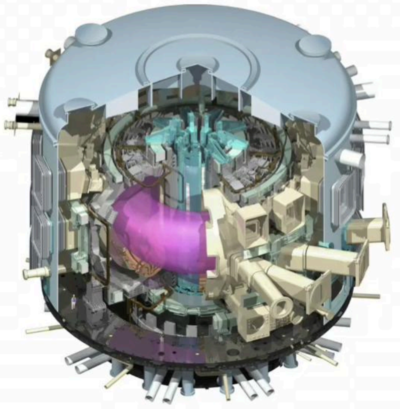
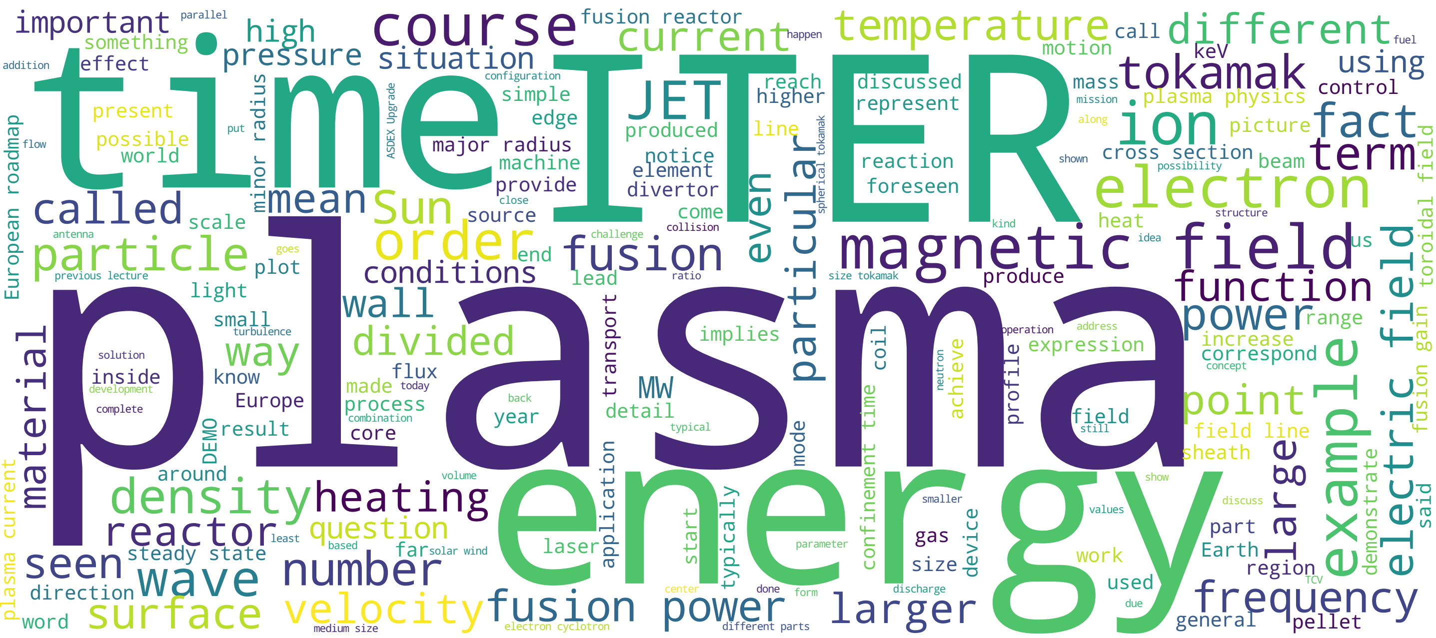


From present day devices to ITER and DEMO

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 7j

Ambrogio Fasoli



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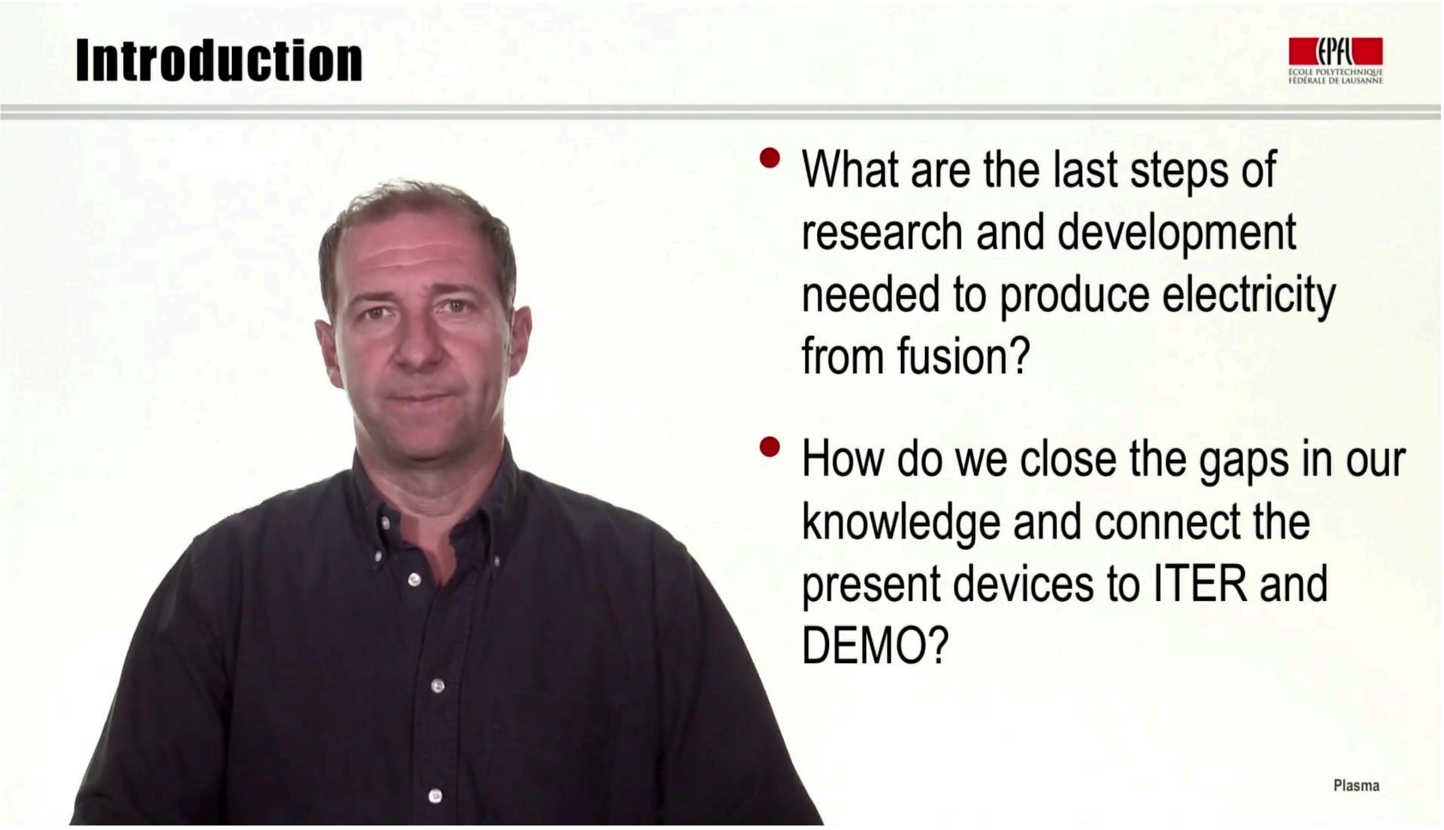


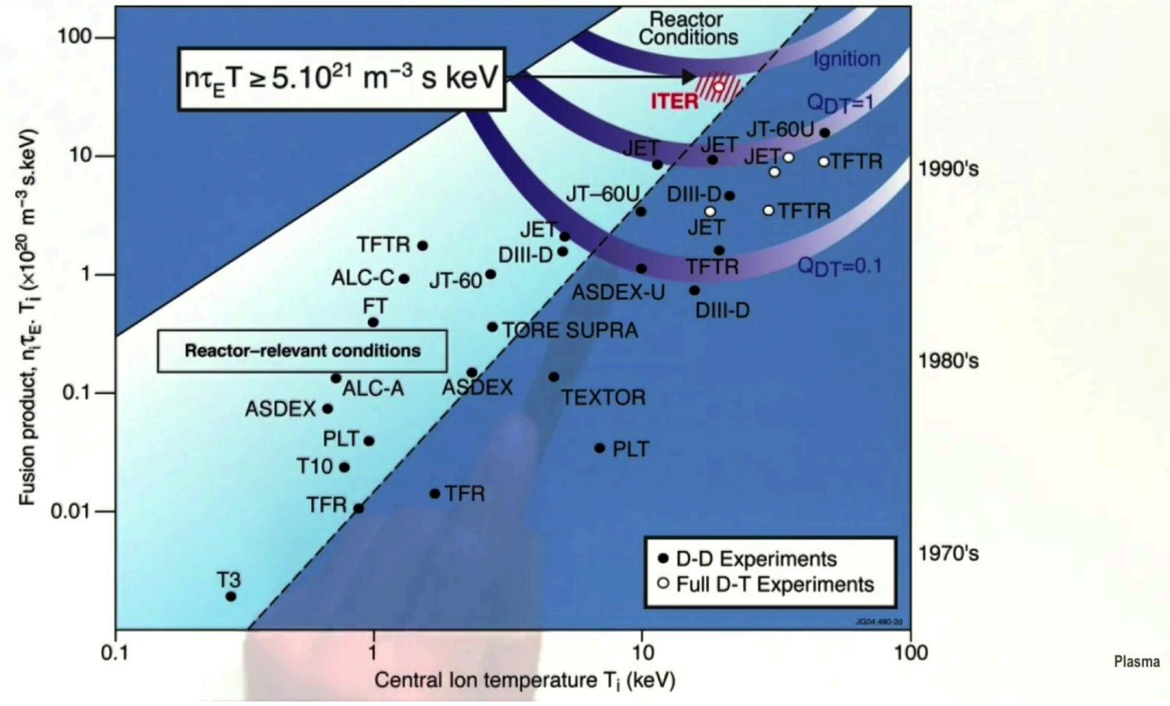
Welcome to the course on Plasma Physics and Applications. Today, in our last lecture, we will complete the discussion of thermonuclear fusion. We will try to address the questions of what are the last steps of research and development that are needed to produce electricity from fusion? And, how do we close the gaps in our knowledge and connect what we do today on the present experiments to ITER and DEMO? I remind you that ITER will be the machine that we'll demonstrate the scientific and technological feasibility of fusion on Earth, while DEMO will be the ultimate step, that is, the step that will demonstrate that fusion power can be deployed commercially.

Notes

Summary

0m 04s

Progress in magnetic confinement fusion



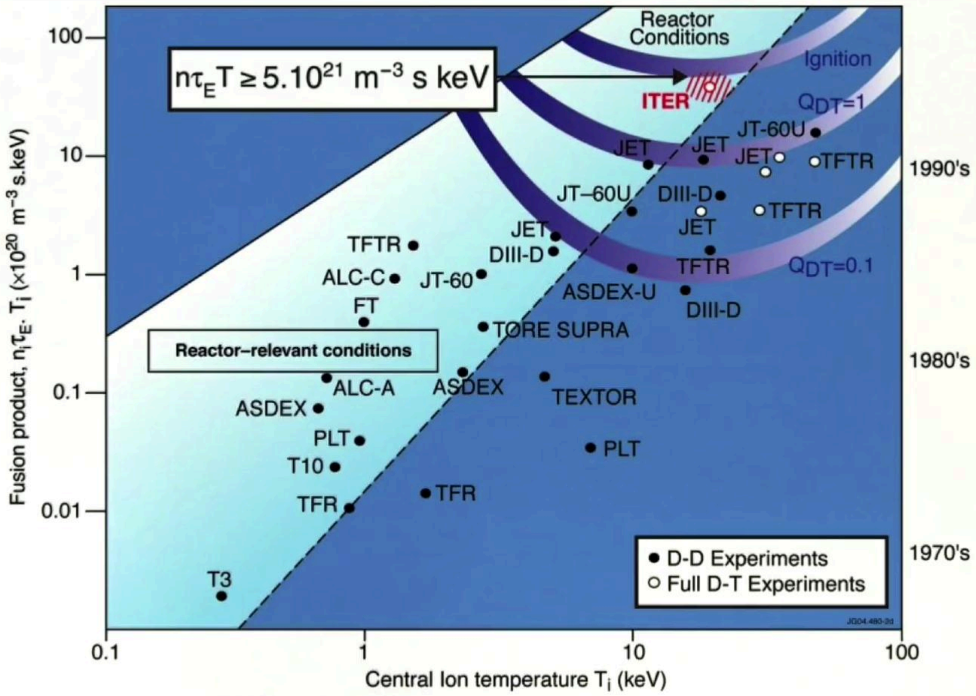
To begin our discussion, I'd like us to remind ourselves of the progress in magnetic confinement fusion represented in this slide in terms of the so-called fusion triple product that is the product of the density of the fuel, the plasma that is the ions, the confinement time for the energy, and the temperature of the ions. This triple product is represented as a function of the central ion temperature in KeV. The different points correspond to different experiments around the world, in fact by far, not all of the experiments are represented in this chart. Nevertheless, we get the feeling that from the early '70s to the '80s and '90s we have made terrific progress towards the reactor condition that we need to achieve for the plasma to actually produce energy. We notice that the white points here correspond to the actual full deuterium-tritium experiments performed at TFTR in Princeton, US, and at JET in England. These points, in fact, don't correspond necessarily to the best triple product that we can achieve. I think the record today still remains with the JT-60, a great machine in Japan.

Notes

Summary

0m 43s

Progress in magnetic confinement fusion



We're still a little bit far from what we need to achieve, that is, a fusion gain of about 10 in ITER, and a step beyond that would be the demonstration for an actual reactor to work which would require a fusion gain of the order of, say, 30 to 40. Not necessarily to ignition, as we have said in previous lectures.

Notes

Summary

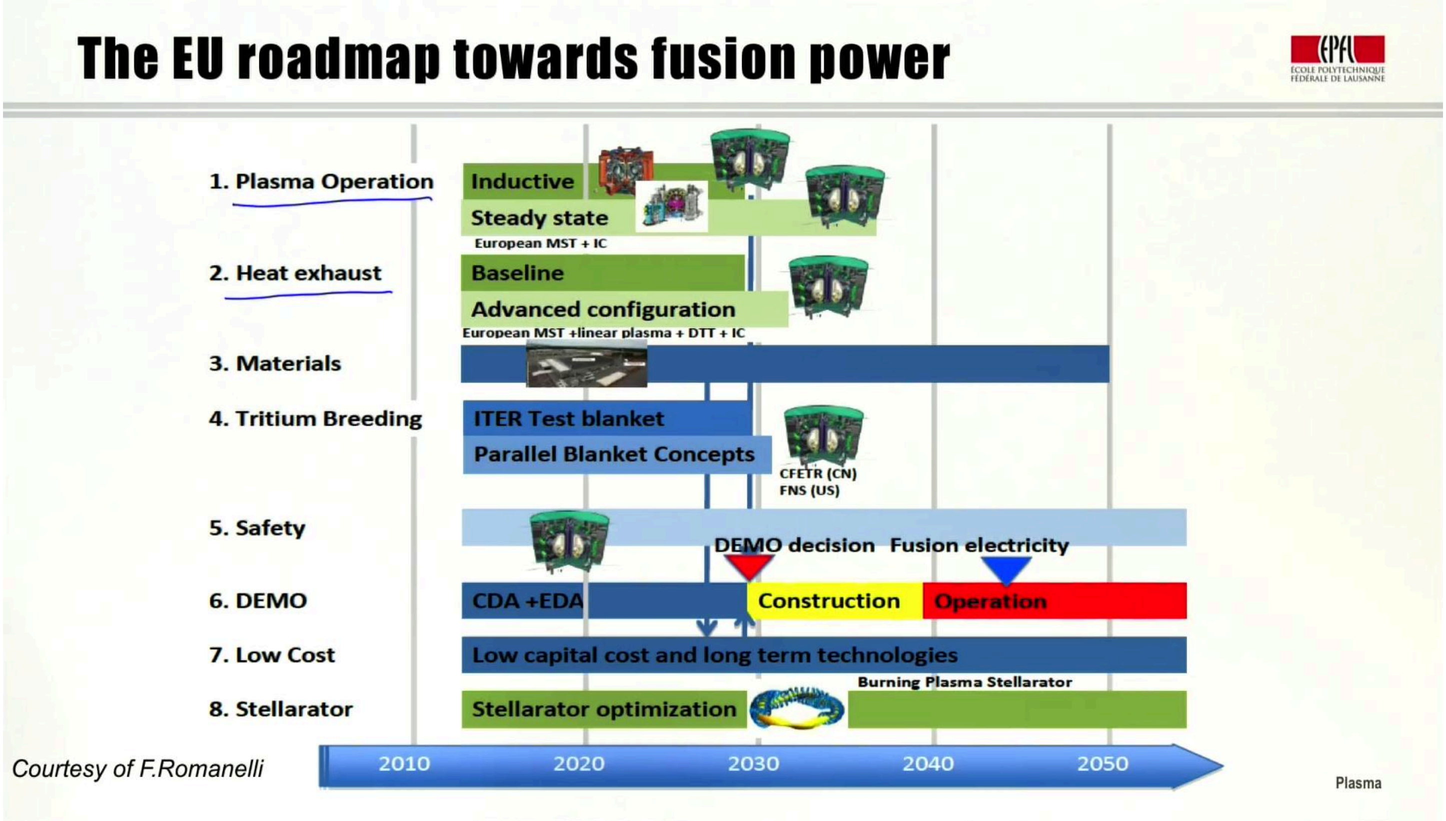
2m 05s

Different parts of the world, different countries, have defined or are defining their strategies to get the fusion power. The different approaches are often complementary, but also reflect the degree of urgency that is perceived in different parts of the world for a new energy source that is compatible with sustainable development. Being in Europe myself, and the whole staff of this course, we will base the lecture on the roadmap that we have developed in Europe which I think is a good example of a combination of pragmatism and ambition. The European roadmap aims at producing fusion electricity by 2050. This requires the construction of DEMO around 2030. It also requires an early involvement in industry and of course, international collaboration beyond the borders of Europe.

