is the difference between that and this one.

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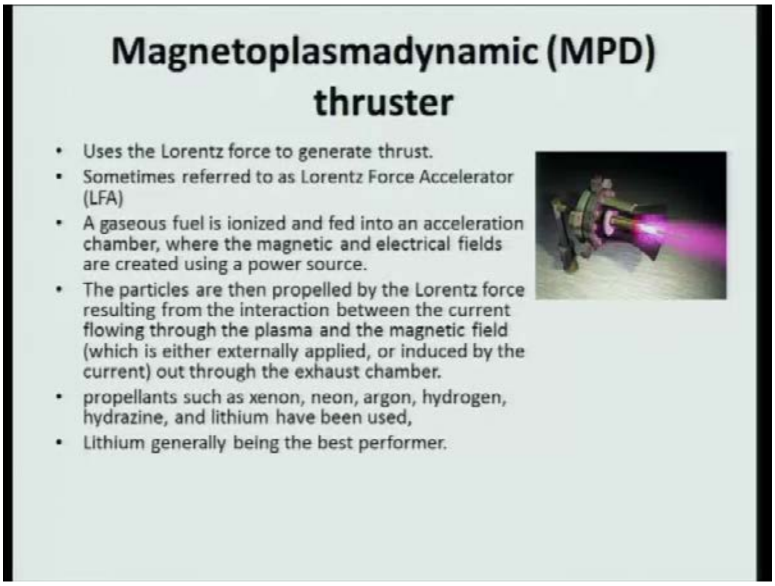

Next, we talk about magneto plasma dynamic thrusters. Again similar to the previous case, this uses Lorentz force to generate thrust; sometime also referred as Lorentz force accelerator. In this case, a gaseous field is ionized and fed into an acceleration chamber, where the magnetic and electric fields are created using a power source. The particles are then propelled by the Lorentz force resulting from the interaction between the current flowing through the plasma and the magnetic field; then it goes out of the exhaust chamber. Typically, the propellant used are xenon, neon, argon, hydrogen, hydrazine, and lithium; however, lithium is generally the best preferred propellant for MPD thrusters. So, this is the schematic of the MPD thruster. The different... So, essentially again is a... This is a similar thing that we have a... We take gas, ionize it, and then accelerate it using a electromagnetic force – magnetic field. In the previous case – in the ion thruster, it was only electric field; here we have electromagnetic field; that is the only difference. So, the concept is similar to an ion thruster.

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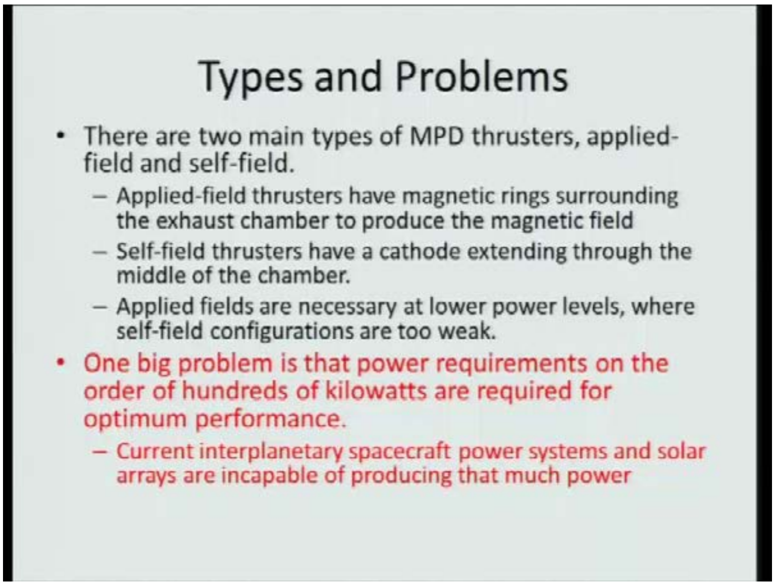

There are different types of MPD thrusters; typically, there are two types. One is in which the electromagnetic field is applied from outside; it is called applied-field thrusters. Other is it is created by the entire system itself because of the electric field that is there, creates the magnetic field. So, that is called the self field. So, applied-field thrusters have magnetic rings surrounding the exhaust chamber to produce the magnetic field. In the self-field thrusters, you have a cathode extending through the middle of the chamber.

