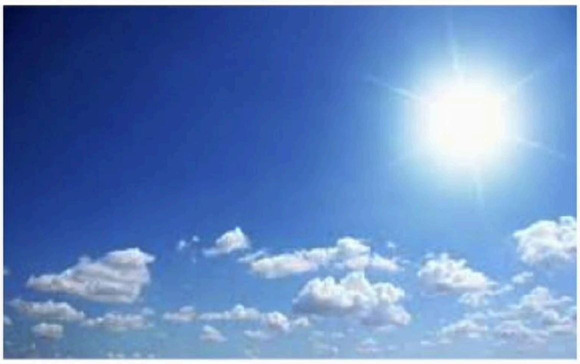
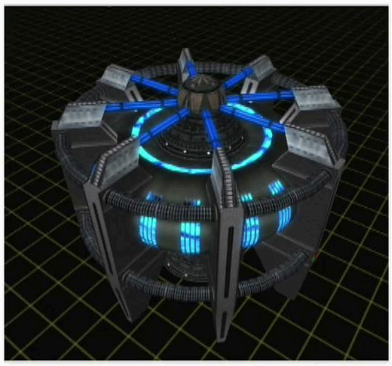


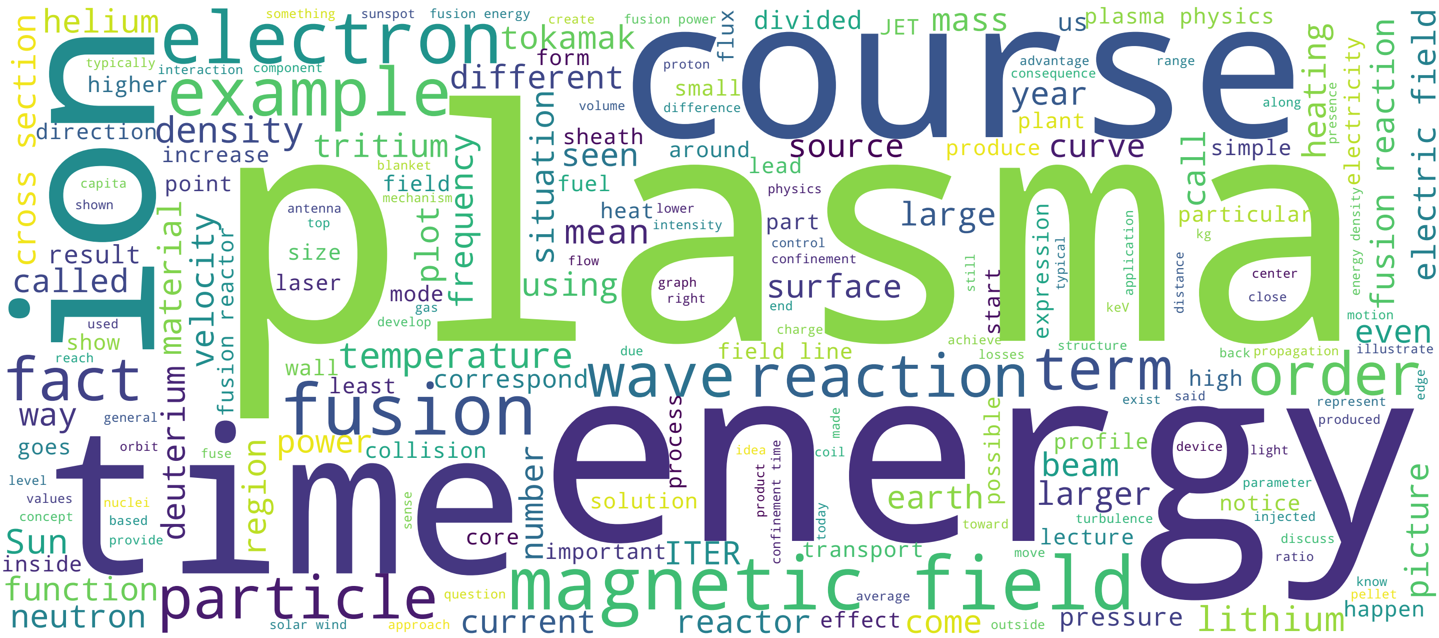


Thermonuclear fusion: the basics

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 6a

Ambrogio Fasoli



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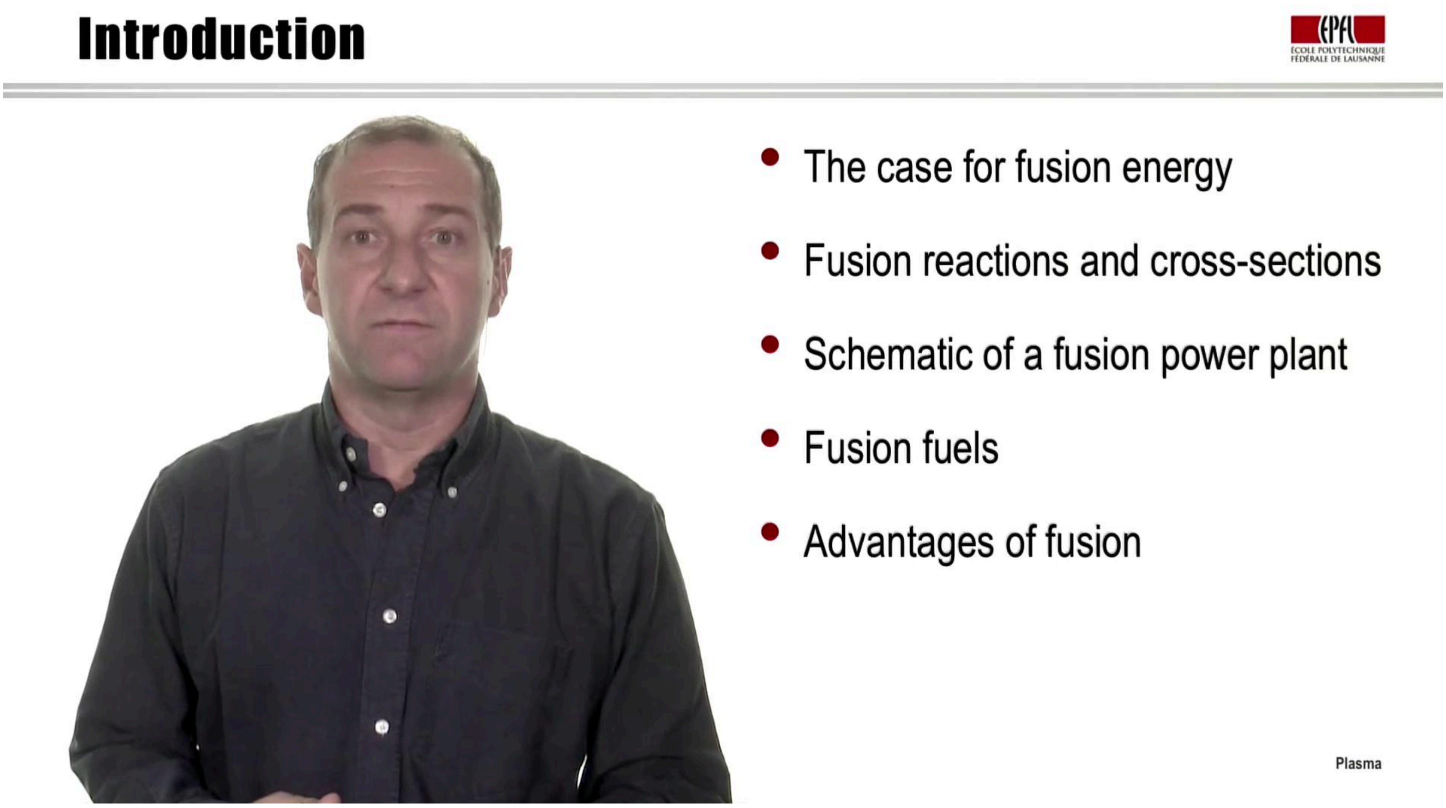


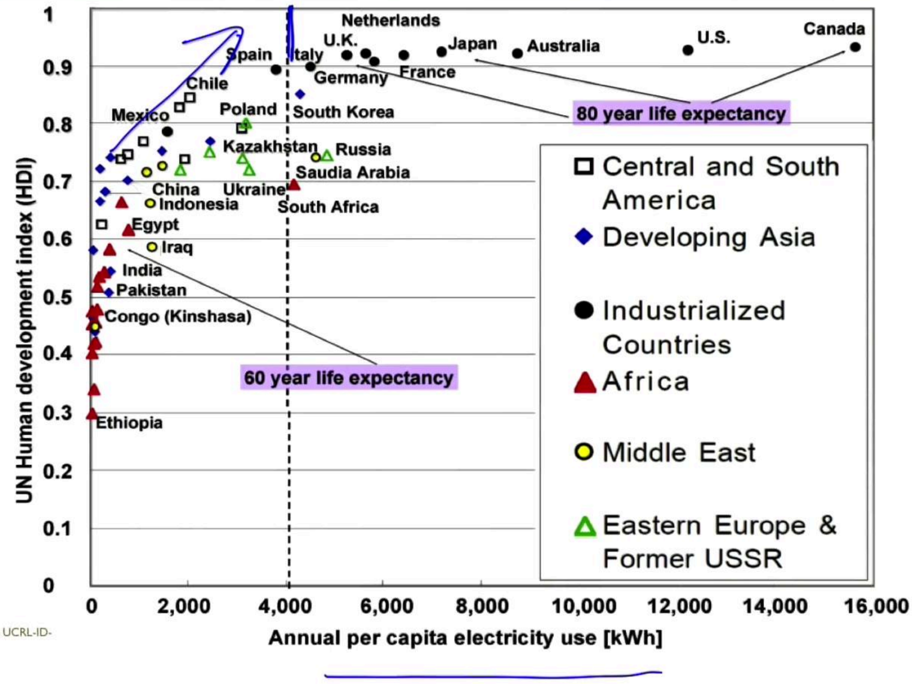
Welcome to the course on Plasma Physics and Applications. Today we will study the basics of thermonuclear fusion. We'll look at a case of fusion energy in general, and the fusion reactions and the relevant cross-sections, and a schematic of a fusion power plant as imagined today, and the fusion fuels and their availability, and of course the advantages that fusion can have.

