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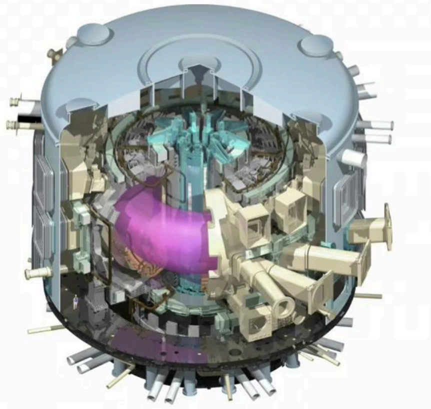
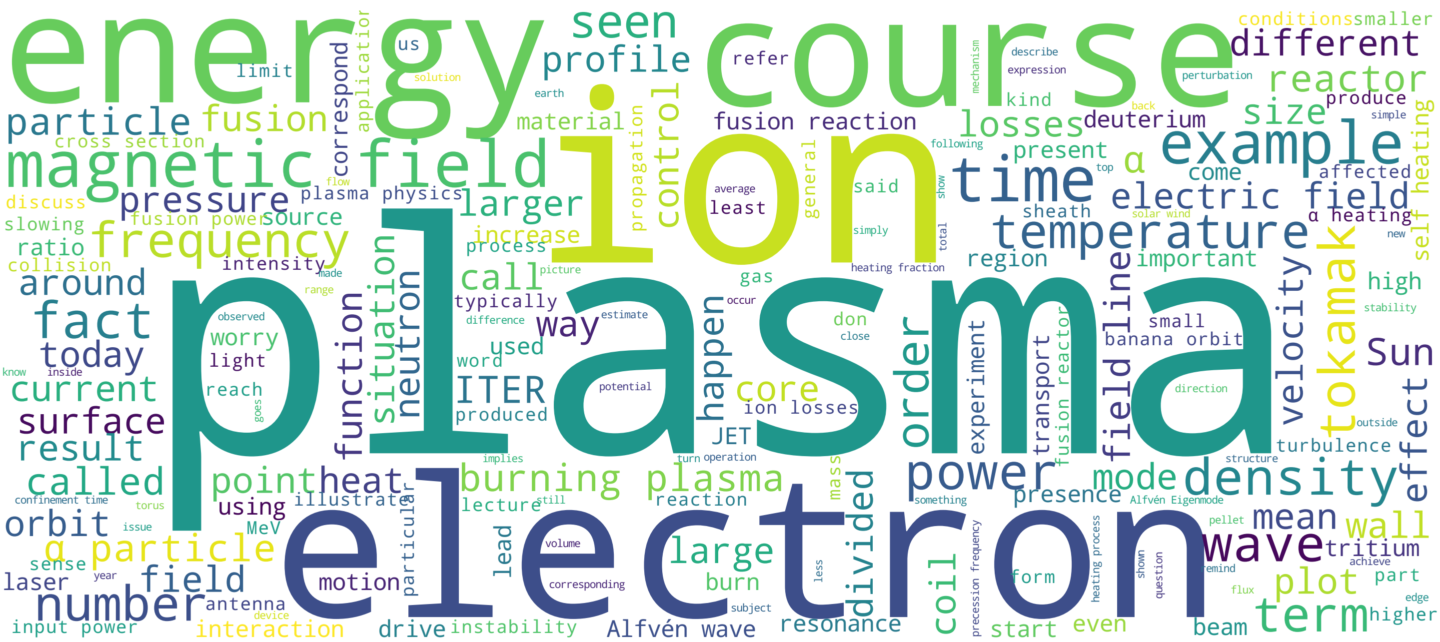


Burning plasmas and the role of fast ions

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 7i

Ambrogio Fasoli



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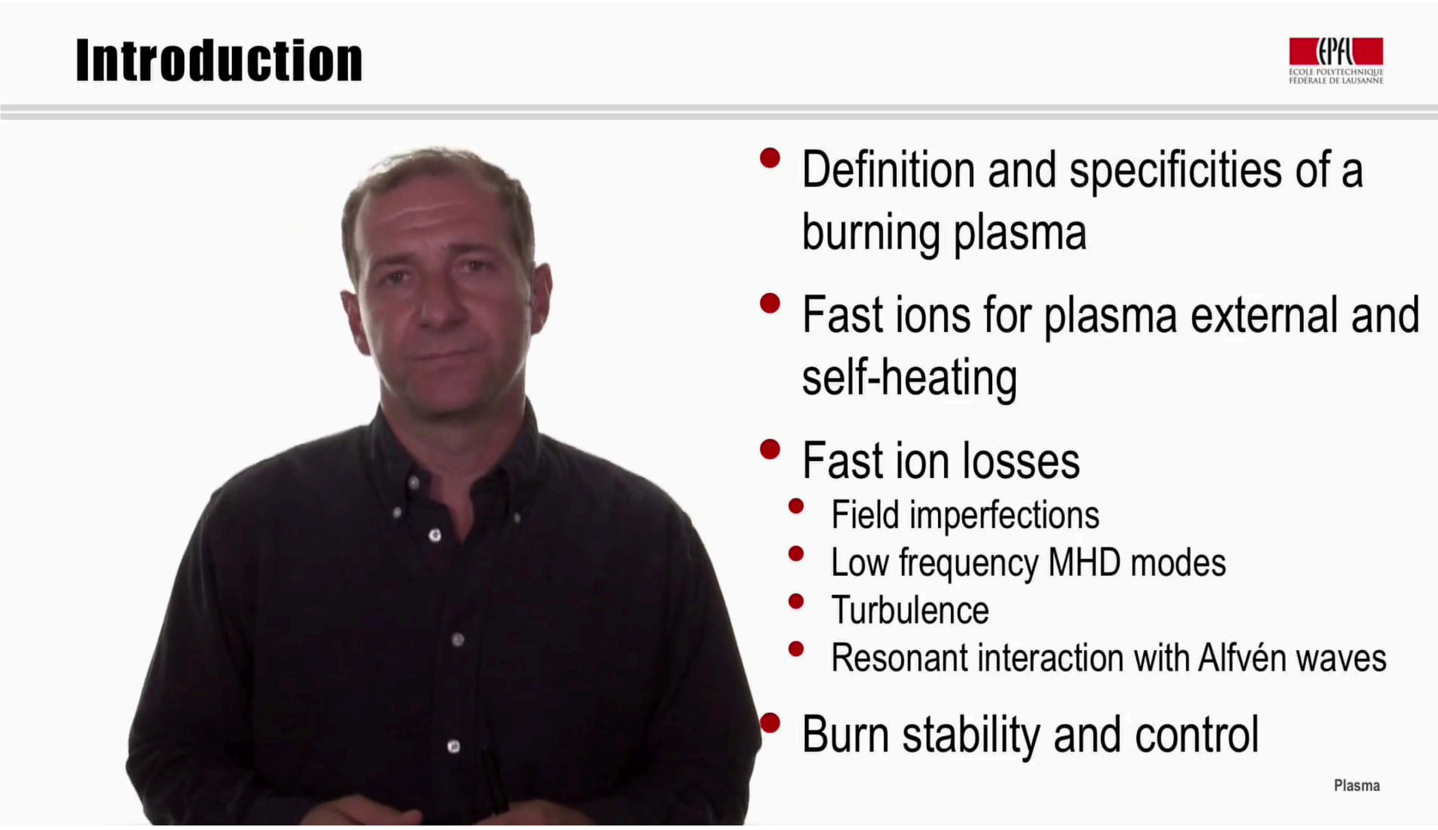


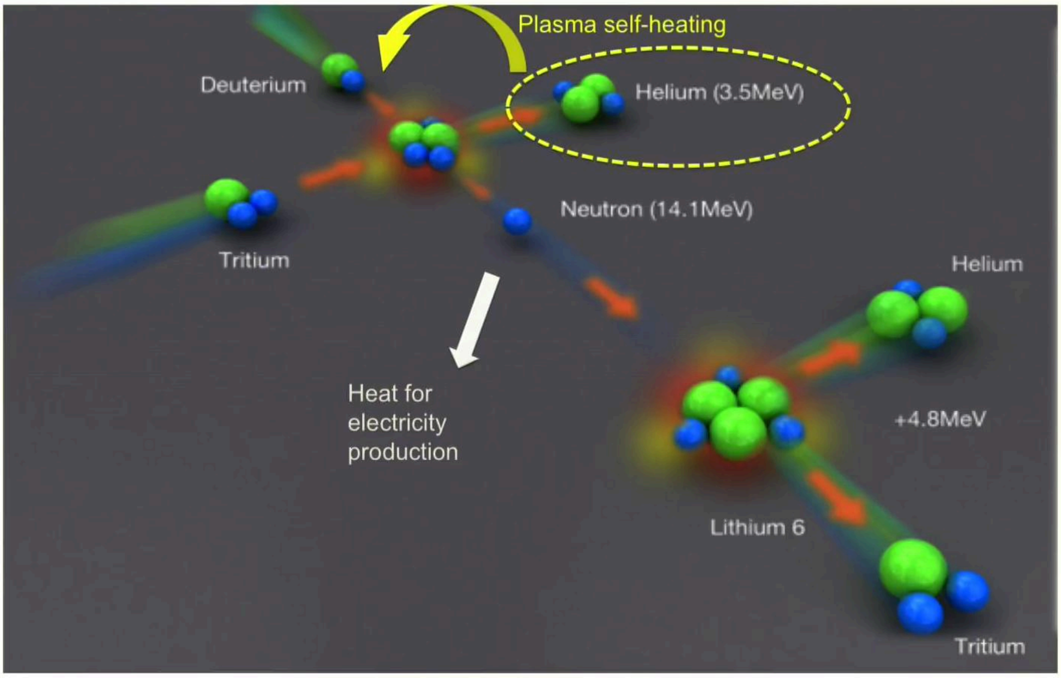
Welcome to the course on Plasma Physics and Applications. Today we will discuss the regime that we refer to as the *Burning Plasma Regime* and the role of fast ions in it. We will start by defining what a burning plasma is and by highlighting its specificities. We will describe the fast ions and their role in the external and the self-heating of the plasma. We will then look at the losses that fast ions can be subject to because of a number of reasons: - inhomogeneities in the field, - low frequency plasma modes, - turbulence, - or resonant interaction with Alfvén waves. We'll then say a few words about the stability of the burn and its control.

Notes

Summary

0m 04s

The DT fusion reaction - reminder



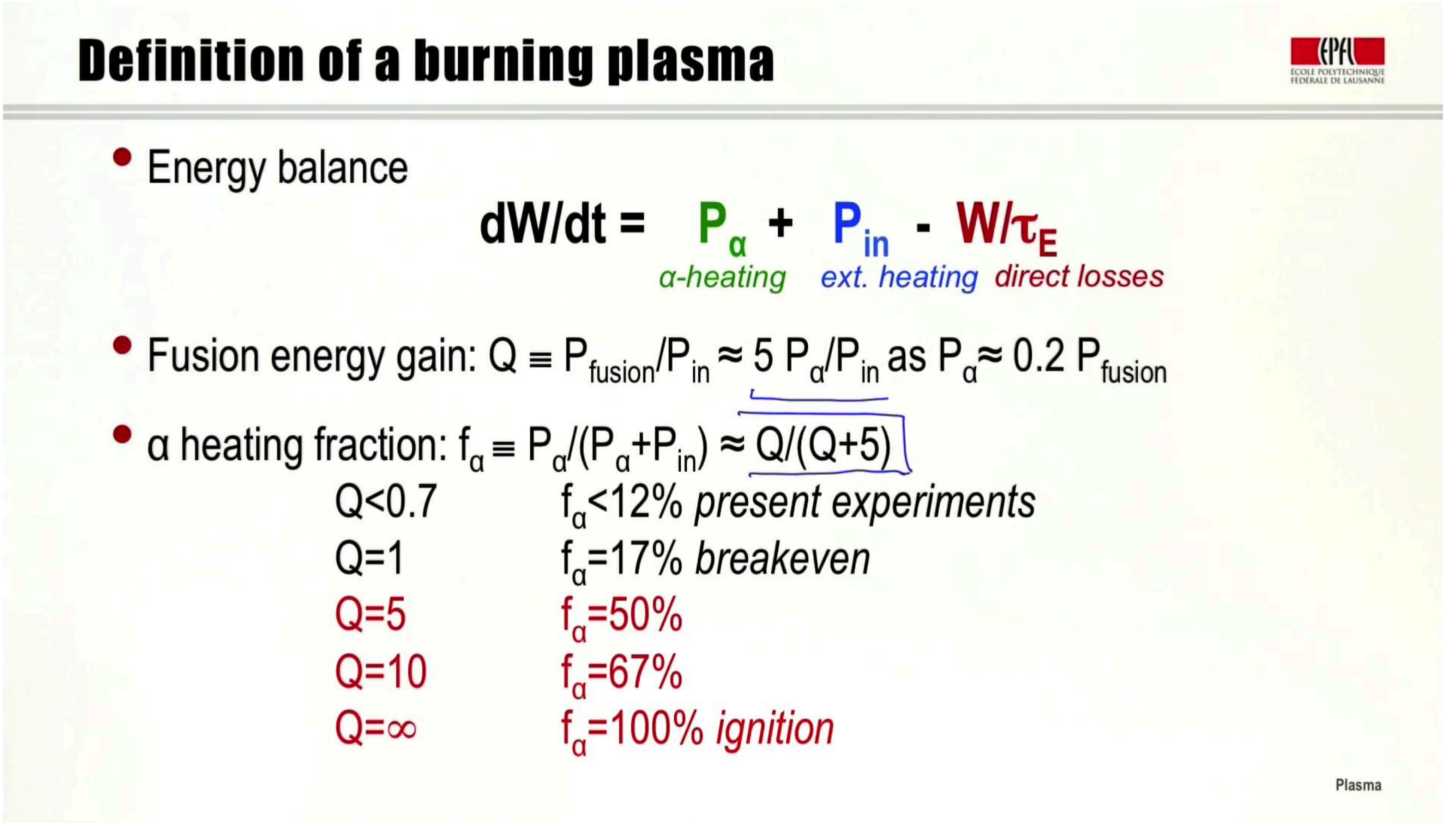
Plasma

I would like to start by reminding ourselves about the DT fusion reaction. The one we'll use for ITER and the first generation of reactors. As we have said already together we have a tritium and a deuterium ion that fuse, producing a neutron, at 14 MeV of energy and a helium nucleus at 3.5 MeV of energy; that's an alpha particle [α-particle] The neutron has two jobs: it will react to the lithium 6 that would be present in the blanket to produce the tritium that we need for the reactions themselves, and of course it will be used to heat a fluid around the plasma that will be used to generate electricity. The α-particle has one single task for us which is very important. It has to be kept in a plasma and heat the plasma ions in the core so that they maintain reactivity. We call that the plasma self-heating.