Notes

Summary

2m 29s

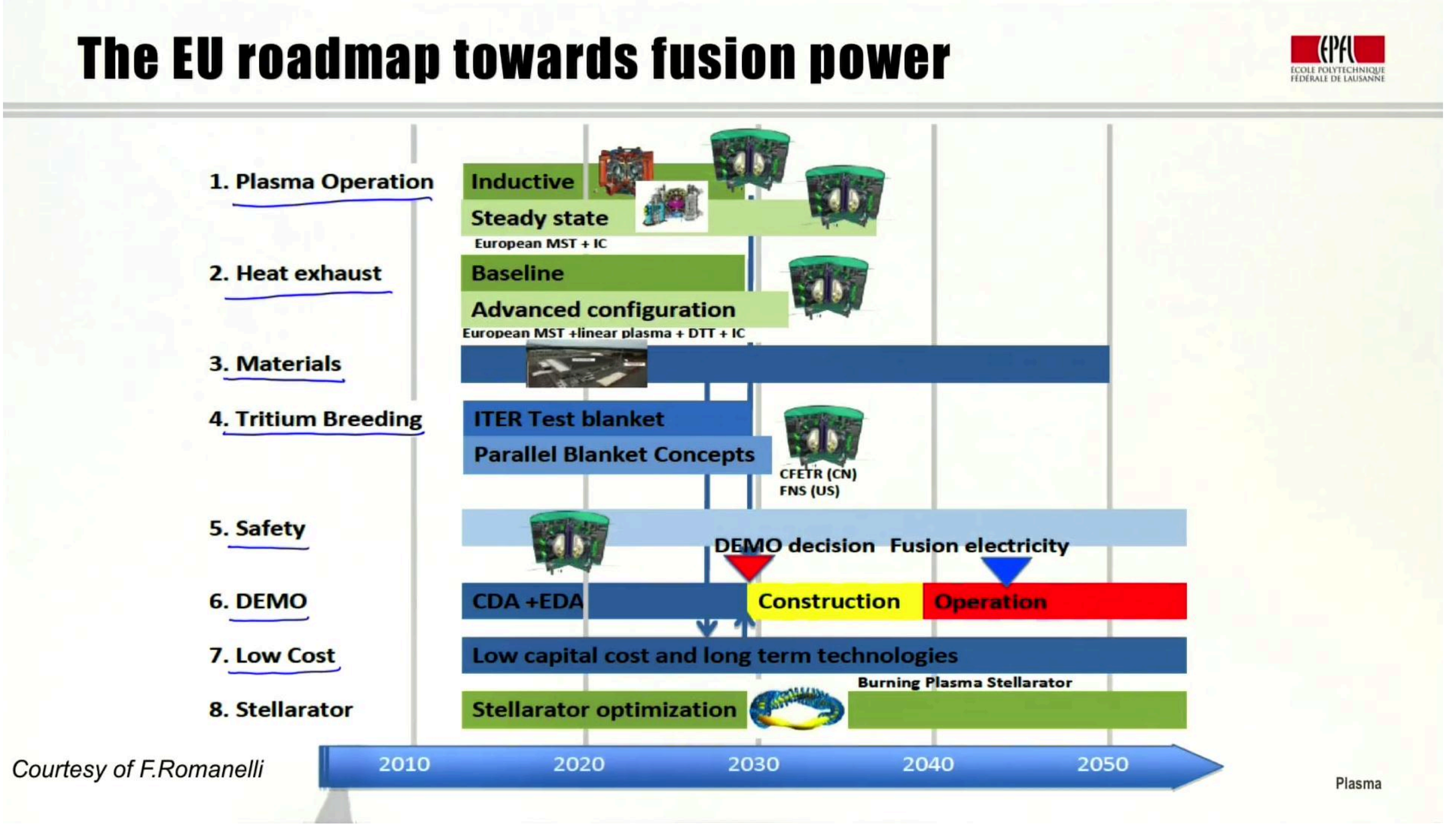


I'd like to say a few words about the main missions into which the European roadmap to fusion power is structured, without the pretension of being exhaustive in this description. There are several missions that have to do with fusion technology, and other missions that have to do with, say, more plasma physics related problems. Let's go through the missions. The first mission is to optimize the operation of the plasma. We can have two approaches, the inductive operation of the tokamak, in which the current is driven primarily by the transformer action, and the possible steady-state regime of operation in which current may be driven primarily not by the ohmic transformer, but by external sources of momentum and by the intrinsic source of current in the plasma due to its own profiles. We need to understand how we can optimize these scenarios in order to get to the conditions for a reactor. We also need to address the question of the heat exhaust, as we have discussed in previous lectures. Both in what we call the baseline configuration, that is what we have in our hands today, and in configurations that are more advanced with possible innovative solutions that we are exploring in parallel with that baseline.

Notes

Summary

3m 22s

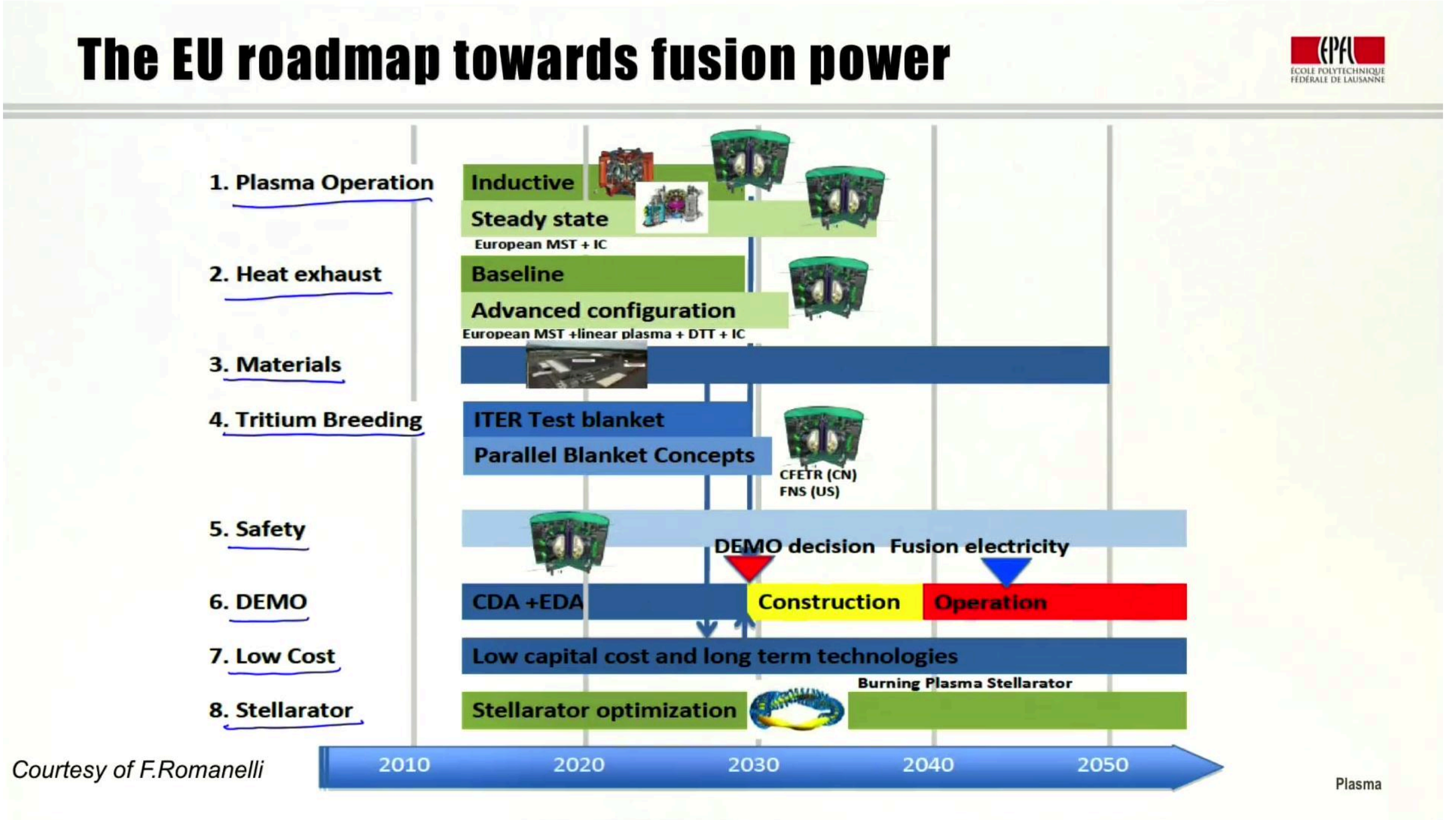


We need to address the question of materials, how we'll cope with a very large neutron irradiation in particular from the tokamak plasma. We need to worry about how, in practice, we can breed tritium. We have discussed the principles behind the idea of breeding tritium in a blanket, but we need to test different concepts for the blanket that will be tested in ITER, but it also will be tested in parallel. An important element of fusion is, of course, the safety of it. The fusion technology can be completely safe, but we need to really demonstrate all the details of this particular feature. We need to get to DEMO. As I said before, in the European view, we need to get to DEMO construction around 2030 in order for DEMO to operate and tell us what the conditions are in which we can deploy fusion power commercially, so we need to concentrate already now on trying to identify what the best concept for DEMO can be. Another point in the European roadmap that is highlighted as really a mission, is to keep the cost of electricity from fusion relatively low. The idea here is that if we go on a path that leads us to gigantic experiments and unsustainable costs for fusion reactors, that path would not lead to the real deployment of fusion as a commercial energy source, so we need to keep that in mind.

Notes

Summary

4m 54s

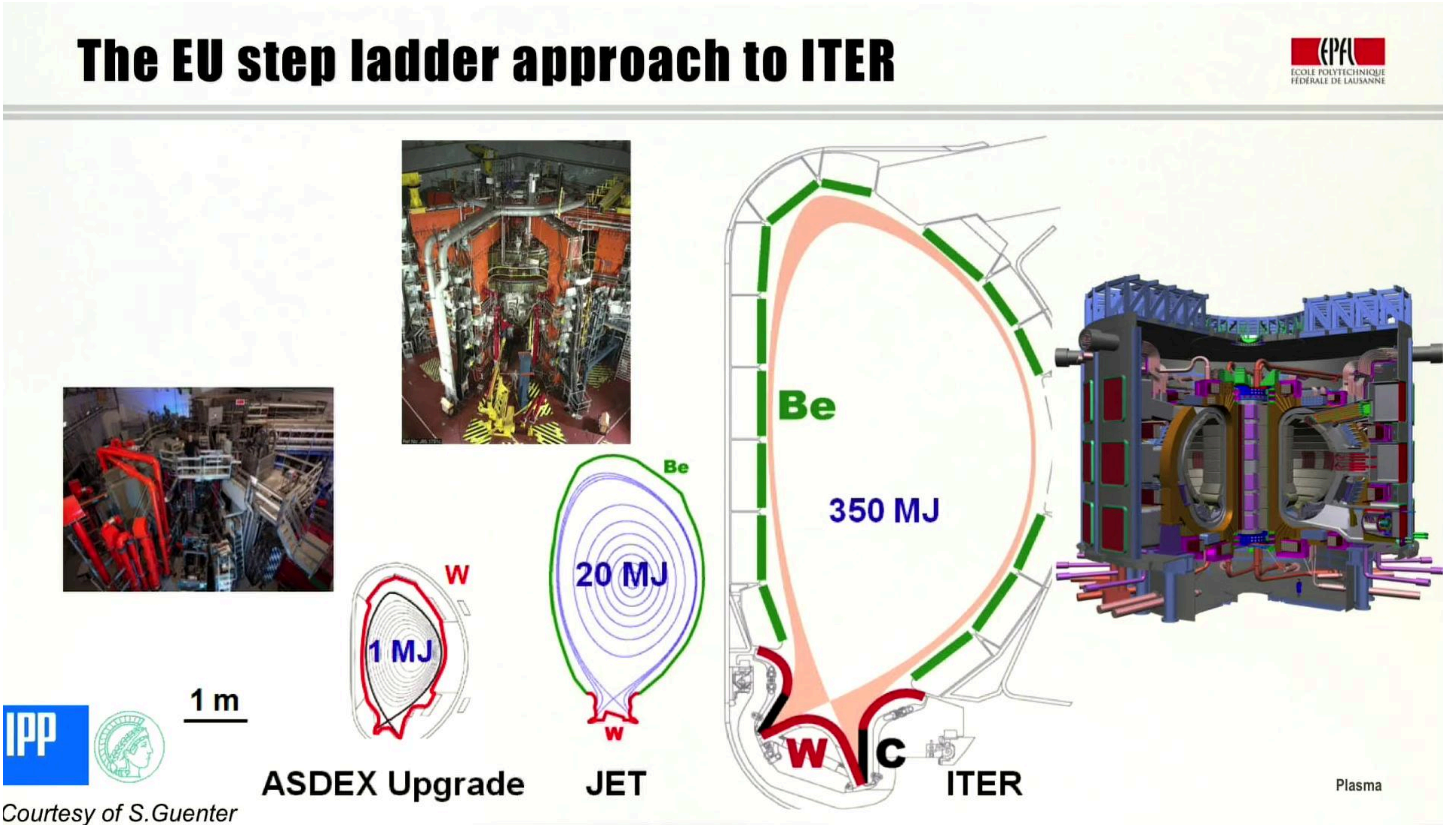


Finally, last but not least, we have the line of the stellarator. This is not the main line in the roadmap, which is based primarily on tokamaks, but it's a line that can provide some sort of insurance policy against possible problems from the tokamak line. Stellarator machines may be a generation behind in terms of readiness for the achievement of the conditions for fusion, but they have, as discussed in previous lectures, quite interesting potential advantages over tokamaks. In fact the largest stellarator ever built will become operational this very year in Germany.

