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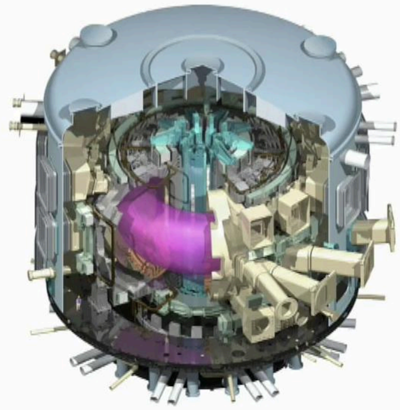
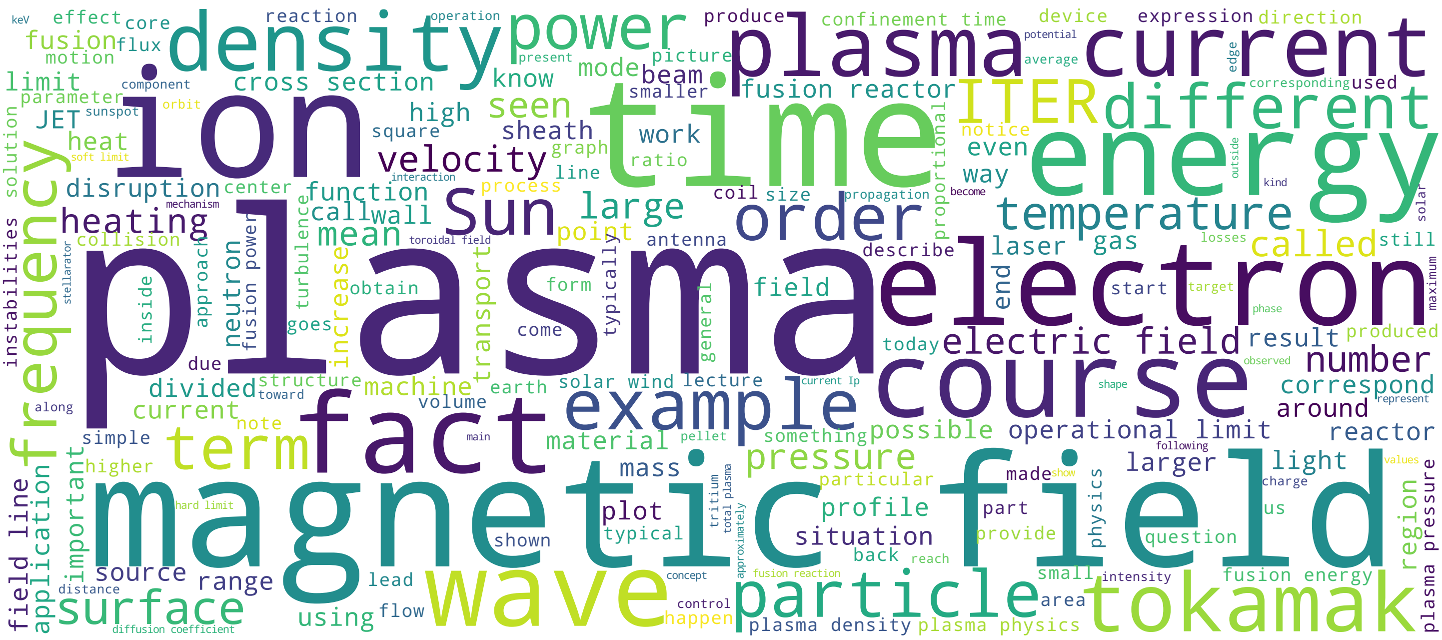