Notes

Summary

0m 45s

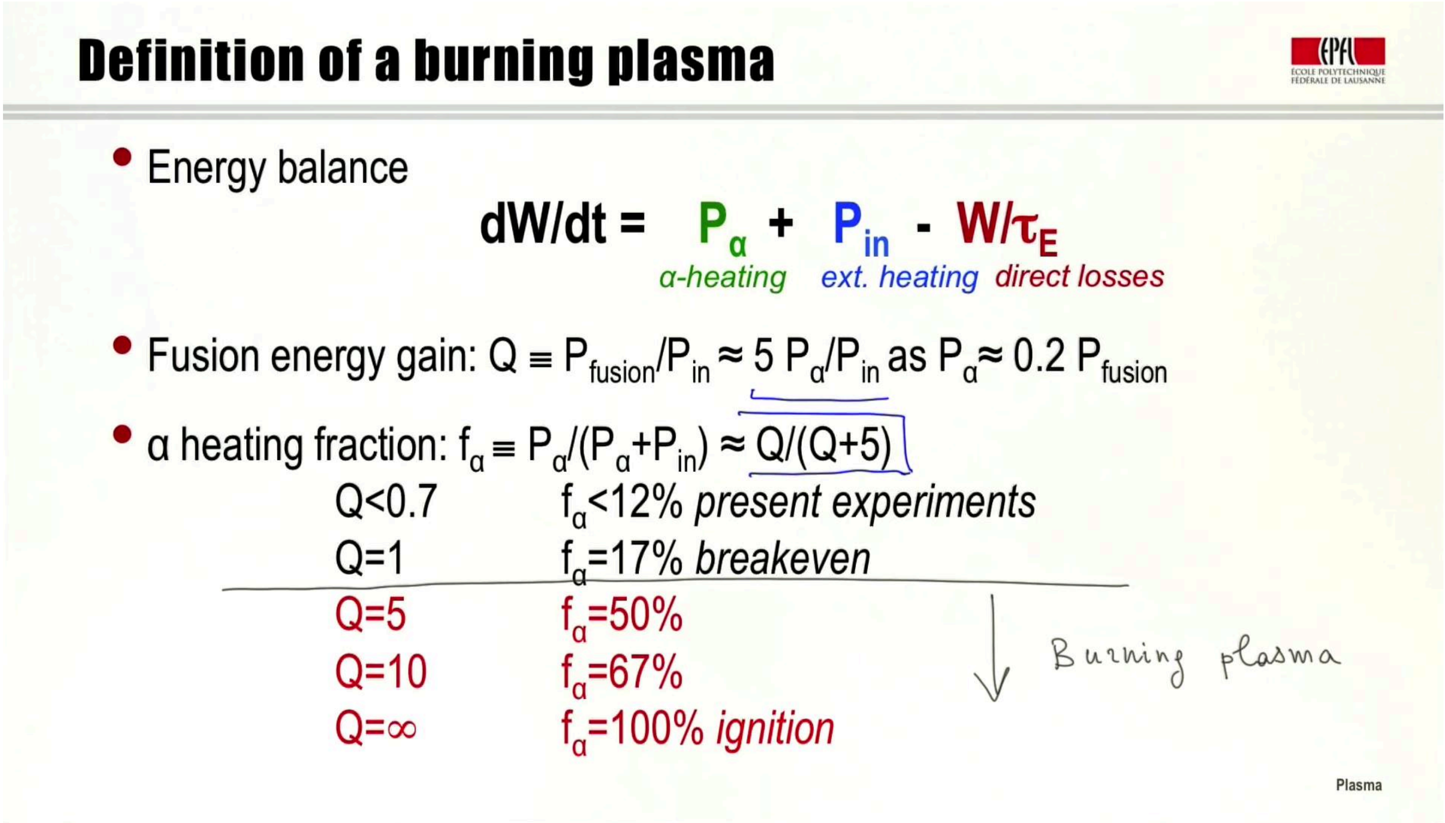


So what is a burning plasma? Let's recall the energy balance. We have a possible variation of the energy contained in a plasma because the α-particles heat it, if we have fusion reactions, or because we put power from the outside, the so-called additional or external heating. And of course with the minus sign we have to include the term for the losses that we have said in the past being dominating in general by direct losses, represented by a single parameter which is the energy confinement time. Let's express the fusion energy gain Q. That's the fusion power divided by the input power, and because the α-power is about one-fifth of the total, we can write - that's about five times the power in the α-particles divided by the input power. So if we are interested in the heating fraction that comes from the α's, the α-heating fraction, fα which is the power in the α's divided by total power, that can be presented in terms of a very simple expression containing Q. That's Q / (Q + 5). So the experiments we have performed so far have reached a Q of less than, say about 0.7, which corresponds to an α-heating fraction of less than 12%. So really the α-heating term is sub-dominant compared to what we heat the plasma with from outside.

Notes

Summary

1m 43s

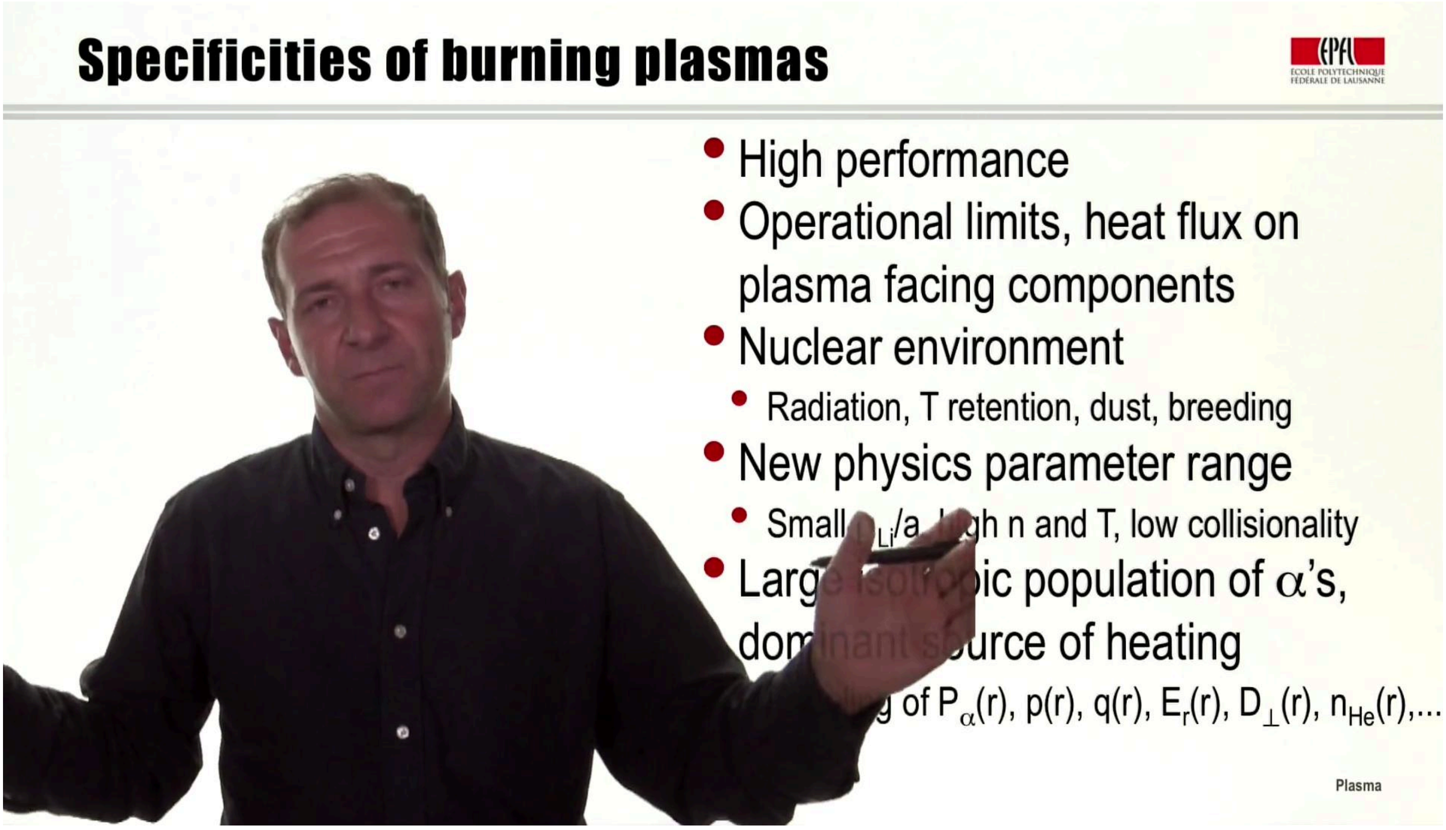


Even here if we had reached *breakeven* which corresponds to Q=1, the α-heating fraction would be only about 17%. So the limit at which we start to have a different regime is Q=5, because at Q=5 we have an α-heating fraction of 50%. So what goes on starting from that value of Q, to higher and higher values of Q's ? It is what we call the burning plasma regime. This is the burning plasma regime because the plasma in a sense is a dominated in its heating by its own by-products. Of course the limit is exactly Q=5 but if you have Q=10 then we have an α-heating fraction which is about 67% and going all the way to 100% when we reach ignition at which point of course the gain goes to infinity.

Notes

Summary

3m 15s

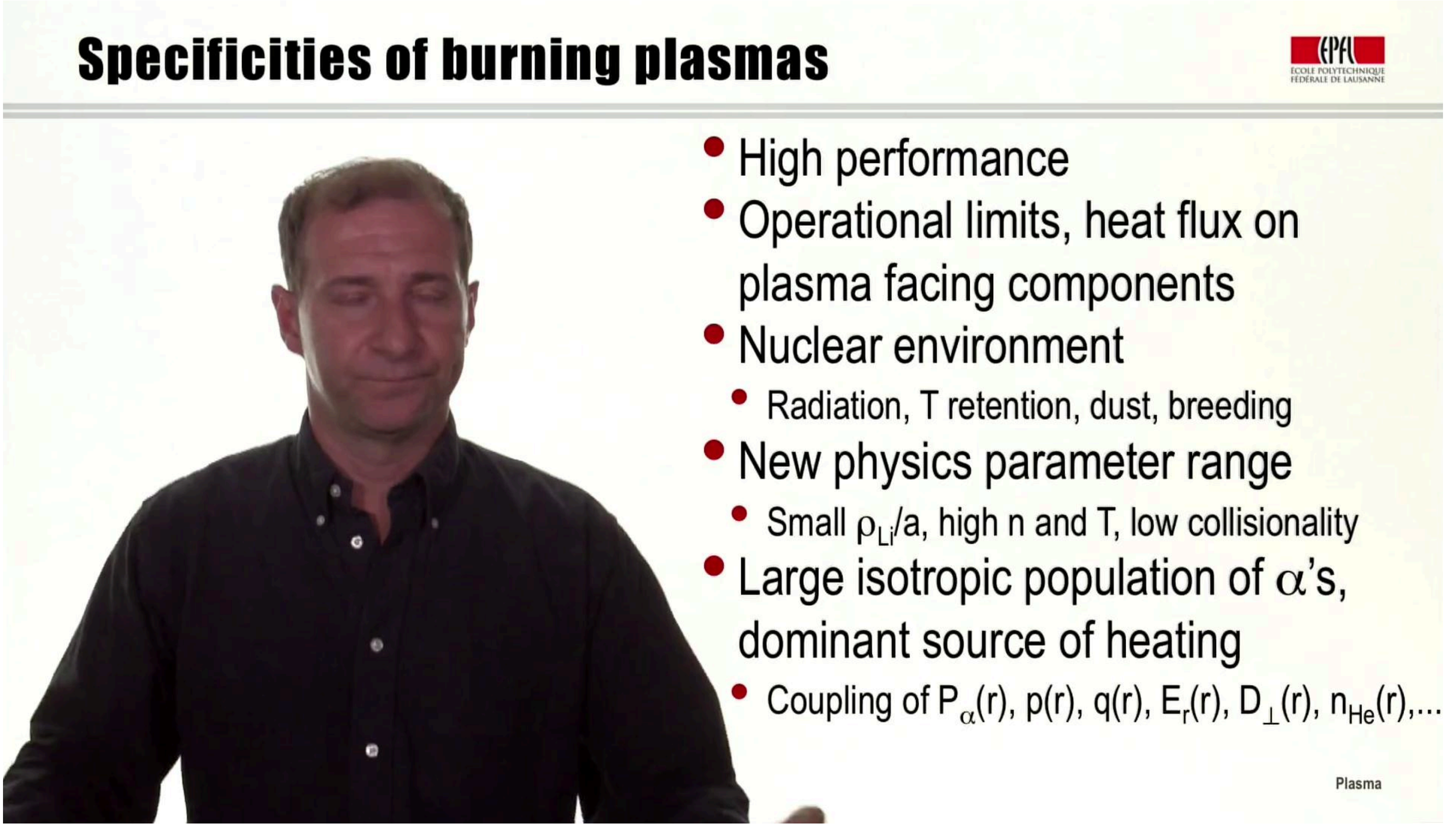


We don’t have burning plasmas as of today. So we can only speculate on what their specificities will be. First of all, we need to reach high performance, so burning plasma would be, sort of by definition, high-performance plasma in a tokamak reactor. It will be close to the operational limits that we can have. It will have very large heat flux on the plasma facing components, as large as you can cope with generally. It would be a nuclear environment, something we don’t have, again, today. There will be a lot of radiation involved, there will be the issue of the retention of tritium, for example in the first wall of the tokamak, there will be the issue of dust production that contains tritium, there will be the issue of course of the need for breeding the tritium using the blanket modules outside the plasma. In terms of the plasma physics specificities, also, we expect something different from today, for a few reasons. First of all, it will be at very high density and temperature compared to what we have today, which implies we are in a regime where we have even lower and lower collisionality compared to what we have today in present devices and perhaps even more importantly in terms of basic physics, we have a very small ratio between the size of the plasma particle orbit and the size of the device.

Notes

Summary

4m 12s



This is not just a detail. This implies that the turbulence, for example, that can develop in the system in which the particle trajectories are much smaller than the typical scale length of the system could be very different. And of course, last but not the least, we have a very large isotropic population of α's which will be, again by definition of a burning plasma, the dominant source of heating. This implies that there will be a coupling between the profile of the α-power, the profile of the pressure of the plasma, the safety factor profile, the profile of the electric field, the profile of transport parameters, the profile of the helium concentration and so on and so forth. So all these elements will be coupled in the burning plasma, whereas in today's experiments, they are completely, or at least partly, decoupled from each other.

Notes

Summary

5m 41s

Building blocks of burning plasma regime

- How to reach burning plasma conditions
  - Heating scenarios (ICRH)
  - Transport and turbulence (isotope effects)
- How to sustain the burning conditions
  - The self-heating process, fast ion losses, the plasma stability in the presence of fast ions
  - Burn stability and control
- Compatibility of burning conditions with reactor operation
  - Plasma wall interaction, power and particle exhaust, He-ashes
  - Heat load, high recycling, radiative fraction, ELM and disruption mitigation
  - Tritium retention and dust production
- Implications for the reactor operation
  - Tritium breeding and burn-up, thermo-dynamical efficiency,…

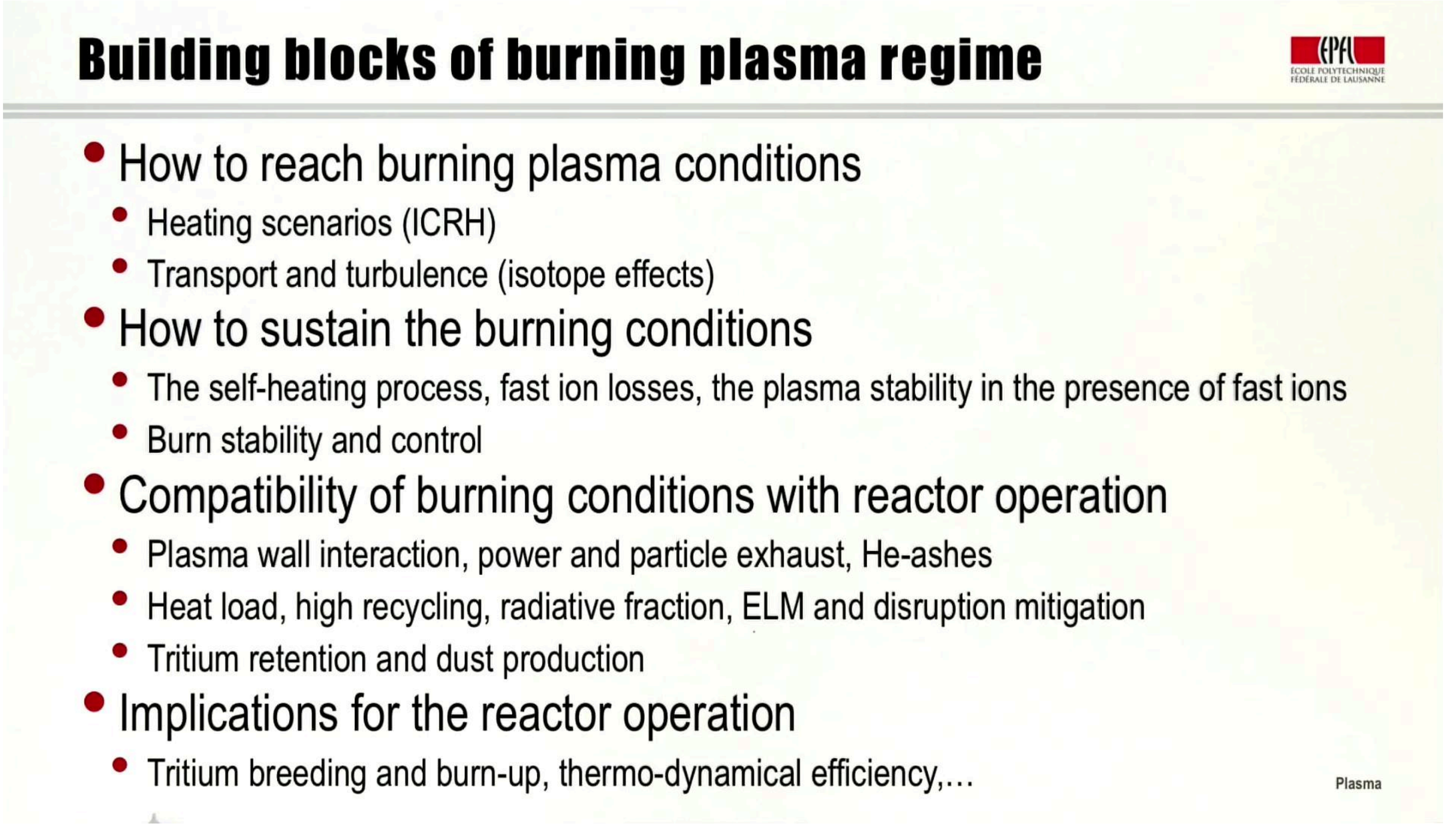
Plasma

These are the main elements that we need to study and issues that we need to solve to get the burning plasma and to control it. First of all, we have to reach the burning plasma condition of course, so we need to identify which heating scenarios, for example, we can have in approaching the burning plasma conditions. We need to understand what a transport and turbulence behavior would be like in these conditions. In particular what would be the effect of different isotopic masses in the plasma. We know that there are differences in the transport that we don't fully understand between for example deuterium and tritium plasmas. We need to learn how to sustain the burning conditions. We need to really make sure that the self-heating process is not affected by any major instabilities or any major problem that can rise in the plasma. Among the problems that we have to worry about are the losses of the fast ions that are of course, those that guarantee the self-heating process in the form of α's produced by fusion reactions. We need to see if the stability of the plasma is affected by the presence of fast ions and in which way is it affected. We also need to have a thought on the stability of the burn and how we control it.