So, the presence of the cathode and the charged plasma creates the magnetic field. The applied fields are necessary at lower power levels, where self-field configuration are typically too weak in the lower power levels. One big problem with the MPD thruster is that, the power requirement is on the order of hundreds of kilowatts for optimum performance; and that is not available in the current systems, because you have to take power from solar energy, is not available; hundreds of kilowatts are not available. That is what typically so far, it has not been used for the intended application; in future, they may be used, but not right away.

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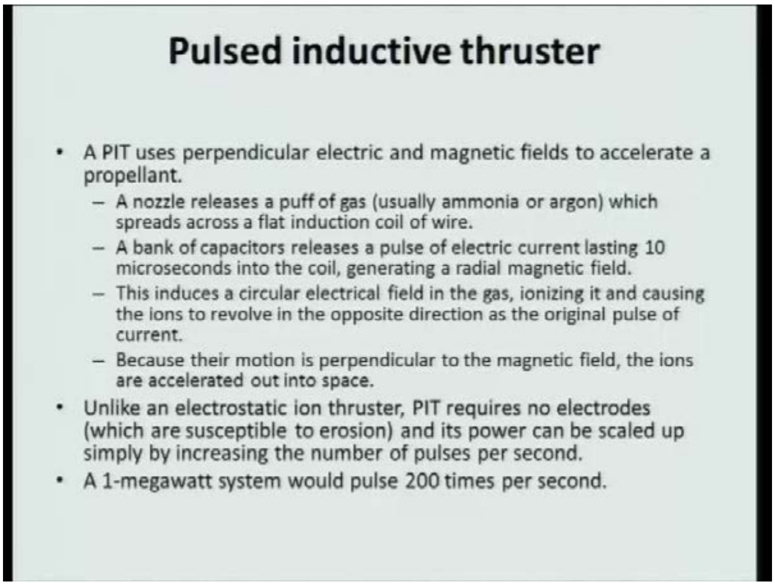

Next, let us talk about pulsed inductive thrusters. A pulsed inductive thruster or PIT uses perpendicular electric and magnetic field to accelerate a propellant. Once gain the concept is similar; a nozzle releases a puff of gas, which is usually ammonia or argon, which spreads across a flat induction coil now; it is like the induction cooker – induction coil or wire. And bank of capacitors releases a pulse of electric current lasting say 10 microseconds are all into the coil generating a radial magnetic field. And this induces a circular electric field in the gas, ionizing it and causing the ions to revolve in the opposite direction. Because of this motion perpendicular to the magnetic field, the ions are accelerated out into the space.

So, just try to visualize what is happening; that we have a plate on which some gas is put; then we are creating magnetic field by discharging from a capacitor; and then because of that, a magnetic field is created, which pushes the gas out. So, that is that is what it is. So, you are creating a magnetic field over an inductive field. That is why it is called pulsed inductive thrusters. Unlike an electrostatic ion thrusters, PIT requires no electrodes, because we are using just capacitor and induction coil. And its power can be scaled up simply by increasing the number of pulses per second. For 1-megawatt system, it will pulse about 200 times per second. But, 1-megawatt system is a lot. So, that is something that is still not practically available. But, this is a concept, which probably will soon be taken up for further development.

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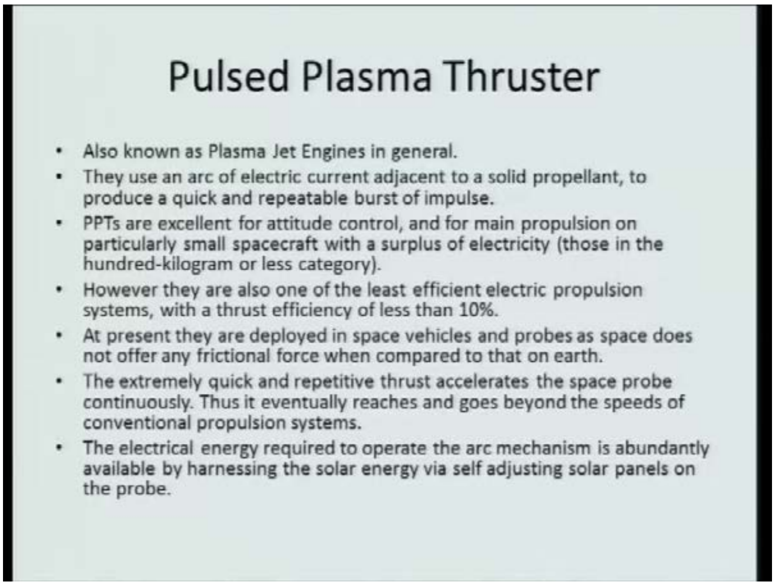

