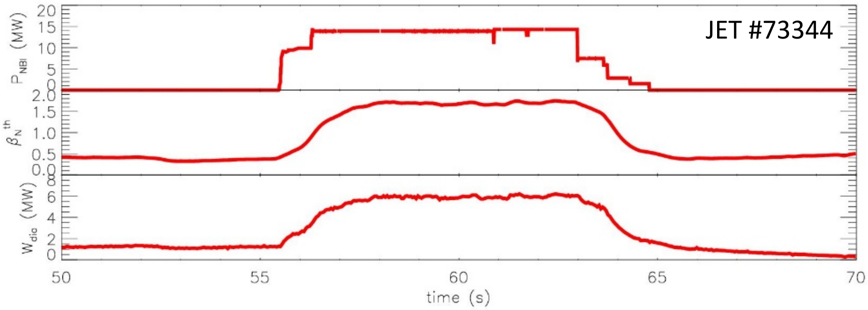
KTH ROYAL INSTITUTE
OF TECHNOLOGY
Stockholm, Sweden

PEDESTAL PHYSICS
a phenomenological introduction

L. Frassinetti

H-mode plasma

- When the input power to the plasma is above a specific threshold, the plasma has a transition from a low confinement regime (L-mode) to a high confinement regimes (H-mode).



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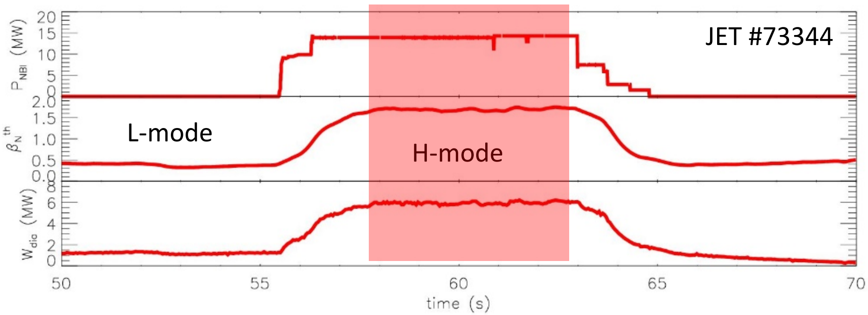

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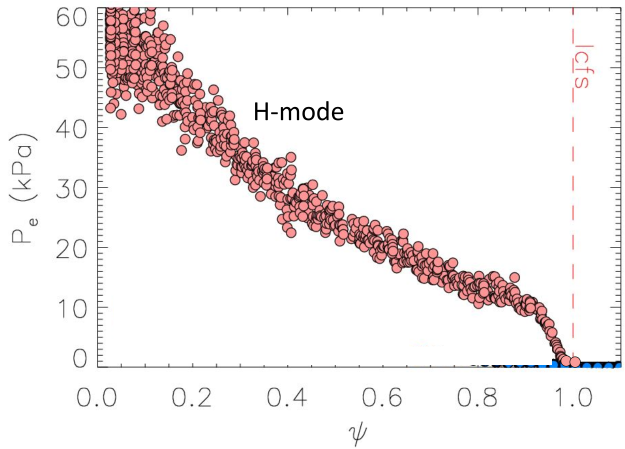
  - steep gradients in the pressure "near" the edge of the plasma. This region is named "**pedestal**".



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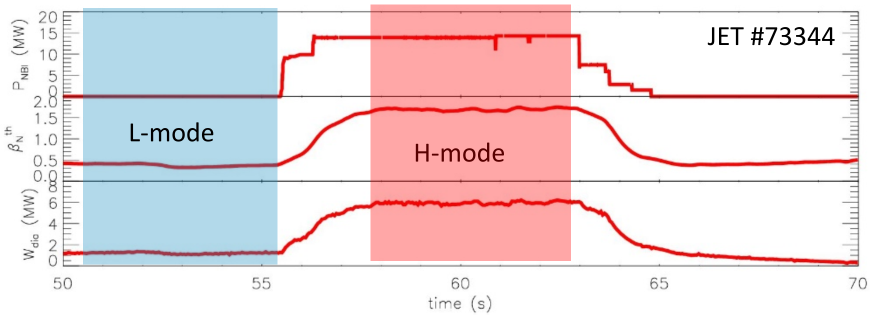

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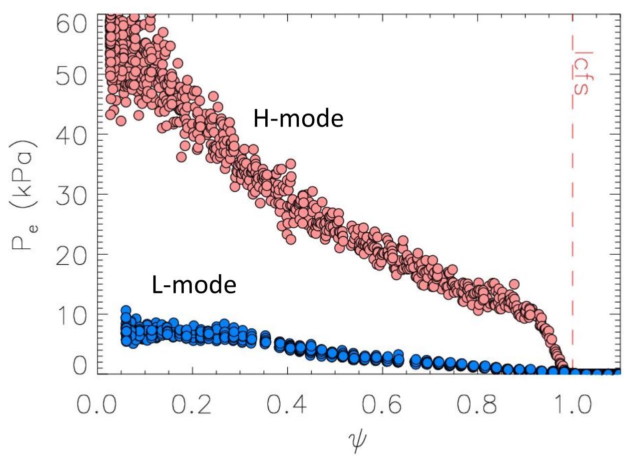

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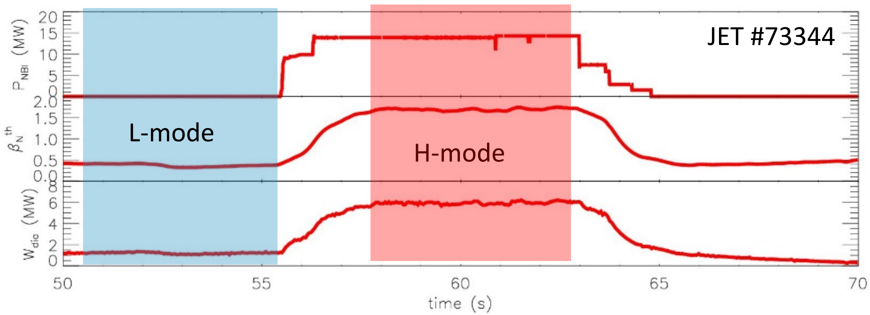
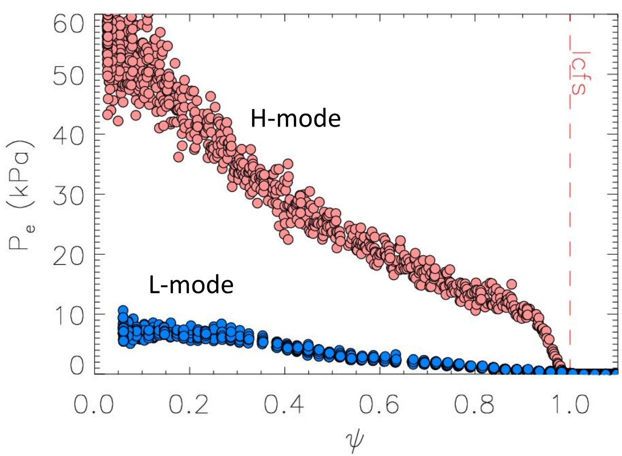


- The H-mode is characterized by:
  - steep gradients in the pressure ”near” the edge of the plasma. This region is named ”**pedestal**”.
  - sudden releases of energy and particles from the pedestal region to the SOL and the divertor. These events are triggered by MHD instabilities and are named edge localized modes (**ELMs**)



OUTLINE

- L-H transition
- Pedestal structure
- Edge localized modes (ELMs)
    - ELM energy losses
    - ELM types
- MHD stability of the pedestal
    - Role of MHD stability (and few words on transport)
    - The peeling-ballooning (PB) model
    - The ELM cycle within the PB model
    - Parameters that influences the pedestal
- Pedestal predictions
    - The EPED model:
        - The PB constraint
        - The KBM constraint
    - Non-linear MHD modelling
- Some of the most active research areas in pedestal physics

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L-H transition

- Above a specific threshold in power (P_{LH}), the plasma enters the H-mode
- The P_{LH} threshold depends on several parameters.
- A scaling law based on results from several machines produces:

$$P_{LH} = 0.049 n_e^{0.72} B^{0.8} S^{0.94}$$ [Martin JPC2008]

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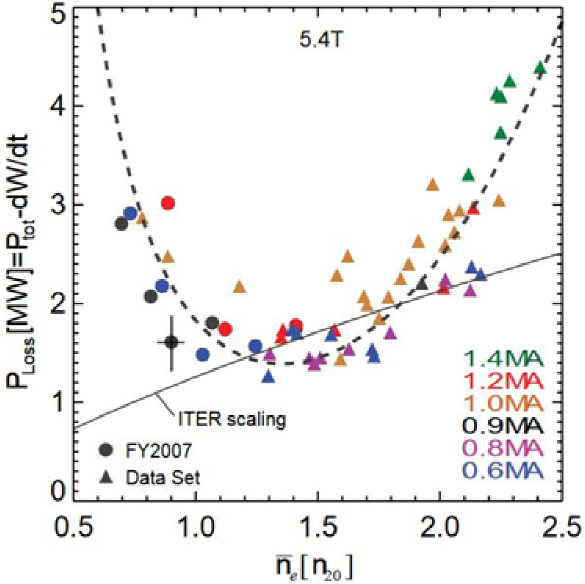