Notes

Summary

6m 32s



Now thinking about the reactor, we need to make sure that the conditions for the plasma to burn are compatible with the operation of a reactor from which we want to extract energy. I'm thinking about the interaction between the plasma and the wall, the exhaust of power and particles, how we get rid of the helium ashes, for example in particular, helium ashes being essentially the α-particles that have given up their energy by collisions, and that we don't need any more in the plasma. We need to worry about the heat loads, the high recycling regimes in which we have a lot of particles that are reinjected in the plasma to the interaction between the plasma itself and the walls. Operating with a large fraction of power that is radiated out from the plasma. How we can mitigate disruptions and other violent events at the plasma edge, such as the *Edge Localized Modes* that we have investigated briefly in the previous lecture. We have to worry about the retention of tritium in the walls and avoid or limit the production of dust. We also need to see how these phenomena can be extrapolated and what they imply for the operation of the reactor.

Notes

Summary

7m 52s

Building blocks of burning plasma regime

- How to reach burning plasma conditions
  - Heating scenarios (ICRH)
  - Transport and turbulence (isotope effects)
- How to sustain the burning conditions
  - The self-heating process, fast ion losses, the plasma stability in the presence of fast ions
  - Burn stability and control
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  - Tritium retention and dust production
- Implications for the reactor operation
  - Tritium breeding and burn-up, thermo-dynamical efficiency,…

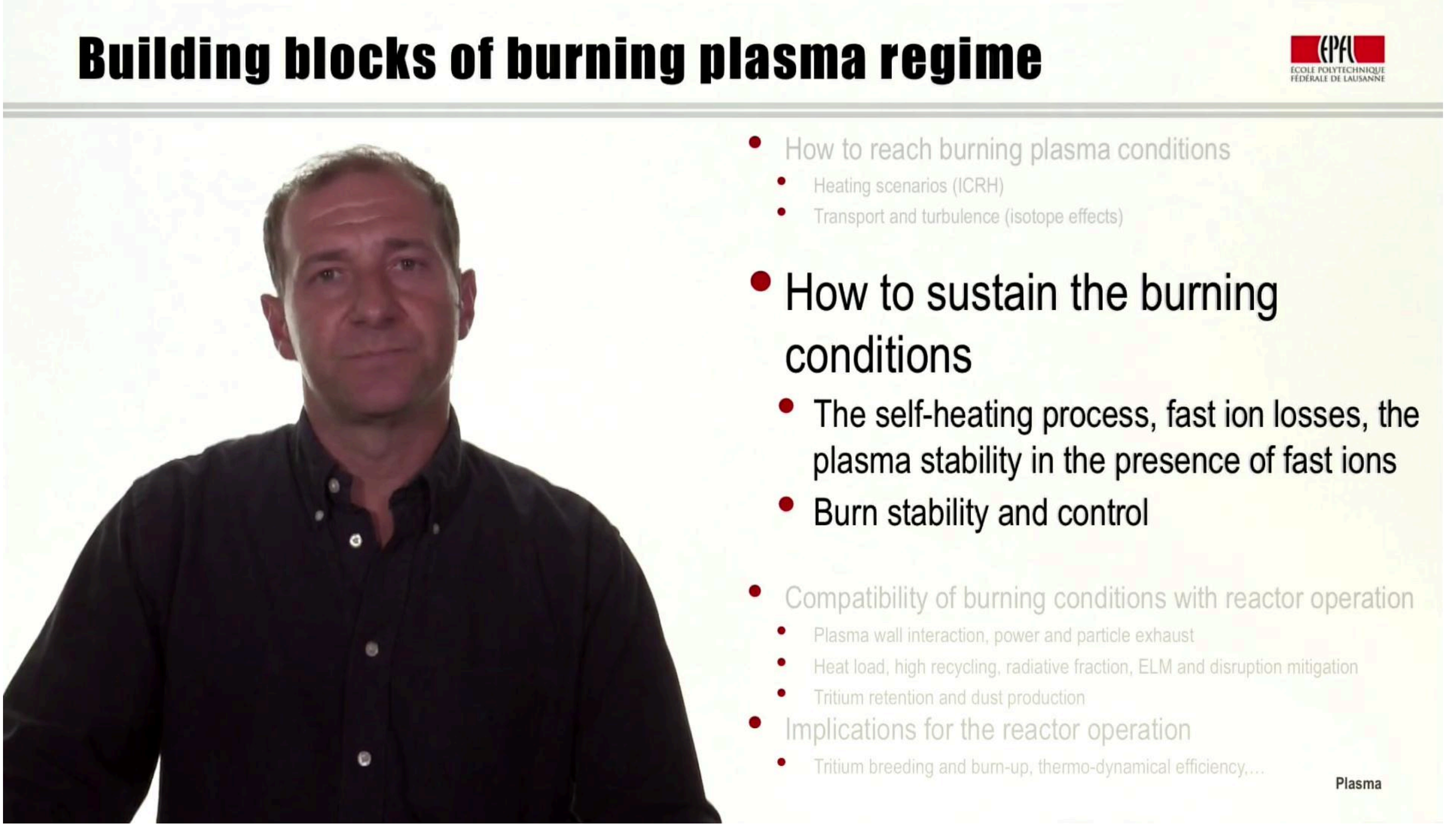
Plasma

We need to worry about breeding tritium, which is a very important element for the economy of fusion in the future, how we can burn tritium efficiently, and the thermo-dynamical efficiency of the reactor itself, for example, giving some constraints on the operational temperatures for the reactor and so on, and so forth.

Notes

Summary

9m 12s

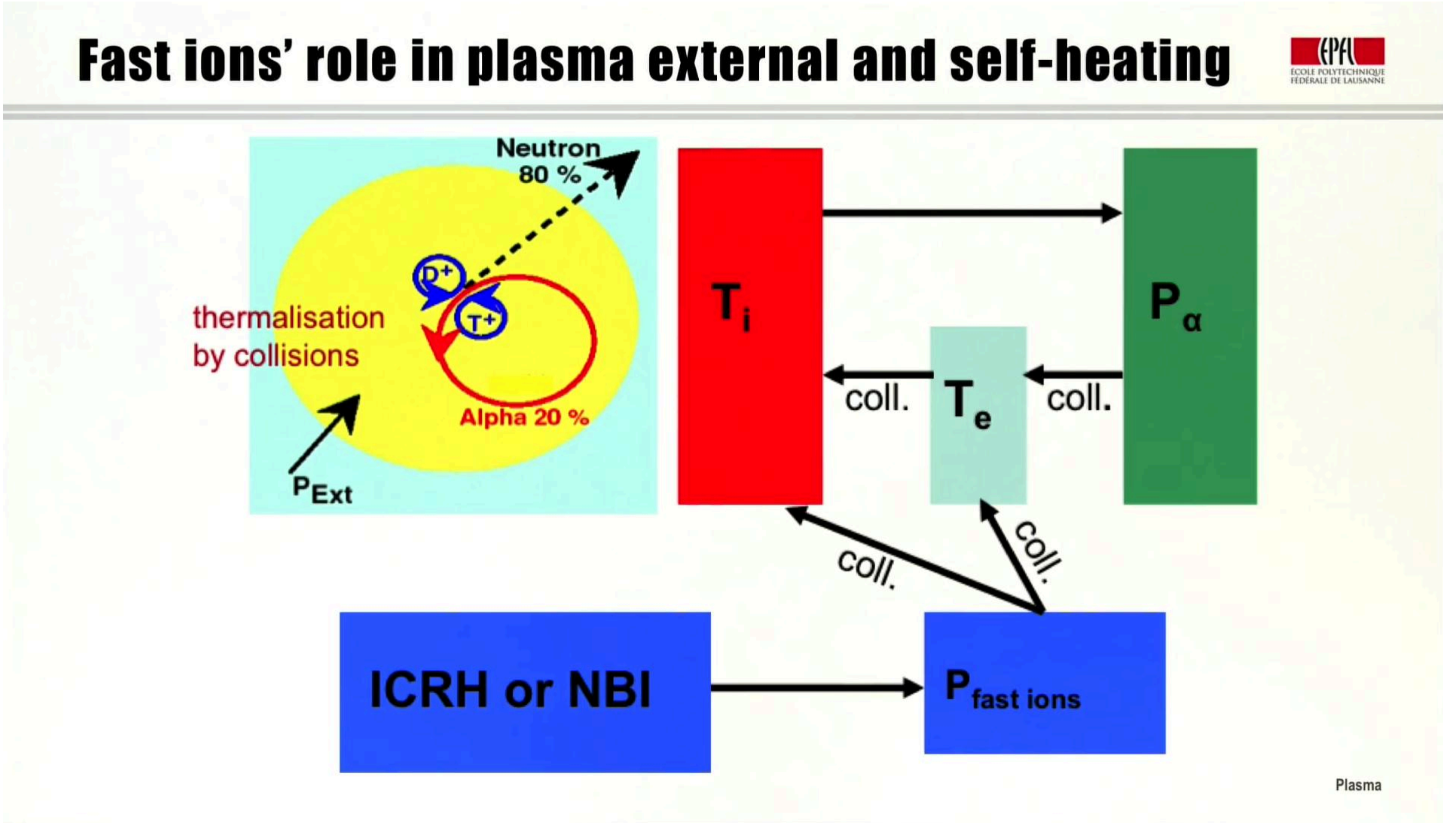


These are many, many elements that one needs to look at for a burning plasma and for a reactor to be compatible with burning plasma. Now we don’t have the pretention to really investigate all of these in this lecture, in this course. I like just to give a few highlights about the specific chapter in which we discuss how we can sustain the burning conditions. So we'll look at the self-heating process, the fast ion losses, the stability of the plasma in the presence of fast ions, and we'll say just a few words about the control of the burn and its stability.

Notes

Summary

9m 31s

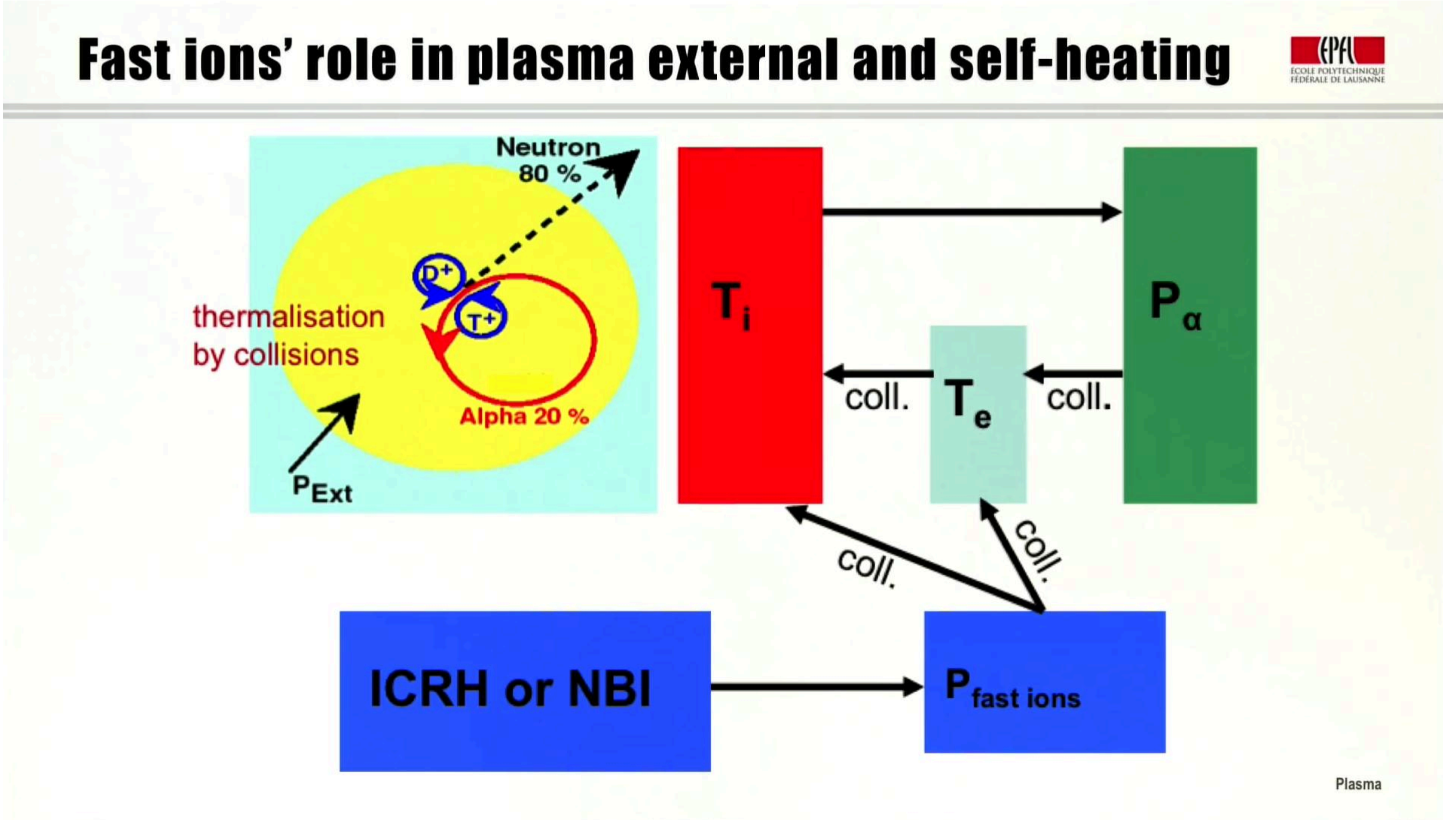


So why are fast ions so important in the plasma external and self-heating process? I remind that here in this sketch, we of course here have the plasma in which inject power from outside and we have reactions that produce α-particles which carry about 20% of the energy which must be kept in the plasma. And the neutrons that come out of the plasma with about 80% of energy. So the loop works as follows: we heat the ions, they fuse, they produce α-particles and therefore a significant α-particles power. Which will therefore, subsequently, be given to the electrons via collisional process. As we have seen when we discussed the neutral beam injection heating method, if the energy of the fast particles is very large, the collisional process will first give this energy to the electrons rather than to the ions. This is why I have represented this loop as the collisional processes giving energy from the α's to the electrons, which in turn have to thermalize on the ions. It will be sort of indirect heating of the ions via the electrons. This is if we count on the α-particle heating, but similarly we have the same situation for the fast ions if we count on ICRH or NBI, because in those cases you produce fast ions they will then again, depending on the energy, giving it to the electrons or directly to the ions.

Notes

Summary

10m 03s



So fast ions are very important in the process of heating a plasma both from external sources, at least for ICRH or NBI, and for the self-heating via the α's.

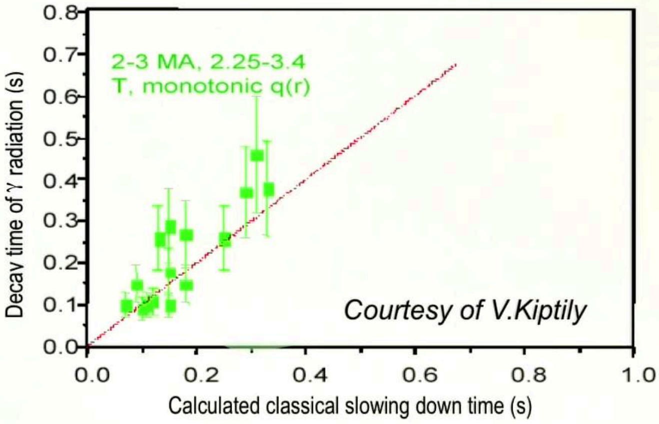
Notes

Summary

11m 36s

Collisional slowing down of fusion α's

- Trace Tritium experiments in JET – DT fusion reactions between beam tritons and plasma deuterons produce 3.5MeV α's
- Emission profiles of γ-rays from reaction $^{9}Be(\alpha,n\gamma)^{12}C$ ($E_\alpha \geq 2MeV$)
- Decay time of γ radiation provides estimate of slowing down time of α's and of beam tritons on electrons
- In quiescent plasmas, slowing down follows classical theory



Plasma

This is just to sketch, sort of what we hope the fusion process will be like. We count on the α's slowing down collisionally on the background electrons and ions. Is that really happening? A number of experiments have been performed to verify that. Take one example here to check that in a simple situation, that indeed is the case. Here we see the result of a trace tritium experiment in JET. Very small amounts of tritium are injected in a deuteron plasma with blips of the neutral beam injector in which we put tritium. So what we cause are DT fusion reactions which in the tritons injected by the beam and the plasma which contains deuterons. And of course this DT reactions produce 3.5 MeV α's, just like any DT reaction. What we're looking at in practice are the emission profiles of γ-rays which are issued from the reaction of the high energy α's with beryllium impurities that are present in the plasma. Now the interesting property of this reaction is that it's a treshold reaction. In other words it happens only if the α's have a certain energy, typically above 2 MeV. So the emission of γ-rays is a signature of the presence of α's with an energy that's about 2 MeV or more.