Performance and operational limits of tokamaks

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 7c

Duccio Testa



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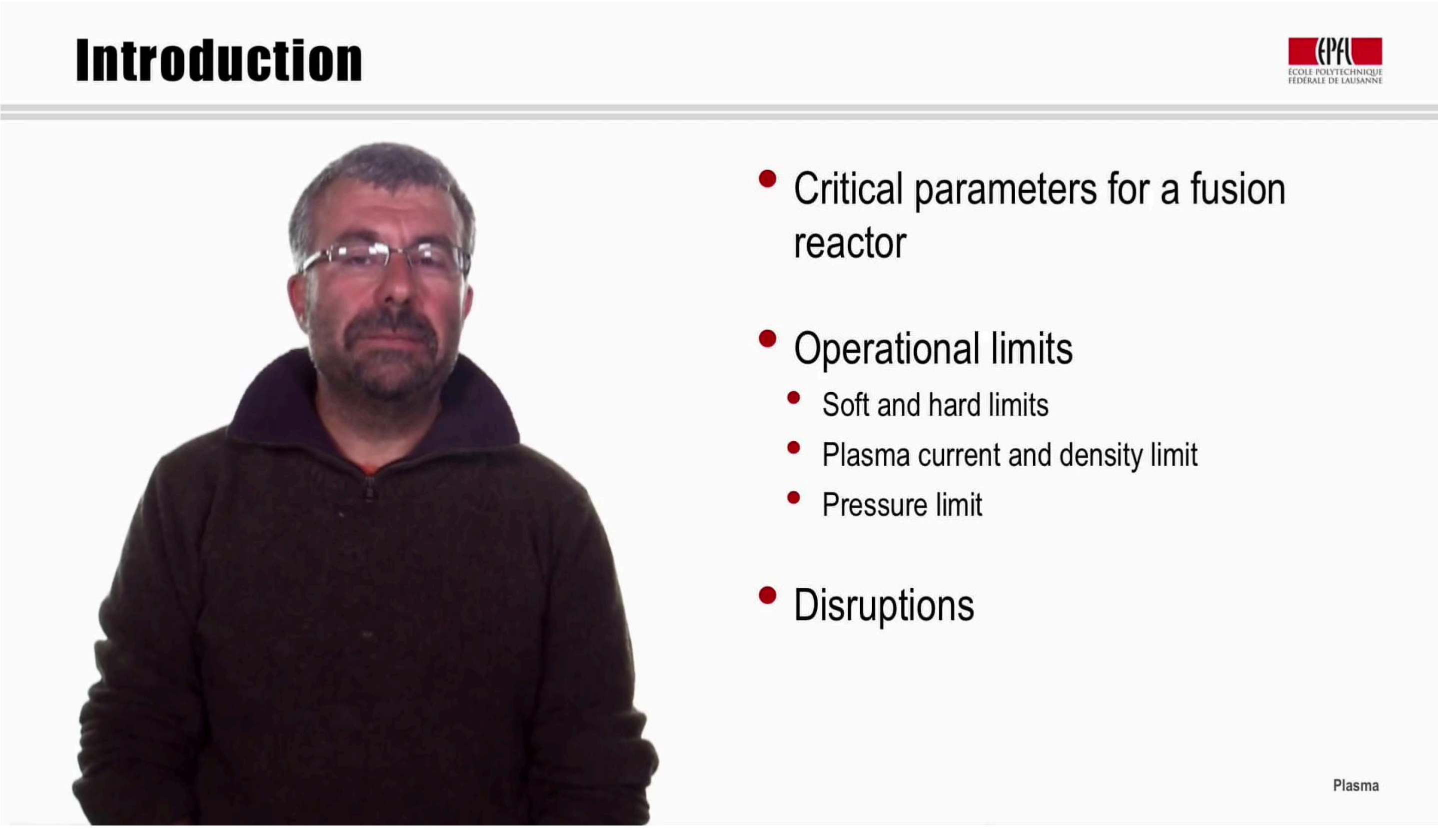
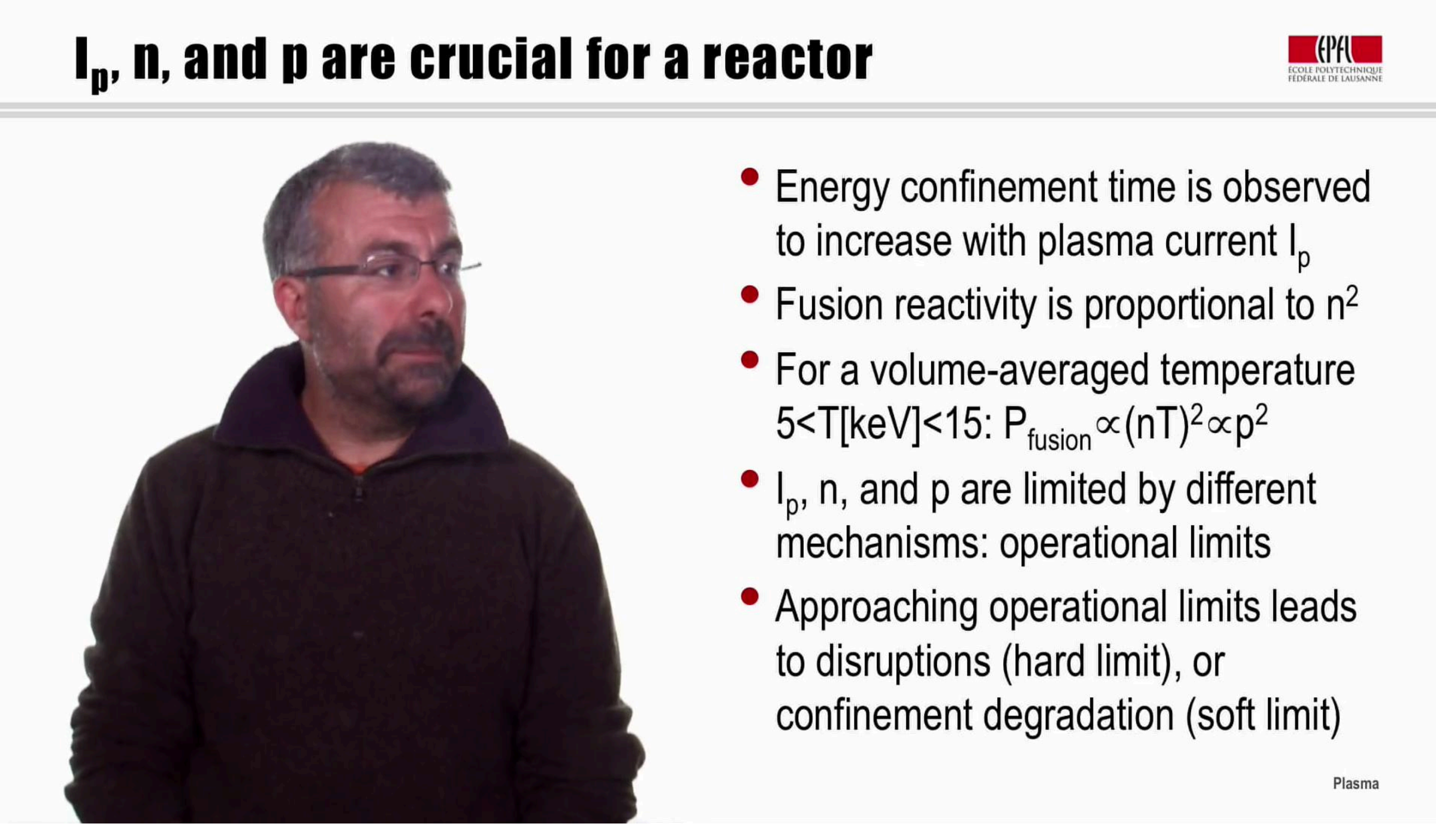