Notes

Summary

6m 42s

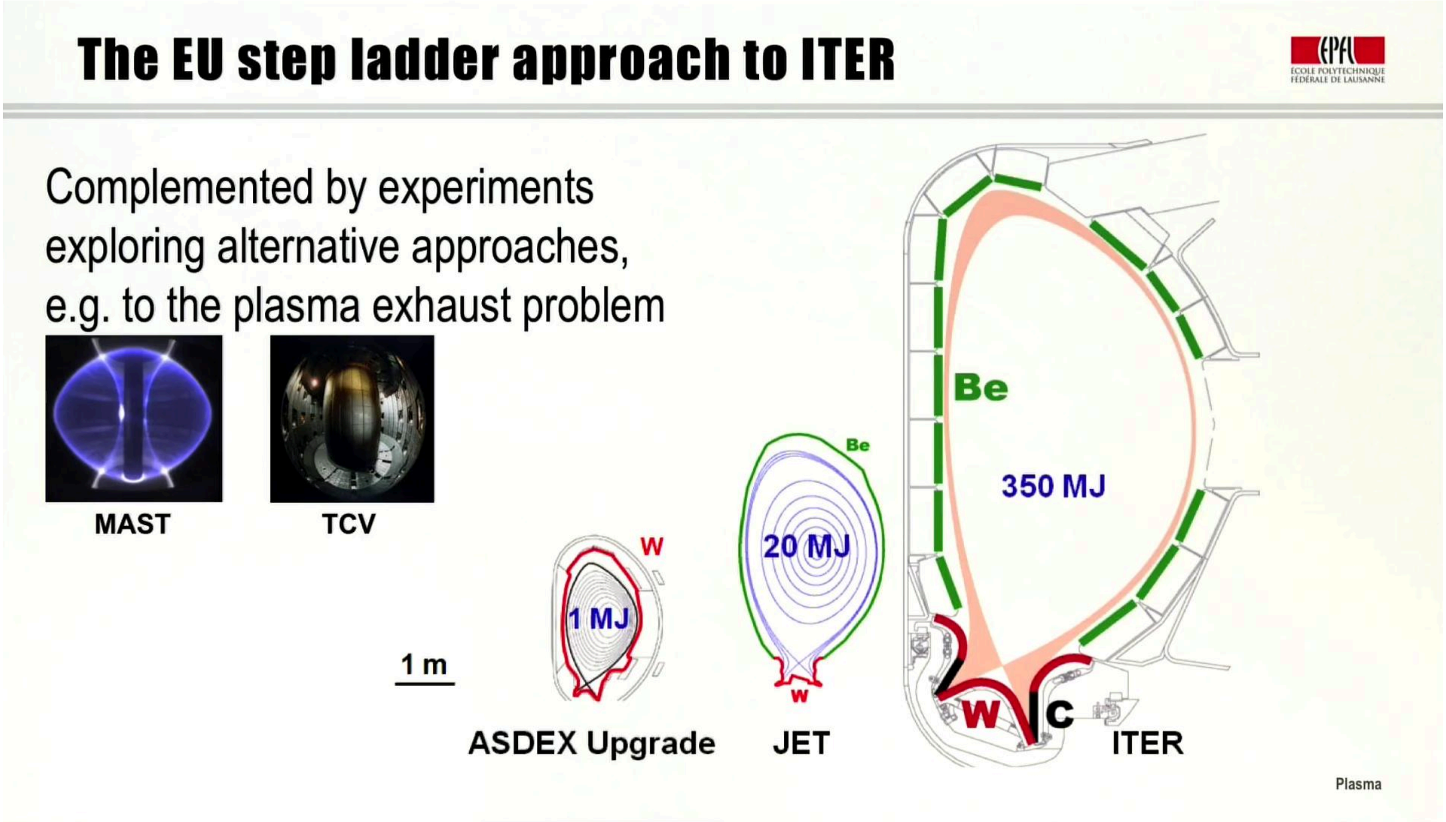


That's Wendelstein 7-x So how do we connect the different devices and their findings on the way to ITER? One way to look at that is a so-called step ladder approach that we have taken in Europe. I represent here the three machines that are of similar shape: - ASDEX Upgrade in Germany, - the JET European device in England, and - ITER. As you can notice, the difference between the machines is really primarily the size, so extrapolations from ASDEX to JET are relatively easy, as it should be relatively easy to extrapolate from JET to ITER, because a number of conditions are kept similar. Particularly we notice that ASDEX Upgrade, which we will discuss a little bit more in detail, as we will for JET, has a full metal wall now, JET has a combination of tungsten and beryllium, as is foreseen for ITER, so there will also be the possibility of investigating the problem of having some kind of materials facing the plasma that will be the same as in ITER. The sizes are more or less in scale here. You also notice that there is a number in megajoules, represented here, that's the energy content of the plasma going from 1 MJ for ASDEX to 20 MJ for JET and to 350 MJ for ITER.

Notes

Summary

7m 26s

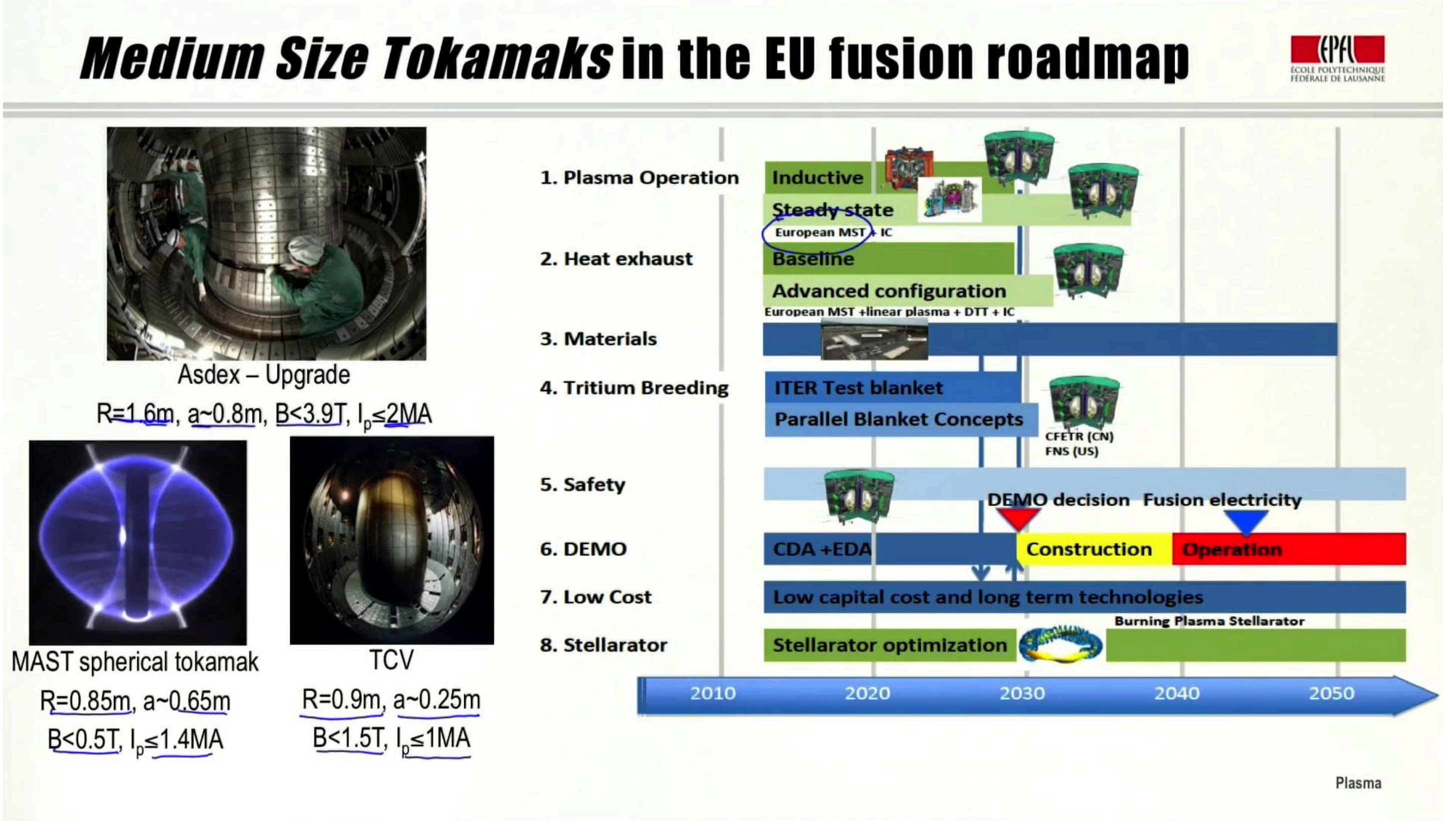


In addition to really having this stepladder that provides similar devices but just very different sizes, we also in Europe are contemplating using other experiments that explore approaches that are alternative to these machines belonging to the stepladder approach, if you like. For examples, alternatives in a sense that we can explore innovative ways of addressing the plasma exhaust problem, and these devices that are at the moment present in the European program are the MAST device, which is a spherical tokamak in Culham, UK, and the TCV device, which is a tokamak of variable shapes which is in Lausanne, Switzerland. It's also important to have different kinds of devices so that validation of numerical models and codes can be done on a variety of scales and conditions.

Notes

Summary

9m 08s

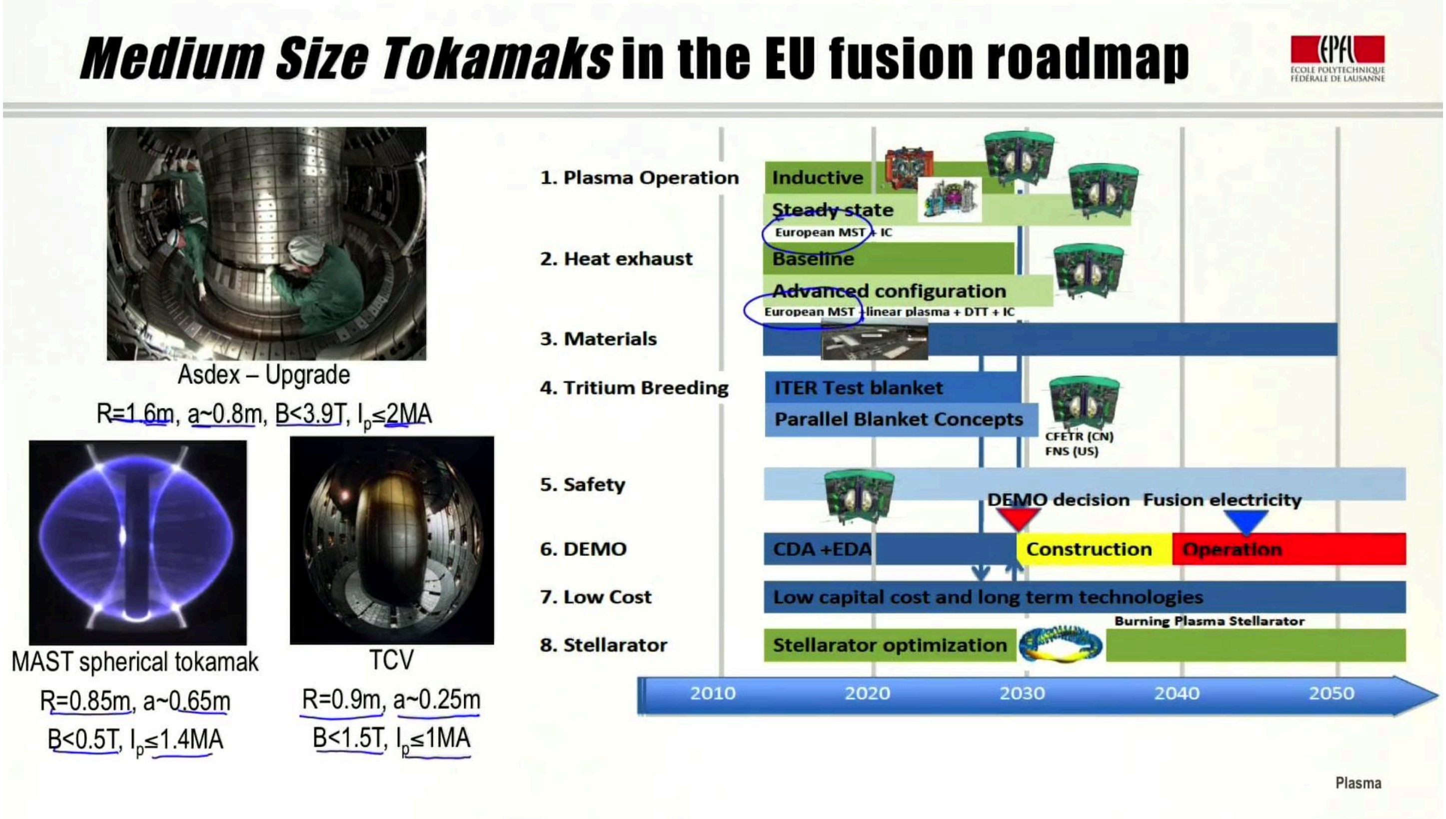


The combination of these smaller tokamaks, smaller than JET, that is, is referred to in Europe as the *Medium Size Tokamaks* and that's an important part of our roadmap. Again, these medium size tokamaks at present are three: ASDEX Upgrade in Germany, which has a major radius of about 1.6 meters, a minor radius up to 80 centimeters, slightly less than 4 T for magnetic field, and up to 2 MA of plasma current. The MAST spherical tokamak in UK is significantly smaller. It's 85 cm of major radius, 65 cm of minor radius, you immediately notice how close the two values are, and that's why it's referred to as spherical tokamak. For the moment, magnetic field has been limited to about 0.5 T, but as I'll say in a moment, there'll be significant upgrades to that and the current is up to almost 1.5 MA. In the Tokamak TCV, we have a similar size to MAST in terms of major radius but a conventional aspect ratio, which implies a much smaller minor radius of about 25 cm with a very elongated cross-section. The field is also up to about 1.4-1.5 T and about 1 MA of maximum plasma current. These medium size tokamaks in Europe are foreseen, as we see on the roadmap, to provide inputs for the physics and the technology even on the steady state approach to plasma operation.

Notes

Summary

10m 12s

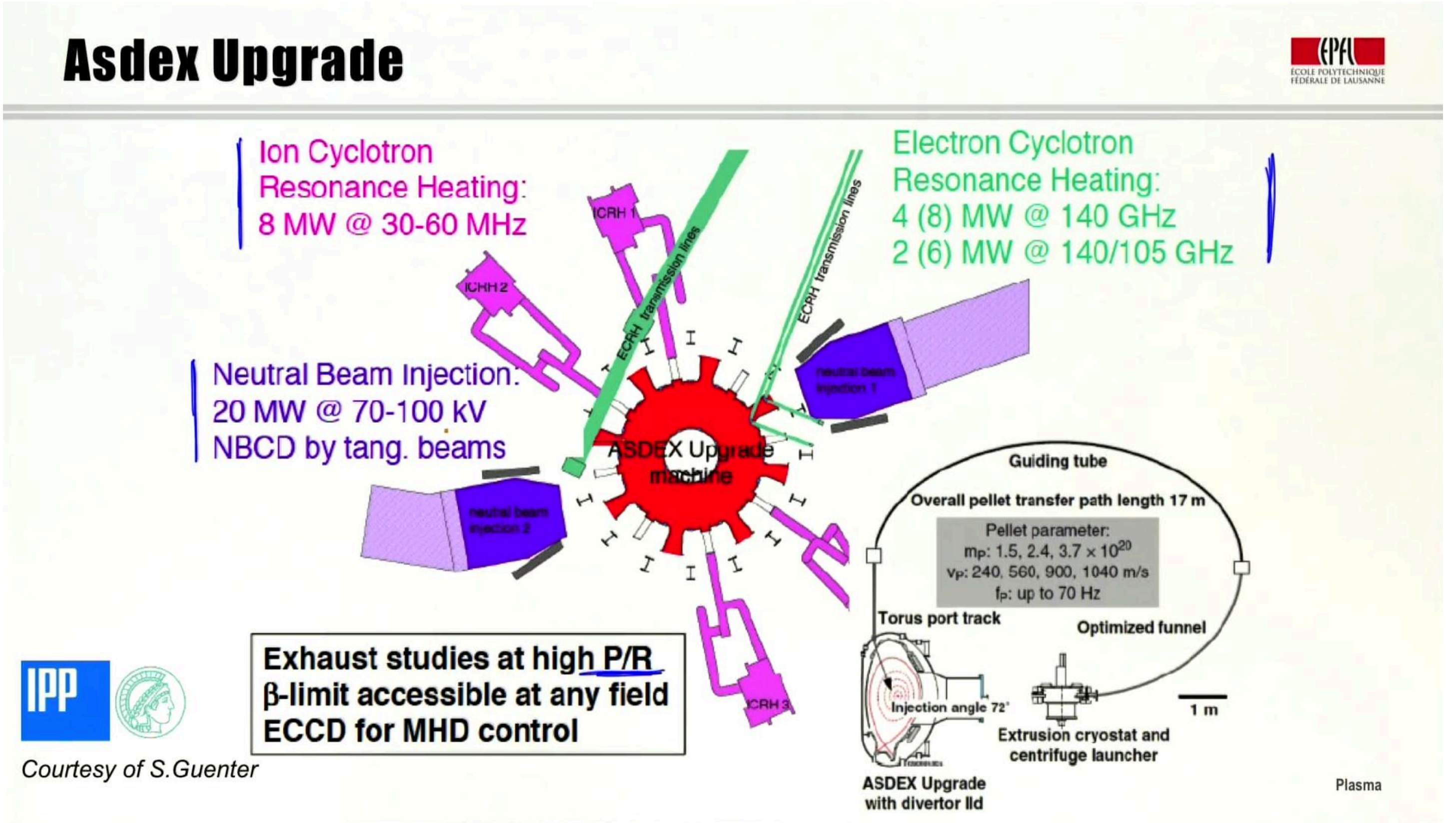


They also are very important in exploring the question of the heat exhaust, in particular by pushing advanced configurations that are now impossible on JET.