Next, we will talk about pulsed plasma thrusters. These are also known as plasma jet engines in general. These devices are the oldest electric propulsion devices; hall thrusters are the most widely used. Pulsed plasma thrusters are the oldest devices. They use an arc of electric current adjacent to solid propellant similar to arcjet thruster. But, arcjet just heats up. Here the heating is such that it creates a plasma. And then this plasma is accelerated by an electromagnetic field that is produced. There are two electrodes, which produce an electromagnetic field and the plasma gets accelerated because of that.

So, we can say there is the combination of conventional plasma thrusters and arcjet thrusters. And the arc essentially is a pulsed arc, because we will be using some electrodes and capacitors to produce pulses. So, it will... That is why it is called pulsed plasma thrusters. So, these are very good for attitude control and for main propulsion particularly small spacecrafts with surplus electricity. The problem is that, they are least efficient electric propulsion system. Efficiency is typically less than 10 percent. At present, they are deployed in space vehicles and probes as space does not offer any... typically in outer space, because the thrust produced is very small and they can be used for long duration.

These are... They produce extremely quick and repetitive thrust. And because of that, that can accelerate the probes in space continuously. Thus, it eventually reaches and goes beyond the speed of conventional propulsion system. They will... Like ramjet, it would not be able to produce, start it from 0, because the thrust produced is very small. But, something is moving at high speed; continuous small push will take it to higher and higher speed. That is the idea of these systems. The electric energy required to operate the arc mechanism is abundantly available by solar energy. Therefore, we can have... Solar energy can provide enough energy for operating this pulsed plasma thrusters.

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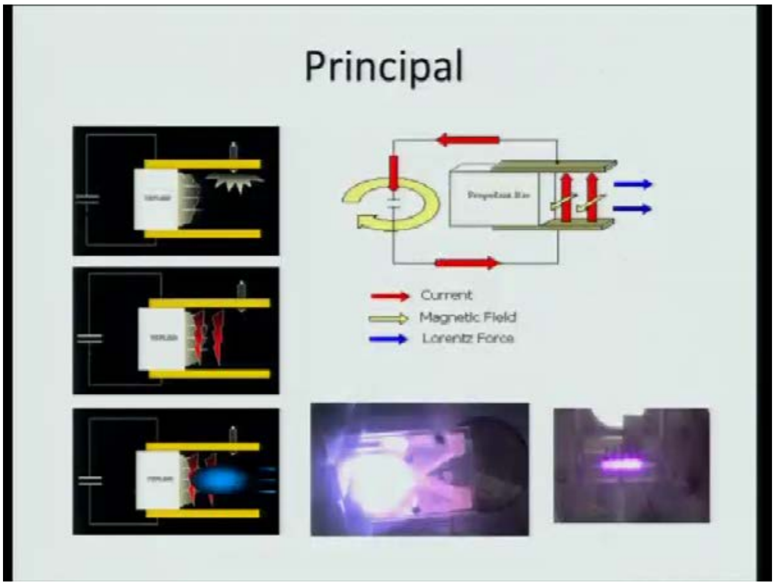

Let us look at how it works. Here is a schematic of a pulsed plasma thrusters. We have a Teflon, a solid propellant bar; on both side of this, we have two electrodes. And this is connected through a capacitor and the power supply. And there is a spark plug board here. What happens is that, when the spark plug is energized, it creates a small pool of electrons around it. And because of these electrons and then the capacitor is charged to a... because these two electrodes are maintained at a high potential difference. In the presence of these electrons, an electric arc is produced here. This arc temperature will be very high as we have just discussed earlier. And this electric arc is very close to this teflon. So, because of this high temperature of the electric arc, teflon particles get ablated; and in the presence of this arc, they get ionized to plasma. So, plasma is created here.