Notes

Summary

0m 05s

The case for fusion energy



PASTERNAK, A., US Department of Energy Report UCRL-ID-140773, LLNL, Livermore, CA (2000) 38.

Plasma

I would like to discuss the case for fusion energy by starting- considering a single parameter that measures the development of a nation called *The Human Development Index*. This combines three parameters: health, education, and richness, evaluated per individual, so per capita in terms of the life expectancy, the number of years at school, and the gross national product per capita. In this plot, the *Human Development Index* is represented as a function of the electricity use per capita again. What we notice is a very striking correlation between the two. In other words, in order to develop more, according to this very simplistic, yet very interesting measure, countries need to use more electricity. Or better, they need to allow the individuals to use more electricity per capita. We also notice that at some point, corresponding roughly to this vertical dotted line, there is no need for an increase- for a further increase in electricity use per capita to develop. This point corresponds roughly to the average of the Western countries. So we want to have an energy source that is available to all countries and in particular, to those that are on the left-hand side of this graph and therefore need to move on and move up in their development index.

Notes

Summary

0m 26s

The case for fusion energy

Muir and Riggs Glaciers

Plasma

We want an energy source that has no negative impact on the environment and on the climate. That is, we want an energy source that doesn't produce a significant emission on greenhouse gases such as *CO2*. Global warming is now accepted as a scientific fact. We have images here that show examples of these consequences. We have the melting of glaciers. We have an increased frequency of extreme events such as droughts, floods or heavy storms.

Notes

Summary

1m 57s

The case for fusion energy

Plasma

Naturally, we want a source of energy that is safe, that doesn't create any significant risks for the population. We don't want situations like that, represented in the picture, which is, of course, that of the Fukushima accident, to happen any more.

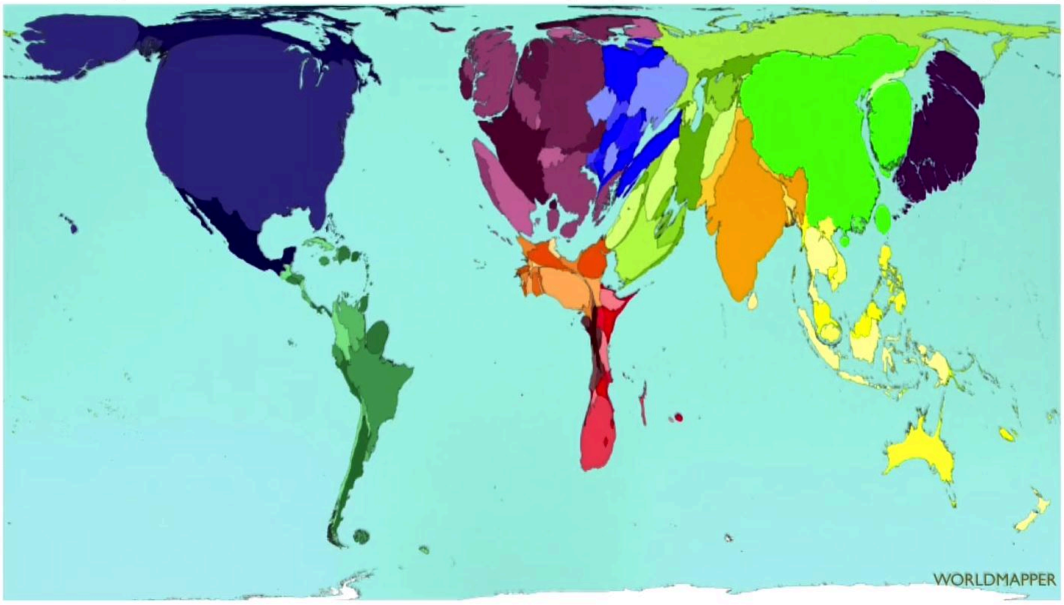
Notes

Summary

2m 24s

The case for fusion energy

World's map in which the size of the countries is proportional to the pro capita energy usage



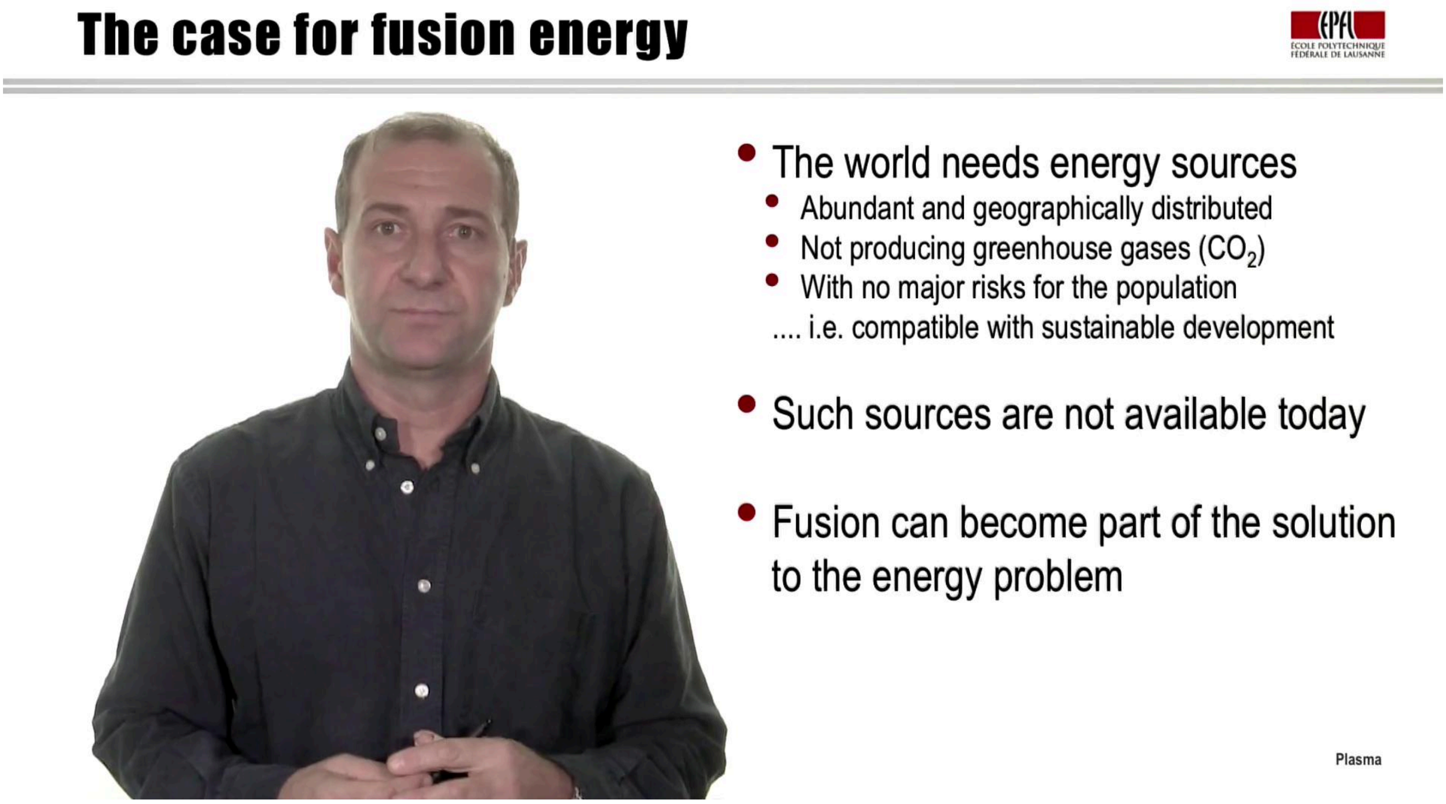
Plasma

As I said before, the sources of energy that we look for must be available equally for all countries. In particular for the countries that still need to develop. We want to avoid the situation in which, as we have today, 1.5 billion people do not have access to electricity. The situation in which, if you represent the world's map in a way that the size of the countries are made proportional to the per capita energy usage or is deformed according to that quantity, well, many countries cannot even be recognized anymore as you can see here. Even continents cannot be recognized, almost cannot be recognized such as Africa here.

Notes

Summary

2m 39s



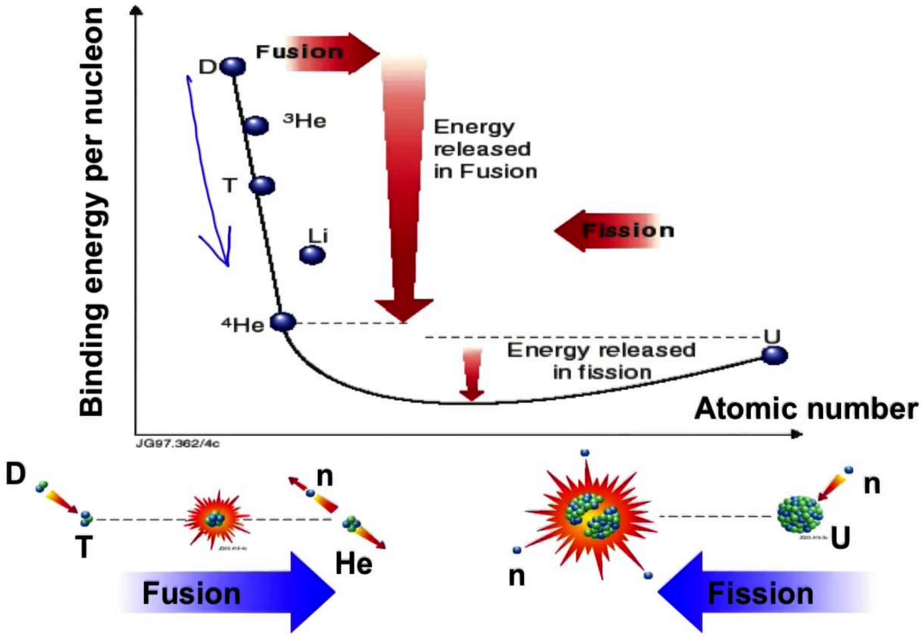
So to summarize this first part, we are looking for an energy source that is abundant, geographically distributed, that does not produce greenhouse gases, that does not create major risks for the population, simply, that is compatible with sustainable development. My point is that such source does not exist today. And what we'll see in the rest of the lecture is that fusion can become part of the solution to this energy problem.