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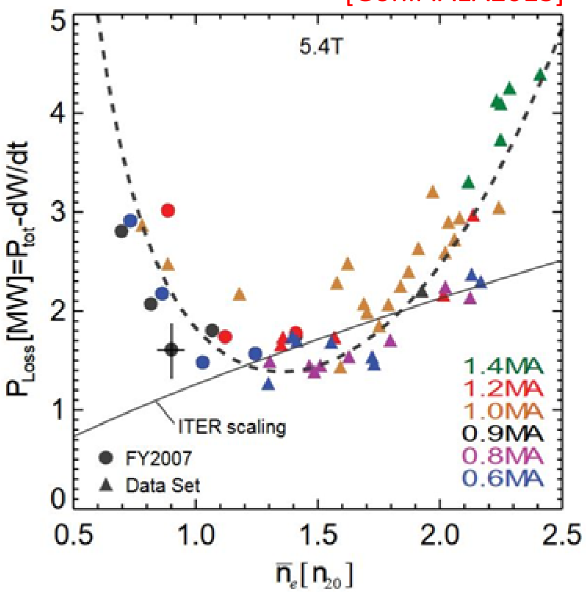
- However, the links between engineering/plasma parameters and P_{LH} is more complex. Some of the main parameters that affects P_{LH} are:
  - Magnetic field
  - Isotope mass (P_{LH} decraeses with isotope mass) [Righi NF1999]
  - Divertor geometry [Delabie EPS2015]
  - Wall material (P_{LH} reduced from carbon to metal walls) [Neu JNM2013]
  - Plasma density [Martin JPC2008]
    - Minimum around 0.2-0.4n_{GW}
    - Non-monotonic behavior seem related to edge ion heating [Ryter NF2014]

[Gohil IAEA2013]



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- Some key experimental and theoretical concepts to explain the L-H transition are well established:
  - The L-H transition is due to stabilization of the turbulence near the plasma edge [Burrel PoP1997], [Terry RMP2000]
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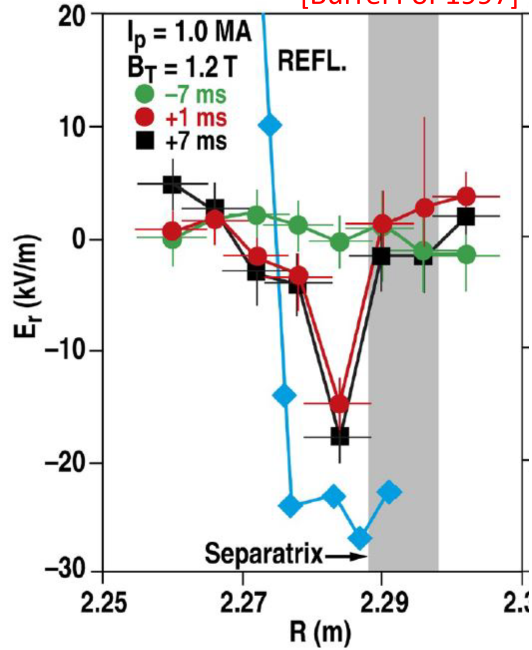
  - $\vec{E} \times \vec{B}$ shear stabilization plays a key role
    - higher $\vec{E} \times \vec{B}$ in L-mode → lower P_{LH}.
    - The formation of a E_r well, just inside the separatrix, occurs as the plasma enters H-mode
    - The well has to reach a certain depth to allow the transition

[Burrel PoP1997]



L-H transition

- Many of the theoretical works are based on the interplay between the L-mode turbulence and E_r shearing. [Connor PPCF2000]
- A large part of other theoretical works are based on the stabilization of RBM via increased pressure gradient. [Rogers PRL1997]

- An example:

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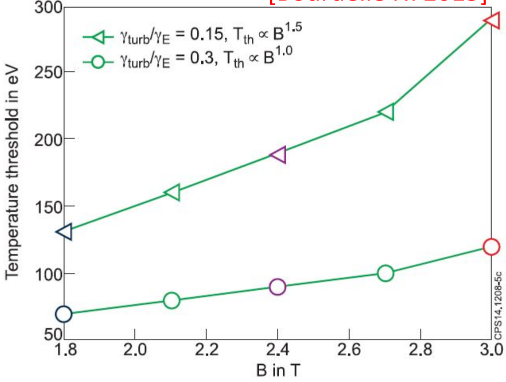
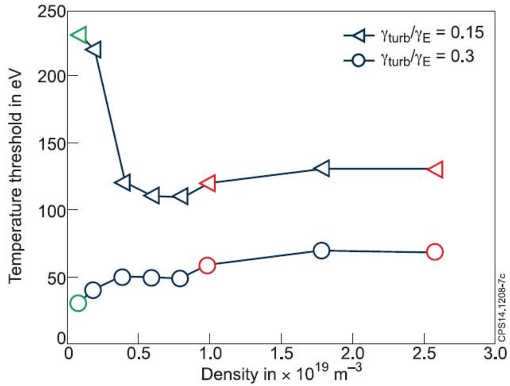
- An example: [Bourdelle NF2015]
  - γ_{turb} (growth rate of the turbulence) can be modeled from theory (either analytically or numerically)
  - γ_E (E_r shear) can be obtained by modelling the E_r profiles.
  - γ_{turb}/γ_E can be used to identify at which temperature the transition occurs
  - → Qualitative trends can be tested

[Bourdelle NF2015]





- For a recent review on L-H transition: [Bourdelle NF2020]

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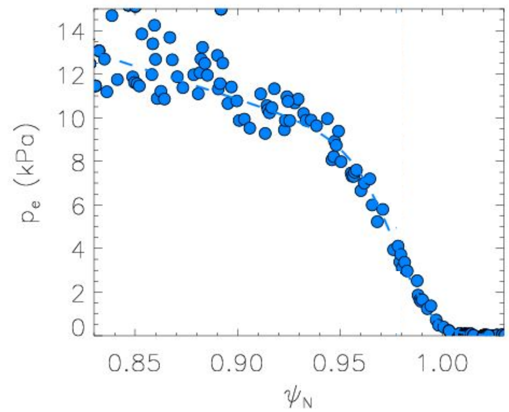
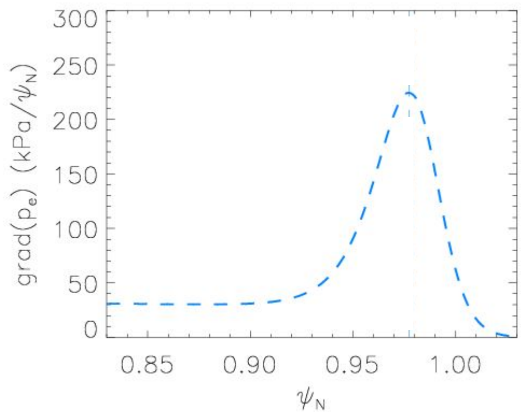
Pedestal structure

- To study the pedestal, it is necessary to quantify the parameters that identify its structure.

- The key parameters are
  - pedestal heigth
  - pedestal width
  - pedestal position (often defined as the position of the maximum gradient).
  - maximum gradient





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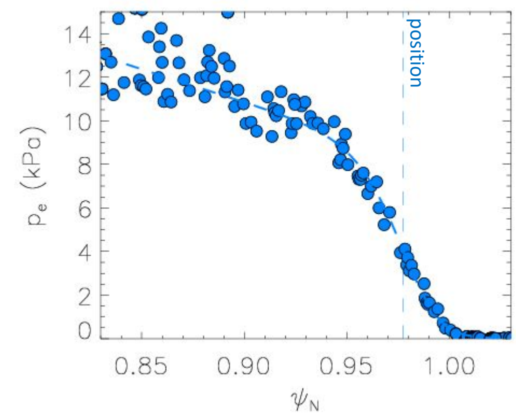

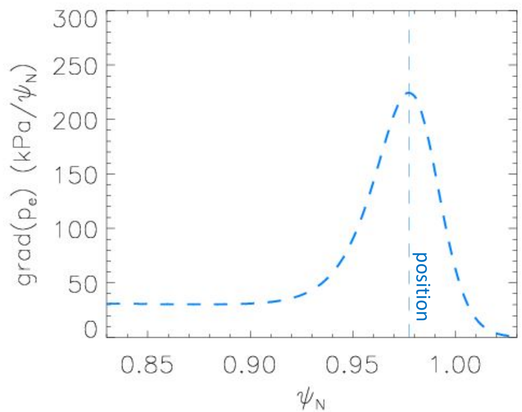

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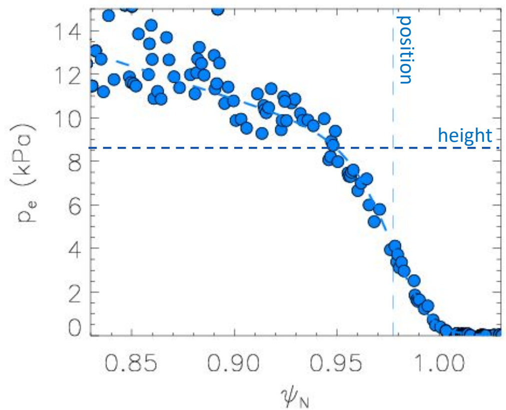

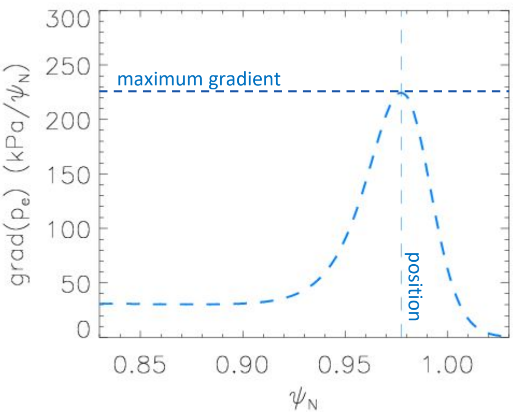

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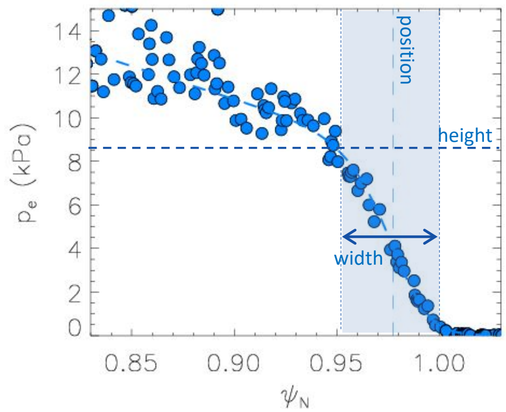