Now, these two electrodes essentially make an electromagnetic field. So, in the presence of this electromagnetic field, this plasma moves in a particular direction. So, here is the electric schematic. This is the current direction; this is the magnetic field; it is the capacitor magnetic field and the magnetic field. So, the Lorentz force will move it in this direction. So, because of the presence of Lorentz force, the plasma, which is produced moves in the direction here. So, here is a picture of a pulsed plasma thruster operating in our lab, where plasma is produced and then it moves out from here; there is another picture with multiple pulsed plasma thruster firing simultaneously – 5 of them. So, this produces again very small amount of thrust in milli newton and micro newton. But, the mass ablation rate is also very small. So, therefore, a small piece of teflon can go for years. That is the biggest advantage of it; the mass ablation – it is so small and you can get specific impulse up to 1500 or 2000 seconds quite easily by these thrusters. So, because of that, they are been widely used.

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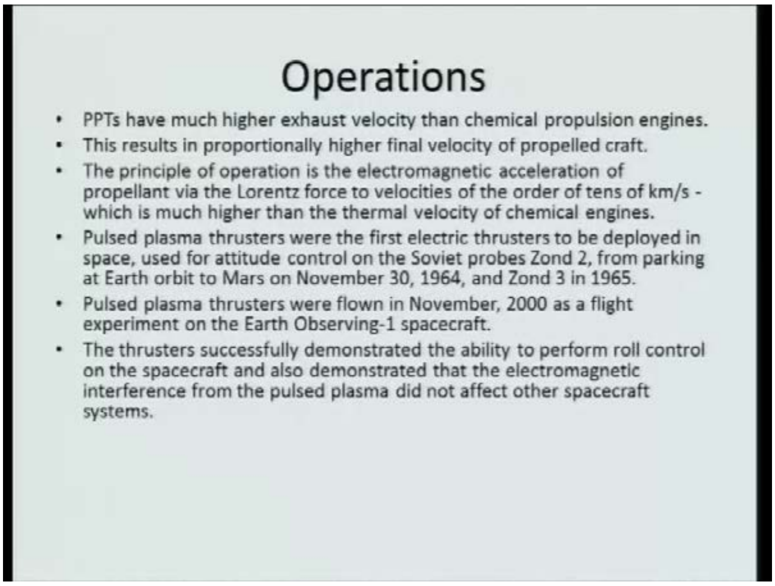

So, the PPTs have much higher exhaust velocity than chemical propulsion engines. This results in proportionally higher final velocity of the propelled craft. The principle operation is the electromagnetic acceleration of the propellant via Lorentz force to velocities of the orders of tens of kilometres per second, which essentially is almost order of magnitude higher than the chemical engines exhaust velocity. The pulsed plasma thruster were the first electric thruster to be deployed in space. These are used for attitude control on Soviet probes zond-2 from parking to earth orbit to mars on November 30, 1964. And then in zond-3 in 1965. Pulsed plasma thruster were flown in 2000 as a flight experiment on earth observing-1 spacecraft as well. They have this successfully demonstrated the ability to perform roll control on the spacecraft and also demonstrated the electromagnetic interference from the pulsed plasma thruster did not affect other space craft systems, because the electromagnetic field is very short duration that, they do not have a long term effect on the other system – other subsystems of the spacecraft. So, this has been successfully flying for years now. For example, in the zond-2 is the first time it was used. By the way in zond, the propellant was not Teflon; they use some gases; whereas, the observer-1 – earth observer-1 spacecraft – they use teflon as the propellant.

Now, Teflon – another thing that is I have forgot to mention here is that, since as the... It starts to work the space of the propellant gets ablated being consumed. So, then it will start to move away from the spark plug. In order to continuously feed it, typically a spring is used at this end. So, the spring will continuously keep on pushing it, so that the distance between the teflon and this spark plug is maintained. The life limiting component in this is the spark plug, which gets eroded. So, if we can replace this spark plug by some other means, then the life will be extended. Now, as I was mentioning the zond, it actually outlive its life by years – few years because of the pulsed plasma thrusters, was able to operate much longer than it was expected to. So, this is what a pulsed plasma thrusters is.