Notes

Summary

12m 08s

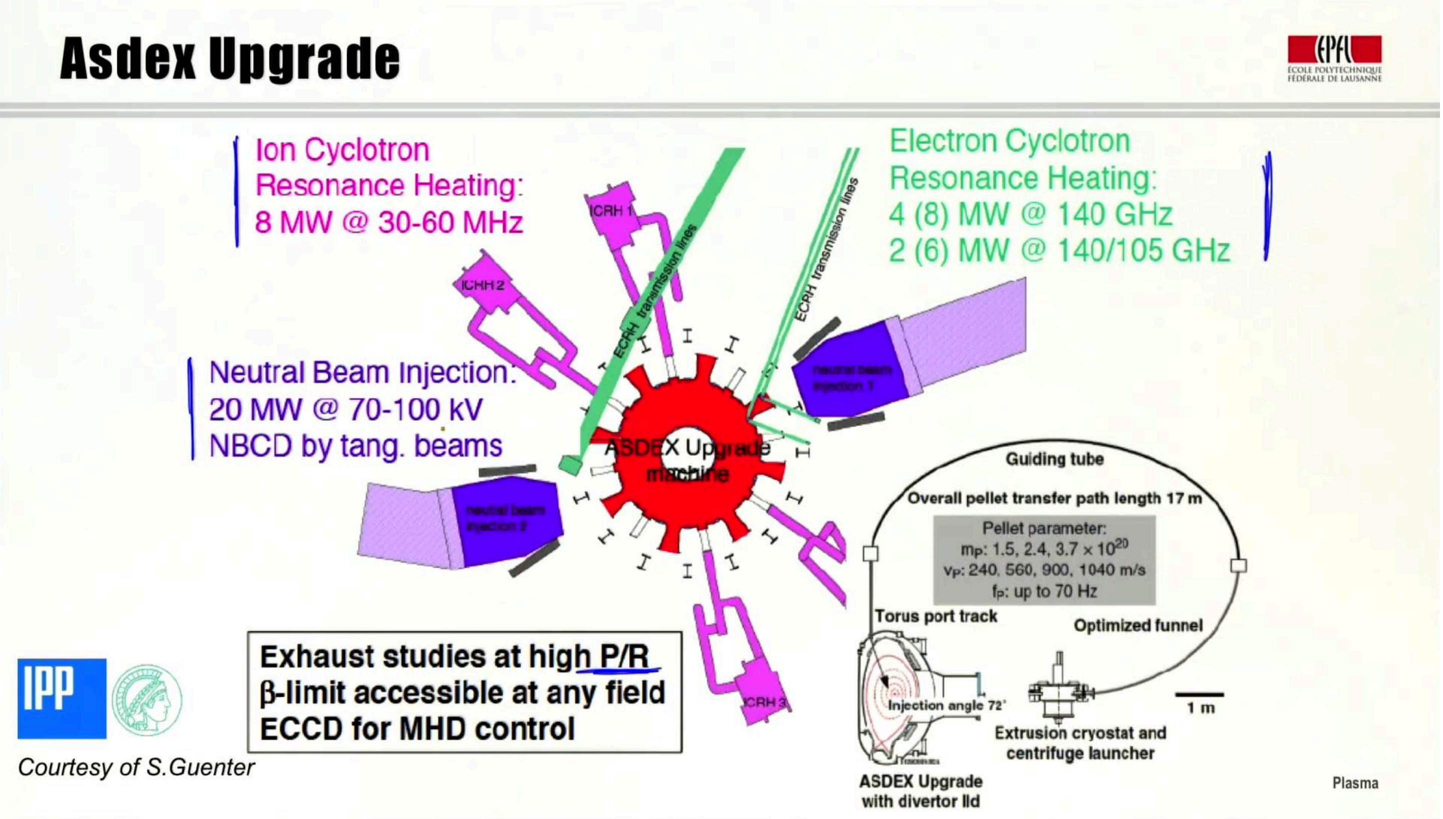


I'd like to say a few words about the individual devices. First, the ASDEX Upgrade, which is the largest of the three, and it's also the one that has the most complete set of heating systems. It has the Ion Cyclotron Resonance Heating up to 8 MW in a range of 30 to 60 MHz, which is the same range as in JET and ITER. It has the Electron Cyclotron Resonance Heating system up to 6 MW, 140 GHz of frequency, and a Neutron Beam injection, 20 MW at energies up to 100 KeV, with the possibility of injecting beams tangentially, that is, to also drive non-inductive current by beams. Among the interesting ancillaries to ASDEX in addition to a very large and complete set of diagnostics, there is the injection of pellets. This is a way to fuel the core of the plasma in addition to what the neutron beam can provide and it's a system that's specifically designed in order for the pellets to reach more effectively the very center of the plasma. Exhaust studies are possible on ASDEX at very high ratio of the power over the major radius, which is an important figure of merit, because the power will be concentrating in a thin layer around the divertor, and we need for ITER and *a fortiori* for DEMO to really reach very high values of this ratio.

Notes

Summary

12m 21s

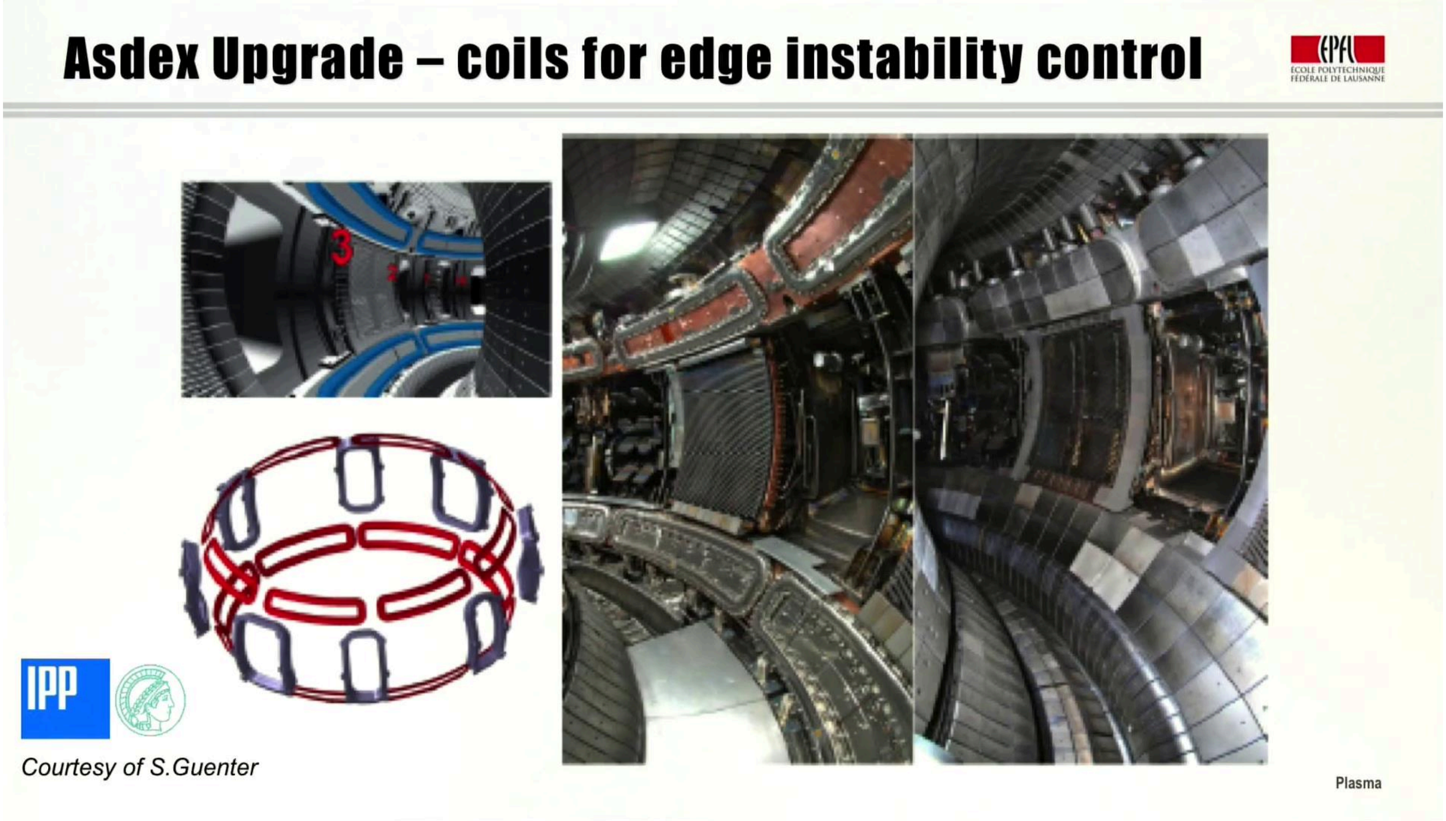


There will also be the possibility of studying the limit on beta with the heating systems that are now implemented and to use electron cyclotron current drive for the control of MHD instabilities.

Notes

Summary

14m 11s

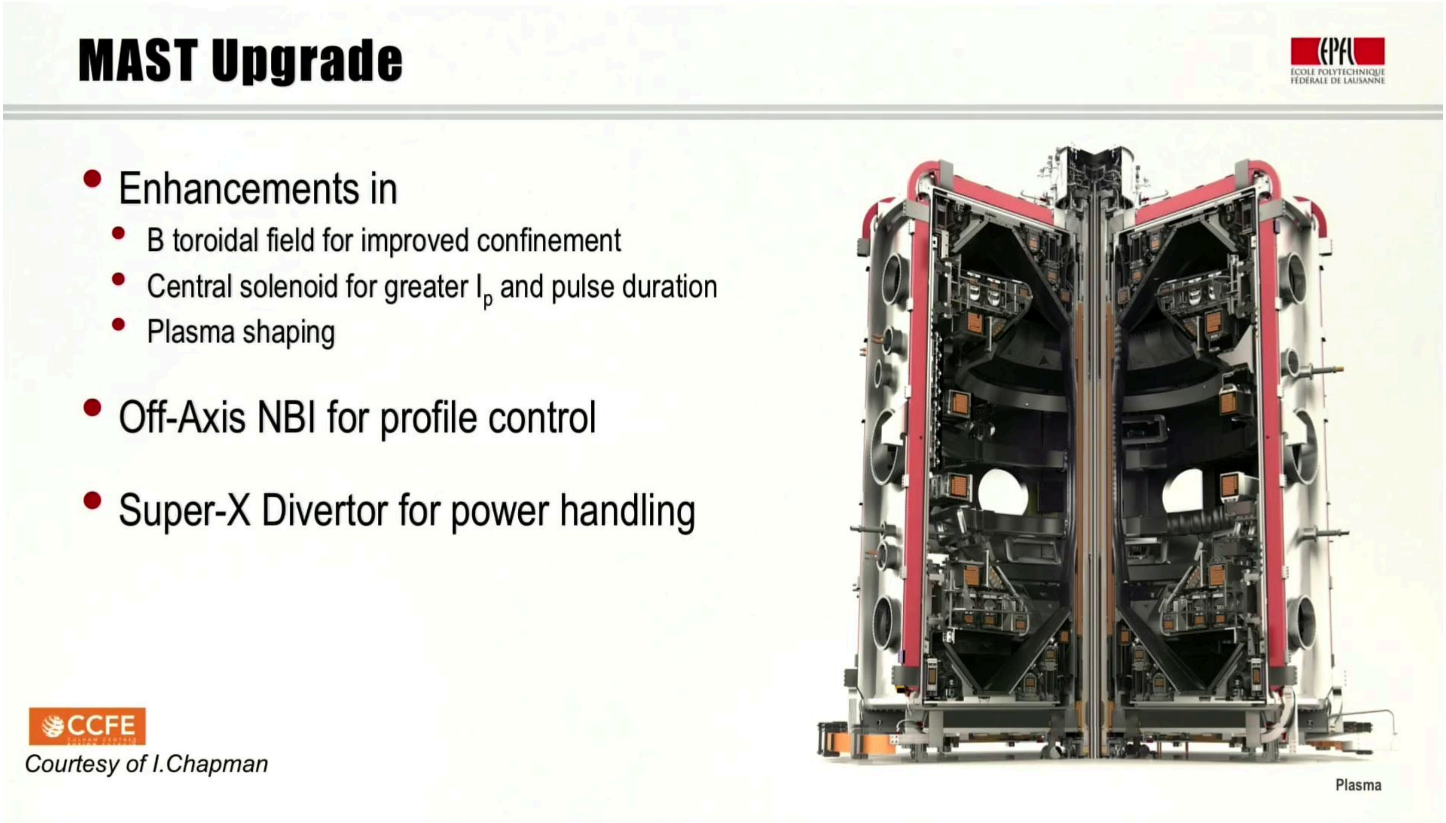


ASDEX Upgrade has also internal coils for the control of edge instabilities, as we have discussed in other lectures, the plasma at the edge develops very, very strong gradients which can, in turn, give rise to very violent instabilities called *edge localized modes* or ELMs which can throw out on a very short timescale a lot of energy and particles, and that may be damaging the first wall, so this is something to be either avoided or mitigated, and the use of coils such as those represented here can help in mitigating these instabilities, and the conditions in which this method can work both for ITER and potentially for DEMO need to be understood.

Notes

Summary

14m 29s

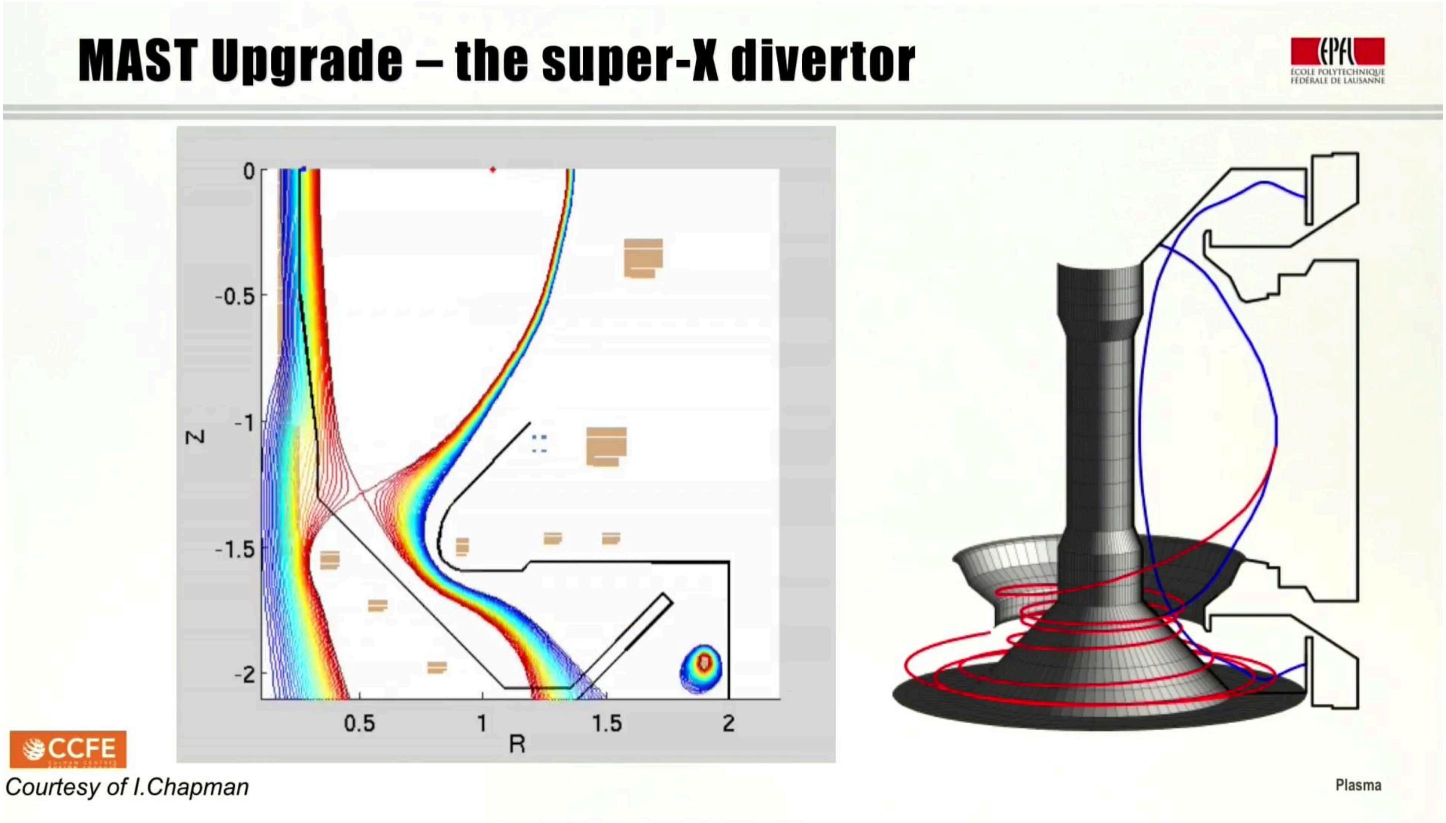


We said that MAST is a spherical tokamak, with a relatively low field, but it is being upgraded and the version of MAST that will be upgraded is part of this European medium size tokamak circle. In particular, there will be enhancements in the toroidal field -- and that will significantly improve the confinement, in the central solenoid for increasing the value of the plasma current and the duration of the plasma pulse; and in the plasma shaping capabilities, to explore different configurations. There will be an off-axis neutral beam injector so that the control of the profile will be possible. There will be a new innovative configuration for the divertor called Super-X for a better power handling.