Welcome to the course Plasma Physics and Application to Fusion Energy, Astrophysics and Industry. My name is Duccio Testa, and in this lecture we will be discussing performance and operational limits of tokamaks. First, we will look at critical parameters for a fusion reactor. This will lead us to describing operational limits. We will see that there are two kinds of operational limits: *soft* and *hard* limits. This will lead us to describe three different kinds of operational limits on the plasma current, on the density, and on the pressure. And finally, we will end up with describing *disruptions*, which are the ultimate consequence of violating these operational limits.

Notes

Summary

0m 05s

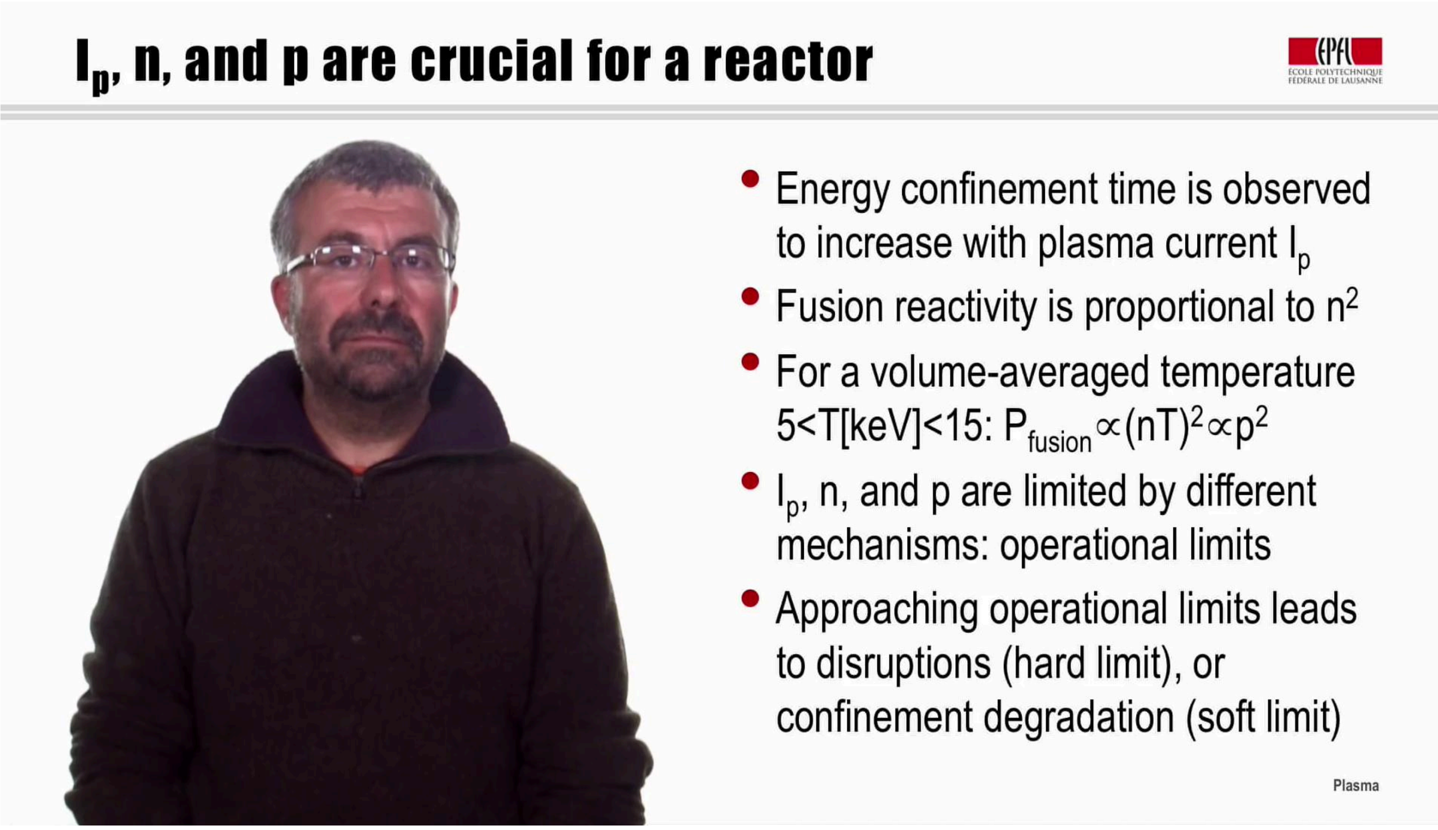


Now let's looks at the fusion performance— let's briefly review what we did in lecture six. What we found is that for thermonuclear fusion to be economically attractive, we need an engineering fusion energy gain, QE, that is in the range between 2 and 10. And this corresponds to a physics fusion energy gain, Q, that has to be in the range of 10 to 40. We also know that, to achieve this sufficiently high Q, we need to have a sufficiently high value of the triple product n T τE. We ask ourselves a question: What are the factors limiting the fusion energy gain, Q? Now, the first thing that we know is that the energy confinement time is observed to increase with the plasma current Ip. The fusion reactivity is proportional to the square of the plasma density. And then if we work in the typical temperature range that is optimal for a fusion reactor, which is between 5 and 15 keV, in this temperature range, the fusion power P increases as $(n\ T)^2$, so the fusion power is proportional to the square of the plasma pressure. Now we have immediately seen that there are three main factors for fusion performance: plasma current, Ip, that leads to the energy confinement time, then density [n], and pressure, p.