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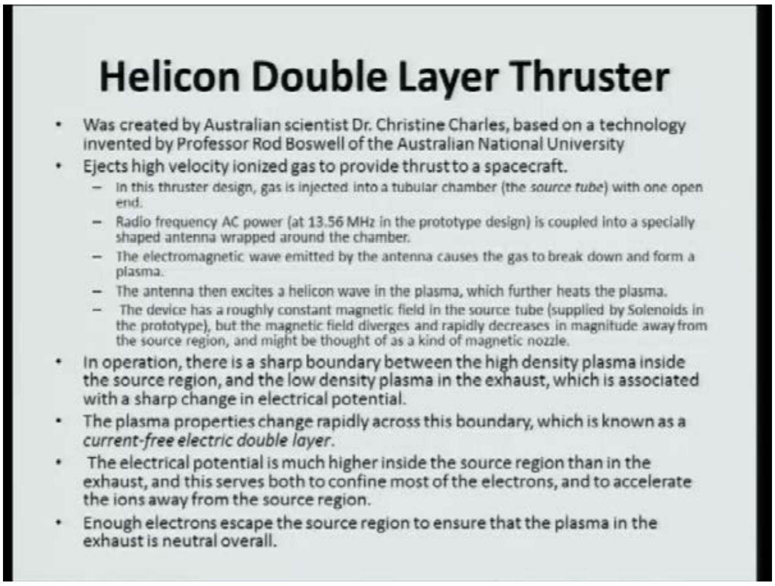

Next, let us talk about helicon double layered thrusters. This was created by Australian scientist Doctor Christine Charles, based on a technology invented by professor Rod

Boswell of the Australian National University. This ejects high velocity of ionized gas to provide the thrust to an aircraft. So, once again, the basic principle is high velocity ionized gas. As we have been seeing again and again, all these devices are doing that; only the method in which we are getting the hydrogen is different. So, here in this case what is done is that, the gas is injected into a tubular chamber or the source tube with one open end.

Then, a radio frequency AC power at 13.56 mega hertz is coupled into a specifically shaped antenna wrapped around this chamber. So, we have an antenna wrapped around a chamber through which the gas is flowing and a radio frequency – high frequency AC power is supplied to that. The electromagnetic waves emitted by the antenna causes the gas to break down and form the plasma; so essentially, in the electromagnetic plasma generation because of this. The antenna then exists the helicon wave in the plasma; excites the helicon wave in the plasma, which further heats the plasma. So, the antenna produces the plasma, heats it also. The devices are roughly constant magnetic field in the source tube, but the magnetic field diverges and rapidly decreases in magnitude away from the source region, and might be thought of as a kind of magnetic nozzle. So, magnetic field is reducing as this goes away. So, the flow will start to move in this direction.

In operation, there is a sharp boundary between the high density plasma inside the source region and the low density plasma in the exhaust, which is associated with a sharp change in the electric potential. The plasma properties change rapidly across this boundary, which is known as a current-free electric double layer. The electric potential is much higher inside the source region than in the exhaust and this serves both to confine most of the electrons, and also to accelerate the ions away from the source region. So, source region is where the plasma is produced and starts to accelerate; then the shape of the magnetic field actually produces the shape of the nozzle, which is a virtual nozzle, not a real nozzle. So, the flow goes in that direction. Enough electrons escape the source region to ensure that the plasma is in the exhaust is in the neutral over all. So, the electron that is produced here will neutralize the plasma also. So, we do not have a charged plasma.

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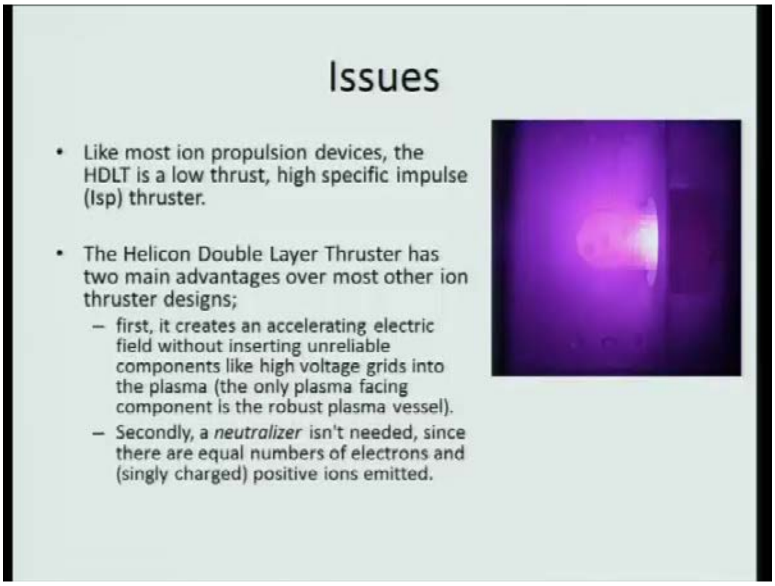