Notes

Summary

11m 47s

Collisional slowing down of fusion α's

- Trace Tritium experiments in JET – DT fusion reactions between beam tritons and plasma deuterons produce 3.5MeV α's
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- Decay time of γ radiation provides estimate of slowing down time of α's and of beam tritons on electrons
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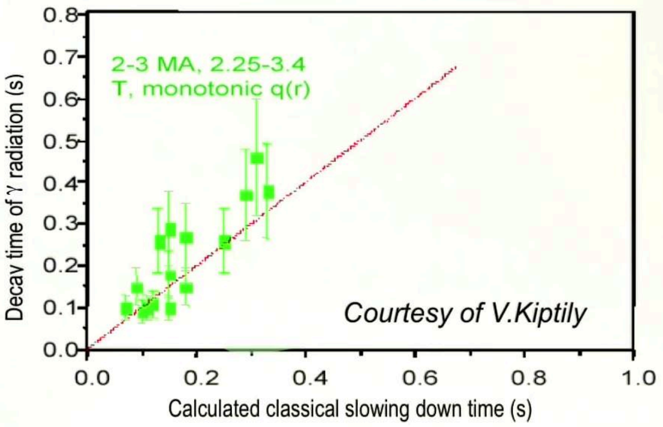


Plasma

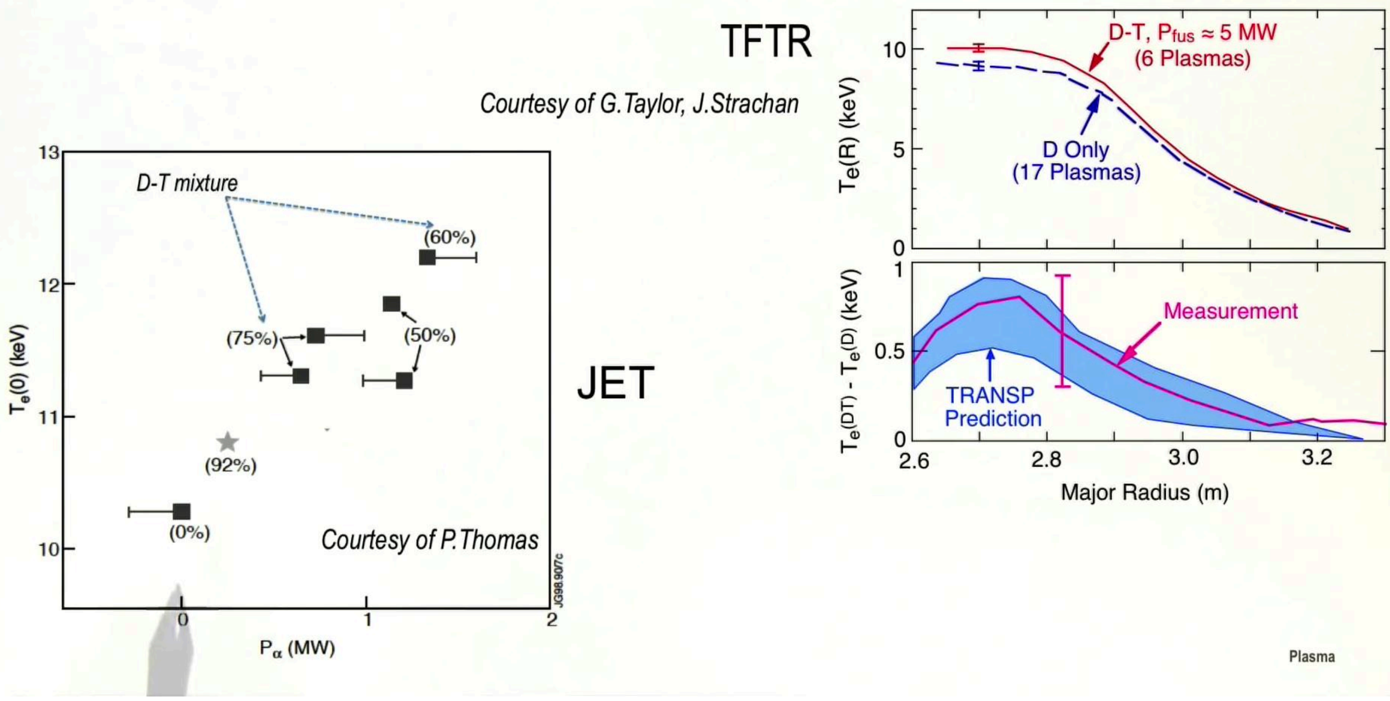
We can therefore take the decay time of such an emission, or in practice decay time of the measured radiation in the γ range of frequencies to get an estimate of the slowing down time of the α's and of course of the beam tritons, slowing down time that is supposed to be given by the interaction with electrons. And that's what we see in this plot. This is in the vertical direction, the decay time of the γ radiation as a function of the calculated slowing down time according to classical theory. And we see that in the situation which we have a few MA of current in the JET tokamak, and the magnetic field between 2.2 and 3.5 tesla, around that, we have a very good correspondence between the two typical characteristic times. So in these plasmas which are quiescent, so we don't have any major instabilities present. The slowing down that we observe, indeed follows classical theory. So everything seems to work according to what we expect.

Notes

Summary

13m 16s

Electron heating by fusion α's

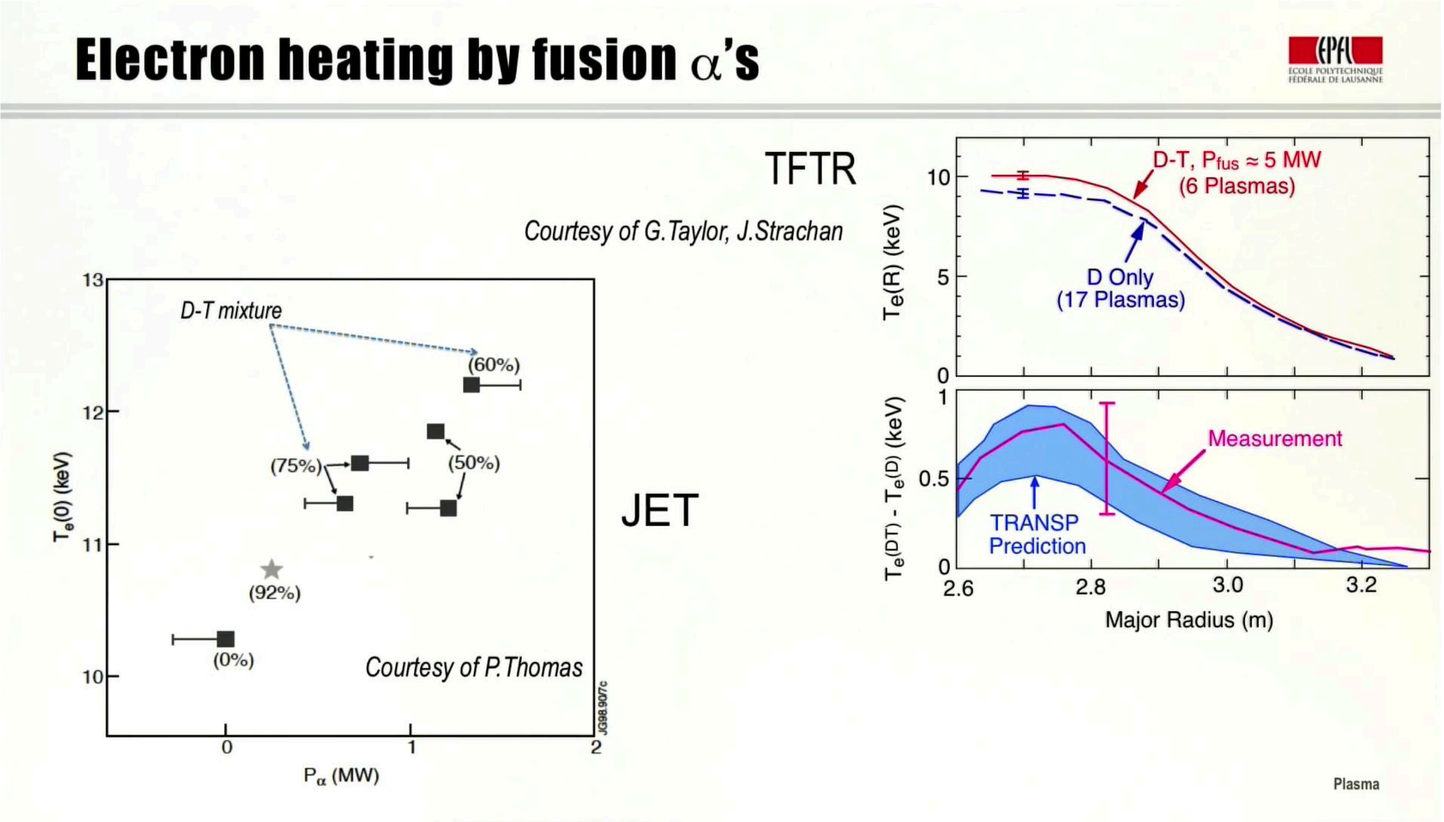


If the α's slow down collisionally on electrons as classical theory predicts, we should see from the point of view of electrons, an increase in the temperature. Because the power from the α's goes directly to the electrons. That was the purpose of two very significant experiments in the TFTR. The tokamak at Princeton, USA and in JET. First in TFTR, the electron heating by the α's was seen quite clearly comparing in deuterium only plasma which is in blue here. This is the profile of the electron temperature with a very similar plasma but in which there is a 50-50 mixture of deuterium and tritium. And you see there is a significant difference or at least a measurable difference between the two profiles in the presence of DT which means in the presence of α-particles. There is a heating by electrons. If we take the difference between the DT case and the pure deuterium case, this difference appears of course in a much more clear way. And you can see that, that difference occurs more in the core of the plasma where the α-particle power is deposited. A similar experiment was performed at JET as well. Here we plot the results in a somewhat different way: it is the core electron temperature as a function of the α-particle power from the fusion reactions.

Notes

Summary

14m 28s

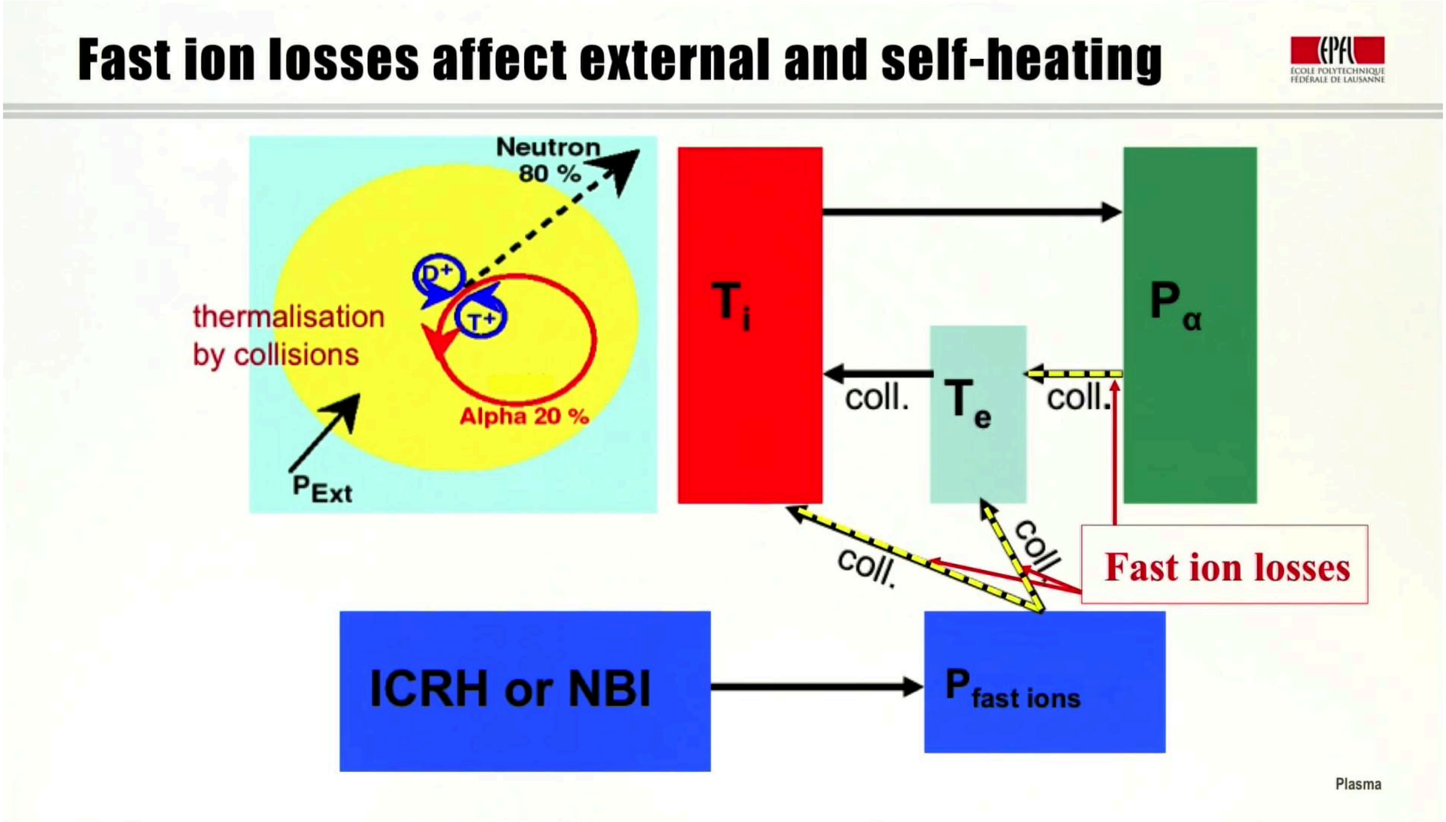


And we can see that we have different mixtures of DT indicated in the brackets here from 0% to say around 50-60%. Of course 0% or even close to 100% the effect is zero, in the sense there is no heating of the electrons because of the α-particle power because there is essentially no DT reaction taking place. The optimal situation, is close to 50% where we have about 1.2, 1.3 MW of α-particle power and that results in a very clearly measurable heating of the electrons in the core. So α's are doing their job. They're slowing down collisioning on electrons and they're giving their power to the electron channel.