Notes

Summary

3m 17s

Fusion and fission



Plasma

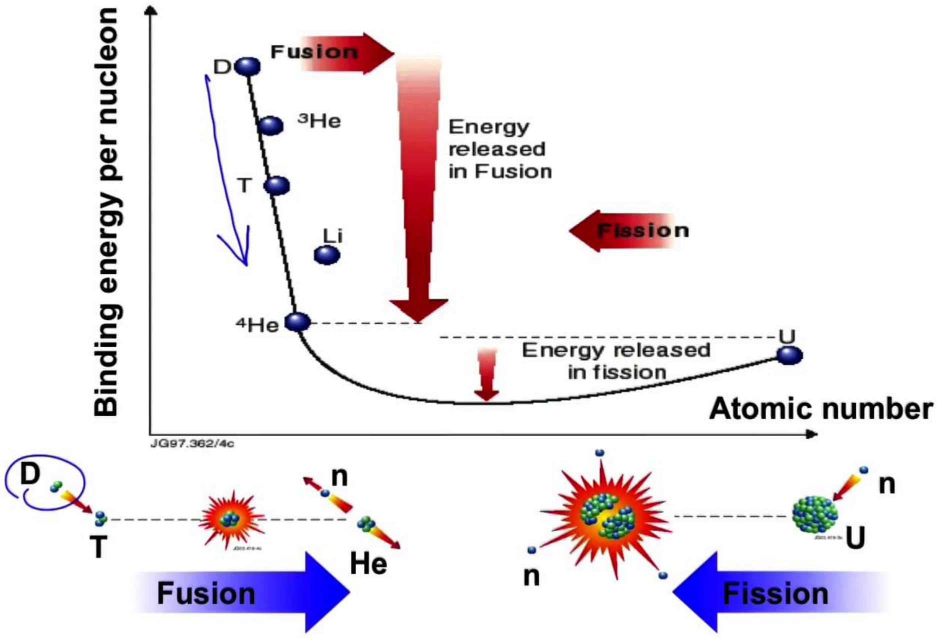
So let us see how fusion works and its analogies and differences with respect to fission. To start the discussion I plot here the bonding energy per nucleon as a function of the atomic number. The curve here has a certain shape which shows a minimum in the center of the plot corresponding to iron. The nuclear reactions can make us move along the curve one way or the other. First way we have to move is to go down from the right. I say 'go down' because as you go from large atomic numbers to smaller atomic numbers on the right side of the graph, the energy per nucleon is lower and lower. So if you have a reaction that takes you on that path that means you can release some energy and that energy that you can release corresponds to the difference in a vertical axis. So of course that's the way fission works as represented here on the bottom. Fission works by breaking a very large nucleus such as that of uranium, bombarding it by neutrons, for example, and creating smaller nuclei and energy. Fusion does exactly the opposite. That is, it combines light nuclei to form slightly heavier nuclei and therefore goes down in the curve from left to right at the left-hand side of the graph.

Notes

Summary

3m 47s

Fusion and fission



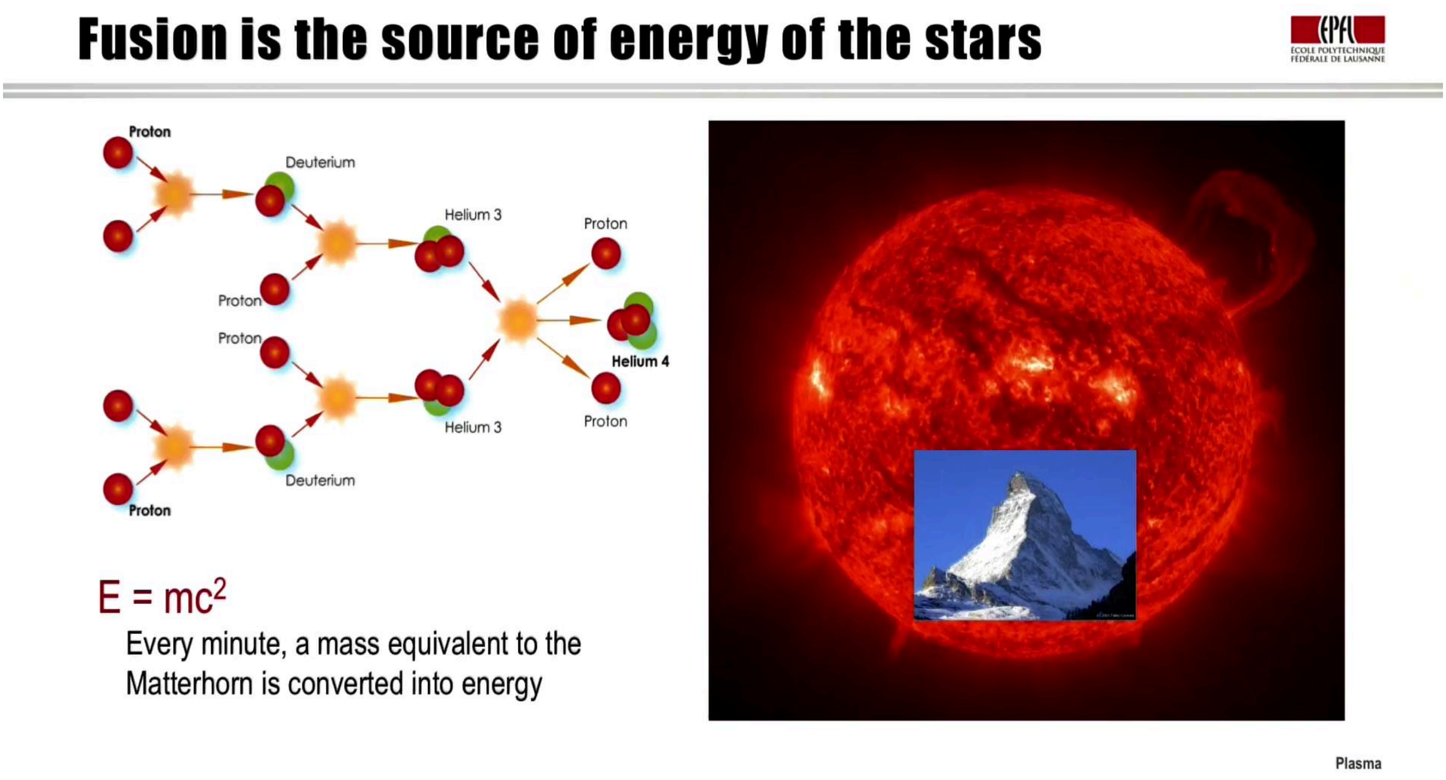
Plasma

And you notice not only that you gain energy by your course going down in this curve but also you gain a lot of energy in the sense that the slope of that curve is very sharp. The example shown on the bottom is that of deuterium and tritium, two isotopes of hydrogen, which, if combined, can be give rise to helium and a neutron, and a lot of energy. Once more, it's a lot of energy because the steepness of the curve is very large.

Notes

Summary

5m 16s



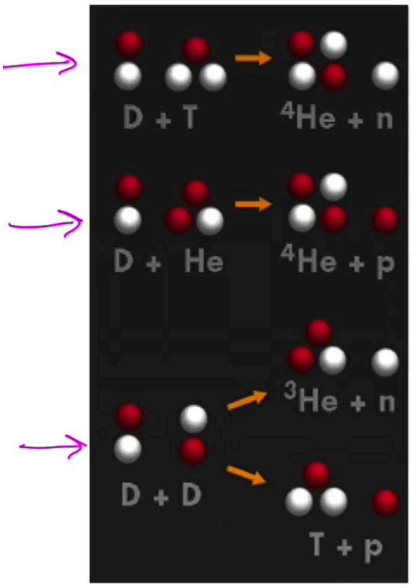
In fact, fusion is the source of energy of the stars, so we know it works in nature. The stars work on the principle of putting together essentially four protons to form a helium-4 nucleus and, again, energy. The energy production comes from the fact that the mass of the products of the reactions is slightly lower than that of the fuels that enter into the reactions. So that creates a mass defect, which according to the equation $E=mc^2$ coming from the Einstein relativity, of course, corresponds to energy. To give you an idea of what happens in the sun, every minute, a mass that is equivalent to the Matterhorn mountain, is converted into energy.