Notes

Summary

15m 20s

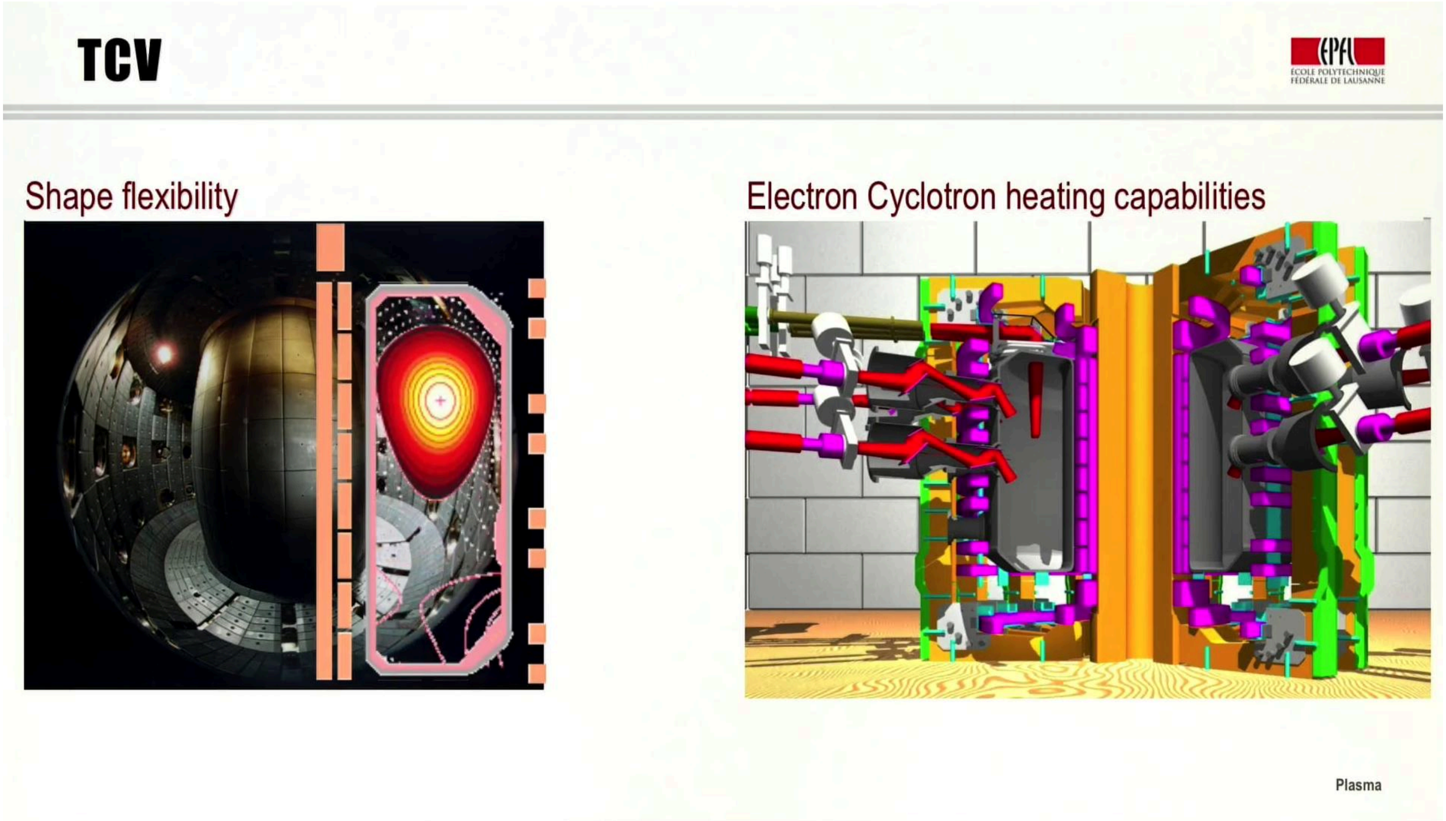


This is a very important exploration, so let's say a few words about that. The Super-X divertor is represented here on the left in a short movie that illustrates its functioning, particularly the Super-X Divertor leads to longer connection lengths, and because it takes the plasma from the boundary and brings it basically to a more external chamber and larger values of R it also leads to a reduced heat flux and because of the surface on which the heat is deposited will be larger.

Notes

Summary

16m 12s

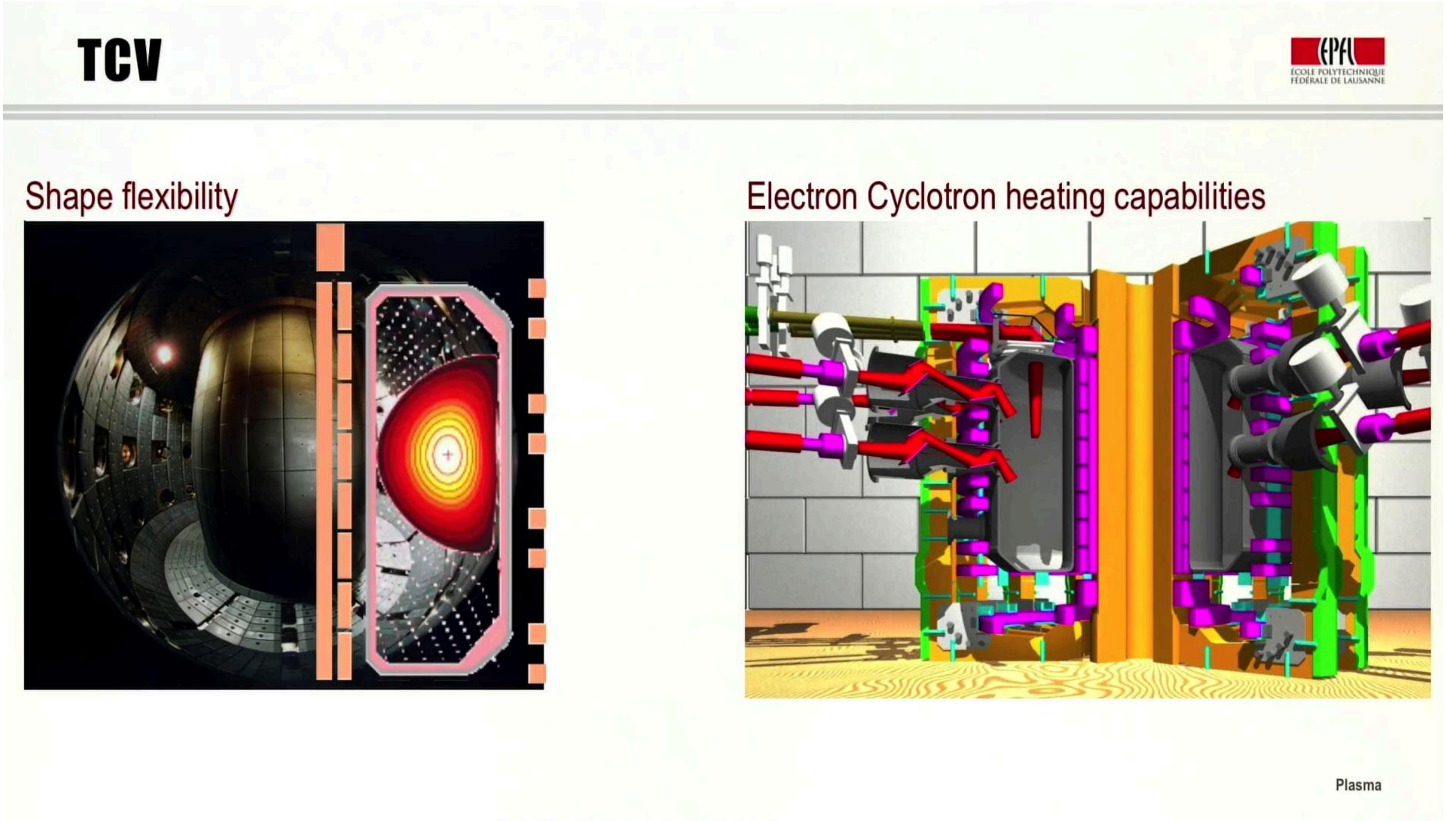


The TCV tokamak in Lausanne, Switzerland, where we are, is also part of this medium size tokamak group in Europe. The reason for that is that it can provide significant input on different physics questions, including the question of potential innovative configurations for the divertor problem. The reason why TCV can do that is that it has an extreme flexibility in its shape, both at the core and at the edge. The illustrations that are going in front of you here are proof of that. You can see different shapes that are achieved on the TCV and you can also see a specific shape that is achieved on the TCV which is the so-called *snowflake divertor*. It has for the first time been demonstrated on TCV. Again, it's an innovative configuration for the divertor to improve the question of the heat flux to that divertor target plate, and possibly even the stability with respect to ELMs. TCV is endowed with a very powerful and flexible electron cyclotron heating and current drive system. At the moment, with six gyrotrons that work at the second harmonic for a total of 3 MW, and 1.5 MW total of 3 gyrotrons working at the third harmonic, that is 118 GHz.

Notes

Summary

16m 50s

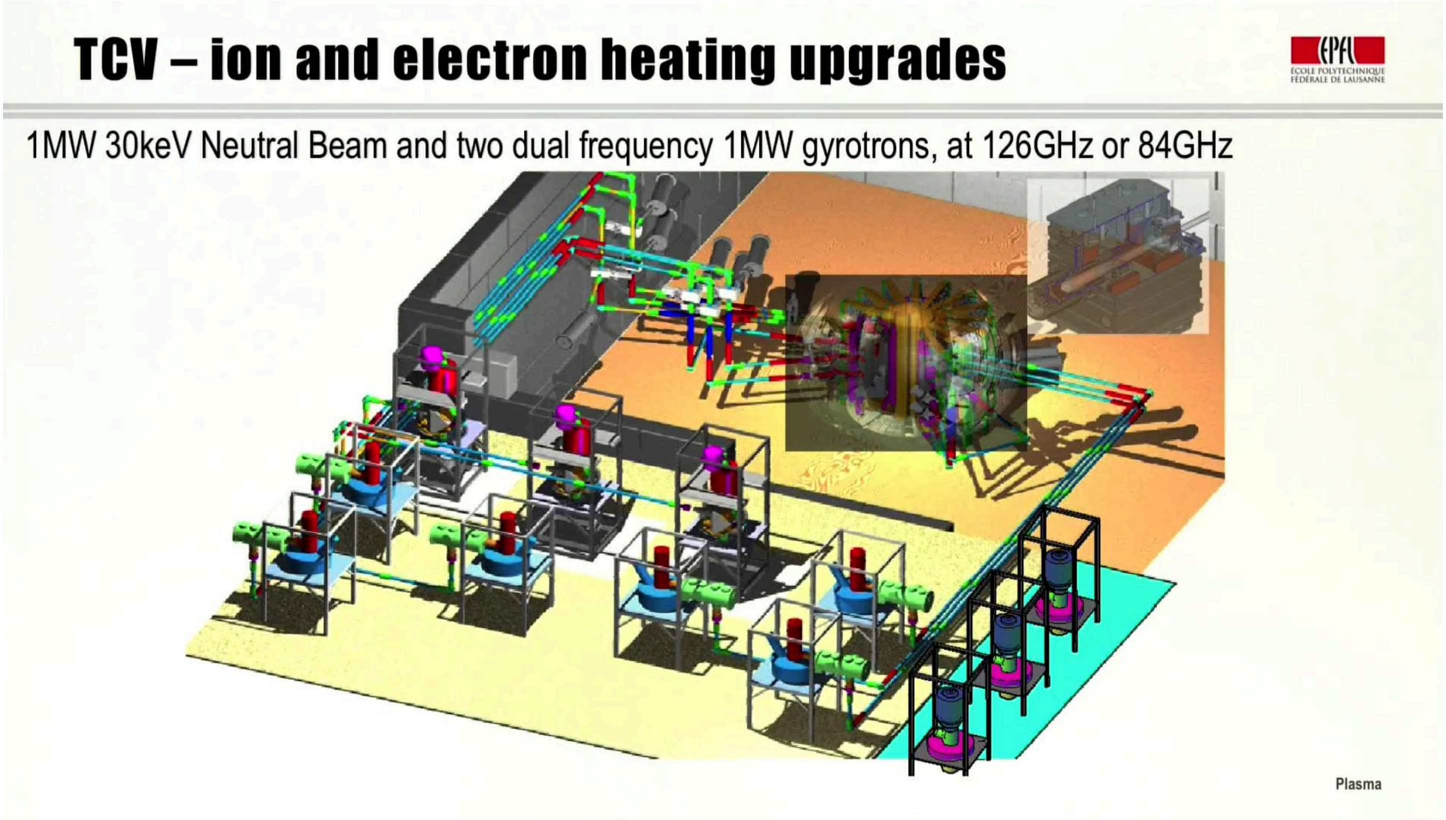


The flexibility in the system is not only because of the frequency choice between the two harmonics but also because of the possibility of injecting the beams in different parts of the vessel with different angles to both heat the plasma locally, treat instabilities locally, and drive current non-inductively.