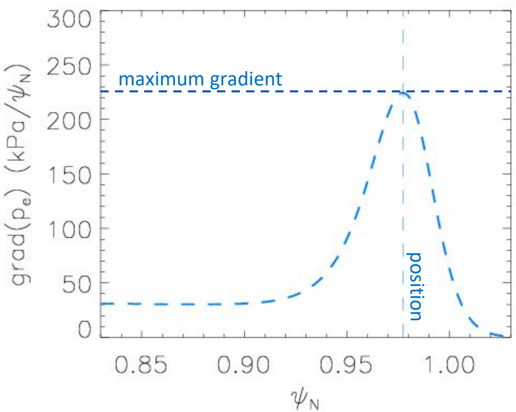

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- The pedestal parameters are determined for:
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  - temperature
  - density

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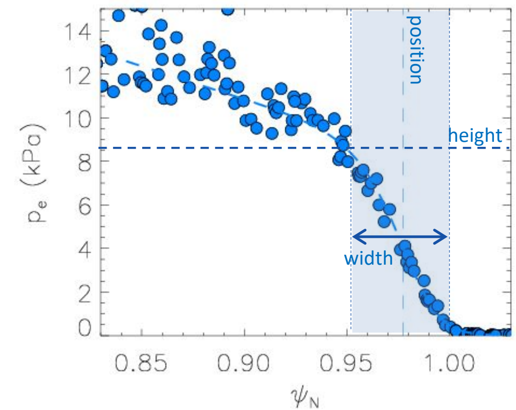

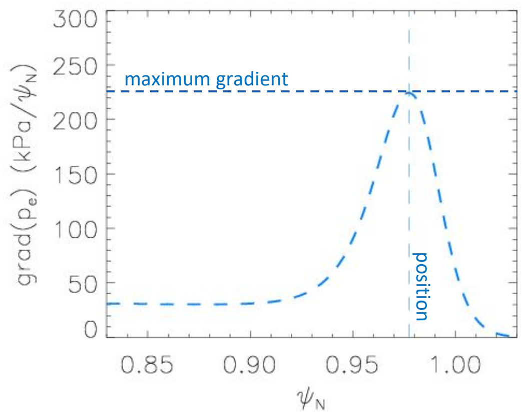

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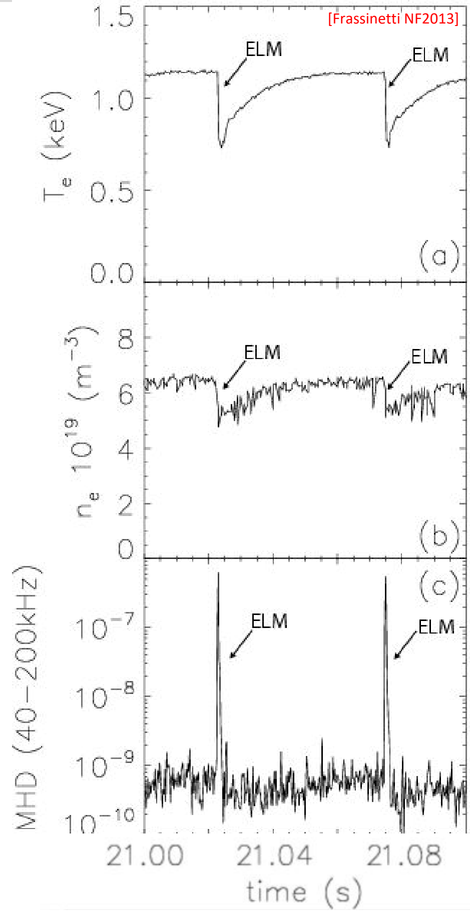

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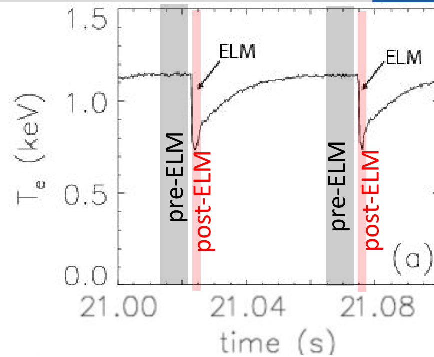

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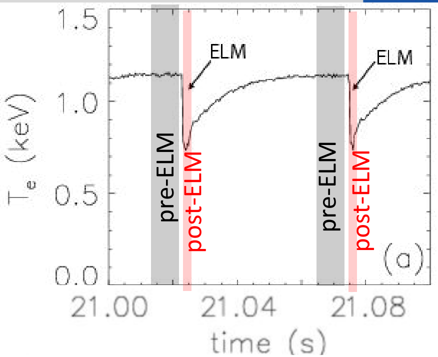

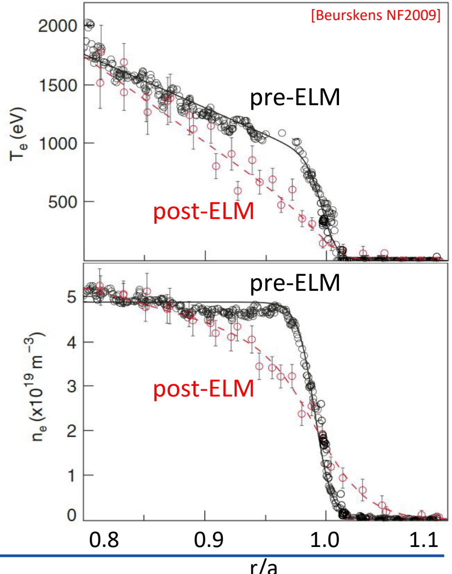

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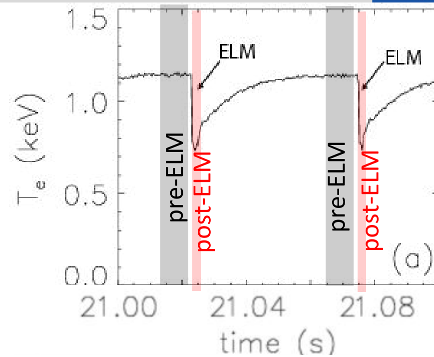
- The ELM collapse affects the kinetic profiles only in the pedestal region.
- The ELM losses can be calculated by integrating the profiles just before and soon after the ELMs:

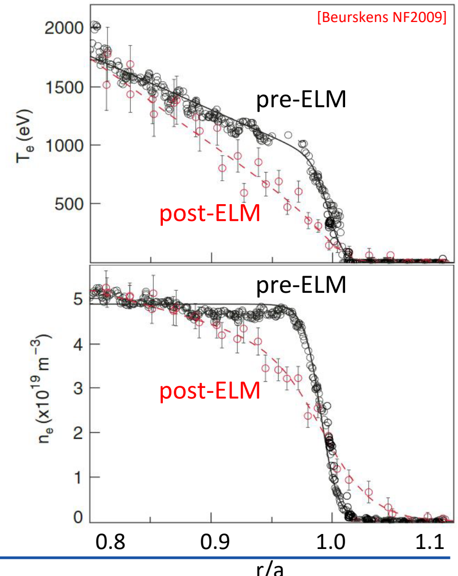
[Beurskens NF2009]

$$\Delta W_{ELM} = W_{pre} - W_{post} =$$

$$= \frac{3}{2} k \int \left(n_{pre} T_{pre} - n_{post} T_{post} \right) dV \approx$$

$$\approx \underbrace{\frac{3}{2} k \int \Delta n \, T \, dV}_{\text{convective losses}} + \underbrace{\frac{3}{2} k \int n \Delta T \, dV}_{\text{conductive losses}}$$





ELM types: definitions

- H-mode plasma can be characterized by several types of ELMs. The ELM frequency (f_{ELM}) is often used to identify the most common ELMs.
- The most common are:
  - **Type I ELMs.**
  - **Type III ELMs.**
  - **Type II (or ”grassy” ELMs).**

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    - typically occurs at $P_{sep} \gg P_{LH}$.
    - they are triggered by ideal MHD.
    - they appear as sharp burst on the D_α.
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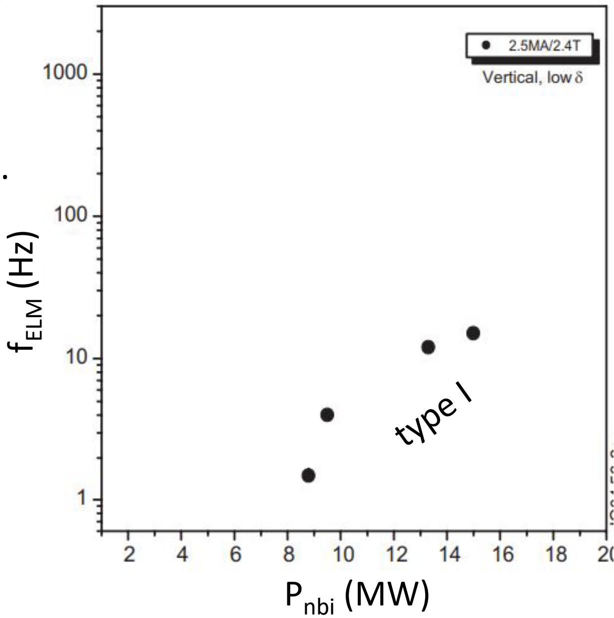
[Sartori PPCF2004]