Notes

Summary

16m 02s

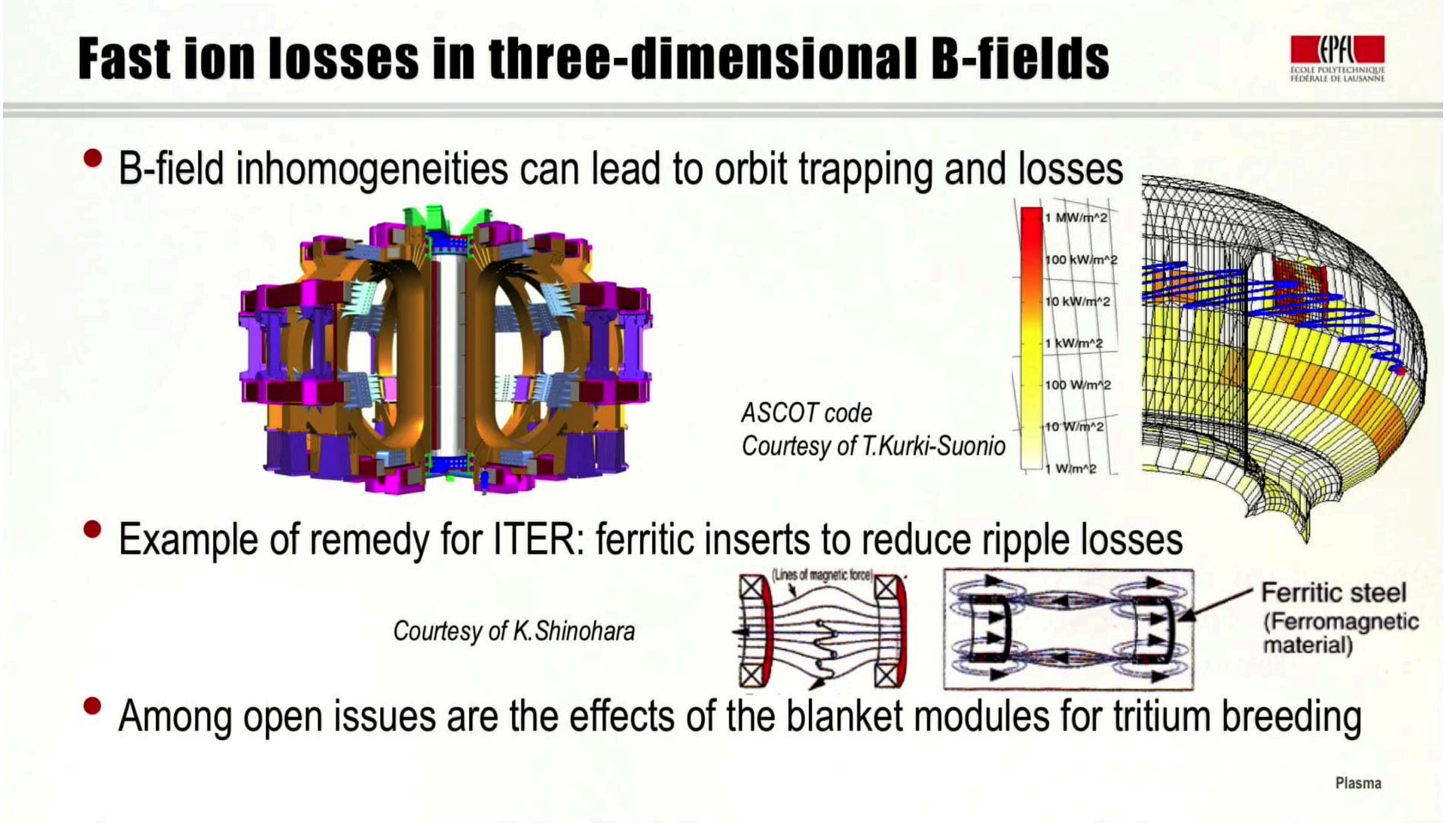


So why do we have to worry about these self-heating processes or external heating process? Well the question is whether that collisional slowing down is always happening in the way we hope it would happen as we have just seen in the two very simple situations in that there were no major instabilities, no major pertubations to the quiescent plasma. What we worry about is if we have fast ion losses for different reasons, then they will influence the power that will be transferred from the α's to the electrons as well as the power that will be transferred from the fast ions issued by collisional, by additional heating. In this case power can be transferred to electrons or to the ions depending on the energy of the fast ions. But in all of these cases, if fast ion losses are present, this transfer will be affected and therefore, the plasma will not be heated efficiently.

Notes

Summary

16m 50s

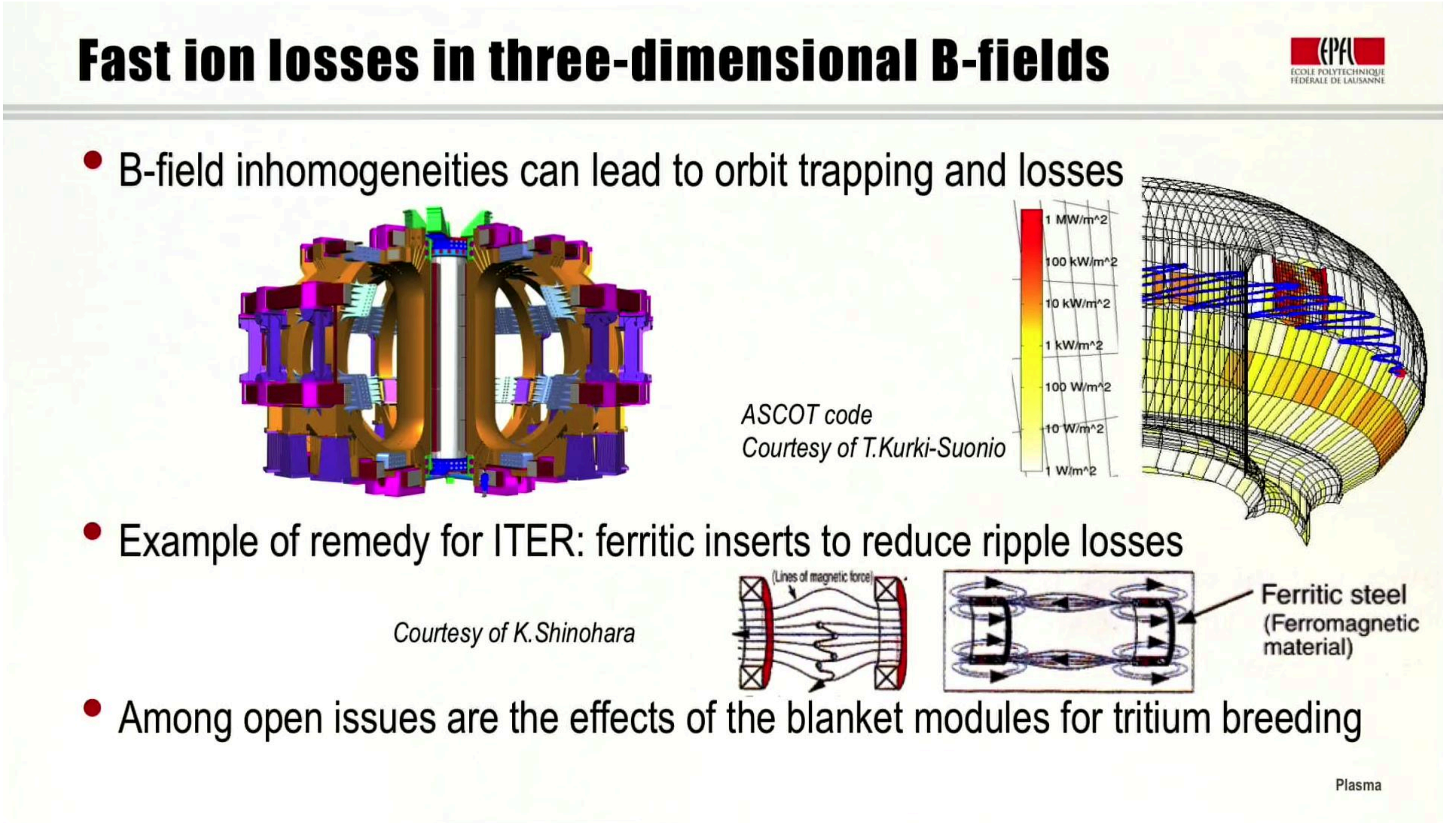


So what mechanics can we have to lose fast ions in a actual tokamak plasma? First of all, we worry about fast ion losses that can happen because of the 3D nature of the magnetic fields. In a practical situation of a tokamak, the number of coils is of course, finite. So if I go around the torus being a charged particle, I don't feel a complete uniform magnetic field, I will feel inhomogeneities, in the intensity of the field. Just below the coil it will be more intense, in between coils it will be weaker. And as a charged particle feels a inhomogeneity magnetic field, it can be subject to trapping. And if particles are subject to trapping, they will not go around the torus, they will not feel the field of the tokamak that we have set up so carefully to compensate the various drifts, and therefore get out of the confinement region being trapped in between coils and then drifting out providing direct losses. These are the so-called *ripple losses* because they are caused once more by the inhomogeneity of the magnetic field due to the number of coils that's finite, which can be simply be called the ripple of the field, felt by the fast particles in their motion around the torus.

Notes

Summary

17m 44s

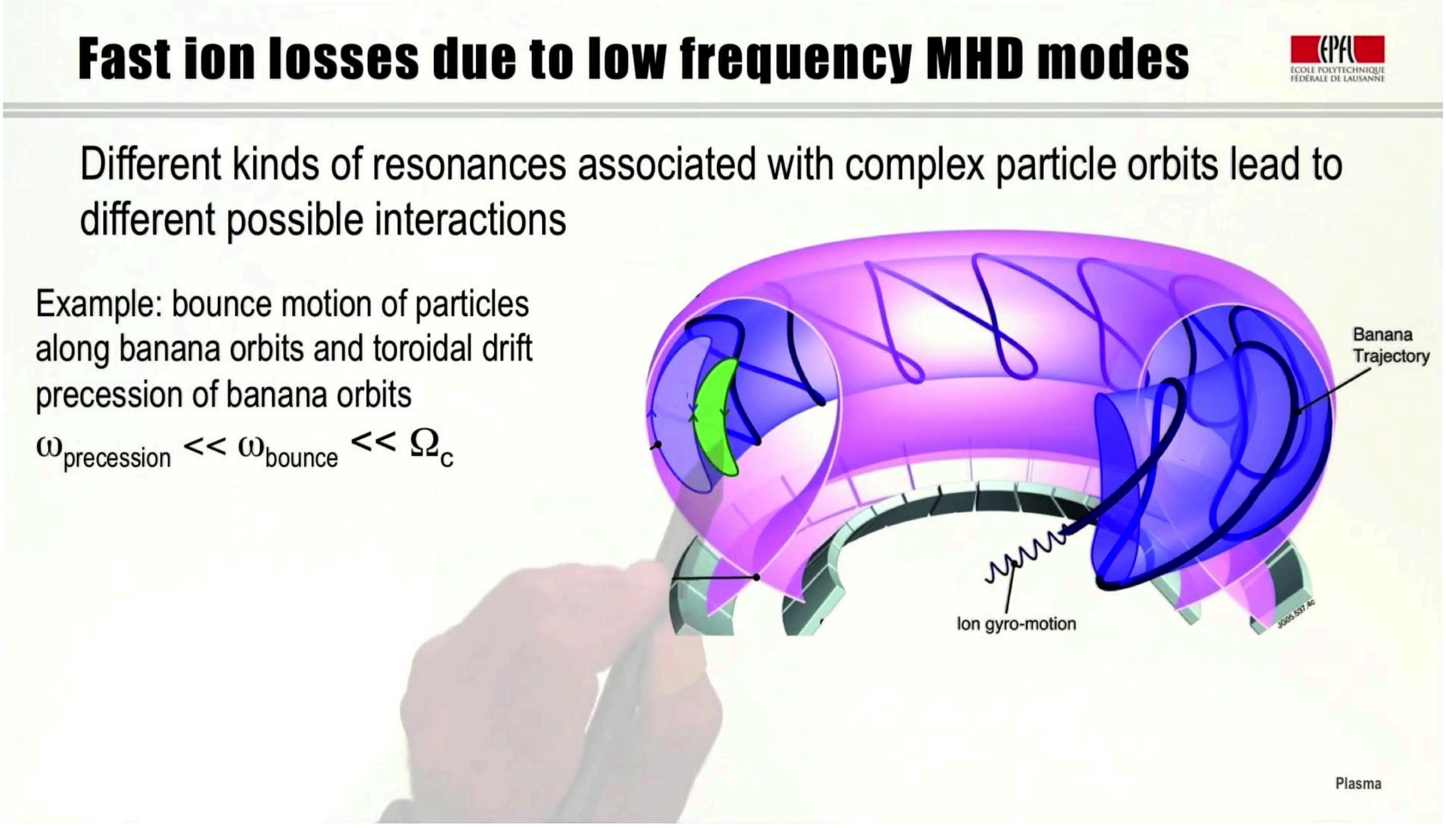


This is something that can be calculated fairly accurately. An example or remedy for a particular scenario ITER is illustrated here. One can actually insert ferritic materials so high μ material to smooth out these variations and reduce losses significantly. This kind of solution is already foreseen for ITER, even considered for the steps after ITER but there is still a few open issues that one needs to address. One of them is the effect of the blanket modules which contain ferromagnetic material, therefore possible perturbations to the field structure. Blanket module are of course necessary for tritium breeding.

Notes

Summary

19m 11s

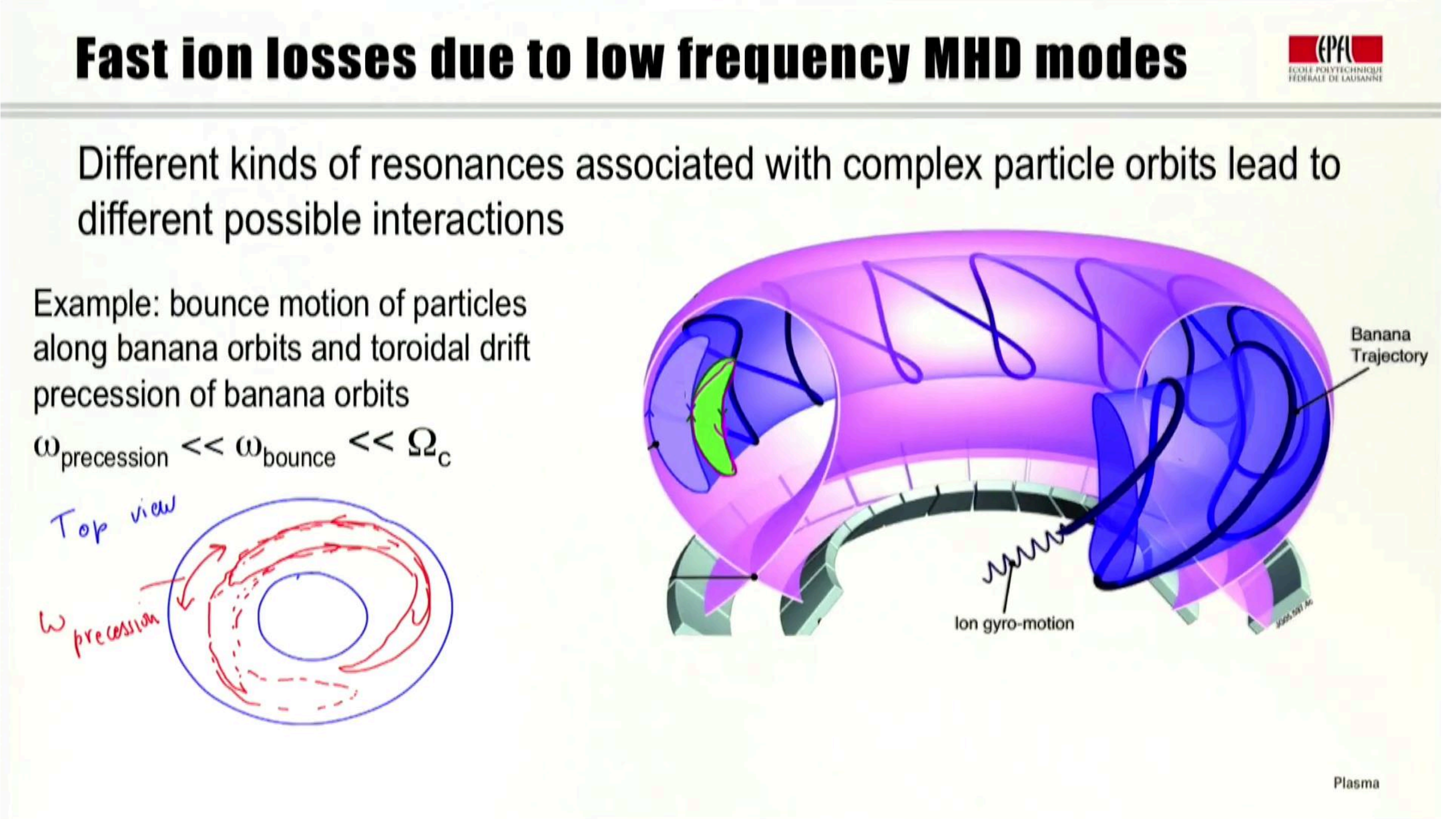


Fast ion losses can also happen because of low frequency magnetohydrodynamics modes. There are many modes that are possible. We illustrate a couple of examples. In general, different kinds of resonances can be associated with the complex particle orbits and lead to different possible interactions. This image that we have seen in previous parts of the course, illustrates the complexity of the orbits in a tokamak, for ions, for example. Of course you have the fast gyromotion around a field lines which is associated with the cyclotron frequency, and that's one resonance. But now we consider much smaller frequencies, much slower time scales. Now we have seen already that the motion of the ions around the tokamak is actually characterized by what we call *banana orbits* which are orbits that are produced by the fact that the particles feel regions of different strengths in a magnetic field and therefore are trapped. And the turning points of this trapping motion are related to the in-out asymmetry of the field. If we project these orbits on a poloidal plane, they look like bananas so we refer to them as banana orbits.