So, here is typically a picture of this operating. The issues like most of the ion propulsion systems; these are also an ion propulsion system. The HDLT is a low thrust high specific impulse thrusters; it has too main advantages over most other ion thrusters. First of all, it creates an accelerating electric field without inserting any unreliable component like high voltage grid into the plasma. In the ion thrusters, you needed grids. So, this is one of the major advantage, And secondly, you do not need a neutralizer, because it is inherently neutralized since there are equal number of electrons and protons emitted. So, it is inherently neutralized. So, you do not need a neutralizer; you do not need a grid to accelerate it. So, the antenna itself – the magnetic field itself provides everything. So, that is what the biggest advantage of this thruster is.

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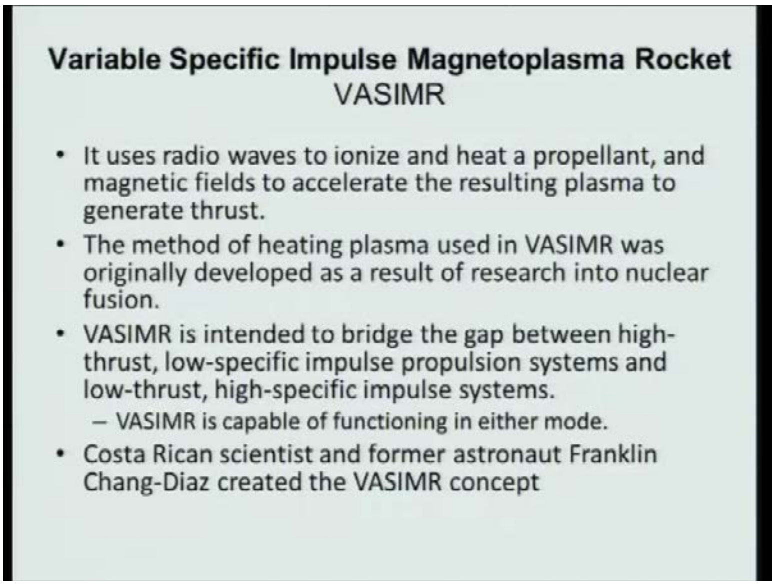

Now, we come to the last one, which is variable specific impulse magnetoplasma rocket are called VASIMR. It uses... It is also similar to the one we just discussed. It uses radio waves to ionize and heat a propellant, and magnetic field to accelerate the resulting plasma to generate thrust. So, it is very similar to the one we just discussed. The method of heating plasma used in VASIMR was originally developed as a result of research into nuclear fusion. VASIMR is intended to bridge the gap between high thrust low specific impulse propulsion system and low thrust high specific impulse system, because it is capable of functioning in both the modes like Costa Rican scientist and former astronaut Franklin Chang-Diaz created the VASIMR concept.

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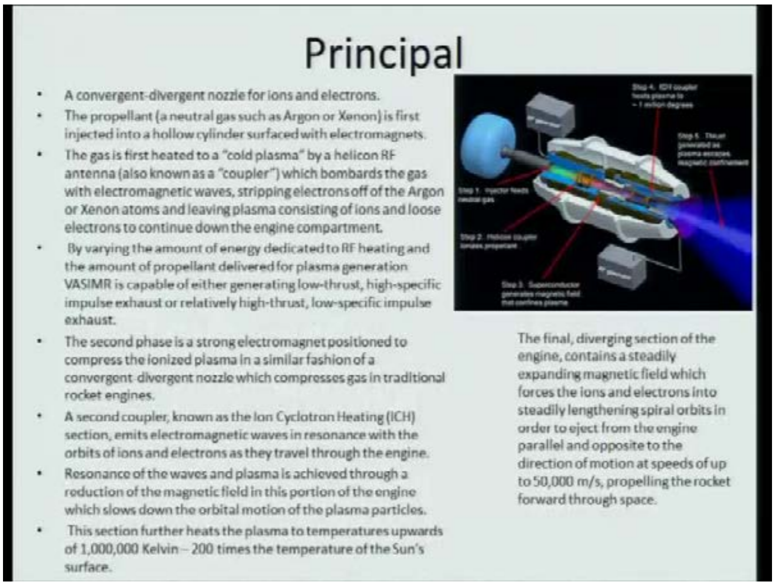