Notes

Summary

18m 30s

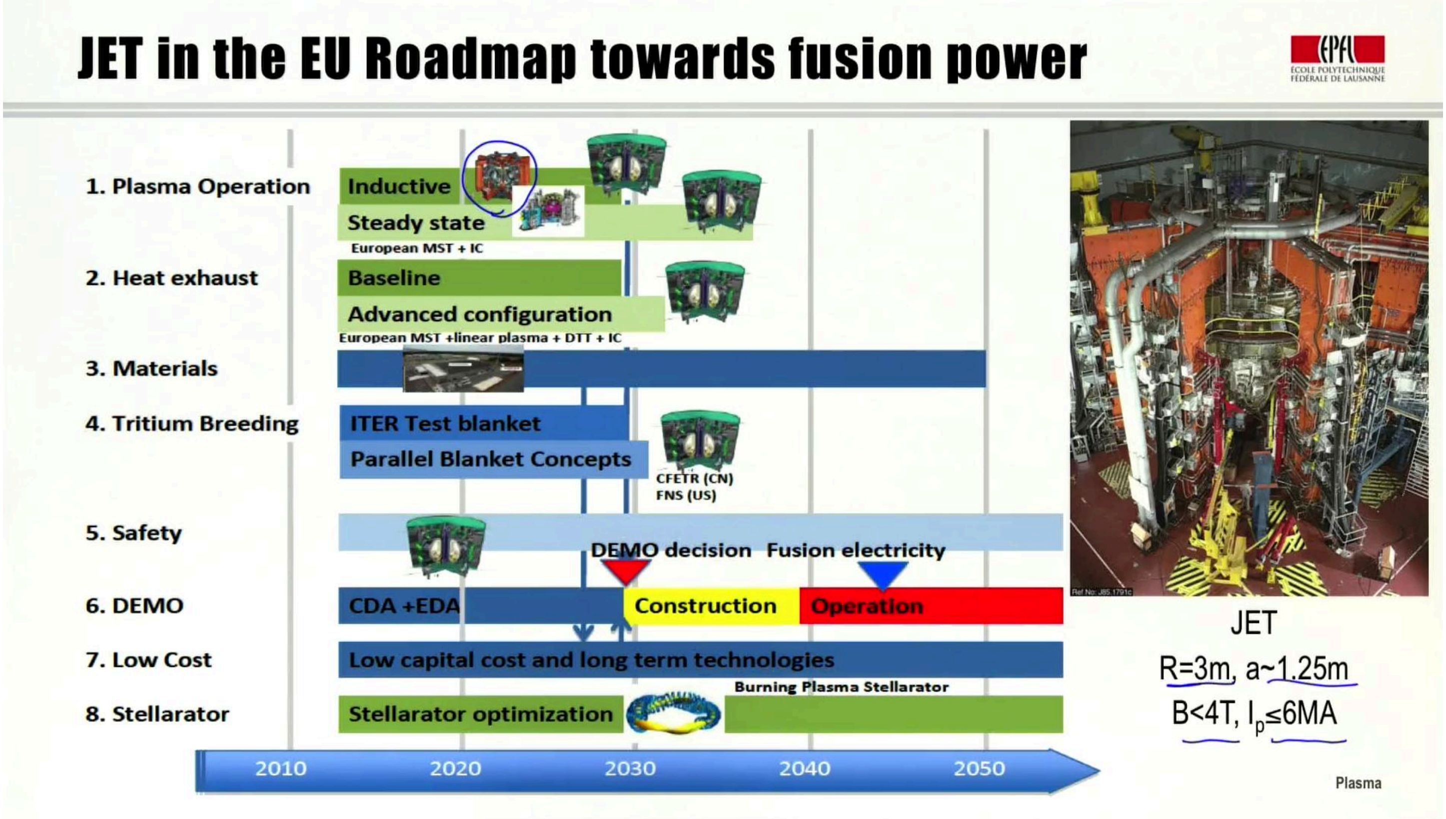


TCV is also undergoing very major upgrades both for ion and electron heating. A neutral beam of 1 MW and about 30 KeV of energy is being installed. Two dual-frequency gyrotrons of 1 MW each, at 126 GHz corresponding to the third harmonic, or 84 GHz corresponding to the second harmonic, are being procured. You see here the different gyrotrons that are installed on the TCV plant or that will be installed soon on the TCV plant with the transmission lines that take the microwave power to the tokamak. The tokamak will also be heated by a neutral beam injector that's being procured at the moment, about 1 MW of power.

Notes

Summary

18m 55s

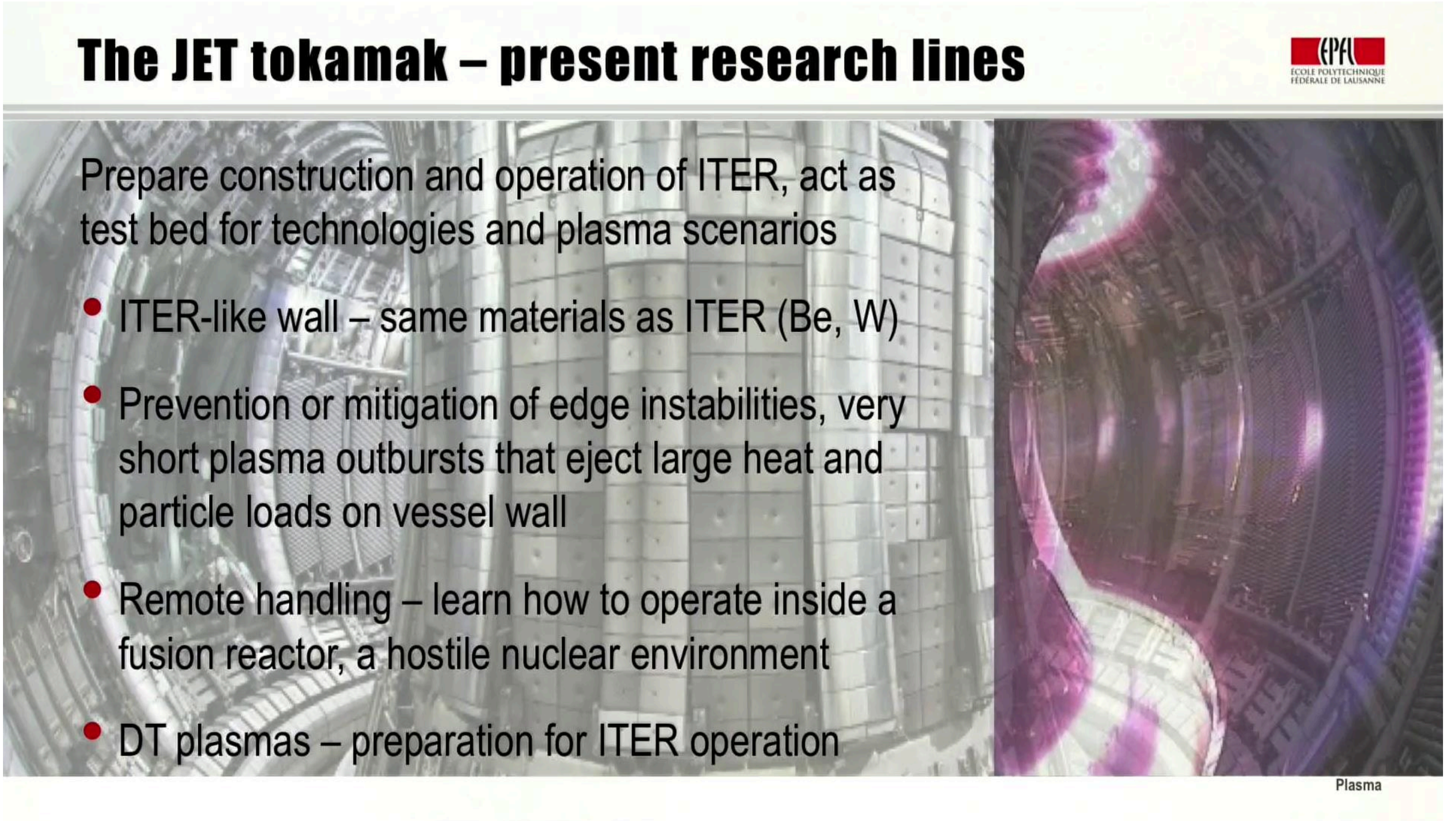


Naturally, one of the main elements in the European roadmap towards fusion power, perhaps also in the world roadmap, is JET. You can see that JET here appears as a major element in the development of the inductive plasma operation. JET is not really foreseen to operate in very advanced modes of operation with the large fraction of the current driven non-inductively, but it has to contribute to a number of open issues related to the inductive scenario. JET has a major radius of about 3 m, minus radius of about 1.25 m, and the field goes up to almost 4 T, with a current up to about 6 MA..

Notes

Summary

19m 48s

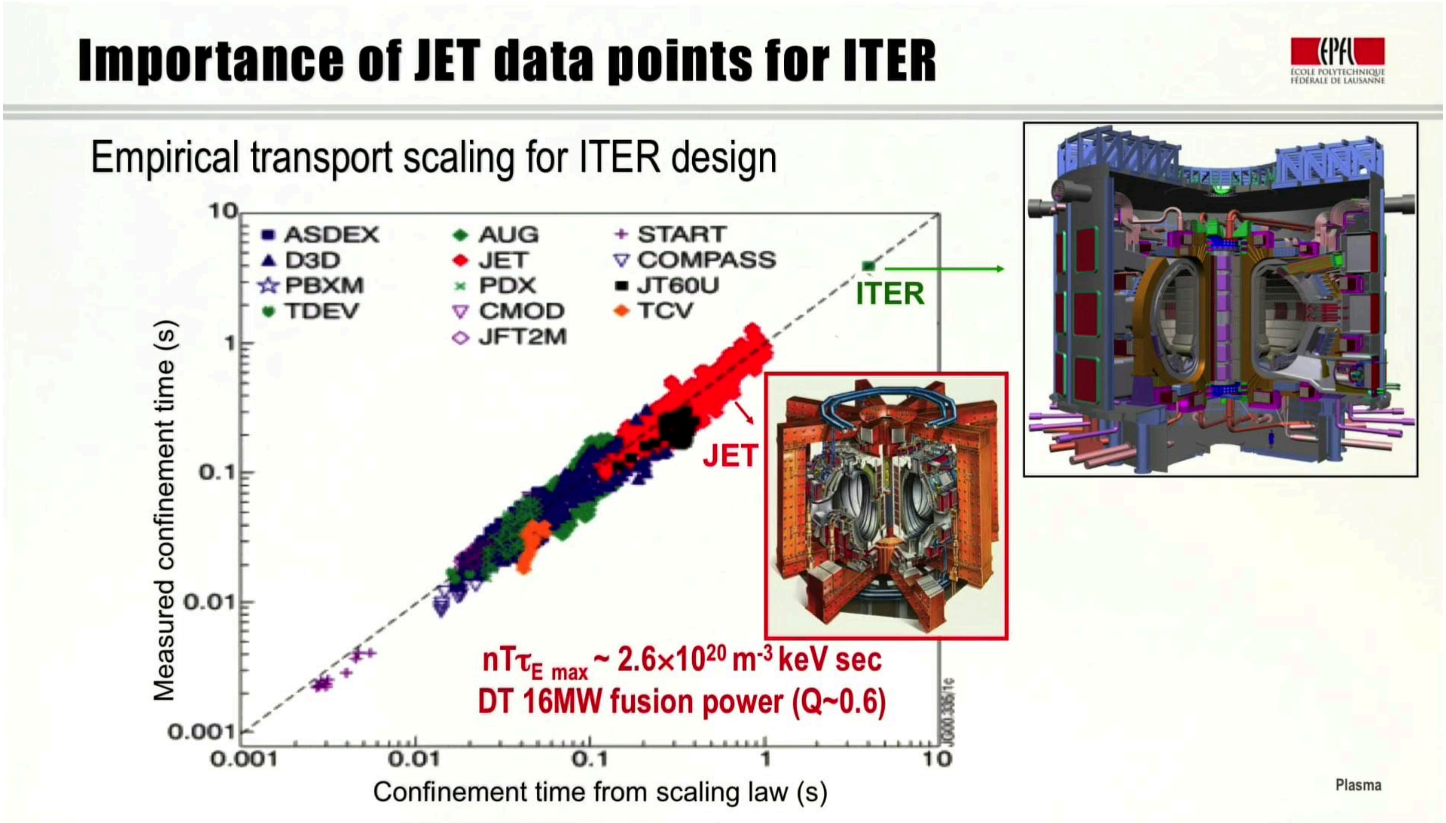


JET is devoted at present to really prepare the construction and the operation of ITER, acting as a testbed for the technology and the plasma scenarios that are foreseen for ITER. In particular, JET has an ITER-like wall. It has the same combination of materials as ITER will have, beryllium and tungsten. JET will explore in this ITER relevant conditions how to prevent or mitigate the edge instabilities we mentioned before, that is, these very short and very violent plasma outbursts that can eject large heat and particle loads on the vessel wall that must be avoided or mitigated for ITER. JET is also placed where there is very large development in remote handling, and this is a technological aspect that is very important to fusion. We need to learn how to operate inside the fusion reactor which is a hostile nuclear environment for human beings. Finally, JET is the only machine in the world now that can do DT plasmas. Doing DT plasmas implies, of course, preparing directly for ITER operation.

Notes

Summary

20m 36s

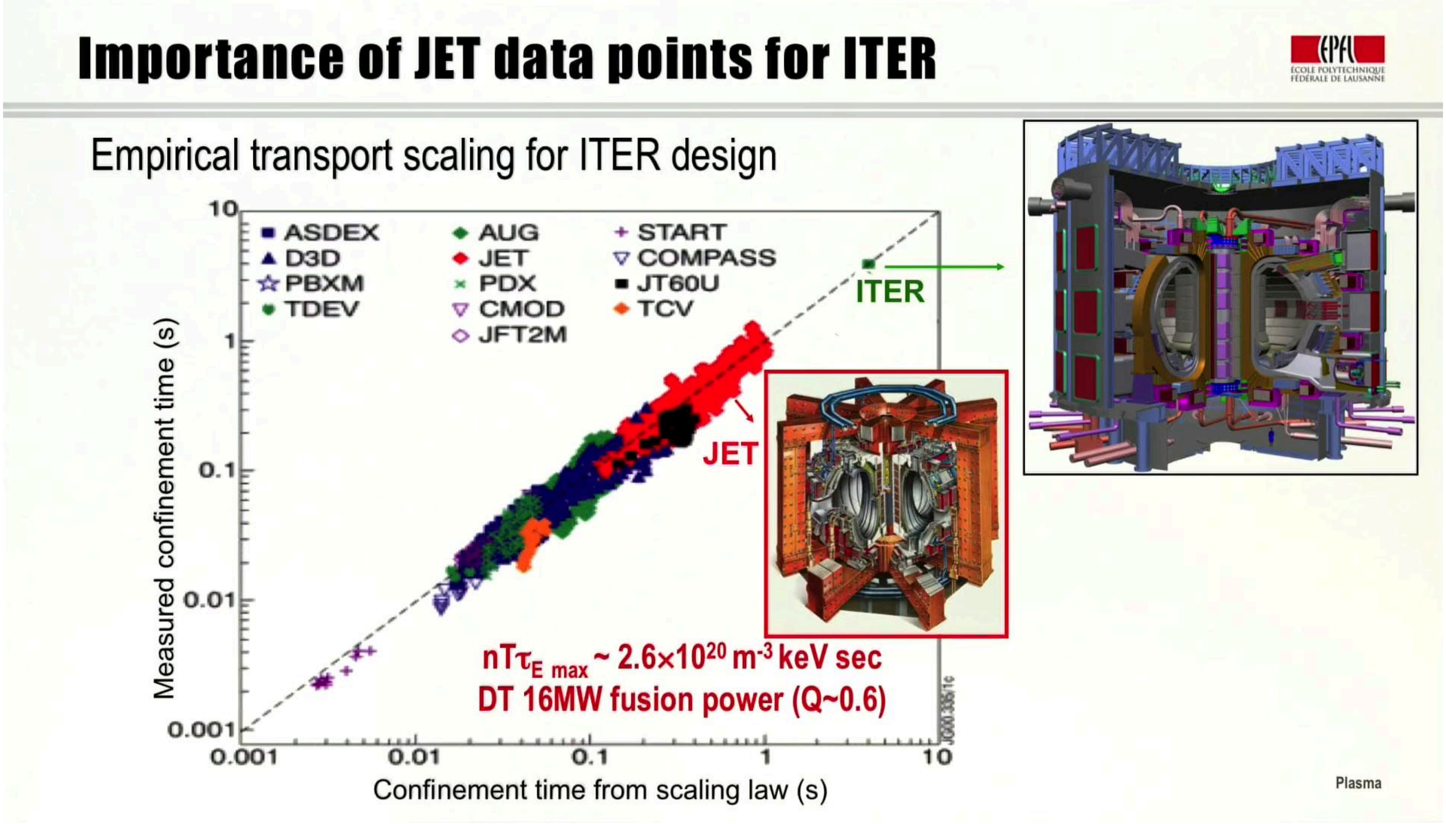


Just as an example of the importance of the JET data points for ITER, I show here the figure that we have seen before in the course: the empirical transport scaling. Which has been used a basis for the ITER design. As discussed before, this scaling is based on a variety of devices. It implies that we can plot the confinement time from the experiment as a function of the confinement time from the scaling law and get a very good correlation, so in other words, a scaling law is representative of the variety of experiments. Now, all of the experiments apart from JET are in a region relatively far away from ITER. You can see this is a log-log plot. The points that are by far the closest to ITER those are coming from JET, so it's essential to have really the minimum possible extrapolation to ITER in order to be sure, or to improve the reliability, of our predictions for ITER, in particular in this case, for confinement time, but this is just an example. There are several areas for which such proximity is essential.