Notes

Summary

19m 50s



And if we look at the motion of the particles along these orbits, if we see again in the poloidal plane, the particles will go around. So there will be a frequency associated with this motion around the banana orbit. And that's one of the frequencies that we can have coinciding with the frequency of an instability. And of course, when the frequency of a motion of a particle coincides with the frequency of an instability, you can have a very efficient exchange of energy momentum. You can have very efficient drive of an MHD instability. Another example is that of the so-called precession or *drift precession* of the banana orbits. For that let's illustrate it with a plot from the top. This is a top view of a tokamak we have seen that the particle orbits can be trapped and therefore not complete a full toroidal circumference. But in fact there is some asymmetry between the - if you like the trajectory forward and the return of the trajectory, so that this orbit will slowly drift in one particular toroidal direction. It is as if the banana orbit would go in fact, around the torus, seen from the top. And the frequency associated with that is a so-called *precession frequency*.

Notes

Summary

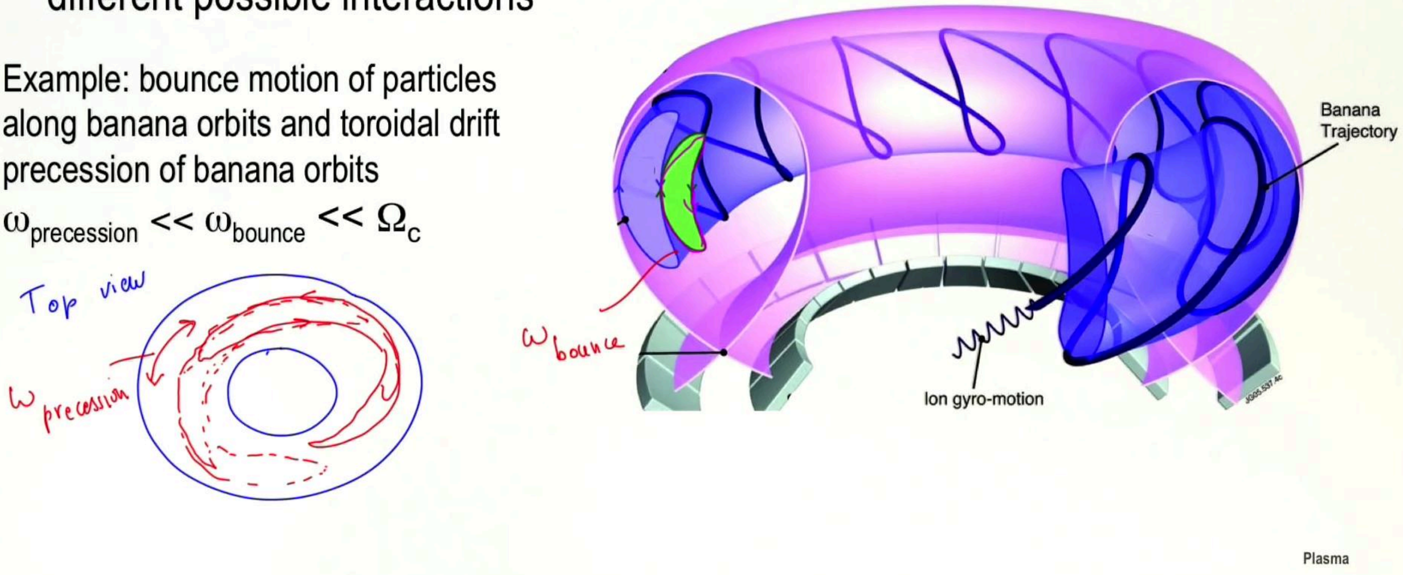
21m 10s

Fast ion losses due to low frequency MHD modes

Different kinds of resonances associated with complex particle orbits lead to different possible interactions

Example: bounce motion of particles along banana orbits and toroidal drift precession of banana orbits

$\omega_{precession} << \omega_{bounce} << \Omega_c$



That is slower than the frequency associated with the motion of the particle along the banana orbit itself which is referred to as the *bounce frequency*. So we have, just using these two examples, two possible frequencies for possible resonances with plasma instabilities. The precession frequency of the particle drift around the torus and the bounce frequency of the particle around the banana orbit. Both of these frequencies are much, much smaller than the cyclotron frequency and, therefore, can lead to resonances with low frequency global modes of the MHD kind.

Notes

Summary

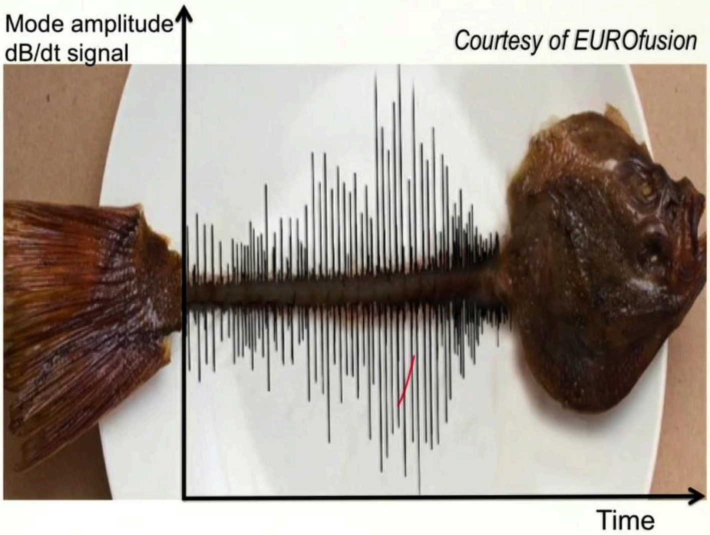
22m 33s

Fast ion losses due to low frequency MHD modes

Example 1 - the *fishbone* instability

Resonant de-stabilisation of an MHD kink mode with $\omega = \omega_{\text{precession, fast ions}}$

Driven by the fast ions, the mode can reach amplitudes that cause ejection of the fast ions themselves - the mode then disappears as its source is gone - a sequence of bursts can occur



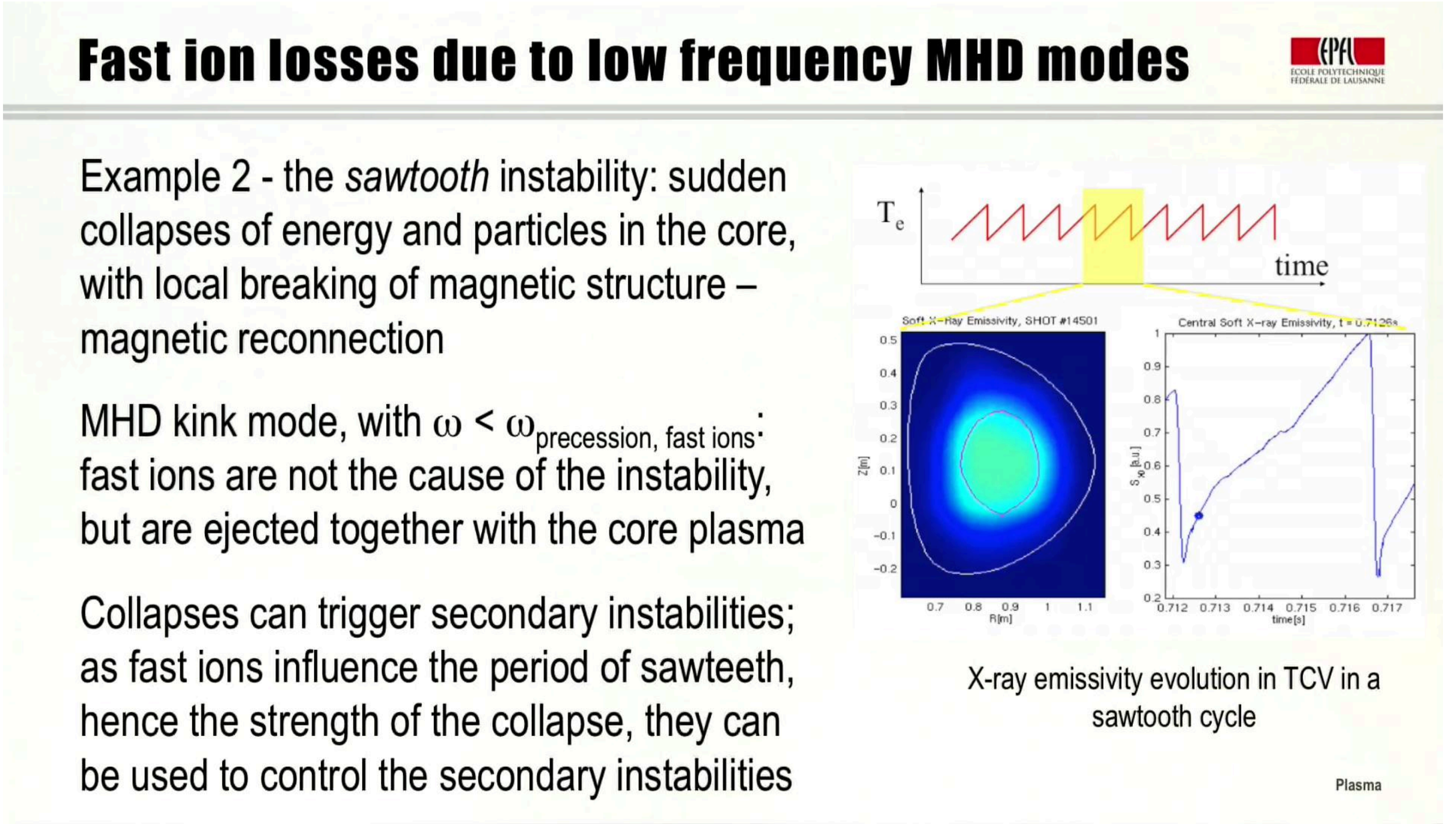
Plasma

And I'd like to take two examples for two of these modes. The first one is the so-called *fishbone instability*. It's a name that was given historically because the signal associated with the perturbation that was observed in a plasma, would have a character of bursts going up. For example in the perturbed magnetic field in a plasma. This is measured typically by a coil mounted on the vessel, so facing the edge of the plasma. It would go up and down with typical occillations that would remind you of the fishbone shape. And that's why in this plot we have a plot on top of an actual fish. This instability is now being understood theoretically as a resulting from the resonant de-stabilization of a kink mode inside the plasma. Resonanr de-stabilization that occurs because the mode frequency coincides with the precession frequency for the fast ions. And the precession frequency is what we have described just two minutes ago. The point is that this kind of modes is driven by the fast ions but in turn can reach amplitudes that cause ejection of the fast ions themselves. Now once you eject the fast ions, this was a source of instability itself, the mode will die again because the source is gone, and there will be a sequence of bursts that will occur. Each burst will lead to ejection of fast ions and therefore reduction in the core performance of the fusion reactor.

Notes

Summary

23m 12s



The second example is even more ubiquitous, it is the so-called *sawtooth* instability. This is an instability that leads to a series of sudden collapses of energy and particles in the core, represented by this shape. And that's why we refer to it as a sawtooth. In this case, I represented the temperature as a function of time. When the collapse occurs, in fact there is a local breaking of the magnetic structure, just like what happens in the geomagnetic tail. in a phenomenon you have seen in other lectures of this course, called *magnetic reconnection*. This is linked to an MHD instability of the kink type, which we have also illustrated to you in previous lectures. But the frequency is even smaller than the precession frequency for the fast ions, so this is not really a resonant and driven instability in the sense of a wave particle resonance with the fast ions, nevertheless, the fast ions are affected by the instability because they are ejected together with the parts of the core plasma. This phenomenon, in fact, is being illustrated as we speak on the little movie on the right which shows the X-ray emissivity evolution in the TCV tokamak over a sawtooth cycle.

Notes

Summary

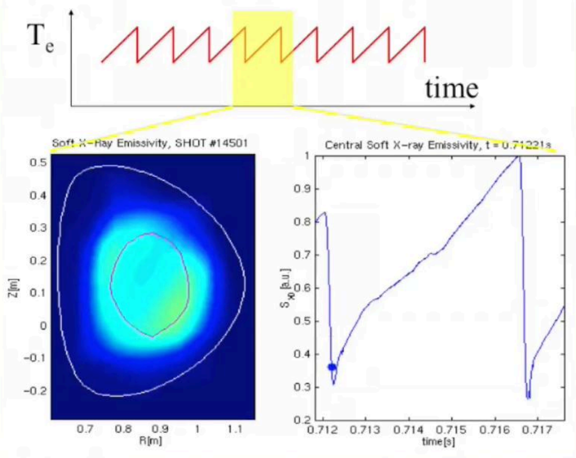
24m 50s

Fast ion losses due to low frequency MHD modes

Example 2 - the *sawtooth* instability: sudden collapses of energy and particles in the core, with local breaking of magnetic structure – magnetic reconnection

MHD kink mode, with $\omega < \omega_{\text{precession, fast ions}}$: fast ions are not the cause of the instability, but are ejected together with the core plasma

Collapses can trigger secondary instabilities; as fast ions influence the period of sawteeth, hence the strength of the collapse, they can be used to control the secondary instabilities



X-ray emissivity evolution in TCV in a sawtooth cycle

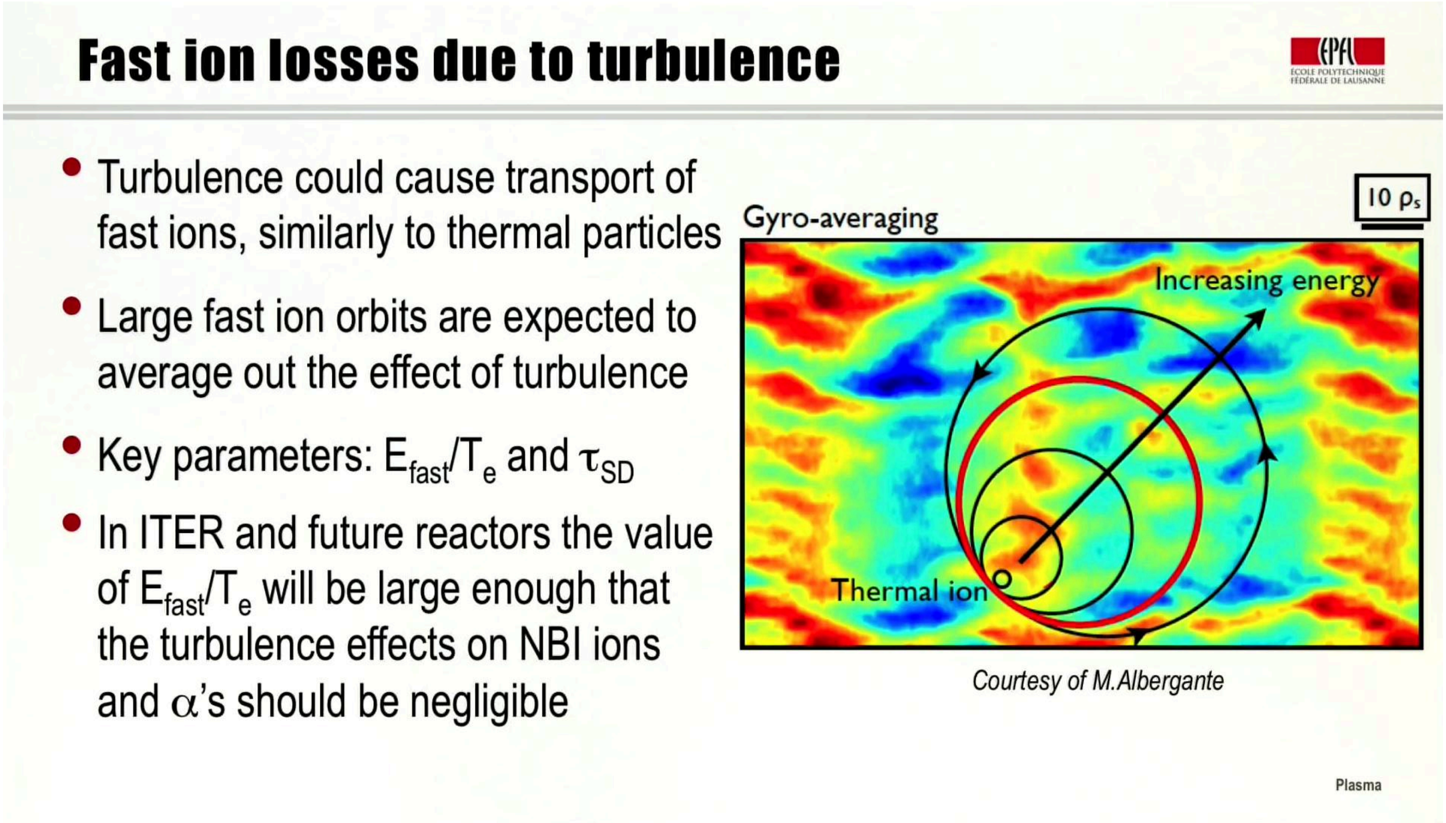
Plasma

This sudden collapses not only are they a problem, because they kick out the fast ions and the core of the plasma or they re-distribute the central region of the plasma, but also they can trigger secondary instabilities. Because the fast ions influence the period of the sawteeth, which in turn determines the strength of the collapse, the fast ions can be used to control these modes and therefore, to control the secondary instabilities. And this is really a very active line of research.