Notes

Summary

0m 49s



And in fact, these three quantities, IP, n and p, are limited by different mechanisms. These are the operational limits in tokamaks. If we approach these operational limits, then we end up in disruptions when we go over this limit, and this is a hard limit for the operation of a plasma, or we end up with confinement degradation, and this will be a soft limit.

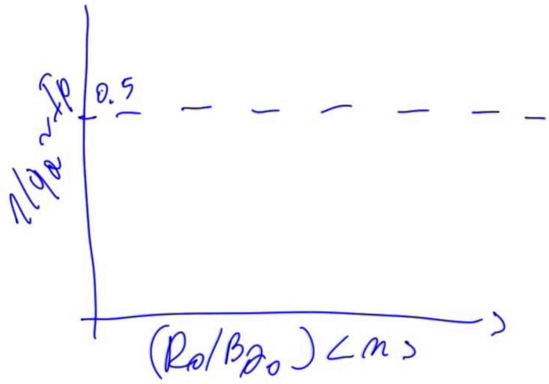
Notes

Summary

2m 24s

Hugill's diagram: I_p and n operational limits

- Global MHD instabilities impose $1/q_a<0.5$ hard limit
- Soft Greenwald density limit: $n_{MAX} \leq n_G[10^{20}m^{-3}]=I_p[MA]/\pi a^2[m^2]$
- Shaped plasmas are observed to exceed the Greenwald limit



Plasma

Now the way to describe these operational limits in tokamaks is the *Hugill diagram* that provides a link between the plasma current and the density for which safe operation is allowed in tokamaks. The Hugill diagram describes the quantity 1/qa — qa, the safety factor of the plasma edge, that we have seen is a measure of the total plasma current — as a function of what we call the Murakami parameter that is proportional to the plasma density n. So what we have here is the definition of the axes of the Hugill diagram: on the x-axis, the Murakami parameter: <n>, written here with brackets, is the volume average plasma density, which is multiplied by R_0, the position of the magnetic axis, divided by $B\varphi_0$, the value of the on-axis toroidal field. This is the Murakami parameter. On the y-axis we have 1/qa. That is proportional to the total plasma current. So the first limit, - it's a hard limit -, is given by the total plasma current, and this limit is set by global MHD instabilities that impose 1/qa < 0.5. This is really a hard limit. It's independent of the plasma density. Then we have a density limit, it's a soft limit, it's called the Greenwald density limit.

Notes

Summary

2m 52s

Hugill's diagram: I_p and n operational limits

- Global MHD instabilities impose $1/q_a<0.5$ hard limit
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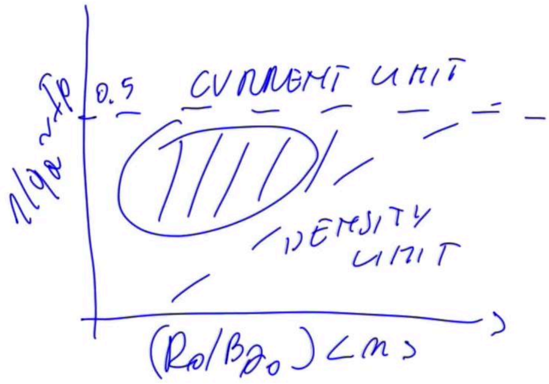


Plasma

This tells us that if we want to operate at a larger density, then we need to increase the plasma current, and correspondingly, by increasing the plasma current, we can work at a larger density. This is basically a line that is oblique in the y-x diagram. What we have here is our definition of the operational space of a tokamak in this range here. This area is the safe operational space for a tokamak. On the top, we have in fact a limit on the total plasma current and this diagonal line is a limit on the density. It is important to note that if we shape the plasma, then we can exceed the Greenwald density limit. In this sense, it is a soft limit.