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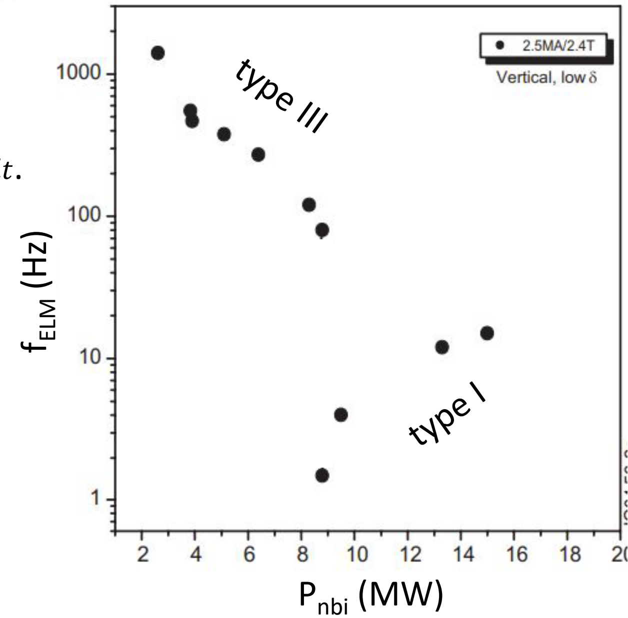

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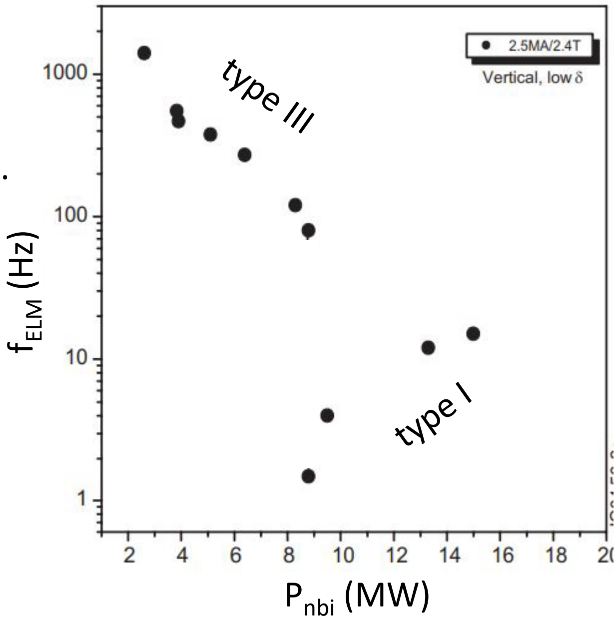
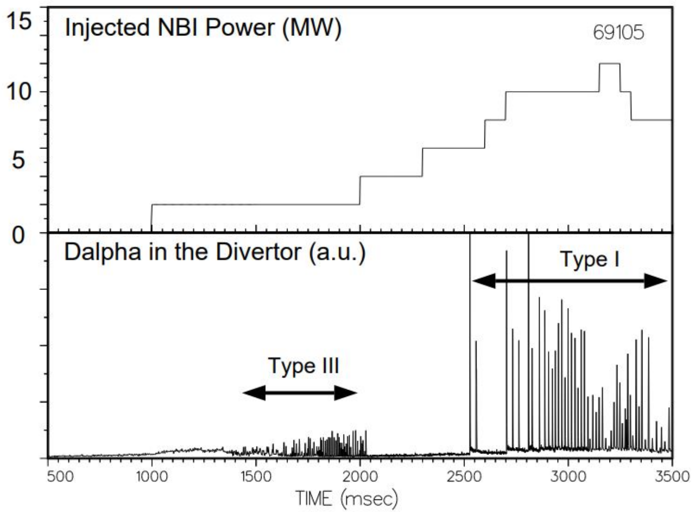
  - **Type II (or "grassy" ELMs).**
    - Not achieved in all machines.
    - Occurs at high confinement and high triangularity.
    - They lead to small but frequent energy losses.

[Sartori PPCF2004]

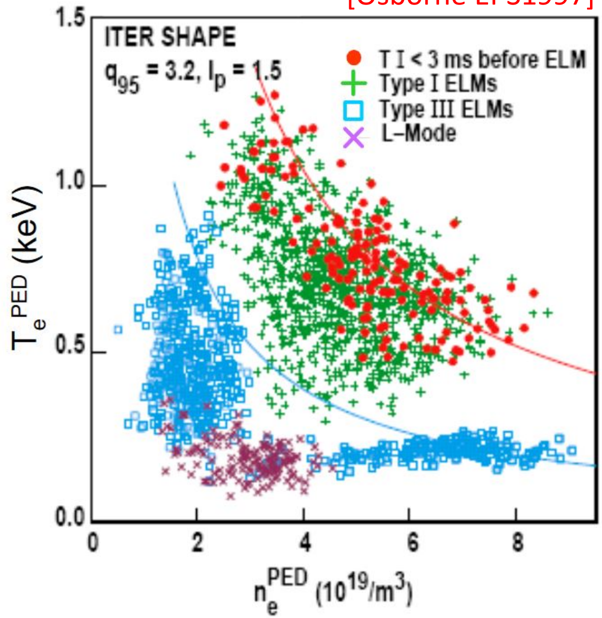


ELM types: examples

[Zohm PPCF1996]



[Osborne EPS1997]



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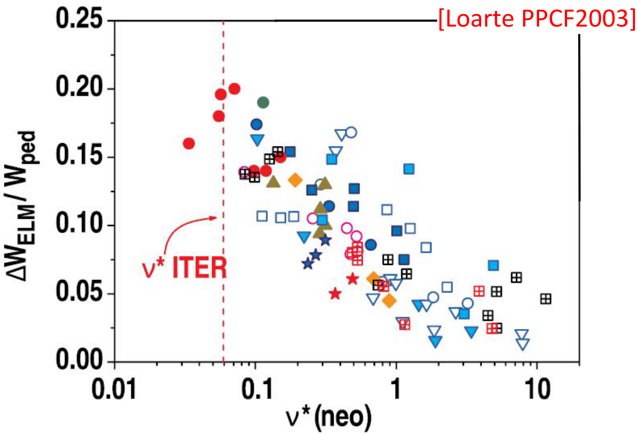
For reviews of ELM types:

- [Zohm PPCF1996]
- [Leonard PoP2014]

ELMs: energy losses and heat loads

- ELM losses tend to increase with decreasing collisionality.
- At ITER collisionalities, the ELM energy losses might be 15%-20% of the pedestal stored energy.



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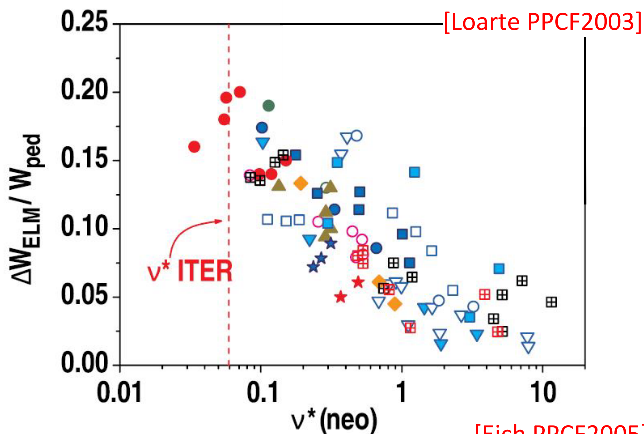
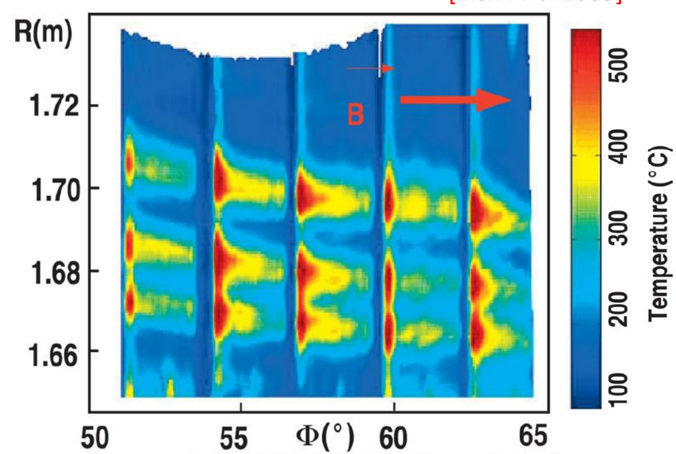
- ELMs lead to fluxes of energy and particles to the divertor.
- The divertor can be damaged or could even melt. This could pose a problem for ITER. [Pitts JNM2013]

→ It is essential to understand ELM pedestal physics to:
  - Minimize ELM energy losses
  - Develop techniques for ELM mitigation/suppressions. Some of the most developed techniques are:
  - RMPs for a review: [Evans JNM2013]
  - ELM pacing with pellets [Baylor NF2009]

[Loarte PPCF2003]



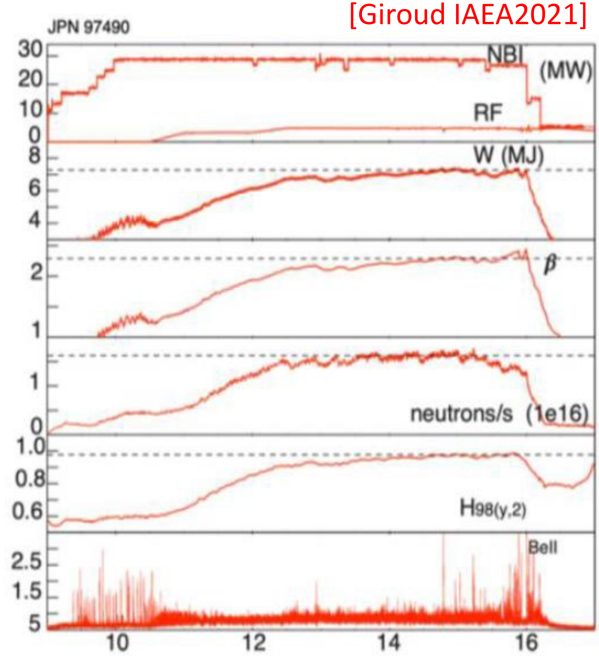
[Eich PPCF2005]



ELM types: small ELMs scenarios

- Type I ELMs have been the most studies, so far
- In recent years, significant experimental efforts have been devoted to identy and study alternatives to type I ELMs that might be useful for a fusion reactor:
  - **Small ELMs (SE)**
    - at very low-gas and high performance baseline plasmas in JET [Garcia PoP2022]
  - **Quasy Continuous Exhaust (QCE)**
    - at high triangularity and high gas rate (type II ELMs) [Stober NF2001]
  - **Enhanced D-alpha (EDA) and quasi coherent mode (QCM)** [Greenwald PoP1999]
    - at high triangularity, low gas rate and power
  - **Quiescent H-mode (QH)** [Chen NF2020]
    - At high NBI torque, which excites a edge harmonic oscillation EHO which increase transport.
  - **Seeded small ELMs** [Giroud IAEA2021]
    - High power seeded plasmas.