Notes

Summary

26m 07s



Another possible channel for losing fast ions is the plasma turbulence. In fact one can argue in a plasma turbulence can cause transport of fast ions similarly, to what it does to thermal particles. So this turbulent structures would kick fast ions out as they do with the thermal ions and thermal electrons. However, we have a good piece of news here, because the fast ions are characterized by relatively large orbits. These large orbits are expected to average out the effect of turbulence. And this plot we illustrate that phenomenon. So if you have a thermal ion which has a very small orbit, it will be influenced by the electric field of the turbulence in one particular direction. It will receive a kick in one particular direction and it will be therefore affected in its confinement and its transport. As I increase the size of the orbit of the ion by increasing typically its energy, I increase the number of turbulent eddies or turbulent structures, that the fast ion interacts with over one orbit and therefore, receiving kicks in different directions along one orbit. These kicks will therefore be averaged out and the net effect will be reduced to zero.

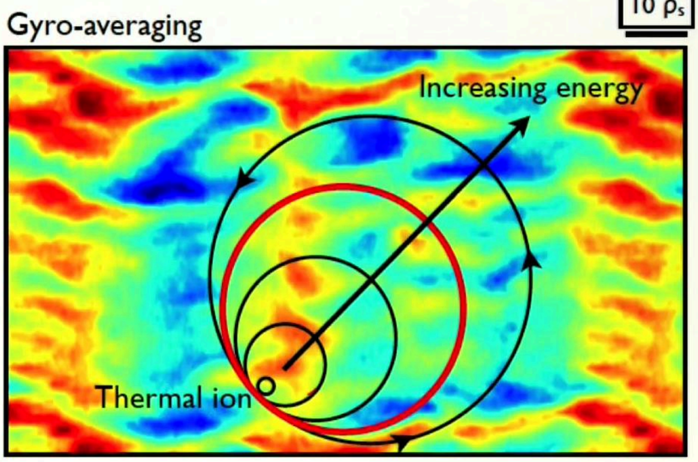
Notes

Summary

26m 43s

Fast ion losses due to turbulence

- Turbulence could cause transport of fast ions, similarly to thermal particles
- Large fast ion orbits are expected to average out the effect of turbulence
- Key parameters: E_{fast}/T_e and τ_{SD}
- In ITER and future reactors the value of E_{fast}/T_e will be large enough that the turbulence effects on NBI ions and α's should be negligible



Courtesy of M.Albergante

Plasma

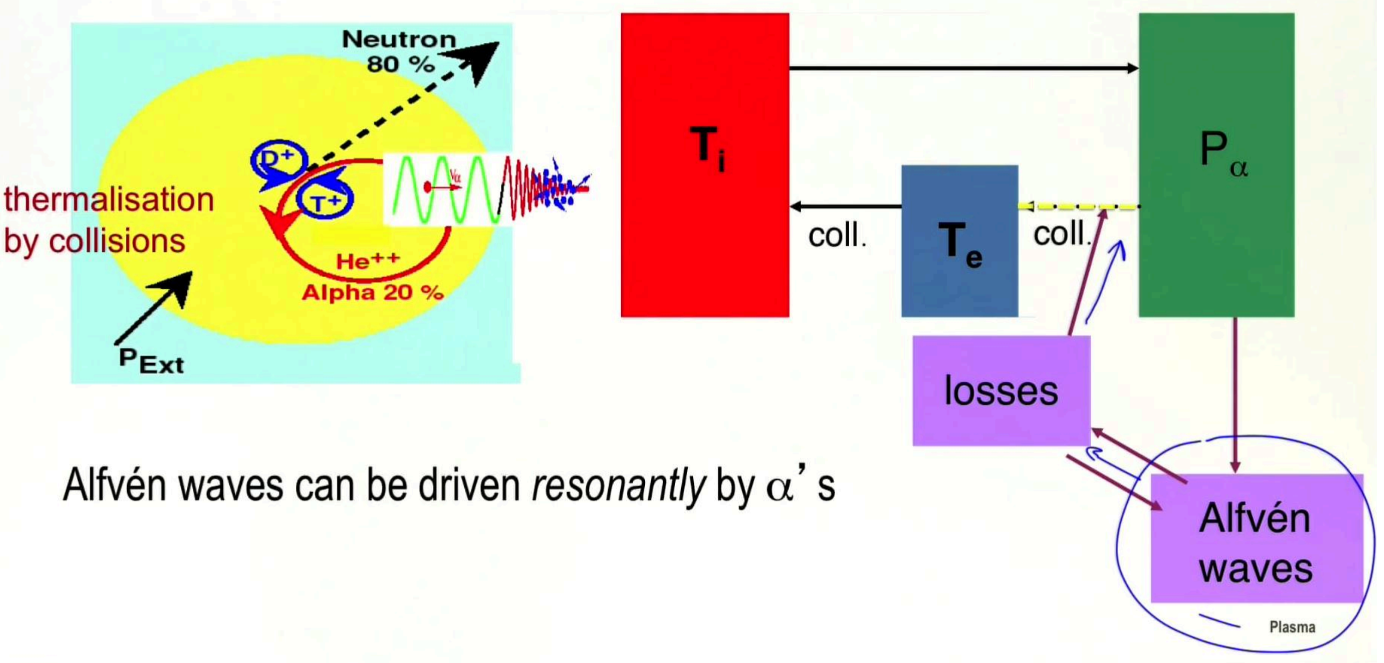
The key paremeter in this orbit averaging effect is the ratio between the fast ion energy and the background plasma temperature. In a sense this ratio is a proxy for the ratio between the size of the ion's orbits and the size of the turbulent structures. The second parameter that of course influences this interaction, is how long do fast ions remain fast in a plasma, that is the slowing down time. Now I said before that in this case we would rather find good piece of news, because if we do the estimates for ITER and future reactors, we find out that the value of this ratio of Efast/T should be large enough that the turbulence effects on the NBI ions and even more importantly, on the α's, should be negligible.

Notes

Summary

27m 58s

Fast ion losses due to interaction with Alfvén waves



Alfvén waves can be driven *resonantly* by α' s

I now turn to the last mechanism of fast ion losses I'd like to discuss, that is due to the interaction with Alfvén waves. So as we said, the α-particles are born at 3.5 MeV. They would slow down collisionally, first on electrons then eventually on ions. And during that slowing down which lasts a microscopic time, of the order of a second, they can encounter a wave-particle resonance. So they can drive efficiently an instability in the form for example of an Alfven wave, - as we will see in a moment, which in turn - if it grows to large amplitudes, could give rise to losses. The losses of the fast ions, in this case of the α's, would of course prevent an efficient transfer of that energy to the background plasma.

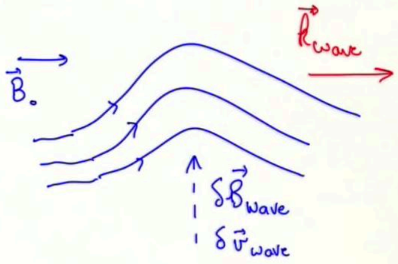
Notes

Summary

28m 53s

Fast ions and Alfvén waves

- B-field and plasma frozen together; field lines are strings with tension and inertia: Alfvén wave propagation
- Slowing down α's (or fast ions from NBI or ICRH) can resonate with Alfvén waves and give energy to them
- Waves unstable if the 'free' energy ∇p_α is sufficient and if α drive > plasma damping



Plasma

We have studied Alfvén waves in previous lectures. I'd just like to remind ourselves that they come from the following very simple mechanism. The B-field and the plasma are frozen together in the frame of ideal MHD. So we can see the field lines as strings subject to tension and subject to the interaction with the plasma inertia. The combination of tension and the plasma inertia gives the propagation of Alfvén waves. Let me just sketch that in a simple way. Say we bend the field lines, - these are supposed to be field lines, because there is a perturbation [δB_wave] of the magnetic field, due to a perturbation of the velocity of the plasma [δv_wave]. So the unperturbed magnetic field is in this direction and we locally have a perturbation of this kind. This combination of tension and inertia in MHD, is such that we have a wave that will propagate in the direction parallel to the magnetic field, with a phase velocity that will be the Alfvén speed that will be related to the intensity of the field divided by the square root of the plasma mass density which is a measure for the inertia that is involved in the mechanism for the propagation of the wave.

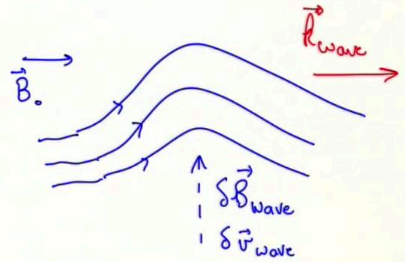
Notes

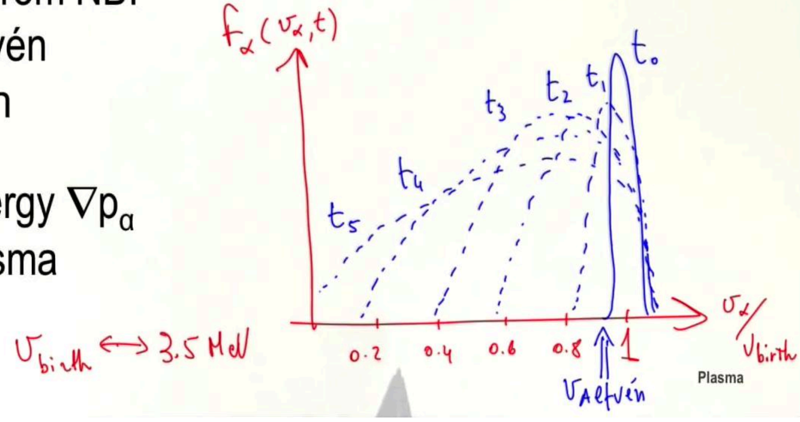
Summary

29m 49s

Fast ions and Alfvén waves

- B-field and plasma frozen together; field lines are strings with tension and inertia: Alfvén wave propagation
- Slowing down α's (or fast ions from NBI or ICRH) can resonate with Alfvén waves and give energy to them
- Waves unstable if the 'free' energy ∇p_α is sufficient and if α drive > plasma damping





So you see the slowing down α's, or for that matter fast ions from NBI or even ICRH, can actually resonate with Alfvén waves and therefore, drive them unstable giving energy to them. Why is this resonance almost inevitable? The reason for that is that if I draw the distribution function for the α's, as a function of time and as a function of their velocity, normalized to the birth velocity. The birth velocity corresponds to the 3.5 MeV of energy. Say this is 1,.2,.4,.6,.8. We have something that is a function of time, so initially the α-particles will be generated at the birth velocity corresponding to their birth energy. And then they will progressively slow down. So if this was t_0, this is now t_1, t_2, t_3, t_4, and t_5. During this slowing down, the Alfvén velocity will be encountered because the Alfvén velocity or Alfvén speed is typically just below the birth velocity. So there's no way we can avoid that resonance. And that's for typical parameters corresponding to a few teslas device, 10 to 15 KeV of temperature and $10^{20}/m^3$ of density. The other point is that there will be a potential for a very effective interaction between the slowing down α's and the Afvén wave corresponding to this range of velocity values.

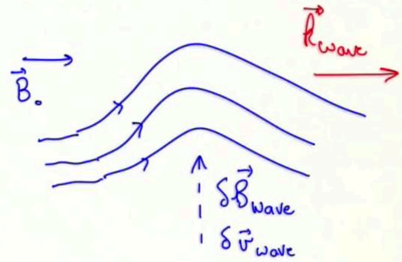
Notes

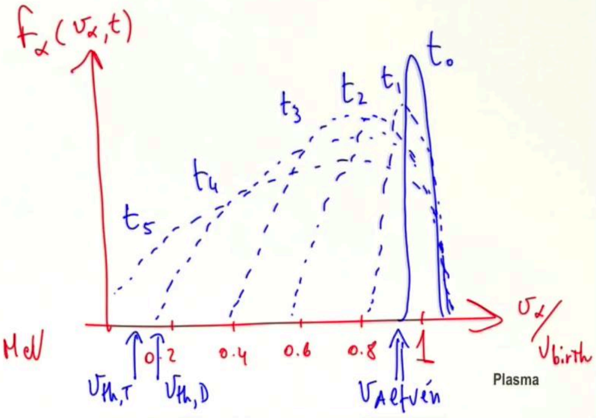
Summary

31m 09s

Fast ions and Alfvén waves

- B-field and plasma frozen together; field lines are strings with tension and inertia: Alfvén wave propagation
- Slowing down α's (or fast ions from NBI or ICRH) can resonate with Alfvén waves and give energy to them
- Waves unstable if the 'free' energy ∇p_α is sufficient and if α drive > plasma damping





Because the thermal speed for the bulk ions is much, much smaller. For example, for deuterium and tritium, there will be something around this region. Tritium's a little lower and deuterium a little higher. So there's a long way for the α's to slow down before they reach the thermal speed of deuterons and tritons, and during that long way, they have also long time to interact with the Alfvén waves with which they will become resonant. So when is the wave driven unstable? Well we have a free energy source which is the gradient in the pressure of the α-particles and if that is sufficiently high, there will be a drive, and of course if this drive will be exceeding the background plasma damping. It will be provided by a number of mechanisms in the plasma.

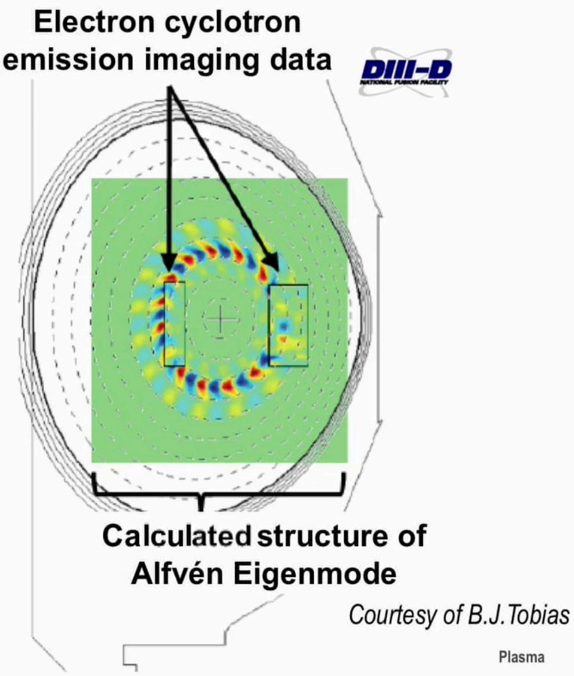
Notes

Summary

32m 59s

Alfvén waves in a tokamak – Alfvén Eigenmodes

- Alfvén waves' dispersion in tokamaks allows for weakly damped global Eigenmodes
- MHD theory has successfully predicted the existence and the main features of these modes, then verified experimentally

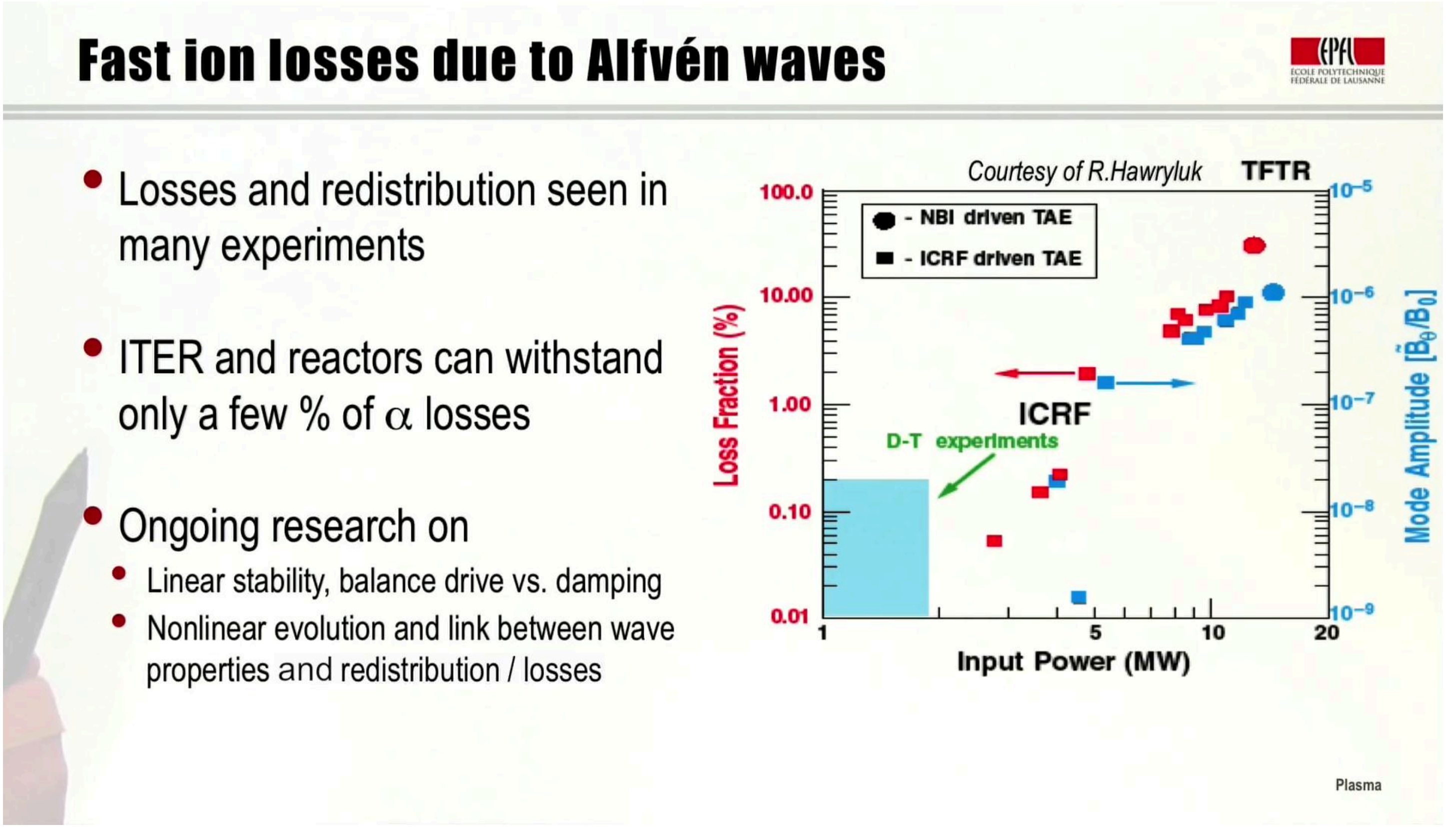


Now we have seen what Alfvén waves look like in general and what their physical mechanisms is, without going to too many complications, we noticed that in a tokamak, the geometry of the field is such that the dispersion is modified and in fact, is much more complex. But the point is that the dispersion of Alfvén waves in a tokamak still allows for very weakly damped global modes we refer to as *Alfvén Eigenmodes*. In fact, it is one of the most striking successes of MHD theory, to predict the existence of these modes and to even predict some of the main features. Features that have been observed experimentally and quite accurately. An example is shown here: this is a structure that's calculated for an Alfvén Eigenmode in which we have inserted in some portions, data corresponding to measurements of the same Alfvén Eigenmode. In this case data taken using electron cyclotron emission imaging. You can hardly notice the difference between the data and the theory prediction.