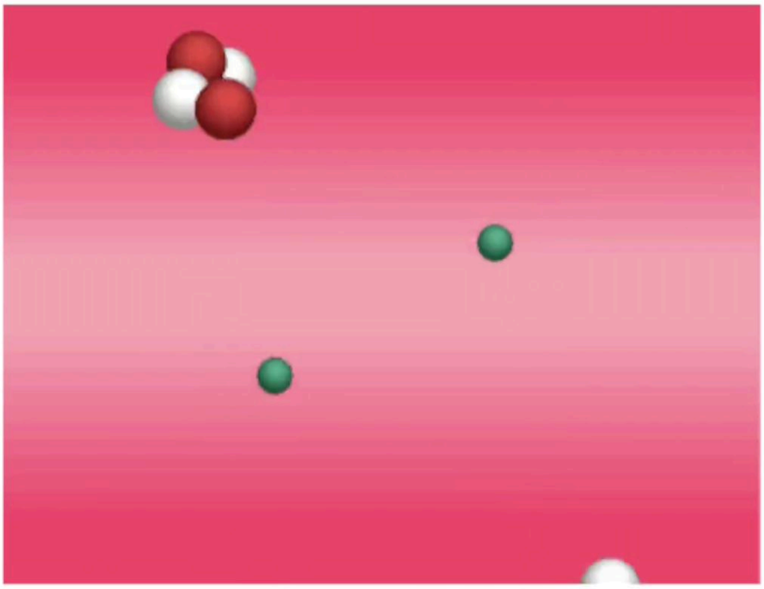
Notes

Summary

5m 45s

Fusion reactions for a reactor on earth





Large kinetic energies (temperatures) are needed to overcome Coulomb repulsion of the positively charged nuclei

Plasma

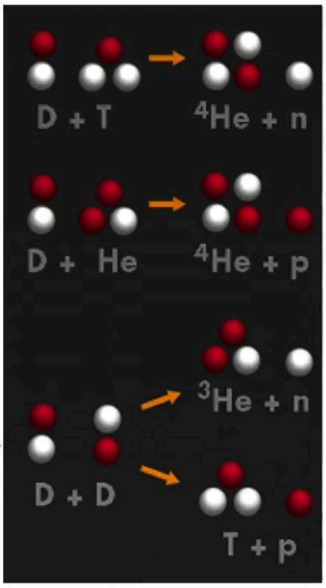
Let us look at the fusion reactions that we can have working on earth in a reactor to produce energy for us. I have taken three examples here: deuterium and tritium that fuse to produce a helium-4 and a neutron, which you have seen already. Deuterium and helium-3 that fuse to produce helium-4 and a proton, or deuterium and deuterium, that fuse to produce two possible outcomes, a helium-3 and a neutron or a triton and a proton. What we're seeing in the movie here is the thermal motion of the particles involved. And that underlies the difficulty of achieving fusion on earth. The reason for that is that all these particles that we're dealing with are nuclei and therefore they're all positively charged and because they have the same kind of charge they repel each other due to the Coulomb repulsion. They repel each other in a way that they are kept sufficiently far for fusion reactions not to happen. Except if the relative motion of this nuclei is strong enough or the collisions are energetic enough, that they can come close enough and the nuclear force can take over. So when I say the motion needs to be fast enough or the collision strong enough, or energetic enough, I mean that the temperature has to be large enough.

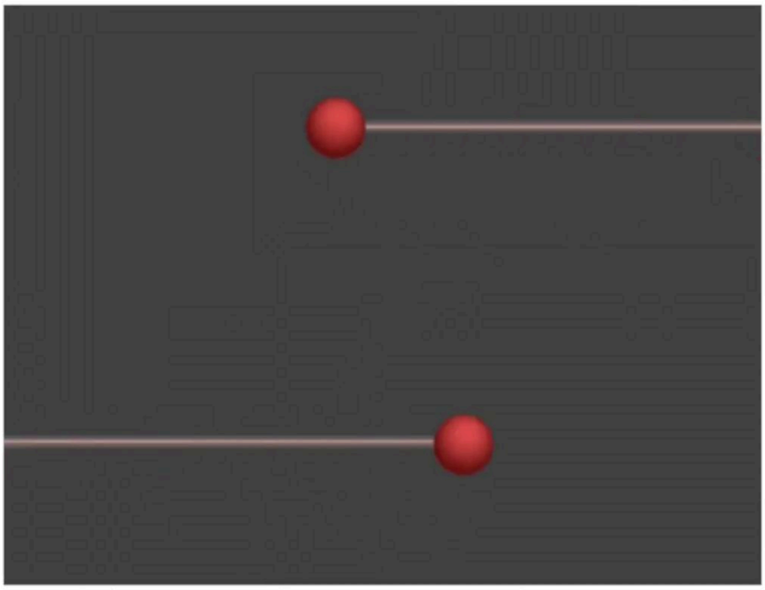
Notes

Summary

6m 28s

Fusion reactions for a reactor on earth





Large kinetic energies (temperatures) are needed to overcome Coulomb repulsion of the positively charged nuclei

Plasma

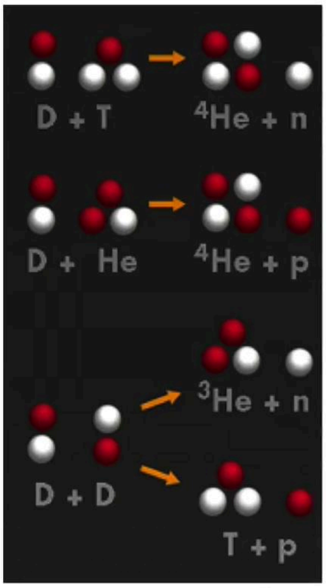
If the temperature is large enough, this random motion of the particles is very fast and therefore collisions are energetic enough for the nuclei to approach each other at a distance where nuclear force can take over and the fusion reactions can happen.

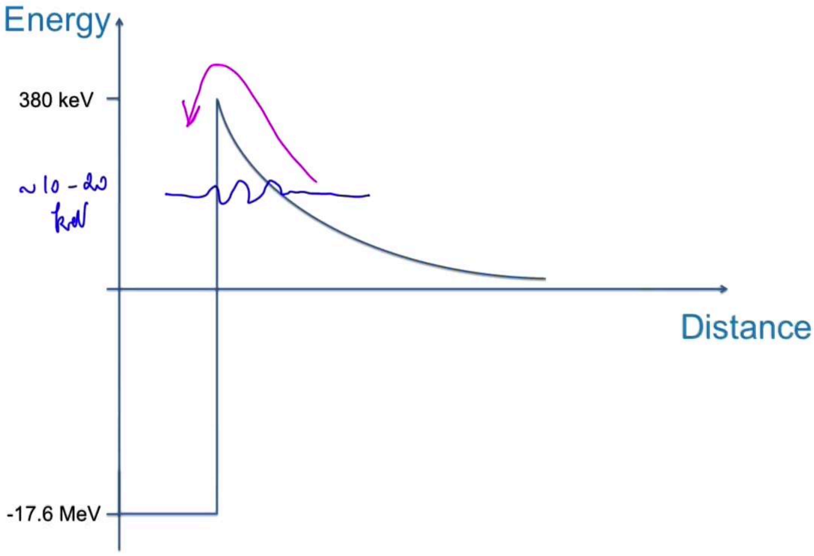
Notes

Summary

7m 52s

Fusion reactions for a reactor on earth





Quantum mechanical effects (tunneling) reduce the thermal energy needed to overcome Coulomb potential barrier

Plasma

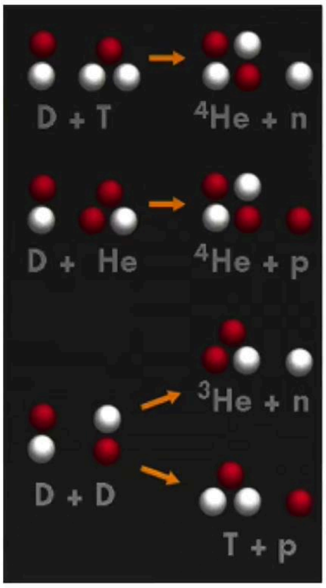
Let's look at this phenomenon slightly- in a slightly more detailed way. We have said that the repulsion comes from the Coulomb potential. So we can calculate the height of the potential barrier that that forms and we can see in this plot that that is pretty high. Almost 400 keV in terms of energy. So if you had to go all the way to the top of the barrier that we would need to have, about 400 keV of energy in the relative motion of this nuclei when they are moving in a random fashion. However, we have an effect that helps us: that is a quantum mechanical tunneling effect, which tells us that we actually don't need to go all the way to the top barrier but we can tunnel through the barrier at much lower levels of energy. So that means we can achieve this passage through the barrier and then fall into the trap corresponding to the nuclear force, which would then lead to the fusion reaction and therefore the energy that's released as a consequence of it. Energies, or temperatures, of the order 10 to 20 kiloelectron volt [keV], which is of course, much easier to achieve than hundreds of kiloelectron volt.

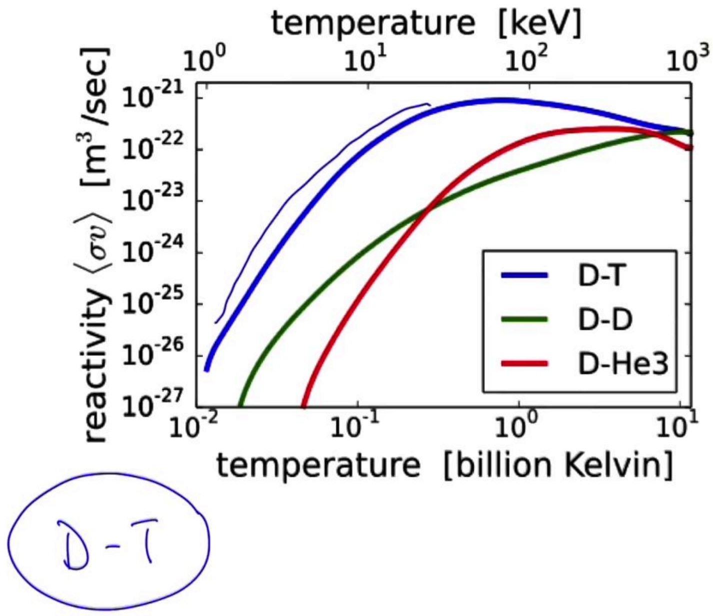
Notes

Summary

8m 07s

Fusion reactions for a reactor on earth





Plasma

Let us look at the fusion reactions we have available on earth to produce energy. We have seen that there are three possibilities: *D-T*, *D-Helium*, and *D-D*. We can quantify the probability for them to happen or the difficulty to achieve them, in a sense, by looking at their cross-section times the velocity average over the distribution function in a nuclei which means their reactivity. And we notice immediately in this plot that the easiest of all to achieve is the one that has the largest cross-section which is the *D-T* reaction. And that's why in the rest of this lecture and in fact, in the rest of the course, we will focus on this reaction only.