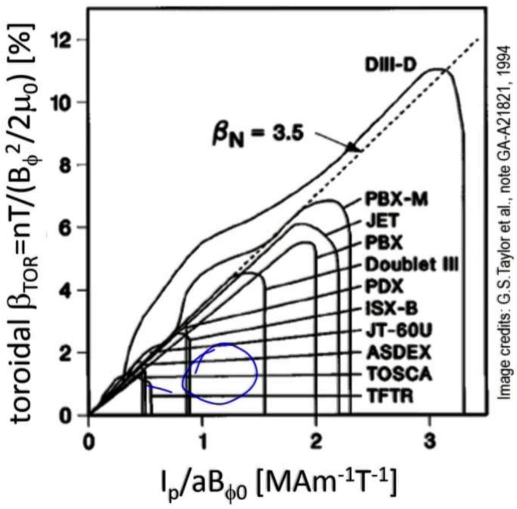
Notes

Summary

4m 21s

Operational limits: plasma pressure

- Ideal β-limit is set by the occurrence of ideal MHD instabilities
  - Fast time scales do not allow real time control
- Troyon scaling defines the maximum value of β%: $\beta_{MAX}=C_\beta I_p/aB_{\phi 0}$
  - C_β~2→5 when optimizing plasma shaping
- Normalized beta: $\beta_N=\beta/(I_p/aB_{\phi 0})$
- Resistive MHD modes can degrade confinement at β below the Troyon limit
  - Slower time scales allow real-time control techniques



Plasma

Another operational limit is due to the plasma pressure. In fact, the ideal β-limit is set by the occurence of ideal MHD instabilities. These are instabilities that work on a very fast time scale, and in fact it is not possible to control them in real time. If we collect data from many experiments, as shown in this graph here, for many different machines, we find that there is in fact a scaling between the maximum value of β in percent, and the ratio between the plasma current Ip, the minor radius a, and the toroidal magnetic field, on axis $B\varphi_0$. If you look at this graph, where we have the toroidal β plotted as a function of $Ip/aB\varphi_0$, we notice that the different machines are basically all aligned under this dotted line that corresponds to a value, βn = 3.5. Three point five is the definition of the normalized βN, β divided by this normalization factor, $Ip/aB\varphi_0$. This range of normalization, Cβ — βn in fact can be between two and five and increases when we optimize the plasma shape. So if you look again at this graph, we see that the first machine like TOSCA AND TFTR, these were circular machines. The plasma cross-section was a circle. In fact, all these machines are set up at the limit of βn = 3.5, if not even below.

Notes

Summary

5m 15s

Operational limits: plasma pressure

- Ideal β-limit is set by the occurrence of ideal MHD instabilities
  - Fast time scales do not allow real time control
- Troyon scaling defines the maximum value of β%: $\beta_{MAX}=C_\beta I_p/aB_{\phi 0}$
  - C_β~2→5 when optimizing plasma shaping
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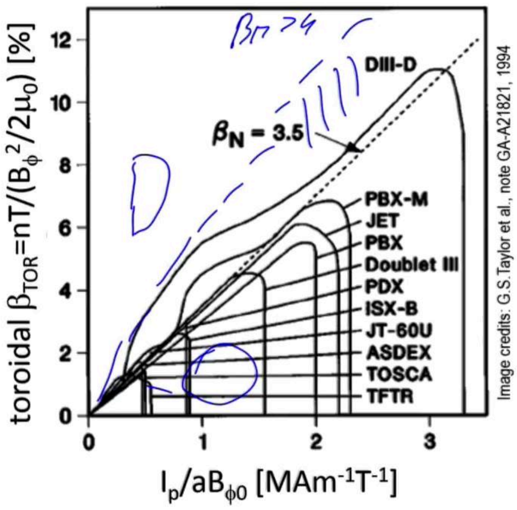


Plasma

However, we note that there is one particular machine in this graph, that is the DIII-D machine, for which in fact, for certain values of $Ip/aB\varphi_0$, clearly, we obtain a βTOR that exceeds this 3.5 limit. But if we draw a line taking this value, this line would correspond to βn in excess of 4, perhaps even 5. So this tells us what we can do to increase the β limits, or the plasma pressure limit on a tokamak, because this DIII-D machine is a machine that is shaped — the poloidal cross-section is elongated and it actually has a quasi-triangular shape. So in fact, by optimizing the plasma shape, we can go beyond this traditional Troyon limit, βn = 3.5. In fact, this also defines the range of operation that you can expect in future plasma devices, such as ITER. What we find, however, is that resistive MHD modes can degrade the confinement at β below the Troyon limit, so we do not manage to get to this value of βn = 3.5, due to these resistive MHD modes. However, these modes are resistive, so they work on a much slower timescale than ideal modes, and then we can do real-time control of these instabilities.