Now, this is... Let us look at how it works. Here is a schematic diagram of the VASIMR system. Here first is that, we have a converging-diverging nozzle for ions and electrons. The propellant, which is typically a neutral gas such as Argon and Xenon is first injected as you can see here into a hollow cylinder surface with electromagnets. So, we have electromagnets here. The gas first is... This is surrounded with an antenna – a radio frequency is going in. So, the gas is first heated to a cold plasma by a helicon radio frequency antenna similar to the helicon system we just discussed. It is converted into a cold plasma; it is also known as coupler, which bombards the gas with electromagnetic waves steeping electrons of the gas either Argon or Xenon we are using, and leaving plasma constituting of ions and loose electrons, which is now continuing down this step.

Now, by varying the amount of energy dedicated to this radio frequency heating and the amount of propellant delivered to the plasma generation, the VASIMR is capable of either generating low thrust high specific impulse or high thrust low specific impulse; both are possible. Now, the second phase, which is shown here is a strong electromagnet positioned to compress now this ionized plasma in a similar fashion like a converging-diverging nozzle. So, in the previous case, in the HDLT, you had one antenna with one electromagnetic field. So, naturally, it was getting weaker and producing this virtual nozzle. But, here you have two of them separately: one is to produce the plasma; other is to give the shape. So, you have much more control over it and can be compressed much more. Gases can be compressed much more. But, this compression is magnetic compression. So, the second phase is the electro-magnetic position – electromagnets positioned to compress the ionized plasma in a similar fashion like a converging-diverging nozzle, which compresses gas in traditional rocket engine.

The second coupler known as the ion cyclotron heating section emits electromagnetic waves in resonance with the orbits of ions and electrons as this travels through the engine. This resonance of the waves and plasma is achieved through a reduction of magnetic field in this portion of the engine, which slows down the orbital motion of the plasma particles. This section further heats the plasma to temperature upwards to 1 million Kelvin – 200 times the temperature of sun's surface. So, it is a electromagnetic heating to that temperature – very high temperature. And after that, there is a final diverging section, which contains the steadily expanding magnetic fields, which forces the ions and electrons into a steadily lengthening spiral orbits in order to eject from the engine. As you can see here, it comes parallel to the engine axis and the speed as high as 50,000 meter per second can be attained.

So, essentially what is being done here is you have electromagnetic heating. First half you create plasma, then electromagnetic heating of that plasma, and then electromagnetic forcing of the plasma by creating a varying electromagnetic field, which works like a converging-diverging nozzle and accelerating this to a high velocity field. So, everything is essentially done by electromagnets; you do not have physical boundaries doing it. So, essentially, what you need is a very good insulation, so that the magnetic field is insulated. And as you can see, there are two radio frequency generators – RF generators used: one for the cold plasma production, other for the hot plasma heating and the acceleration part.

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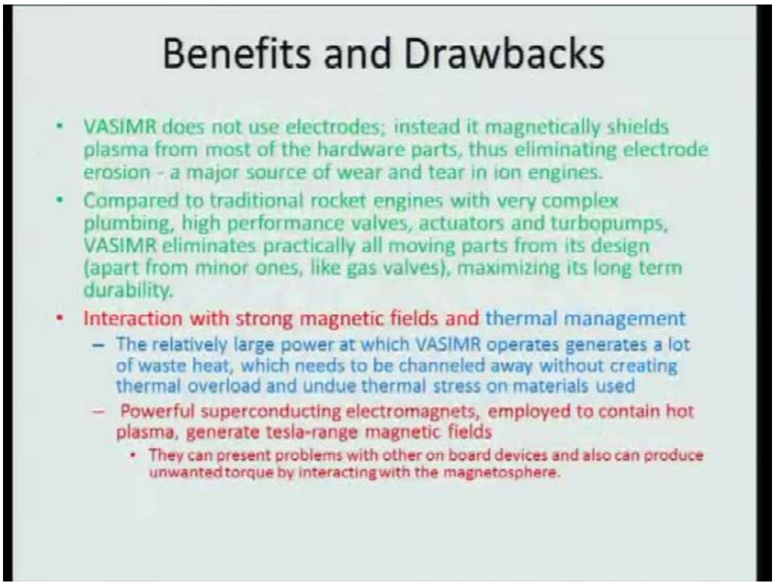