Notes

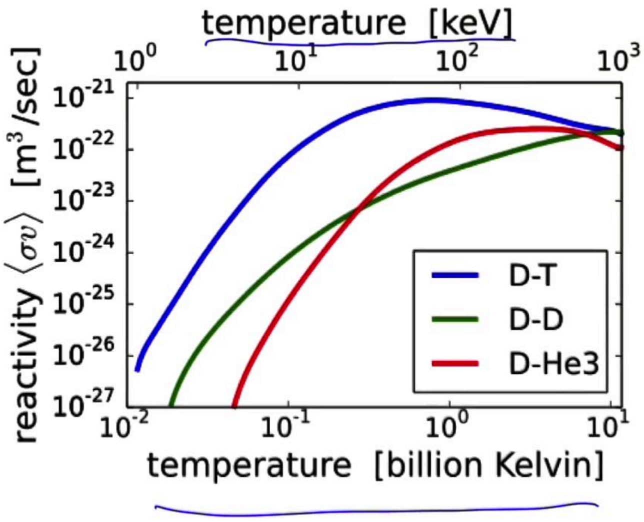
Summary

9m 22s

Fusion reactions - discussion

Why is *plasma physics* an essential element for fusion energy research ?

Even for D-T the fusion cross-sections are significant only at temperatures at which matter can exist only in the form of plasma !



Plasma

One question naturally arises: Why are we coupling plasma physics with fusion? Why is plasma physics an essential element of fusion energy research? Well the answer comes exactly from the same plot we have just seen, because if we look at that scale of temperatures, either in billions of Kelvins or in kiloelectron volt at the top, we notice that we are in a range of values that corresponds to a situation which no ordinary matter can exist in form of either solid or liquid or even gas. Only plasma can exist at these temperatures of the order of 10 to 100 keV or of the order of hundreds of millions of Kelvin. So plasma physics is an essential element of fusion energy research because at the temperatures required for fusion only the plasma state of matter can exist.

Notes

Summary

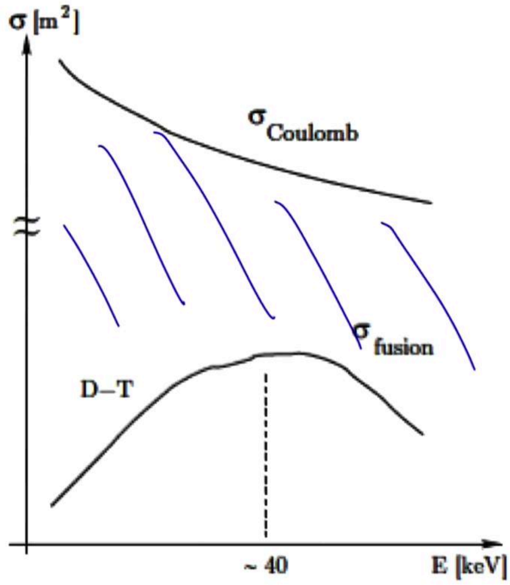
10m 03s

Fusion reactions - discussion

- Why do we speak of *thermo*nuclear fusion ?

Cross-section for fusion reactions is much smaller than cross-section for Coulomb collisions

As Coulomb collisions are much more frequent than fusion reactions, mono-energetic beams are scattered before they can fuse.
We need to deal with a Maxwellian equilibrium generated by Coulomb collisions, like in a gas.



Plasma

The second question I'd like to quickly address is: Why do we speak of *thermo*nuclear fusion? Why the term *thermo*-? Well, the answer is in the plot I show here, which compares the cross-section for the Coulomb interactions, which means the interactions are dictated by the electric force and the cross-section for the fusion reactions in the case of D-T here as a function of energy. And we notice that for all the energies there's a huge difference between the two. The Coulomb interactions have a much higher cross-section than the fusion collisions. So that means the Coulomb collisions are much more frequent than fusion reactions. So if we think of a mono-energetic beam, well that would be scattered in a plasma before the particles can fuse. So in practice, that also means that we need to deal with a Maxwellian distribution which results when- from an equilibrium generated by Coulomb collisions, a little bit like in a normal gas. That's why we speak of thermonuclear fusion.

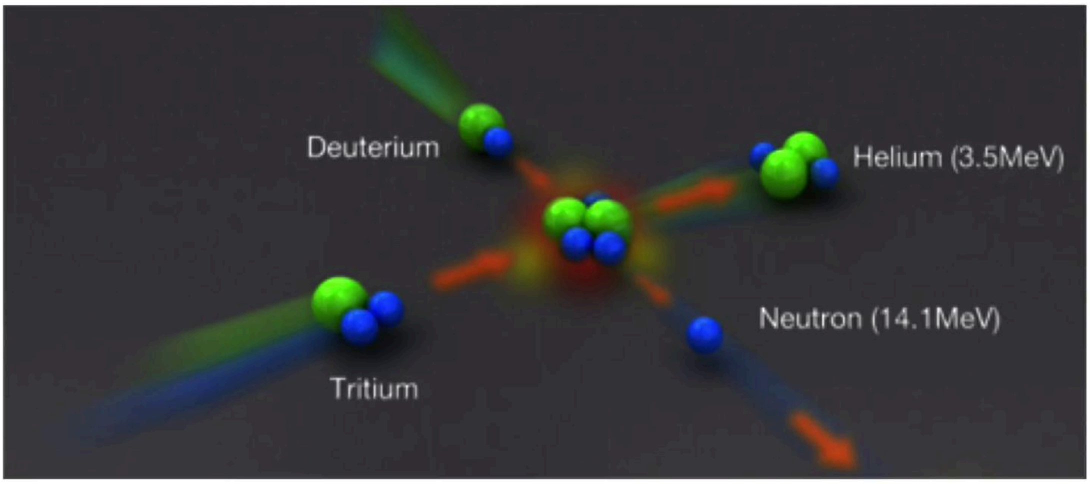
Notes

Summary

10m 57s

The D-T reaction

The D-T reaction has the largest cross-section, hence is chosen for the first generation of reactors



Plasma

So let's go back to our reaction that we have chosen for the first generation of reactors at least that is, the *D-T* reaction. Once more, there's the deuterium and tritium that collide energetically enough to fuse. Helium nucleus comes up for the reaction with three and a half MeV of energy and a neutron also comes out with 14.1 MeV of energy.

Notes

Summary

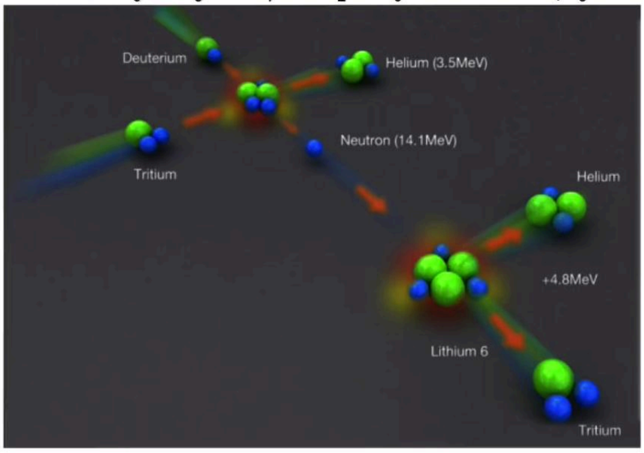
12m 01s

Fusion fuels – Tritium breeding

- Deuterium is ~0.014% of hydrogenic atoms in oceans, i.e. 1.6g/l
- T does not exist in nature, as is radio-active and short-lived (12.5 years), but can be produced from Lithium, which can be mined or found in ocean water (0.15g/m^3)

$n_0^1 + Li_3^6 \rightarrow T_1^3 + He_2^4 + 4.8MeV$ (Li_3^6 is ~7%)

$n_0^1 + Li_3^7 \rightarrow T_1^3 + He_2^4 + n_0^1 - 2.5MeV$ (Li_3^7 is ~93%)



Plasma

So the fusion fuels are therefore deuterium and tritium. Deuterium is about.014% of the hydrogenic atoms everywhere, including in the oceans. That corresponds to about 1.6 grams per liter. So it's relatively easily available. Tritium, on the other hand, does not exist in nature because it's radio-active and short-lived. It's life is about 12-and-a-half years. However, it can be produced from lithium in a process we call *breeding*. Lithium, in turn, can be mined or found in the ocean water in the amount that's about.15 grams per cubic meter. How is tritium produced from lithium? There are two possible reactions. The neutrons that come out from the fusion reaction itself, can react with the lithium that's present around the plasma, that we will actually install around the plasma, in two ways: there's a reaction with lithium-6 on the top or a reaction with lithium-7 here at the bottom. We'll concentrate on the first of the two for the simple reason that despite the fact that the lithium-6 is only about 7% of natural lithium, the cross-section for this reaction, which implies that it's probability, is much larger than the other one.

Notes

Summary

12m 26s

Fusion fuels – Tritium breeding

- Deuterium is ~0.014% of hydrogenic atoms in oceans, i.e. 1.6g/l
- T does not exist in nature, as is radio-active and short-lived (12.5 years), but can be produced from Lithium, which can be mined or found in ocean water (0.15g/m^3)

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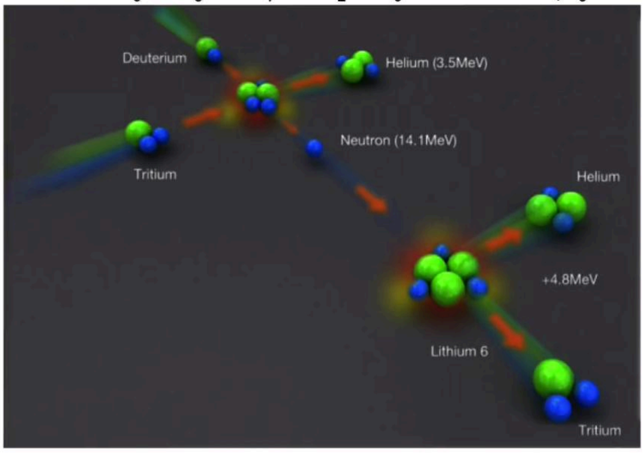

Plasma

In fact, that's why in the picture represented here, we only show that possibility, so it's lithium-6 that would react with a neutron. And what would be the by-product of this reaction? It would be exactly what we want, it would be a tritium, it would be also helium-4 and, in fact, even some energy. So that's how we produce tritium in a plant.