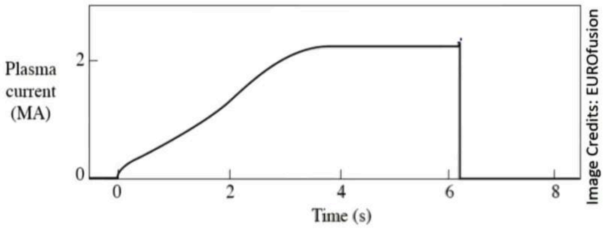
Notes

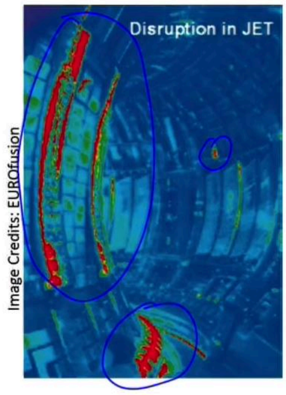
Summary

6m 53s

Hard operational limits: disruptions

- Plasma confinement is lost over ~ms time scale
- Rapid I_p quench
  - Note: stellarators in principle disruption-free
- Damage to plasma facing components when the heat flux exceeds the limits of the materials
- In ITER, only ~5 disruptions allowed over its entire ~30 years life-time
- Disruption mitigation techniques under development





Plasma

Now if we really exceed hard operational limits, what we end up with is a disruption. Here we have a plot that describes the evolution of a plasma current for a JET discharge that ends up in a disruption. It's characterized here by the sudden drop of the plasma current. If we lose the plasma current, and we see the time scale here is very short, a millisecond, then the plasma confinement is lost, because we completely lose the poloidal magnetic field. What is important to note is that stellarators are in principle disruption-free, because there is no inductively driven toroidal plasma current; all magnetic field is provided by external coils. We can look here at a photo of a disruption in JET, and we see these red patches along the plasma wall. We see one here, one here at the bottom of the machine, and clearly in this area of the machine, on the high field side. In fact, these red patches are areas where the plasma touches the wall. So in a disruption, we can have damage to plasma-facing components when the heat flux exceeds the limits of the materials. So if you look at future fusion devices such as ITER, we can only have five disruptions that are allowed over its entire 30-years lifetime.

Notes

Summary

8m 19s

Hard operational limits: disruptions

- Plasma confinement is lost over ~ms time scale
- Rapid I_p quench
  - Note: stellarators in principle disruption-free
- Damage to plasma facing components when the heat flux exceeds the limits of the materials
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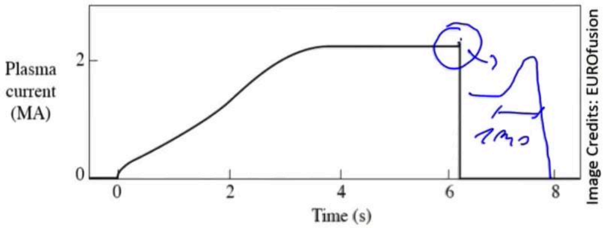
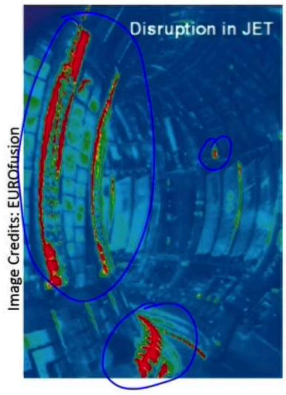