Notes

Summary

21m 50s

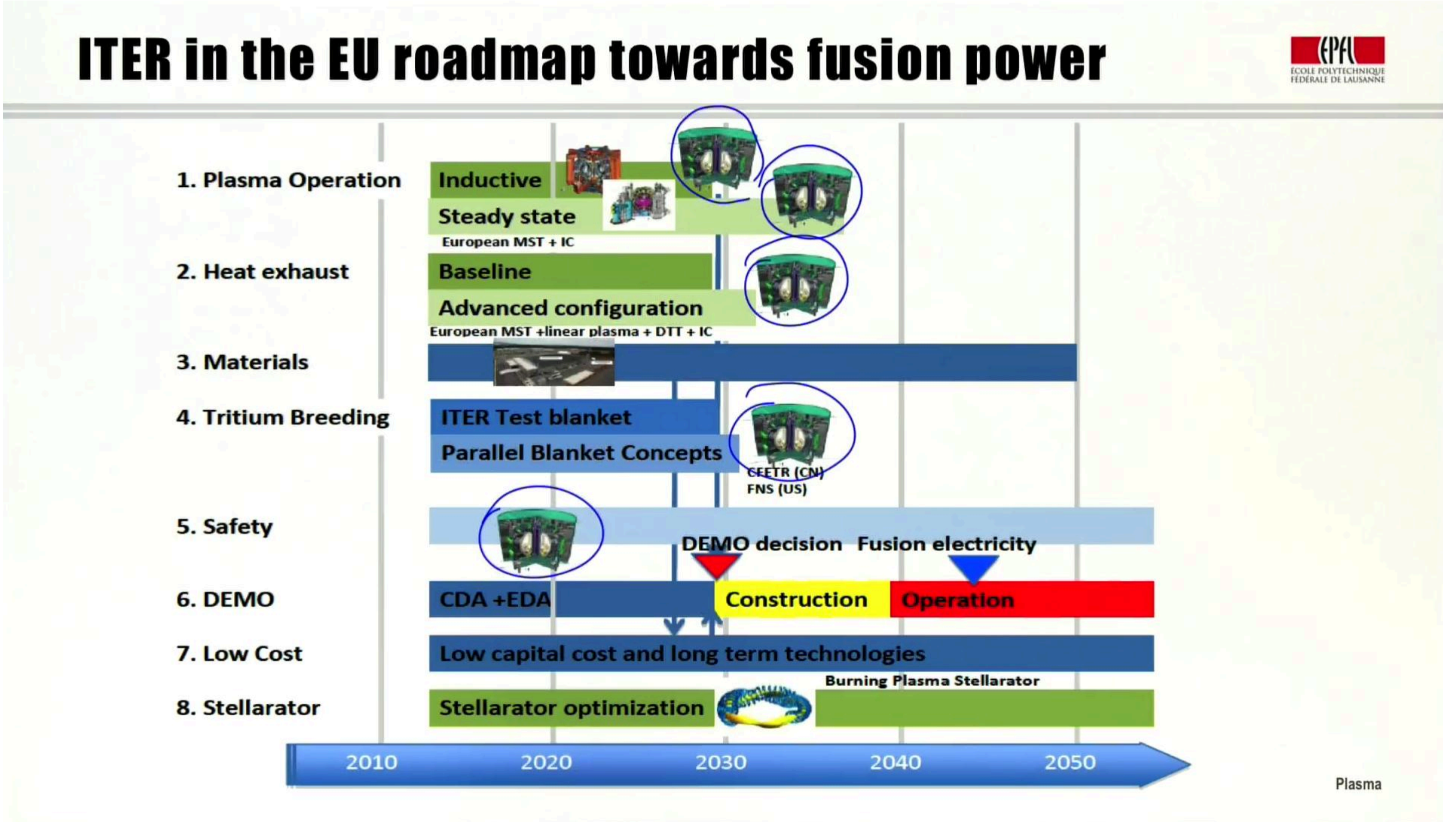


JET has achieved a triple product of about 2.6 x 10^{20} m^{-3} keV seconds, close to the record ever achieved anywhere, and it has achieved the record fusion power on Earth with 16 MW, obtained in the end of 1997 in DT, with a fusion gain about 0.6 One point I like to underline in the European roadmap, on which I focused for this lesson, of course, is not the only one in the world.

Notes

Summary

23m 04s



Even the European roadmap is based on a number of international collaborations. I'd just like to highlight one. This IC stands, in fact, for international collaboration and this is a picture which I took here in a simplified and enlarged version of the Japanese tokamak JT-60 Super Upgrade which is being completed at the moment, which will contribute very significantly to the R&D needed in particular for steady-state operation of the plasma. This is a superconducting tokamak about the size of JET, 3 m major radius, not very different minor radius either, 1.2 m, up to 2.25 T and up to 5.5 MA, so it will really concentrate on the steady-state advanced regimes that JET cannot address. This is an example of complimentarity in the world program, in fact beyond the European frontiers. I now come to what I would say is *the* main element of the European roadmap, and that is ITER and you can see that the image of ITER in fact, appears in many different locations here and that's because ITER is the cornerstone for a variety of the missions we have highlighted before.

Notes

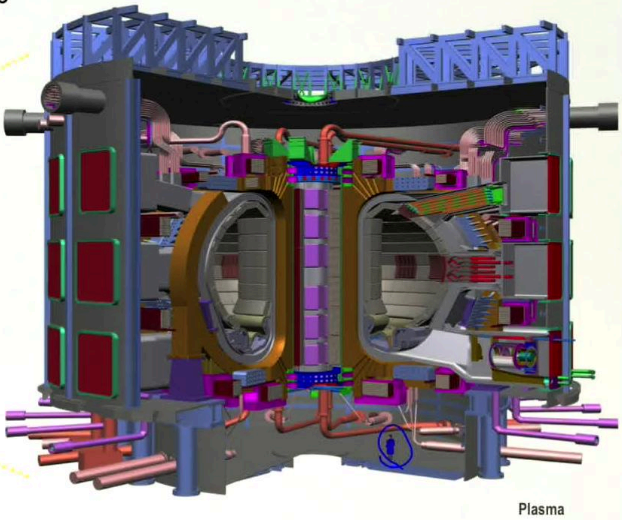
Summary

23m 41s

ITER – the first burning plasma

- Demonstration of scientific / technological feasibility, and safety of fusion energy
- $Q \geq 10$; Fusion power ≥ 500MW; ~500s; R=6.2m, a=2m
- I_p=15MA, B_{tor}=5.3T; plasma volume = 840m^3

Courtesy of ITER Organisation



ITER will be the first burning plasma. ITER will be the first demonstration of scientific and technological feasibility of fusion and also of its safety. ITER is designed to produce plasmas with a fusion gain Q ≥ 10, so that's the goal. But that will not be done for small amounts of power. For fusion power they should exceed half a gigawatt [0.5 GW] and for a duration of at least 500 seconds. ITER has a size of about 6 m, major radius, 2 m, minor radius. The plasma volume is slightly less than 1,000 cubic meters. The toroidal field is 5.3 T, and the current flow in the plasma of about 50 MA. Here you can see the construction site for ITER in Cadarache in the south of France which is in fact evolving every day at present as you can see. Here is an image of the layout of ITER with a human being represented in the bottom reminding us of the scale of the project.

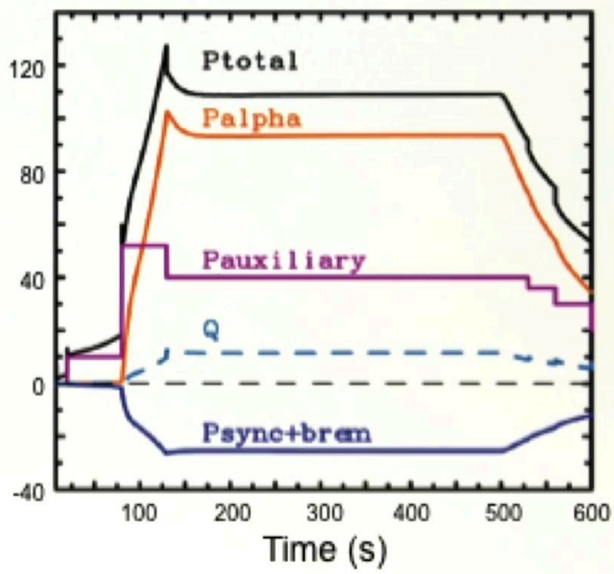
Notes

Summary

25m 12s

ITER – the first burning plasma

- Q=10 scenario
- I_p=15 MA, P_{fusion}~500 MW
- Total α energy in single shot ~50GJ
- Total α energy produced by JET and TFTR DT campaigns ~5GJ



Courtesy of Y.Gribov, ITER Organisation

Plasma

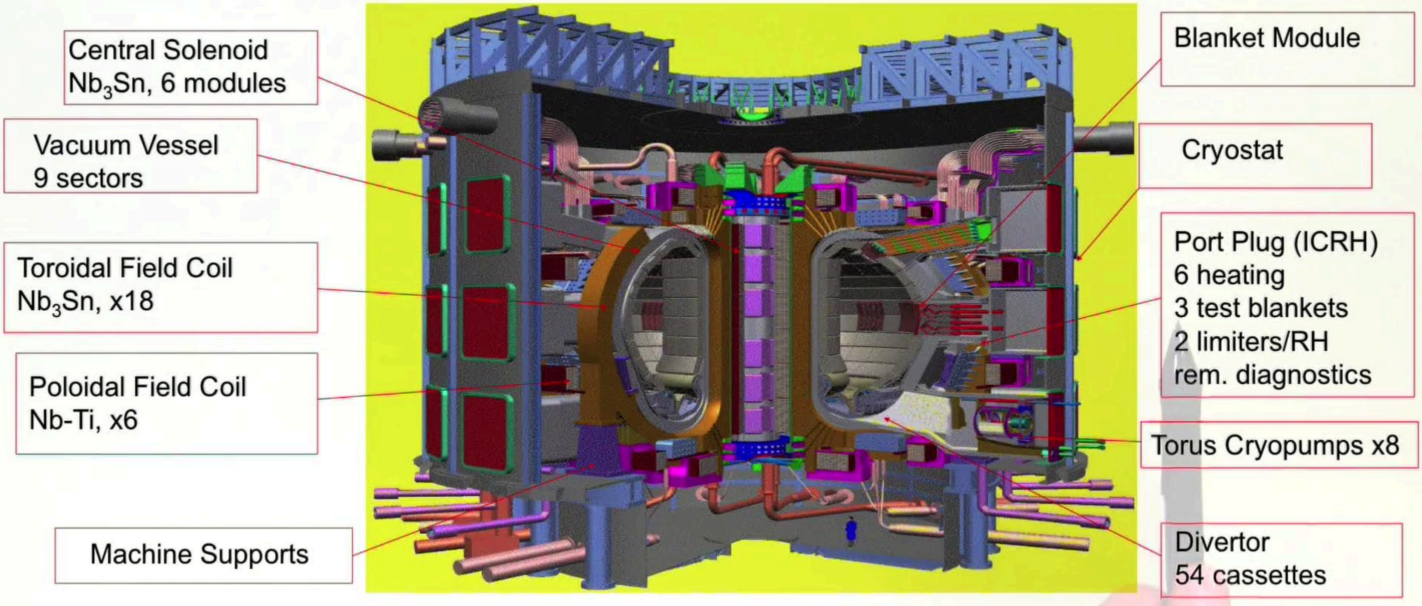
Just to highlight one of the novelty elements of the ITER plasmas I have represented here the foreseen Q=10 scenario so that's the one we promised to achieve. With 15 MA, 500 MW fusion power, and you see here as a function of the time in the discharge, which lasts 700 seconds, you see the Q, i.e. the fusion gain, going up to 10 and then coming back down at the end of the discharge but the point I want to make is that we really have a different regime in ITER compared to what we have in machines today, even on the DT experiments we have done on TFTR and JET. Look at a plasma α-particles power. It's about one fifth of the total fusion power, so it's about 100 MW, and if we take a single shot, one shot of ITER of this kind, we'll have energy in alphas that would be of the order of 50 gigajoules [50GJ]. This is to be compared with the total energy that we have ever produced in all the DT experiments in the world so far, particularly in JET and TFTR, which is 10 times less. So, one single shot of ITER will produce 10 times more α-particles energy than the whole history of fusion so far.

Notes

Summary

26m 20s

The main components of ITER



Courtesy of ITER Organisation

Plasma

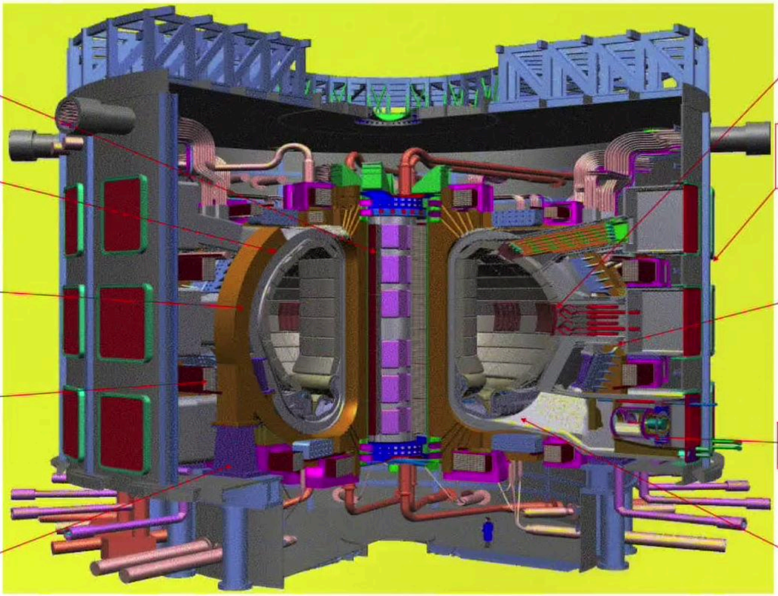
Without going into details of the ITER design, which is extremely complex, as you can imagine, I'd just like to highlight in this picture the main components of ITER. Starting from the top here, the central solenoid. This is the superconducting coil of niobium and tin, six modules of it. Then we see the vacuum vessel which is being constructed. It's divided into 9 sectors. A very important piece of the project is the toroidal field coils, represented here in orange. These coils are made of niobium tin, and there are 18 of them, whereas there are 6 poloidal field coils, - you can see here a cross section of one, they are made of niobium titanium. We can also see the machine supports and going to the other side, you can see the divertor structure here. The divertor is made of what are called *cassettes*, 54 cassettes. These are modular elements that can be replaced on a relatively short timescale. There are 8 cryopumps, very large size. There are many openings to access the inside of the tokamak. The example here is that of the ICRH antenna which comes on a port plug as we've discussed in a previous lecture.