Notes

Summary

13m 51s

Fusion fuels – Tritium breeding

- Deuterium is ~0.014% of hydrogenic atoms in oceans, i.e. 1.6g/l
- T does not exist in nature, as is radio-active and short-lived (12.5 years), but can be produced from Lithium, which can be mined or found in ocean water (0.15g/m^3)

$n_0^1 + Li_3^6 \rightarrow T_1^3 + He_2^4 + 4.8MeV$ (Li_3^6 is ~7%)

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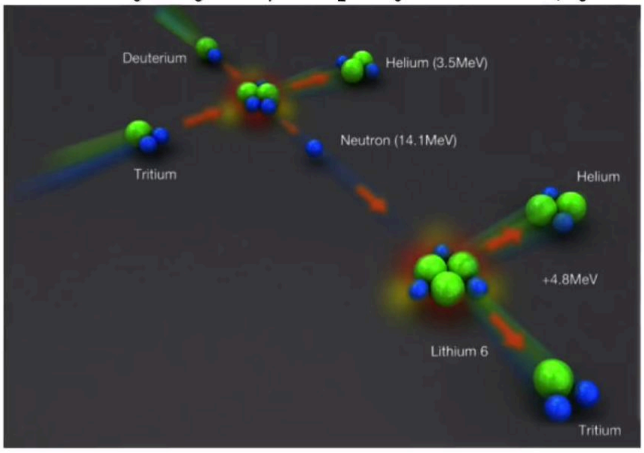
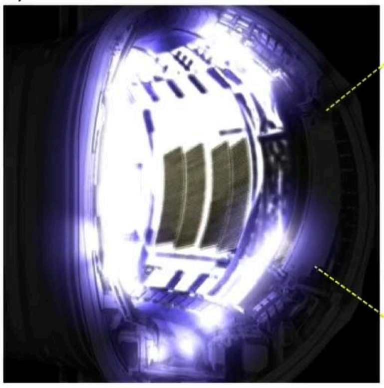
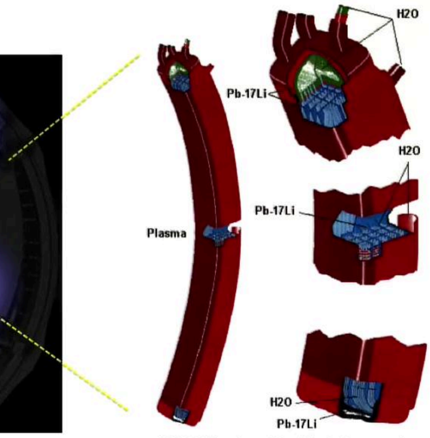






CEA tritium breeding blanket concept

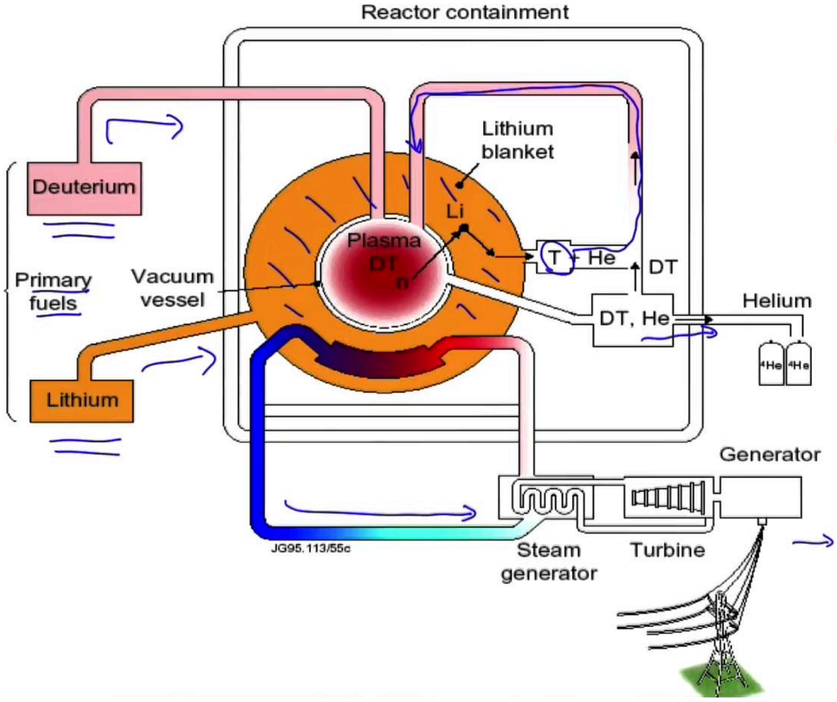
In practice, what we'll do, we will surround the plasma with a 'blanket' as we call it. That is a system that has, essentially, lithium in it, so that this nuclear reaction between the neutrons produced by the nuclear fusion reactions and lithium can occur. Of course, there are different concepts and technological details in different approaches -- we see here a picture from CEA in France -- different concepts for this blanket for breeding tritium, but all of them are based, again, on the presence of lithium.

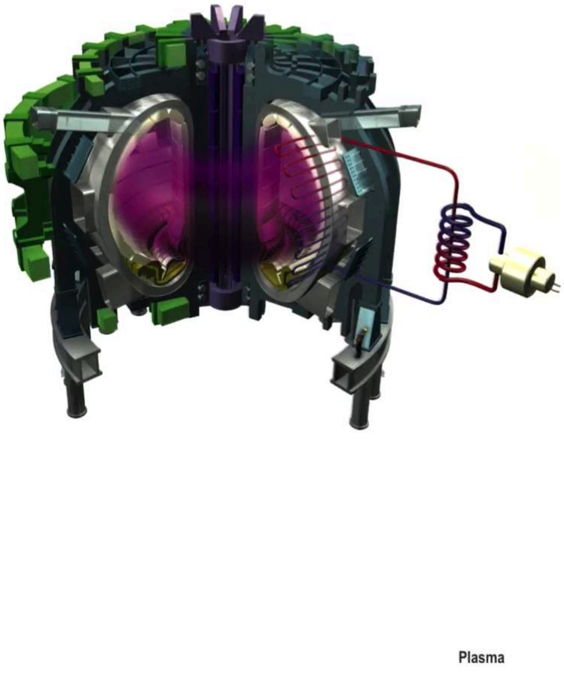
Notes

Summary

14m 18s

Schematic of a fusion reactor





We're now ready to look at the schematic of a fusion reactor, at least as we imagine it today. So from the outside, what I call the *primary fuels*, we would have lithium, that will come, and deuterium, that we injected in the plant. Lithium will go and will stay in the blanket around our plasma. Deuterium will be injected directly in the plasma. In the core of the plant, of course, we have the plasma itself which will be hot enough to produce fusion reactions. And neutrons that are issued by these fusion reactions, will react with the lithium in the blanket and form tritium. This tritium will be purified and injected again into the plant. So no tritium will come in; no tritium will come out of the plant. What will come in again will be deuterium and lithium. What will come out will be some helium, and most importantly, energy. Energy will be collected in the blanket by a fluid that will exchange heat and that fluid will make a conventional turbine work via the usual cycle that we operate in different kinds of power plants. The result will be some electricity we inject in the grid.

Notes

Summary

14m 56s

Advantages of fusion

High energy density

Fuel	Specific Energy (MJ/kg)
Water, 100m high dam	0.001
Coal	30
Oil	50
Fission (U-235)	85'000'000
Fusion (D-T)	**350'000'000**
$E = mc^2$	***90'000'000'000***

Plasma

I'd like to discuss the advantages of fusion now. First of all, there's a fantastically high energy density. And to illustrate that I prepared a table here with different kinds of fuels for different kinds of sources of energy we have available today. And I sort of ranked them in terms of their specific energy. That's the energy content they have in terms of megajoule per kilogram (MJ/kg) so energy per mass. I start with water; I consider a 100 meter high dam just as a reference. The number that water has as energy content is very small. It's.001M J/kg. I'll move on to coal. Coal, of course, needs to be burned so it needs to give rise to *CO2* -- greenhouse gas and so on. It's specific energy is about 30 MJ/kg. Oil, same issue of fossil fuels. 50 M J/kg. Then we have a huge jump, because I'm moving to nuclear reactions. First example is that of fission; I take here Uranium-235 instead of 30, 50 or tens of M J/kg now we have a total game changer. We have 85 millions of M J /kg. In the next step, which is even much higher than fission itself, is fusion. For D-T, in this example, we have 350 millions of M J /kg. That's as close as you can get to just transforming directly all the mass into energy according to the $E=mc^2$ equation, which corresponds to having 90, 9 0 billions of M j/kg. So fusion is as close as we can get to that number. Fantastically high energy density.