[Giroud IAEA2021]



Advantage compared to standard type I ELMy scenarios: small ELMs, small heat loads on the divertor but good confinement

OUTLINE

- L-H transition
- Pedestal structure
- Edge localized modes (ELMs)
  - ELM energy losses
  - ELM types
- **MHD stability of the pedestal**
  - **Role of MHD stability (and few words on transport)**
  - **The peeling-ballooning (PB) model**
  - **The ELM cycle within the PB model**
  - **Parameters that influences the pedestal**
- Pedestal predictions
  - The EPED model:
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- Some of the most active research areas in pedestal physics

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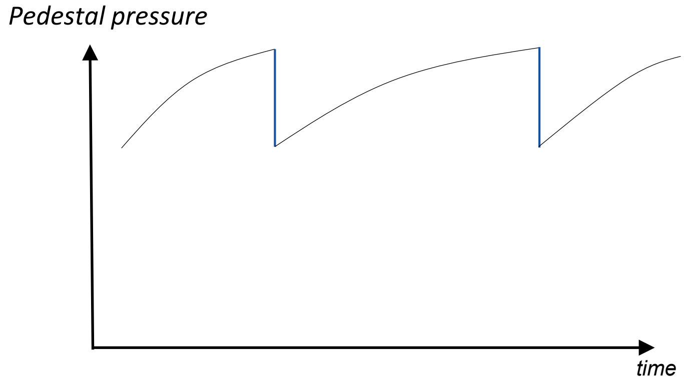
MHD stability and transport

- What are the physical mechanisms that determines the pedestal structure and trigger the ELMs?
- Two main concepts
  - MHD stability
  - Heat and particle transport



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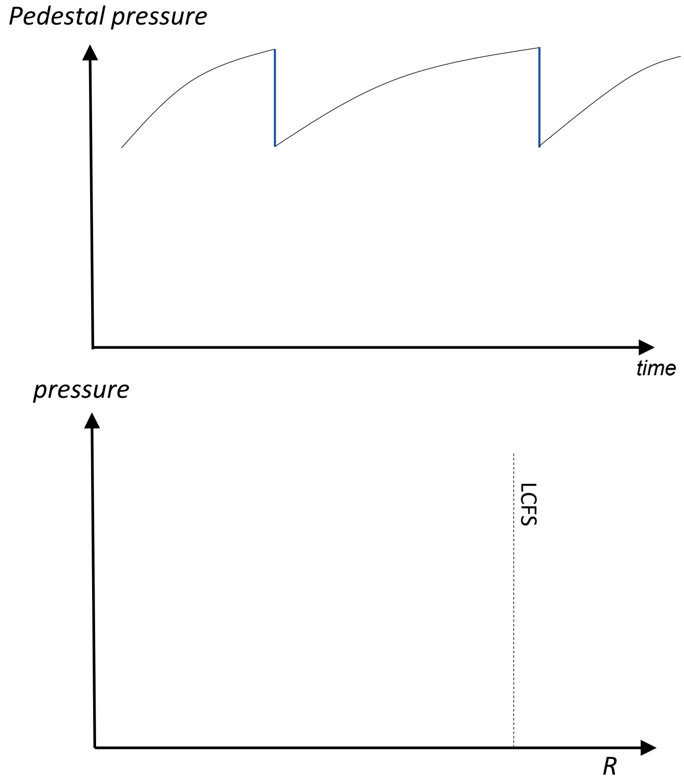

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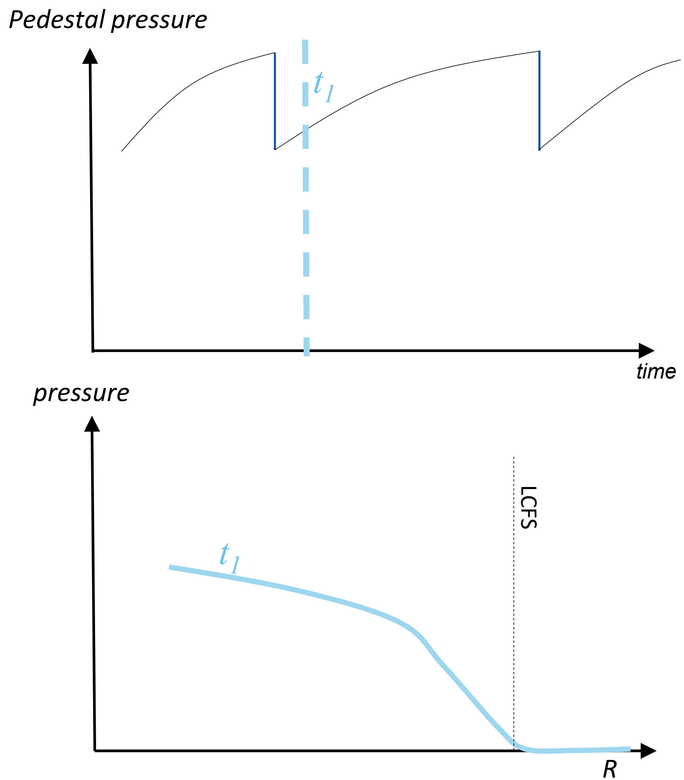

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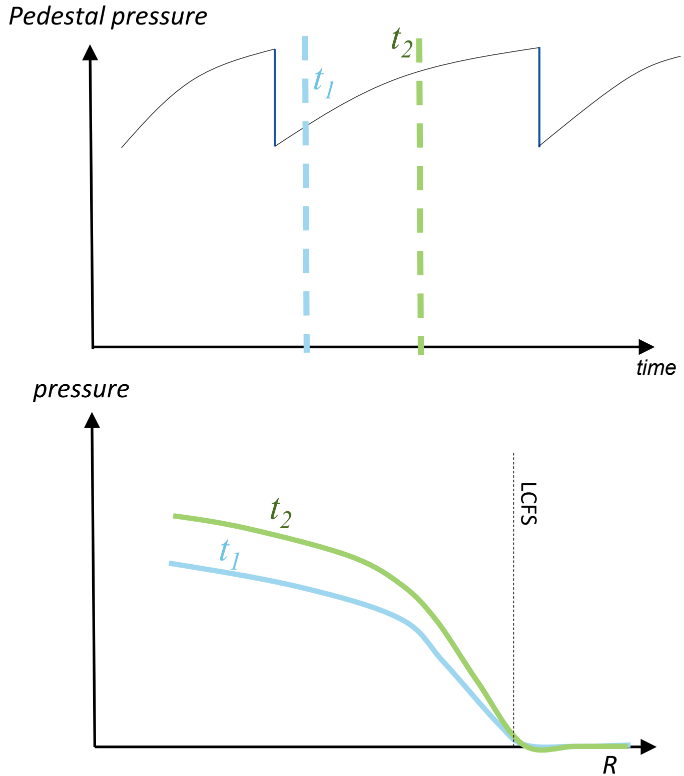

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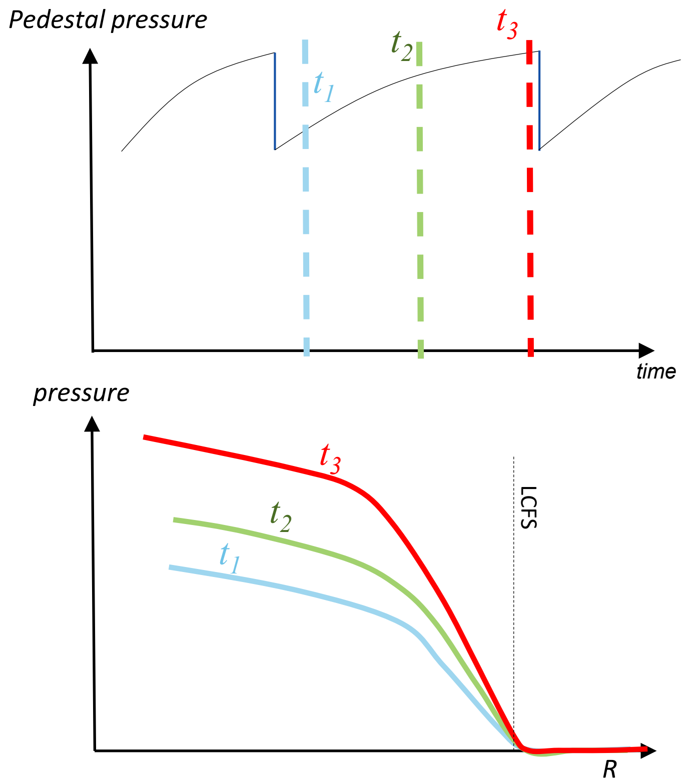