So, this is what a VASIMR is... The benefits are of the VASIMR system is – it does not use electrodes; instead it magnetically shields plasma from most of the hardware parts; thus, eliminating electrode erosion, which is a major source of problem for ion engines. Electrode erosion is a major source of problem. Compared to traditional rocket engines with very complex plumbing, this does not require any valve, and neither actuators nor turbo pumps. So, eliminates all moving parts from its design. And because of that, it maximizes the long term durability of the system, because you do not have turbo pumps, you do not have valves, you do not have actuators. However, the problems are first of all introduction with strong magnetic field and thermal management.

First, let us talk about the thermal management. A relatively large power at which the VASIMR operates generates a lot of waste heat, because the temperatures are going to be very high; I mentioned about 1 million Kelvin. So, lots of waste heat is generated, which needs to be channelled away without creating a thermal overload and undue thermal stress on the material used. So, material can melt because of the high temperatures created. So, the thermal management becomes an issue. And secondly, the magnetic field that is generated requires powerful superconducting electromagnets, which are employed to contain the hot plasma, generate tesla-range magnetic fields, which are very high magnetic field. They can present problem with other onboard devices and also can produce unwanted torque by interacting with the magnetosphere. So, these are the two major issues with VASIMR system. But, if used properly, this system has potential to work both as a high thrust low specific impulse and low thrust high specific impulse system; that is the major advantage. So, it will be a universal system.

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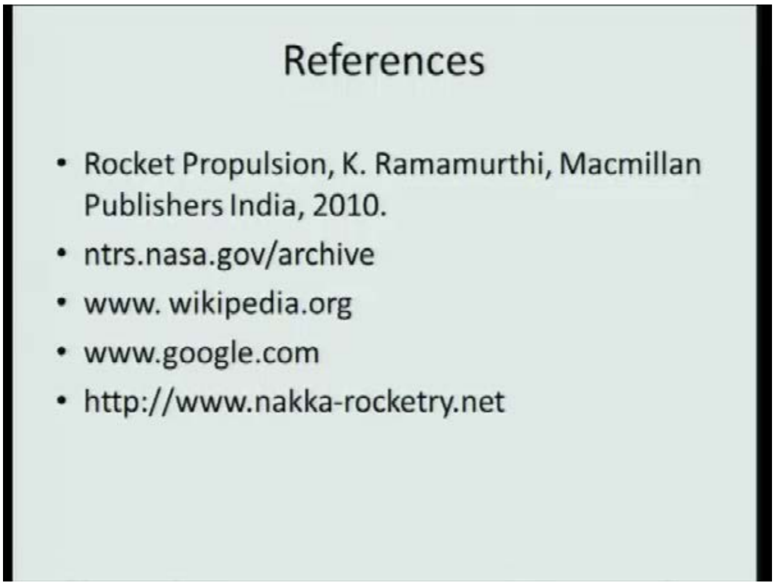

So, with this, we come to our discussion. So, first, I would like to once again thank the references from which I have taken the material – Doctor Ramamurthi's book, then Nasa's web page, Wikipedia, Google and this personal webpage – nakka-rocketry dot net, which provided me the material for this part of the course. So, let me just summarise what we have discussed in this course. We started off with type of rockets, rocket equations, the space dynamics, then the rocket performance, then the multi-staging, then the rocket performance as the chemical rocket performance, then combustion, then nozzle design. After that, we talked about solid propellant rocket, liquid propellant rockets, and then couple of lectures on electric propulsion system. So, I think we have fairly covered the entire gamut of rocker propulsion. And I will just stop it here.

Thank you.