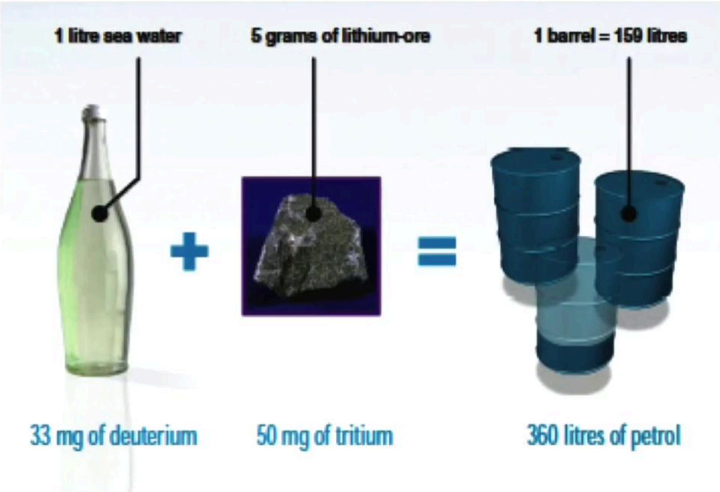
Notes

Summary

16m 20s

Advantages of fusion

High energy density



Fuel	Specific Energy (MJ/kg)
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Coal	30
Oil	50
Fission (U-235)	85'000'000
Fusion (D-T)	**350'000'000**
$E = mc^2$	***90'000'000'000***

Plasma

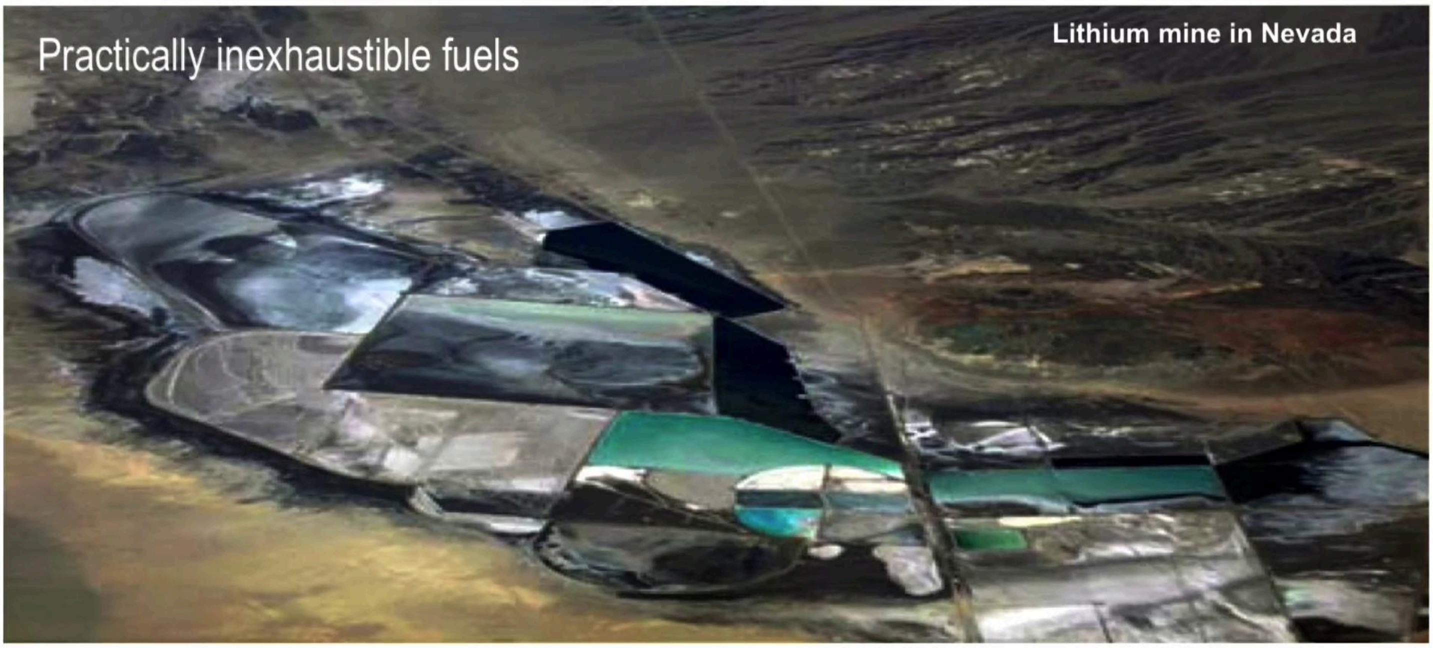
To quantify this in a practical example, as shown in the picture here, I'd like to take one liter of sea water. That corresponds to 33 miligrams of deuterium. Then I take 5 grams of lithium-ore, corresponding to 50 mg of tritium. The energy content in this combination corresponds to the energy content of almost 400 liters of petrol, which is more than two barrels.

Notes

Summary

18m 19s

Advantages of fusion



Plasma

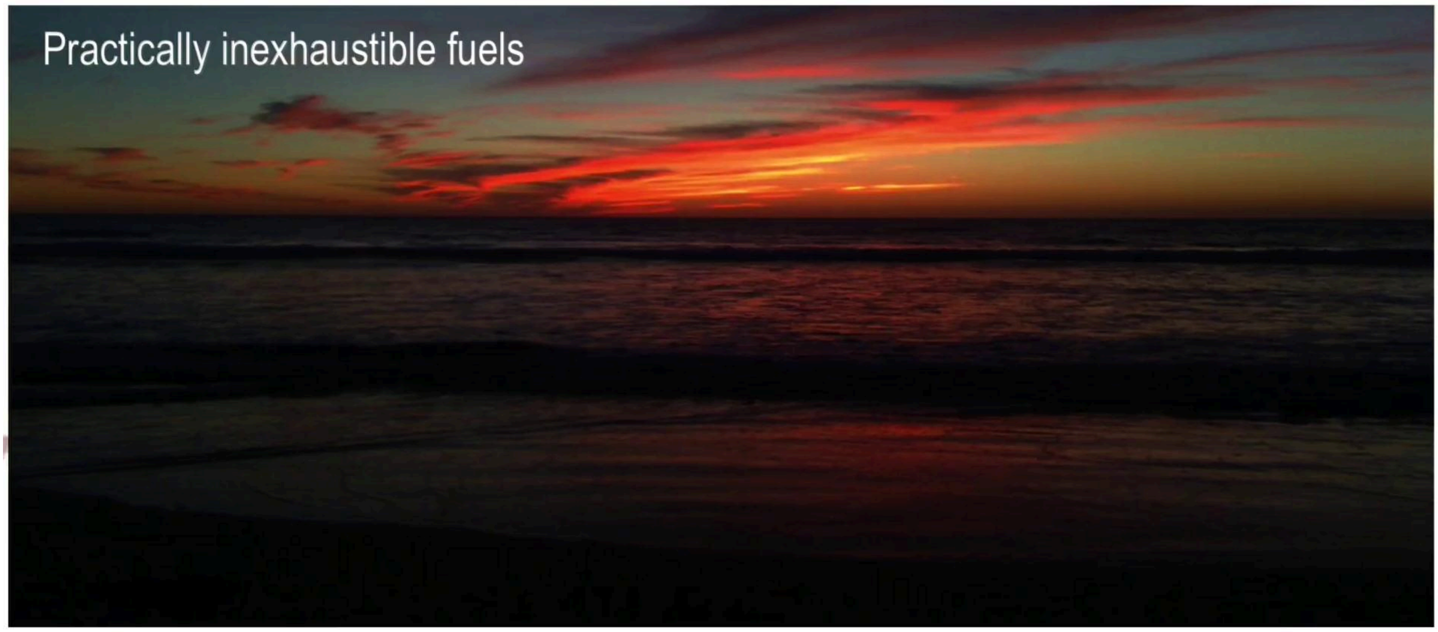
Because of this huge energy density and because of the amount of fuels that we have available on earth, fusion is practically inexhaustible in terms of its fuels.

Notes

Summary

18m 46s

Advantages of fusion



Plasma

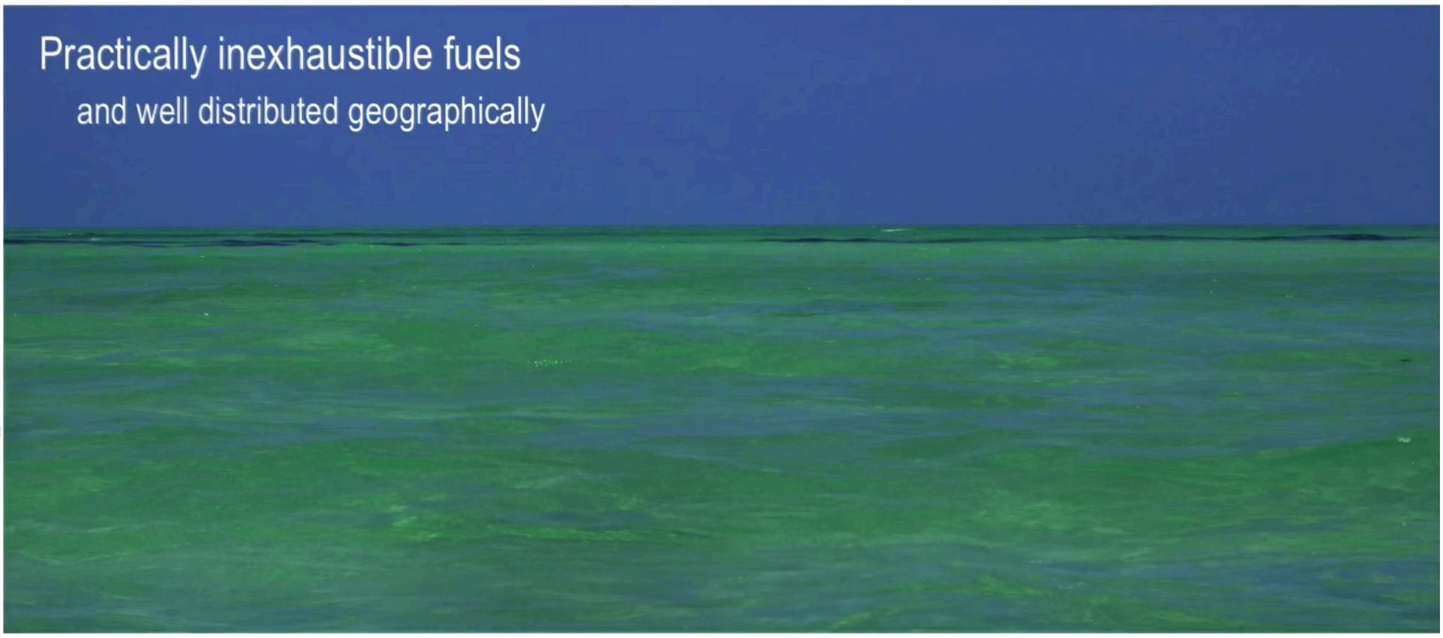
The picture here shows a lithium mine in Nevada so lithium can be mined on the earth crust, but both lithium, in fact, and deuterium can be found in ocean water. Ocean water is everywhere, almost everywhere, and in large amounts.