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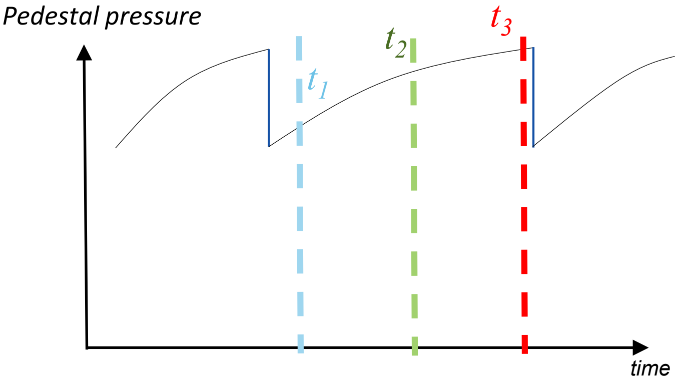
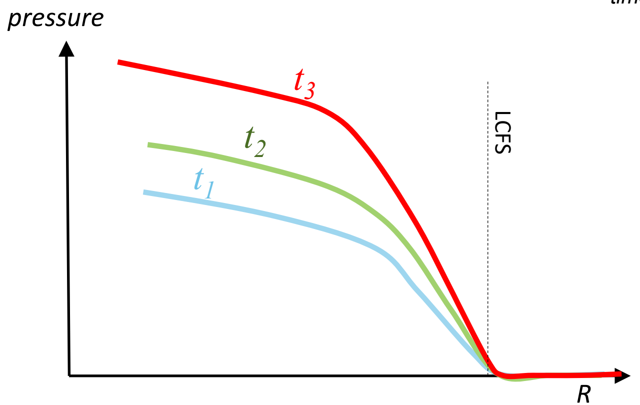
    - pedestal gradients
    - pedestal heights
- The pedestal grows till a critical threshold in pressure. Then, the MHD stability triggers an ELM.
  - MHD stability determines:
    - pedestal height
    - the maximum gradient.
  - In the pedestal, the main MHD instabilities are:
    - **ballooning (B) modes**
    - **peeling (P) modes**
    - **coupled PB modes**





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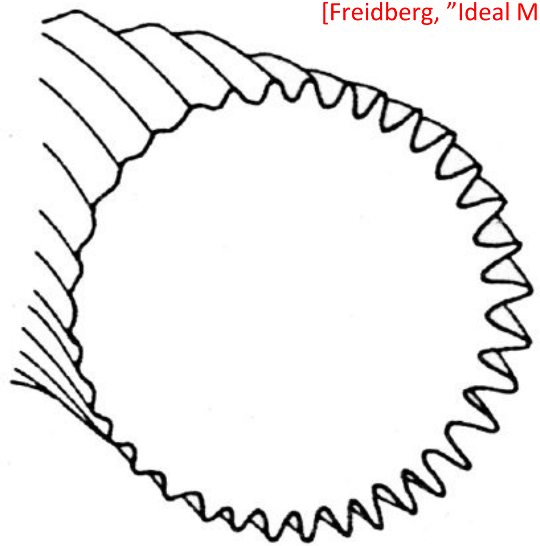
The ballooning modes

- The ballooning instabilities are pressure driven: they are triggered when the pressure gradient exceeds a critical threshold.
- They arise from toroidicity
- B has an unfavourable curvature low field side→ balloning modes develop mainly on the LFS

[Freidberg, ”Ideal MHD”]



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  - **the normalized pressure gradient α**

    $$\alpha = -\frac{2\mu_0 R q^2}{B^2}\frac{dp}{dr}$$

    has a destabilizing effect.
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    $$s = -\frac{r}{q}\frac{dq}{dr}$$

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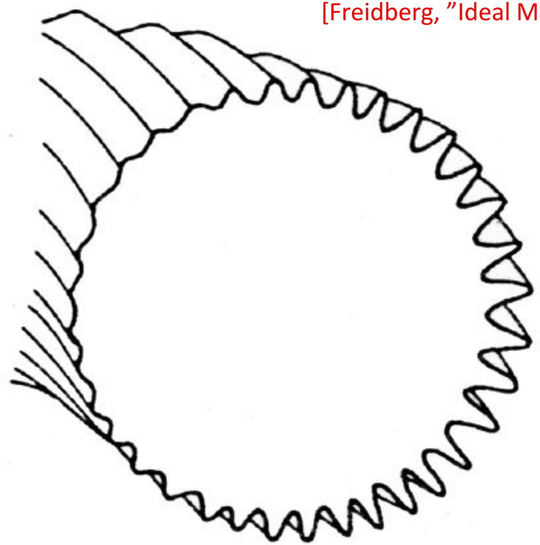

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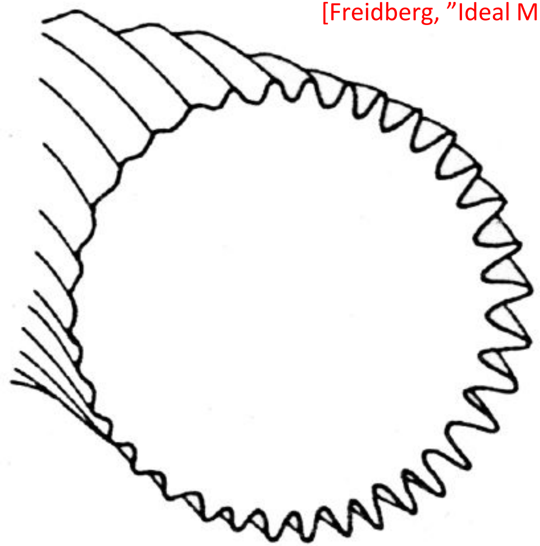

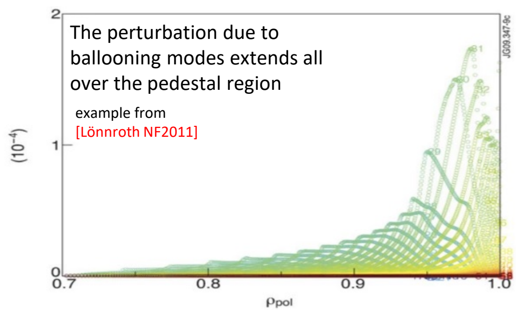

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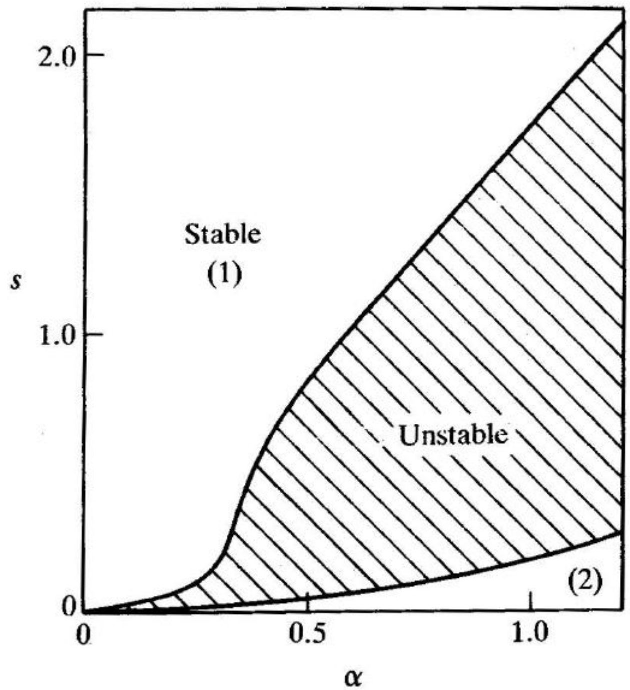

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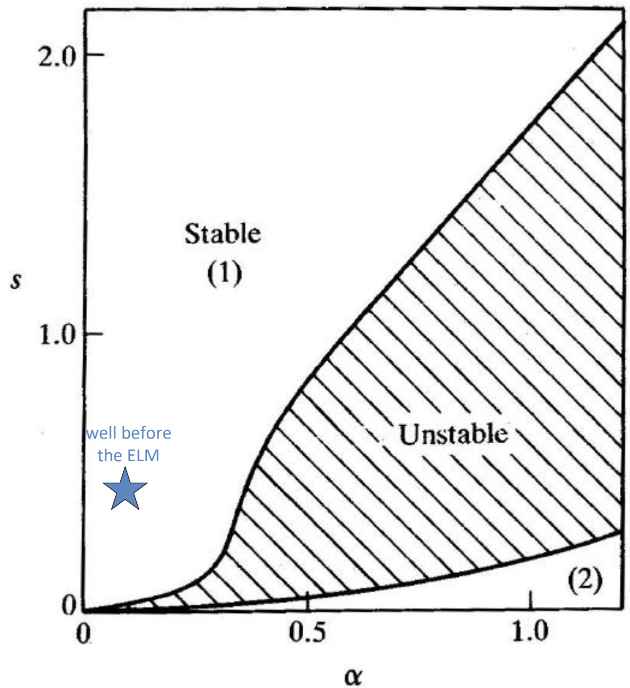