Notes

Summary

27m 40s

The main components of ITER



Courtesy of ITER Organisation

Plasma

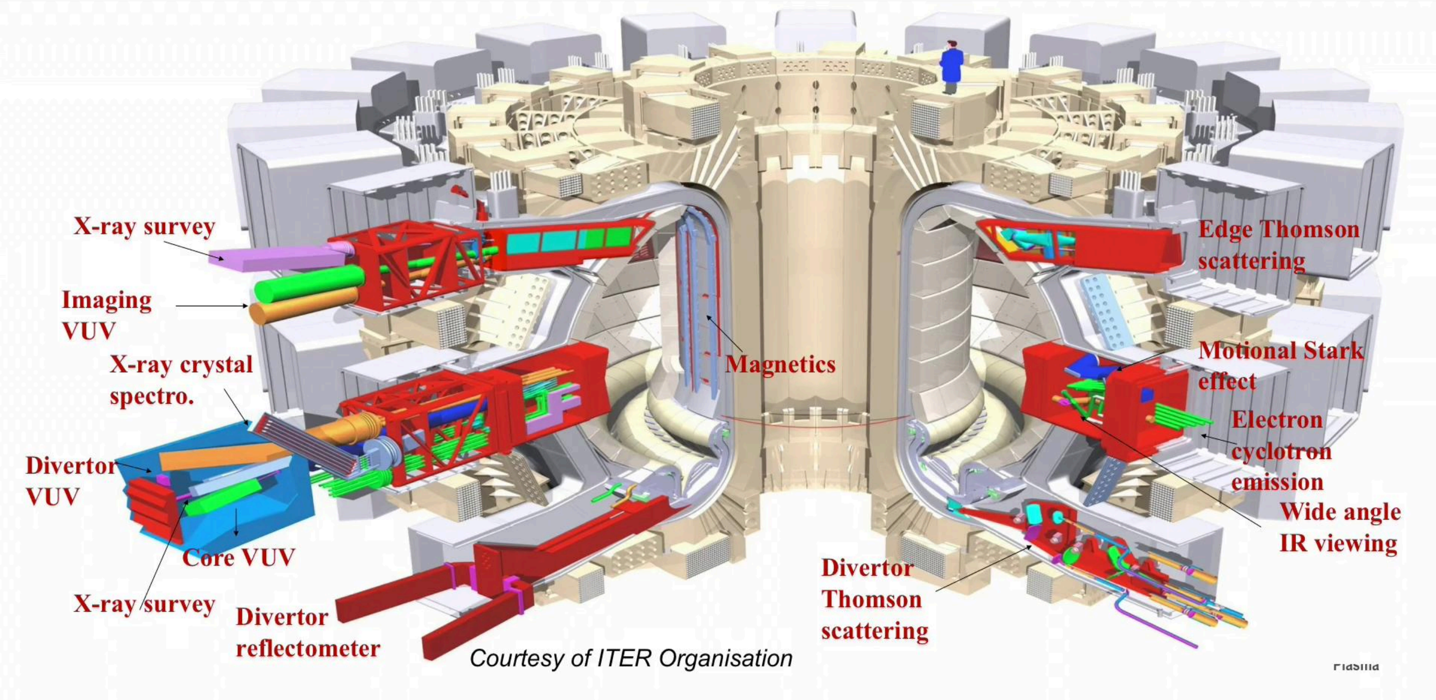
Six of these port blocks are dedicated to heating, three are dedicated to the test blanket modules two are for limiters and remote handling, and the others are for diagnostics. A blanket module is shown here, as an example, and of course, the whole of the machine is enclosed in what I believe will be the largest cryostat ever built.

Notes

Summary

29m 13s

Diagnostics on ITER



Courtesy of ITER Organisation

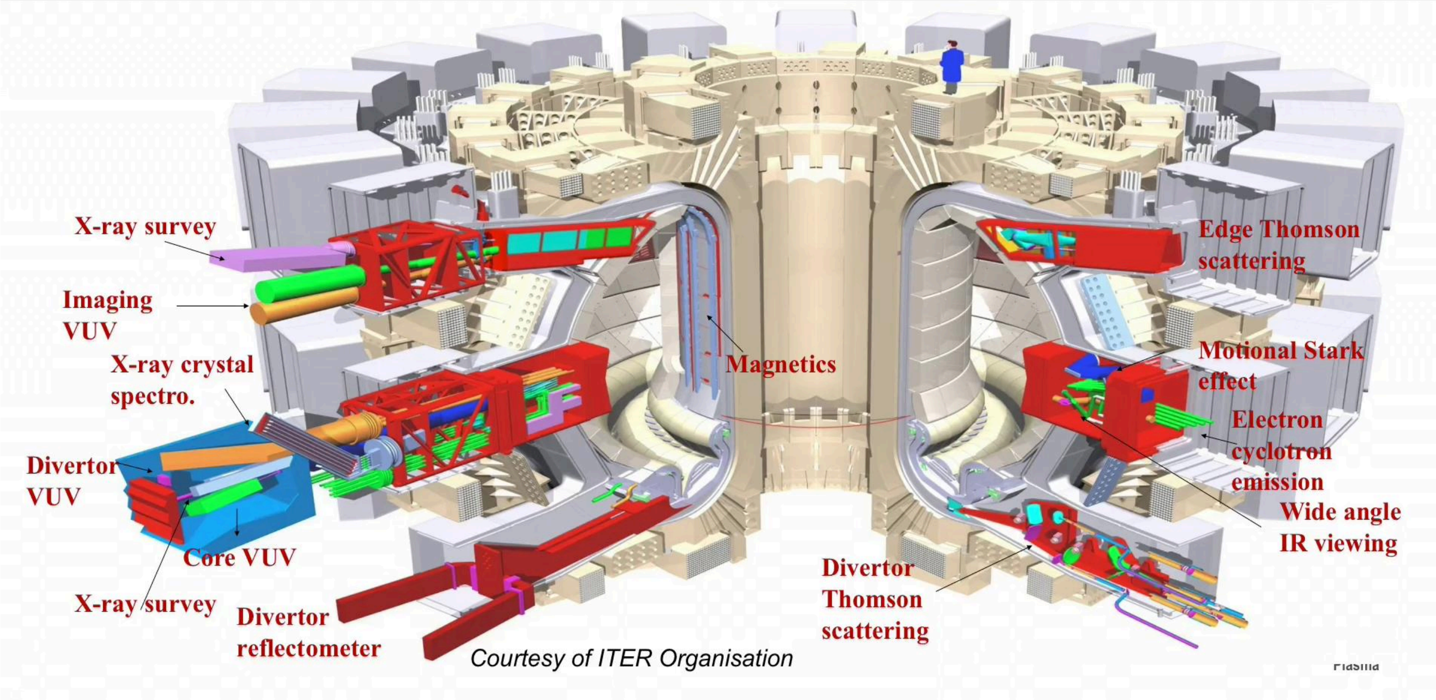
In this picture you see the different diagnostic systems foreseen for ITER. Again, we will not go into any details but you can imagine that the challenges we had for hot plasmas in general, are, of course, applicable to ITER, but on top of those, --which implies that you cannot put any material surface inside the plasma to measure anything, and that you really need to be clever in interpreting your data from known thermal components on the plasma, etc.. In addition to this, we have a hostile nuclear environment so far. For example, neutron irradiation, so there's a strong implication of that. For example, on the difficulty of having mirrors close to the plasma for light to be extracted at different wavelengths. There's also the question of the feed-throughs for the diagnostic passages. They need to be compatible with the machine safety constraints, and so on.

Notes

Summary

29m 39s

Diagnostics on ITER



Courtesy of ITER Organisation

You can see a survey X-ray measurement, you can see ultraviolet of different kinds for spectroscopy, another spectroscopy system for X-rays, reflectometry for the divertor region, Thompson scattering for the divertor region, infrared viewing, electron cyclotron emission, for electron temperatures, motional Stark effect, for having the internal structure of the magnetic field, Thompson scattering, more at the edge, --There will be Thomson scattering in the core, of course, so a large variety of diagnostics which different partners of ITER are building, all, of course, compatible with the constraints that will be dictated by the machine environment that will be very different from what we are used to today.

Notes

Summary

30m 47s

Constructing ITER – the world's largest puzzle

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Plasma

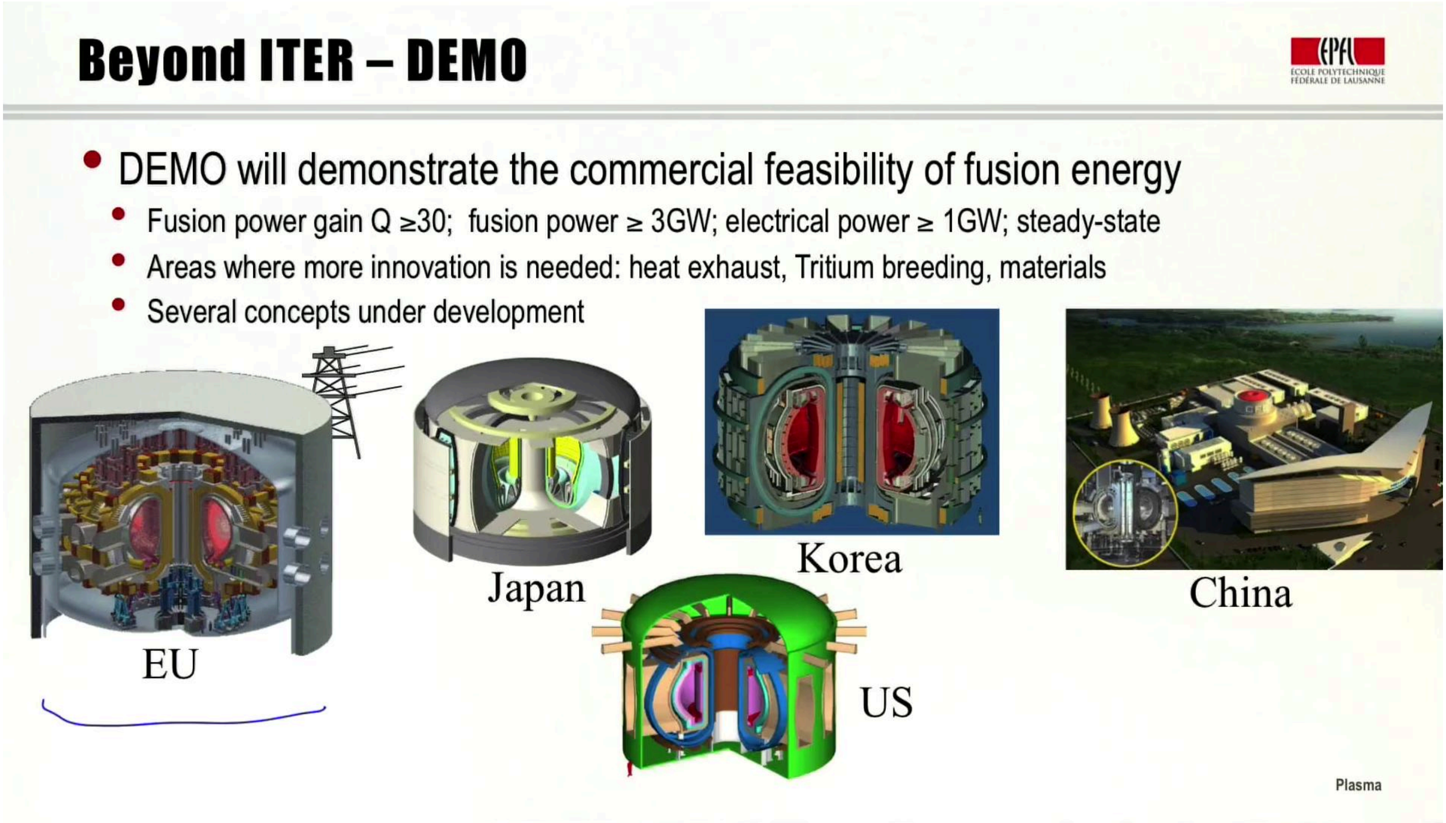
Courtesy of ITER Organisation

So there are challenges in building the individual components for ITER, each one being state of the art, each one being subject to a number of constraints, including constraints on availability, maintainability, and durability, but it will also be a major challenge to put these pieces together. What you're seeing here is a movie that represents the assembly of ITER. We say that this is the world's largest puzzle ever constructed. It will be quite a challenge to really assemble all of these pieces together in a relatively short time.

Notes

Summary

31m 39s

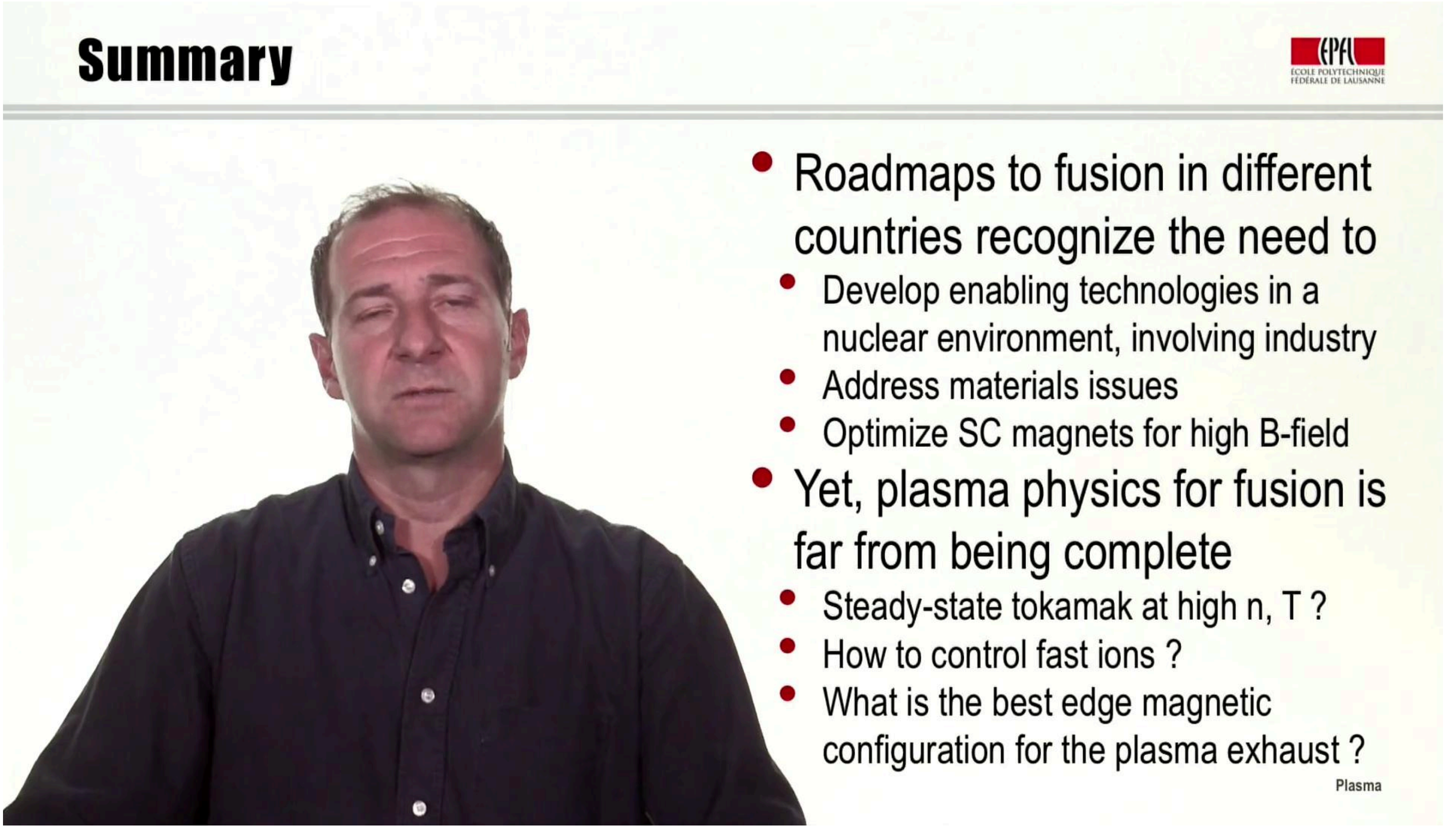


ITER is not the end of research for fusion. ITER will demonstrate that fusion can be controlled on Earth, scientifically and technologically, but we need one step more. We need DEMO. DEMO will demonstrate that fusion energy is also possible commercially. DEMO will need to have a fusion power gain of 30 or a bit more with a fusion power of the order of 3 GW, corresponding to electrical power of the order of 1 GW and it will need to work in steady-state. In my opinion, this is a personal opinion, the areas where more innovation is needed are: - the exhaust heat from the plasma, - the breeding of tritium, - the materials. Several concepts are under development in different parts of the world. There's a European concept being developed in Europe, maybe even two versions of that. There's a concept in Japan, a concept in the US, in Korea, and in China. While I don't want to go into any details for the different concepts, I stress once more that there are elements of competition, which is, of course, natural, but there are also elements of complementarity among all of these approaches.

Notes

Summary

32m 23s



In summary, we have seen that roadmaps to fusion are being developed in different countries, in different parts of the world. They all recognize the need to develop enabling technology in nuclear environment which is something that we've not seen so far. We need to involve industry in the progress towards the DEMO step, towards a fusion reactor. We need to address materials issues. Materials are a very crucial element of fusion technology. We need to optimize the magnets that'll be superconducting for high field. All of these are elements of fusion technology that are absolutely essential; yet, I believe we can say that plasma physics for fusion is really far from being complete. For example, we don't know how to operate a steady state tokamak at high field, high density, and high temperature. We have made enormous progress in controlling the plasma, in controlling its instabilities but we don't know yet how to control the fast ions entirely, for example. We don't know yet what is the best magnetic configuration at the edge in order to alleviate the problem of the plasma exhaust. These are just examples of plasma physics related problems that are not fully understood, not fully addressed, and not fully optimized to get as efficient as possible to the fusion reactor.

Notes

Summary

33m 48s