Notes

Summary

19m 02s

Advantages of fusion



Plasma

Two pictures of different oceans here remind us that ocean water is very well distributed geographically. For example, as opposed to fossil fuels. So not only are the fuels practically inexhaustible, but they are also extremely well distributed geographically.

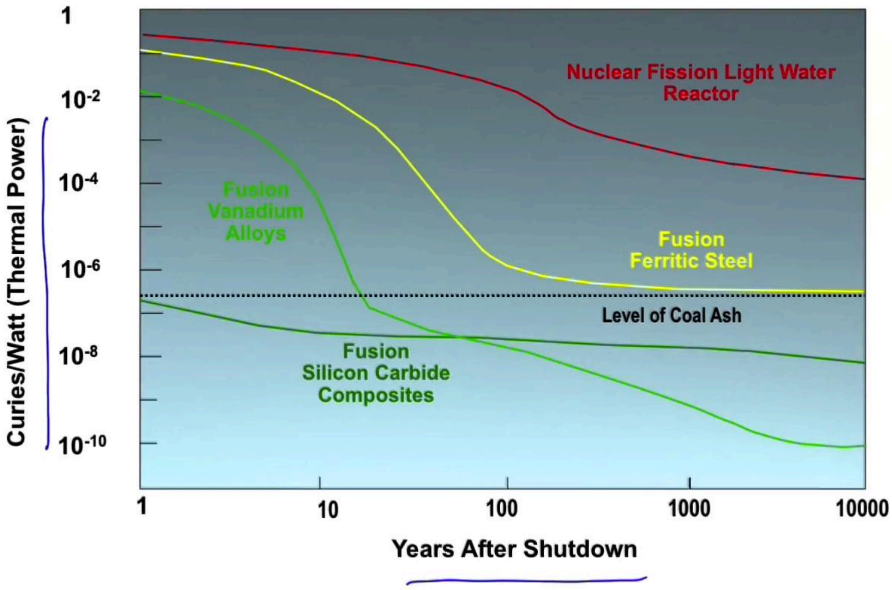
Notes

Summary

19m 16s

Environment

- No greenhouse gas emission
- No long lasting radioactive wastes



Plasma

In terms of the environmental impact, first of all, there's no greenhouse gas emission from fusion. There are no waste products because the by-product of the reaction is simply helium. There is no long-lasting radioactive waste. Even the activation of the reactor itself is a relatively minor problem. This is illustrated in this plot which shows the radioactivity level of the plant after shutdown is a function of the number of years after this shutdown for different cases. We see the red line here is that of a *fission reactor*. It's a light water reactor in this case, which stays very high in this curve all the way to about 10,000 years after it's shut down. Situation of fusion is very different. Even with materials that we have available today for example the *ferritic steel* -- this is the yellow curve here -- we go down relatively fast in this radioactivity level. We reach the level of the coal ashes, so the level at which we really don't worry any more about the radioactivity of the plant after tens of years as opposed to tens thousands of years. If you go for more advanced materials such as vanadium alloys or silicon carbide composites for fusion, that level is reached, really, after only very few years or even reached from the very beginning in the case of silicon carbide composite.

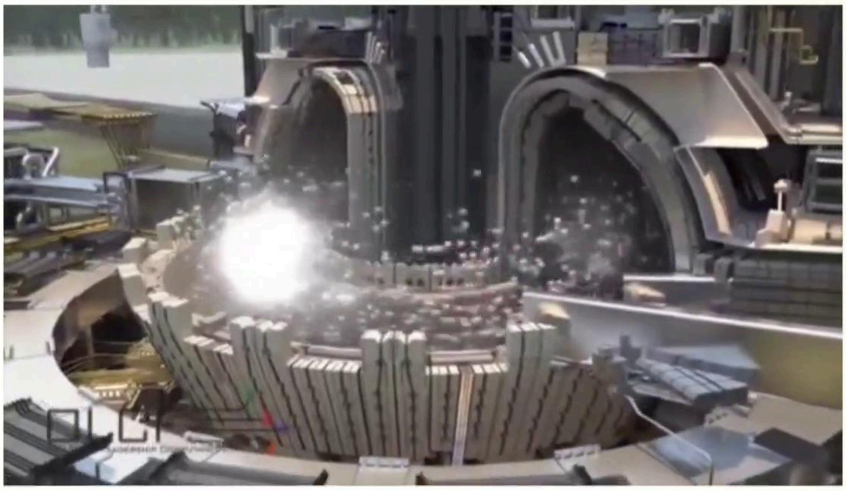
Notes

Summary

19m 33s

Advantages of fusion

- High energy density
- Practically inexhaustible fuel
- Environment
  - No greenhouse gas emission
  - No long lasting radioactive wastes
- Safety
  - No link with nuclear proliferation
  - No risk of loss of control of reactions
  - Minimal quantity (~1g) of fuel in reactor



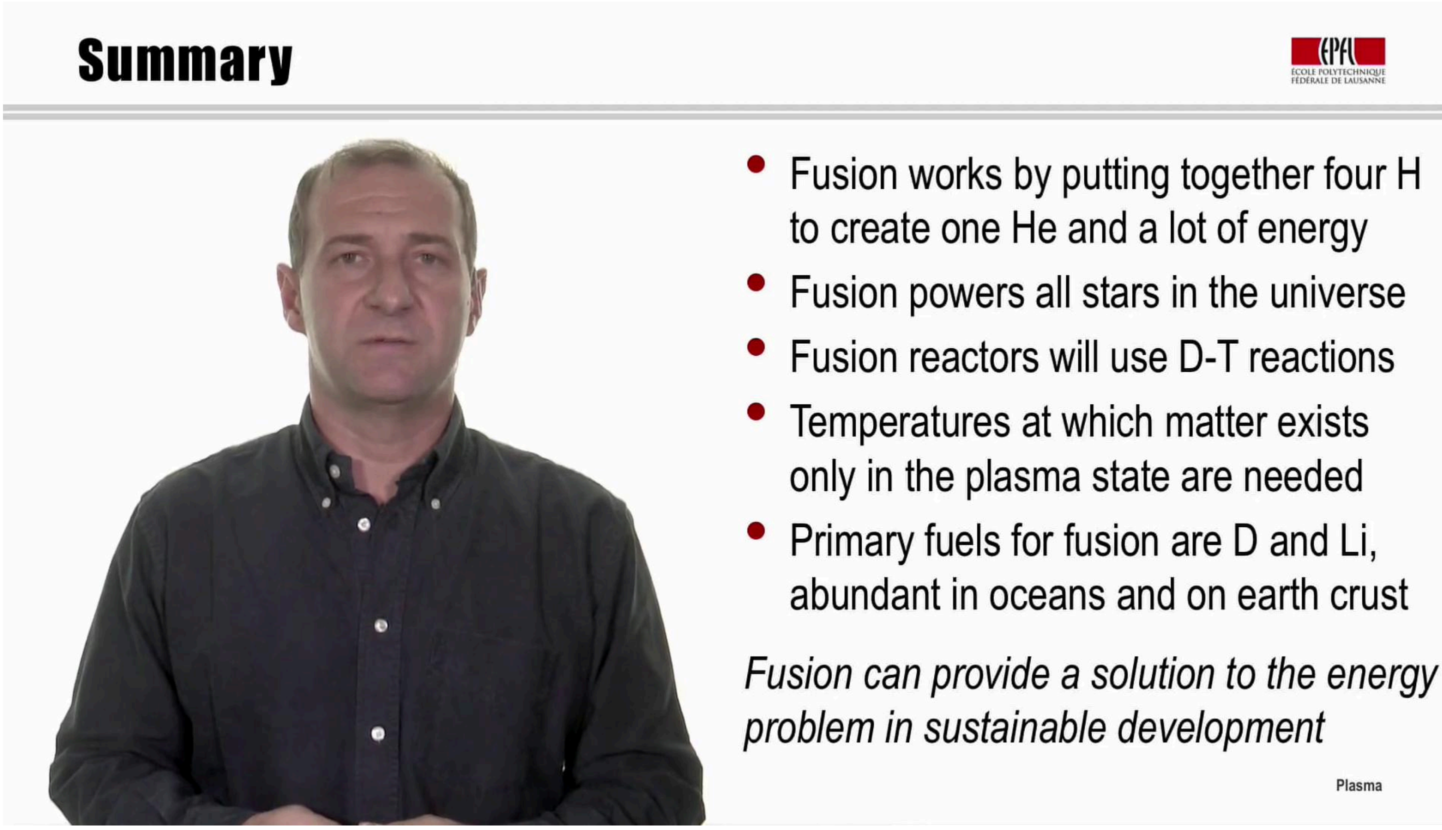
Plasma

So we have seen that fusion has a huge energy density, that its fuels are practically inexhaustible, that fusion has no bad effect on the environment. What about its safety? Well thats also a very, very important advantage of fusion. First of all, there is no link between fusion and nuclear proliferation. Second of all, the concept of fusion reaction is not based on a chain reaction so there is no risk of loss of control of the reactions in the sense there is in a fission reactor. And last but not least, there's always a very, very small amount of fuel in a reactor at any given time. We're talking about grams of fuel present even in a gigawatt level reactor as illustrated pictorially in the movie that you're watching on the slide and even in the case of a major accident, the release of the fuel would be in such minute amount that there would be no risk for the population, even just around the reactor site.

Notes

Summary

21m 10s



In summary, we have seen that fusion works by putting together four hydrogen nuclei, to create one helium and a lot of energy. Fusion actually works already in nature because it powers all the stars in the universe, including our sun. The fusion reactors on earth will use the D-T reactions. Even for the D-T reactions, we need temperatures at which matter exists only in the plasma state. The primary fuels for fusion are deuterium and lithium which are both abundant in the oceans and the earth crust. So I believe fusion can provide a solution to the energy problem that's compatible in sustainable development.

Notes

Summary

22m 19s