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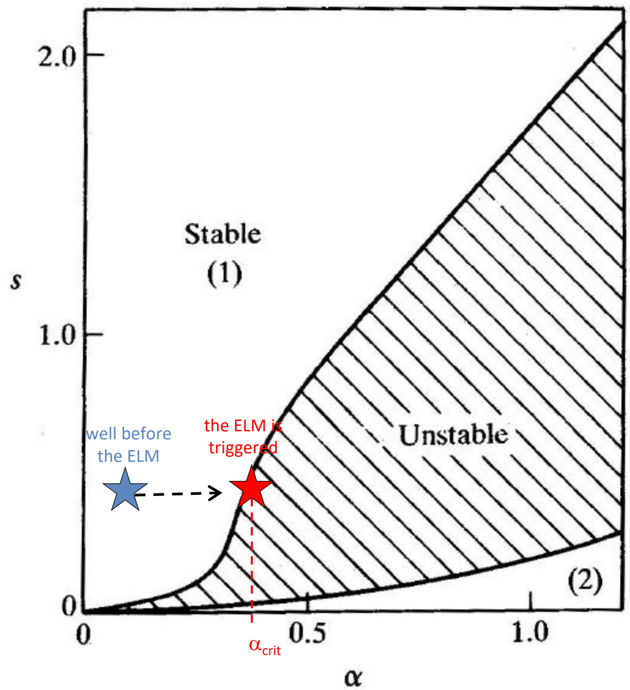

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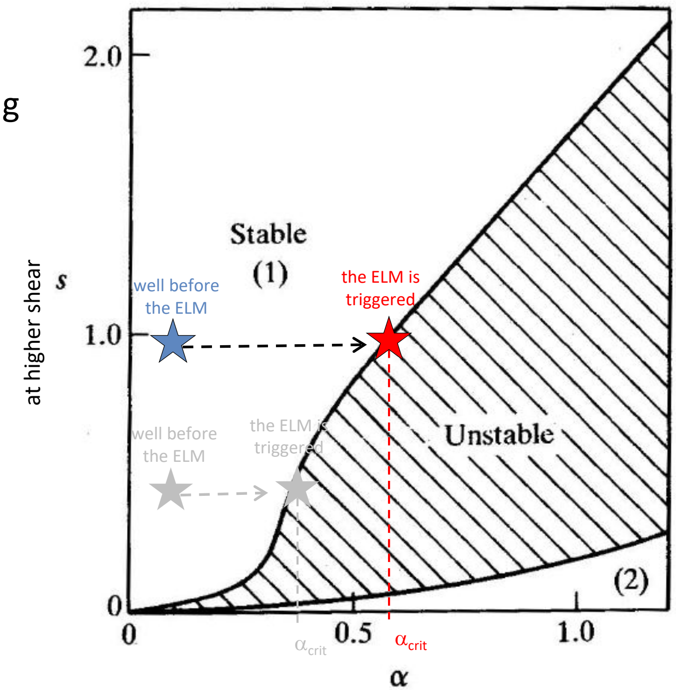

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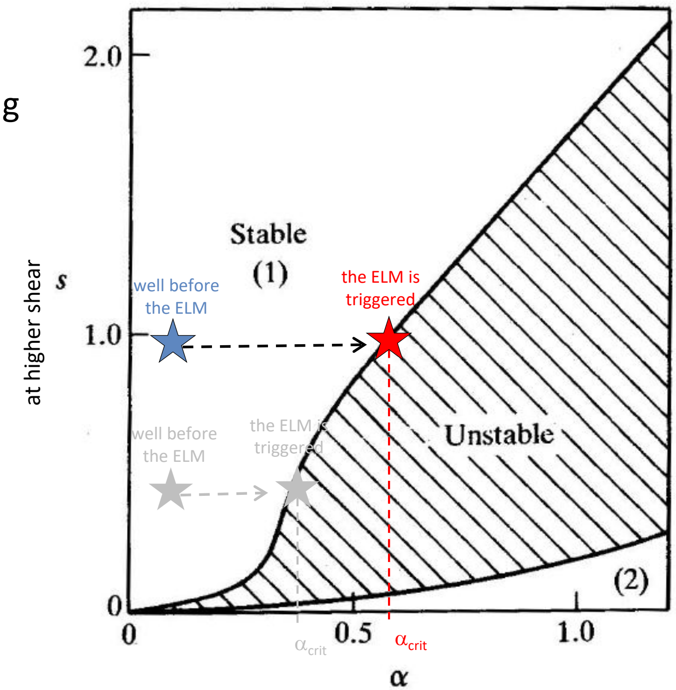

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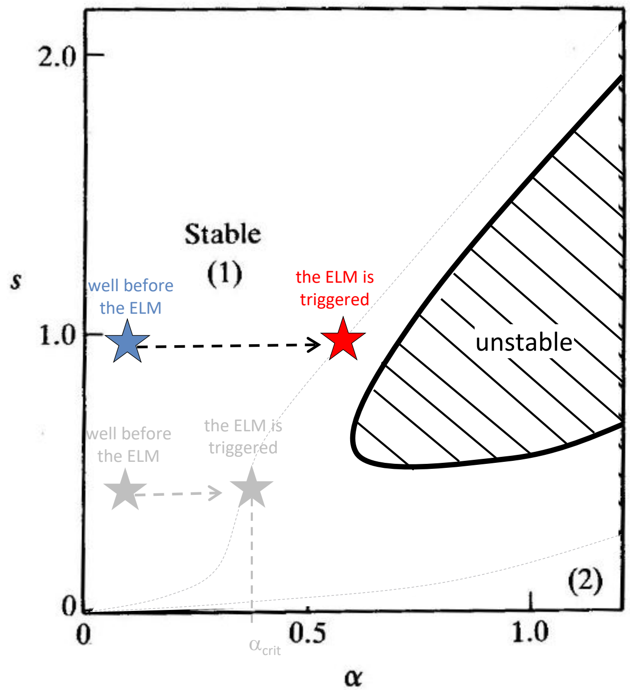

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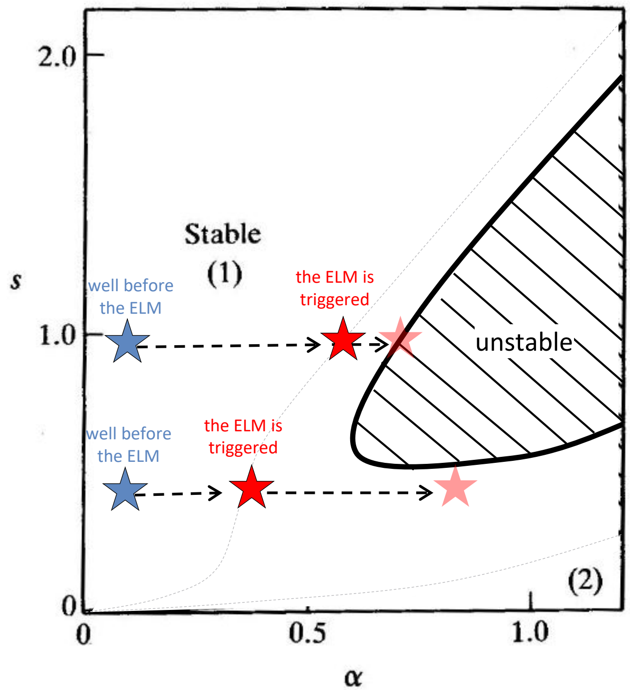

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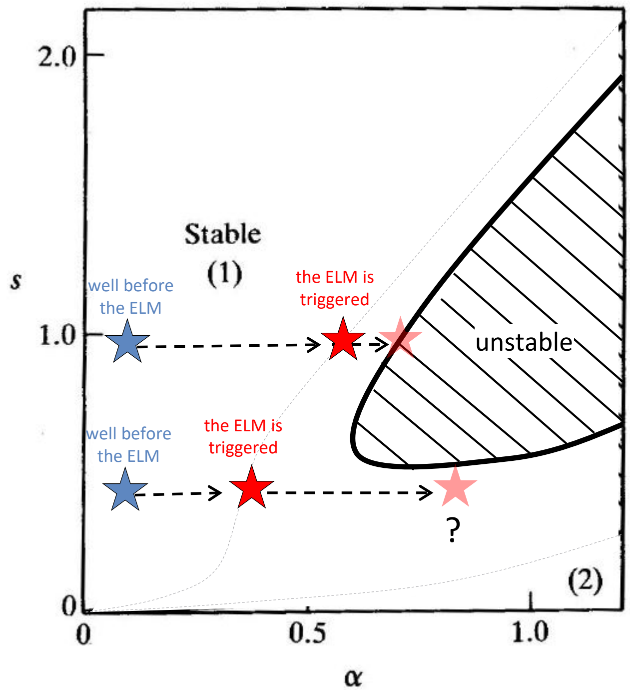
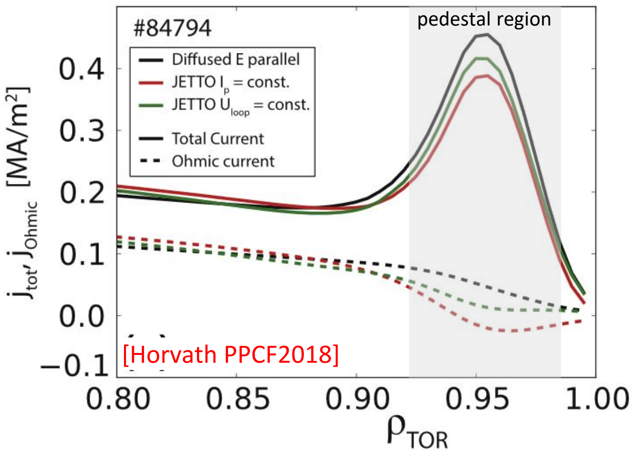


No!
There are further instabilities→see later.
But first…

The bootstrap current

- Due to the steep gradients in the pedestal region, the bootstrap current (j_{bs}) can give a significant contribution to the total current density.
- For an expression of j_{bs}: [Sauter PoP1999]



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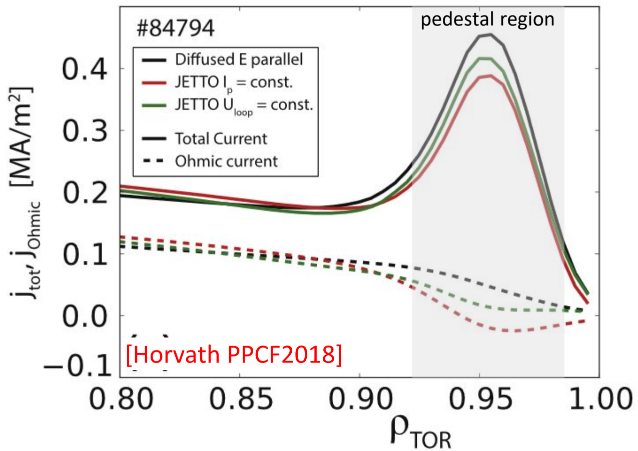
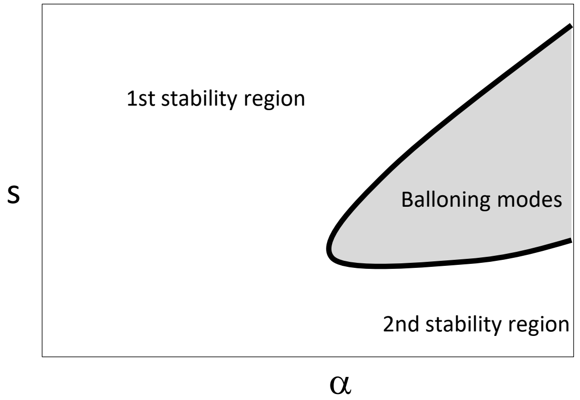
→ j_{bs} has an effect on the pedestal stability.