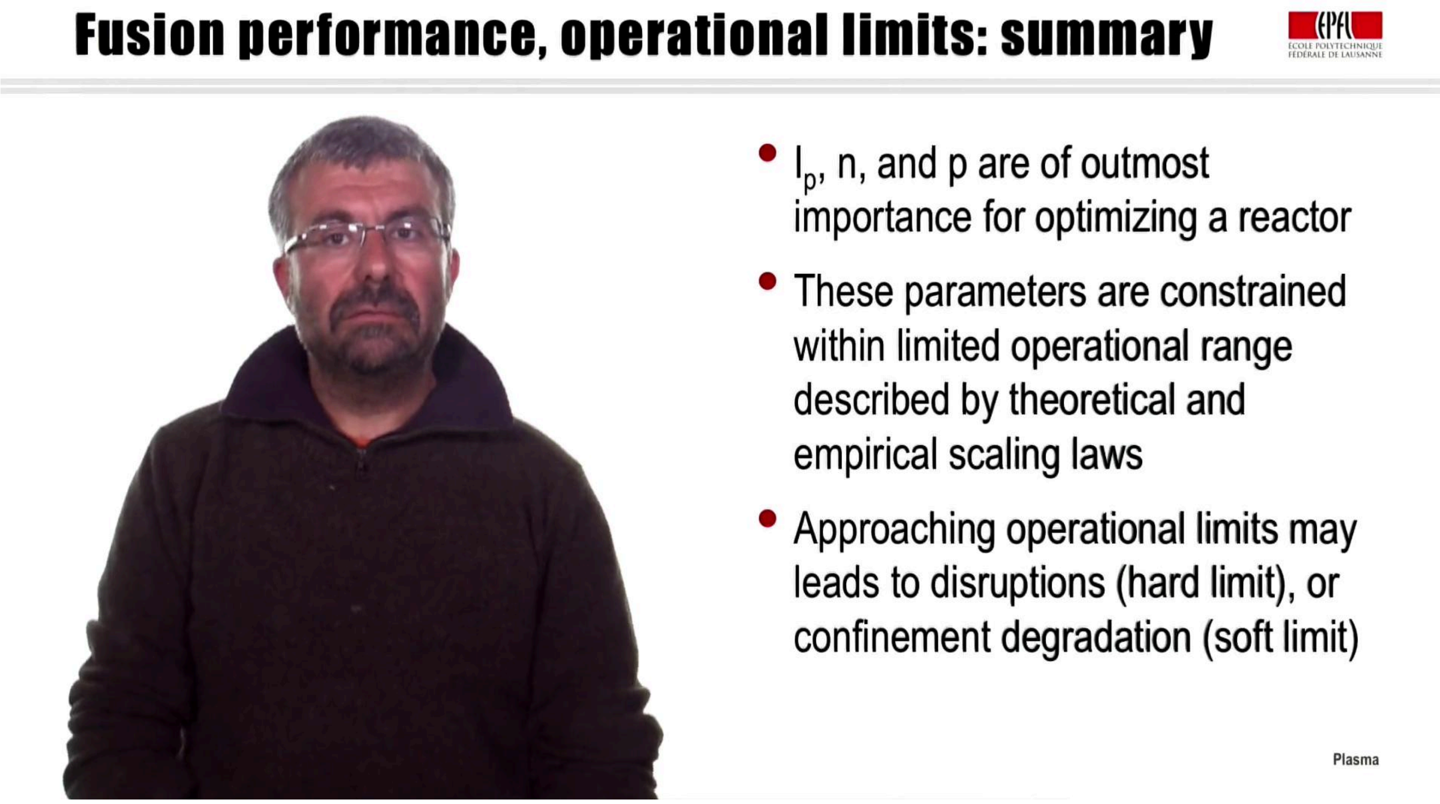
Plasma

In fact, the problem of disruptions is so major, that we are studying disruption mitigation techniques that are under development. These mitigation techniques work on a real-time basis, and in fact, the principle we can see here, if you go back again to this plot of the plasma current, we note that just before the plasma current drops, there is a slight spike in the plasma current, where I can just highlight this section. The plasma current is flat, there is a spike, and then it drops. This is a very short timescale, on the order of a millisecond or so. But in fact, this spike in the plasma current is what we call a disruption precursor. If we can detect it, and we usually can detect it very efficiently, then it is possible to apply disruption mitigation techniques that in fact mitigate the damage to the plasma wall due to a disruption.

Notes

Summary

9m 48s



We can now summarize what we have seen today. The plasma current Ip, plasma density n, and plasma pressure p are of the utmost importance for optimizing a fusion reactor. These parameters are constrained within a limited operational range, which is described by theoretical and empirical scaling laws. If you approach these operational limits, and when we exceed them, this may lead to disruption, which is a hard limit, or to confinement degradation, which would be a soft limit.

Notes

Summary

10m 45s