Notes

Summary

34m 01s



So the modes are there. The modes follow, at least in their main feature, the theory predictions. Do they also cause losses as we fear they would? The answer is: in many circumstances, they do. Losses and redistribution due to Alfvén waves have been seen in many experiments. In this plot compiled by a Rich Hawryluk from data from TFTR, we see that the fraction of losses here is plotted as a function of the input power. On the other side of the plot the other axis corresponds to the mode amplitude. Of course the larger, the more amplitude, the larger the fractional losses. We see that for both NBI driven Alfvén Eigenmodes or ICRF driven Alfvén Eigenmodes, we can have significant levels of losses. In DT experiments, very weakly Alfvén Eigenmodes were observed and so no significant losses were observed but that doesn't mean we should not worry about them in the future, because it was really corresponding to a very small input power in the drive, in that case in the α drive, and therefore, to a very small mode amplitude range for these modes. In fact we have to worry about loss and redistribution because in ITER and in the future reactor we can only withstand a few percent of α losses.

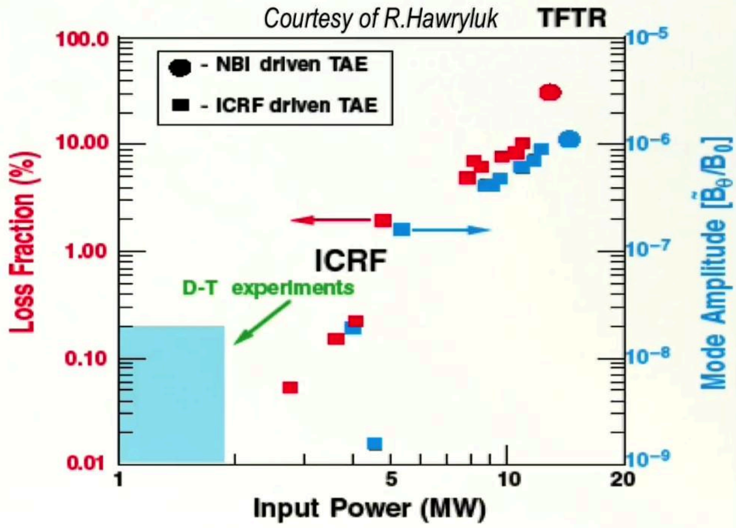
Notes

Summary

35m 12s

Fast ion losses due to Alfvén waves

- Losses and redistribution seen in many experiments
- ITER and reactors can withstand only a few % of α losses
- Ongoing research on
  - Linear stability, balance drive vs. damping
  - Nonlinear evolution and link between wave properties and redistribution / losses



Plasma

There is therefore an ongoing research to investigate the linear stability of the modes, when are they present at all, -which results from the balance between the drive to the fast particles, and the damping from the background plasma, and to also see how the modes evolve non-linearly and what is the link between the wave property and the redistribution and the losses that the waves cause.

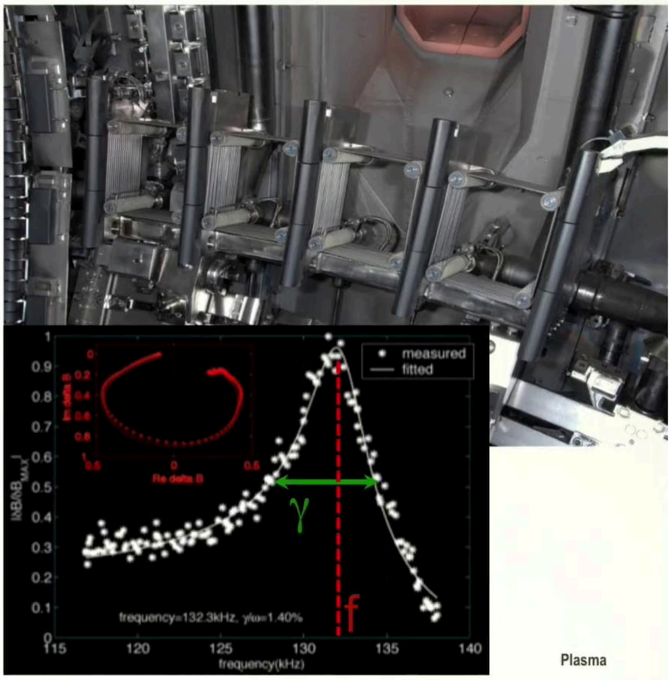
Notes

Summary

36m 42s

Example of Alfvén wave studies in tokamaks - JET

- Linear stability investigated using antennas to drive stable modes
- Alfvén Eigenmodes appear as resonances in plasma response to antenna signal
- Width of resonance → damping rate γ
- Mode tracking allows many (real time) γ measurements in a single discharge

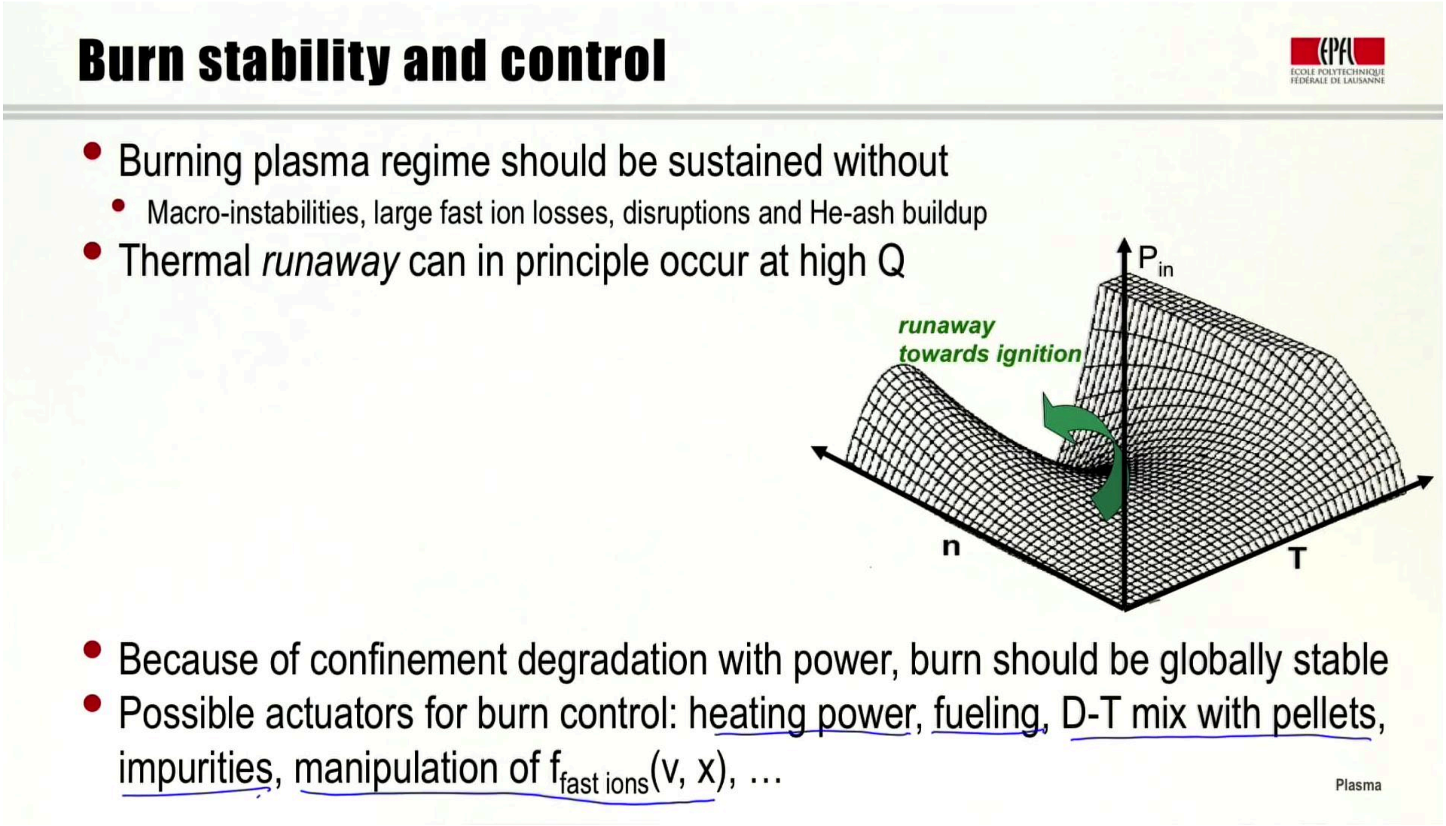


Just to give you one example of this kind of investigations, this is what we studied on the JET tokamak in terms of the linear stability. The idea here is that the linear stability mode is investigated using antennas, these are the four antennas installed inside the JET vessel that launch low amplitude stable modes in the plasma. The frequency of the antenna is swept and the eigenmode appears as a resonance in the plasma response to that antenna signal. And this is a driven mode so its frequency of course corresponds to the peak of this resonant response. In simple terms, the width of the resonant response is actually the damping rate of the mode. So one can drive these modes and even track them in real time. So drive them one after the other as the plasma evolves and extract their width in real time. The measurement that is of the damping rate for the mode that would be present in the burning plasma.

Notes

Summary

37m 05s

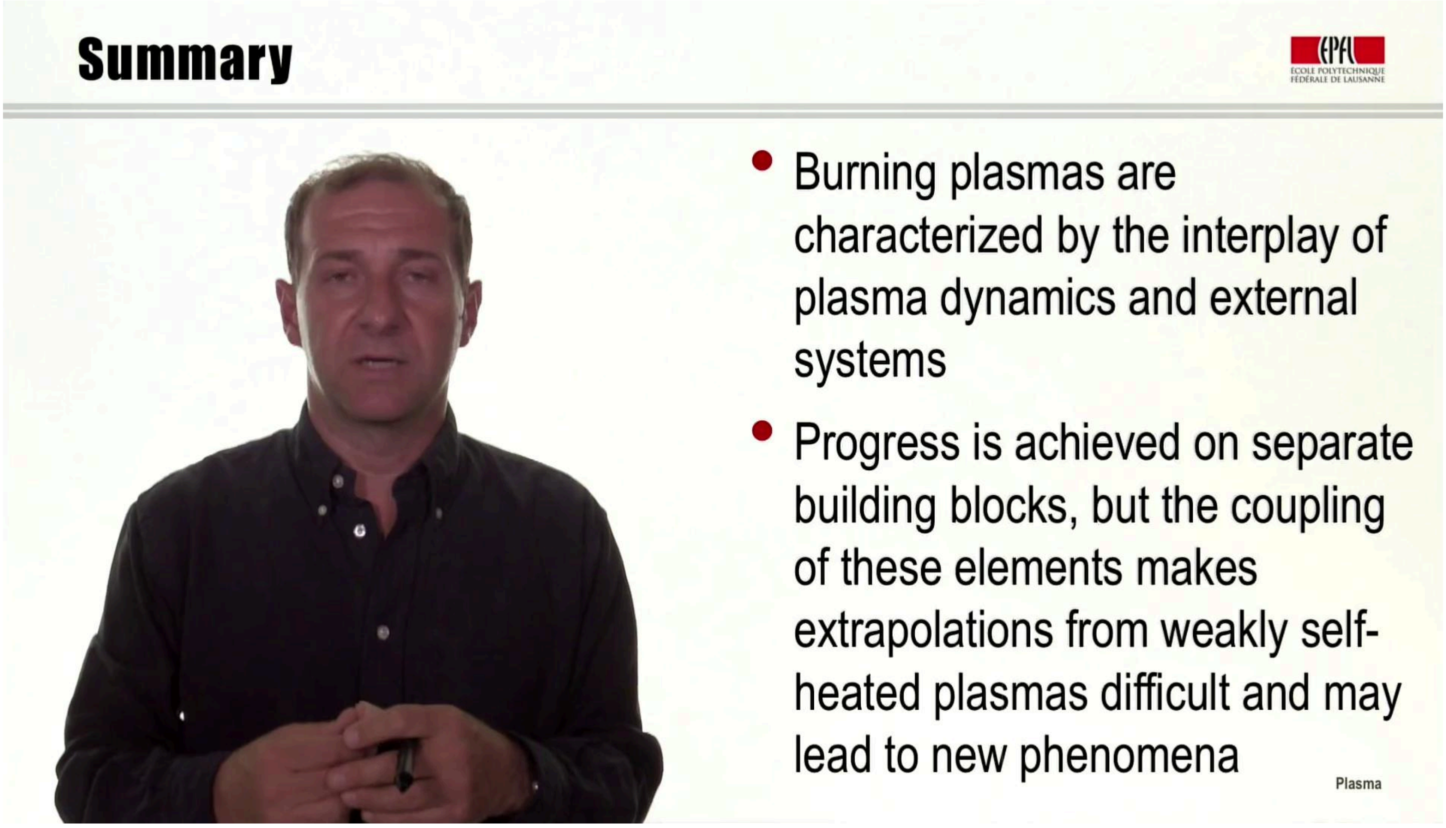


Finally, I would like to say a few words about the stability of the burn and its possible control. We want to achieve a burning plasma regime that sustains without - any major macro-instabilities, - any significant fast ion losses, - any disruptions, and - any build-up of the helium ashes. In principle, a thermal runaway can occur at high fusion gain. This is represented in this plot where the input power is represented as a function of density and temperature, to achieve a certain level of fusion power and we can see that the input power could go to zero in particular regions of this plot, which means that we would have a runaway towards ignition, which we don't necessarily want. We will lose control of the plasma burn. As we will see in an exercise, however, we have a confinement degradation with power. Which means that the burn, in fact, should be globally stable. To control the burn, we have a number of possible actuators, although, as we said, the plasma is really a self-organized system when we have the burning plant regime. We can nevertheless try to act on the heating power, on fueling of the core, on the DT mix, on impurities that we have in the plasma, and we can, in fact, even manipulate the fast ion phase space distribution to optimize our burn.

Notes

Summary

38m 12s



So in summary we have seen together the burning plasmas are characterized by the interplay of plasma dynamics and external systems. The core of the plasma is a complex self-organized system on which we can have a small amount of control. In today's experiment we can achieve some progress on seperate building blocks for the burning regime. But the coupling of all of these elements makes extrapolations from the weakly self-heated plasma we have today very difficult and may lead to new phenomena. And that's why we need to build an experiment that runs a plasma in a burning regime. This is what we will discuss in the next lecture. And that is ITER.

Notes

Summary

39m 47s