[Snyder PoP2002]

→ the parameters that affects j_{bs} will affect also the balloning stability:

- collisionality
- plasma shape





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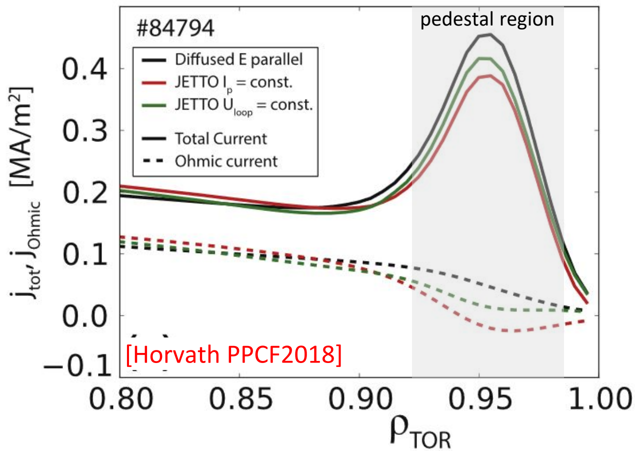

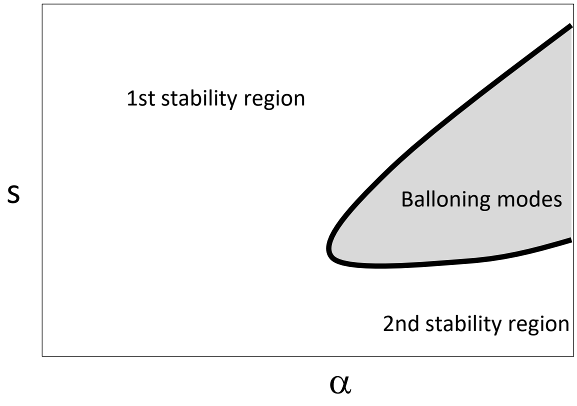

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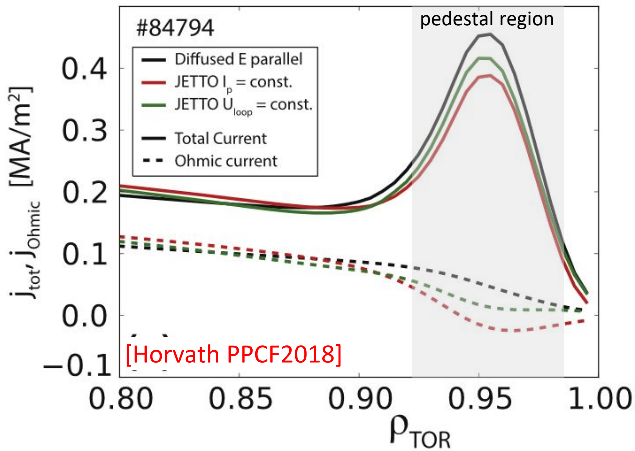
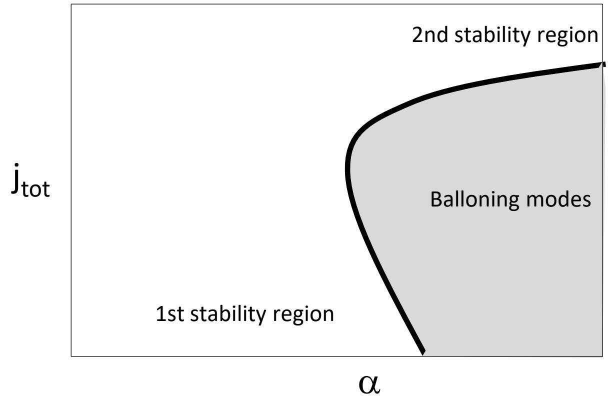
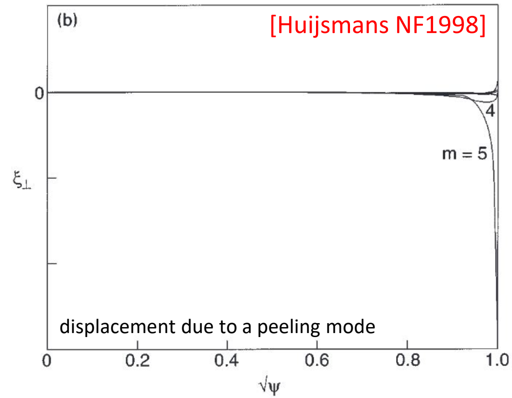




The external kink / peeling mode

- The external kink mode is current driven
- The kink mode (m, n) is destabilized when q at the plasma edge is low enough that $q_{edge} < m/n$ and the resonance is very close to the plasma
  - the kink mode is resonant outside the plasma
  - the kink mode is strongly localized at the plasma edge.



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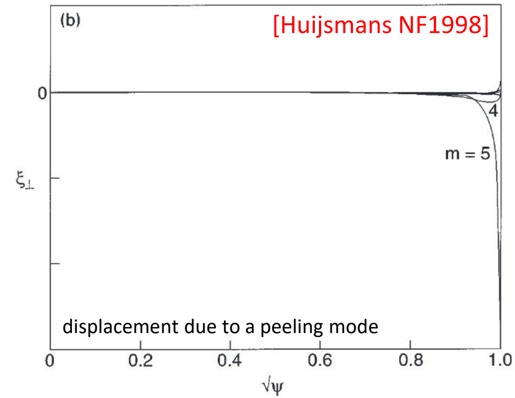

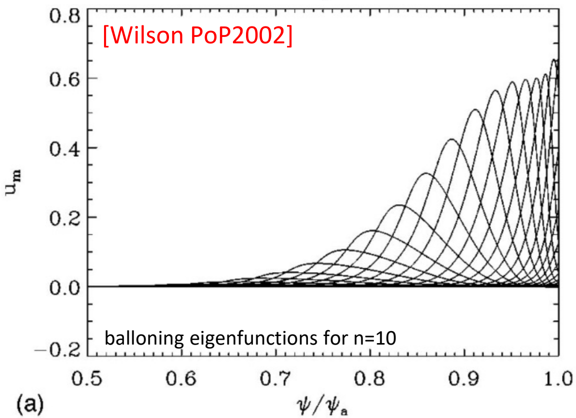

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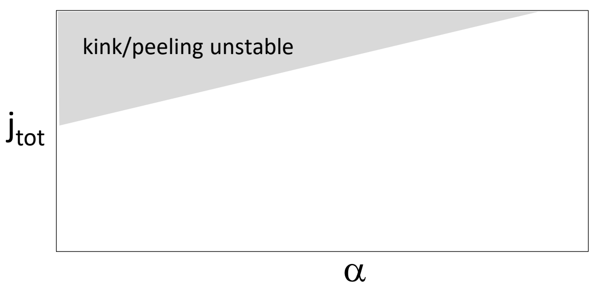
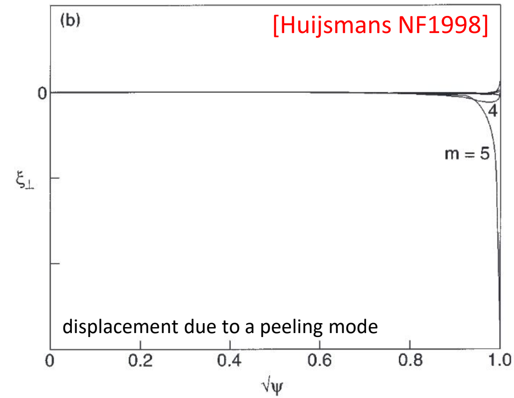
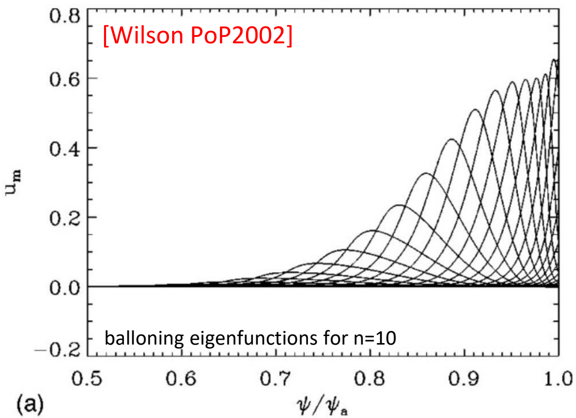
- The kink mode depends on the edge current
  → j_{bs} has a strong role

[Huijsmans NF1998]







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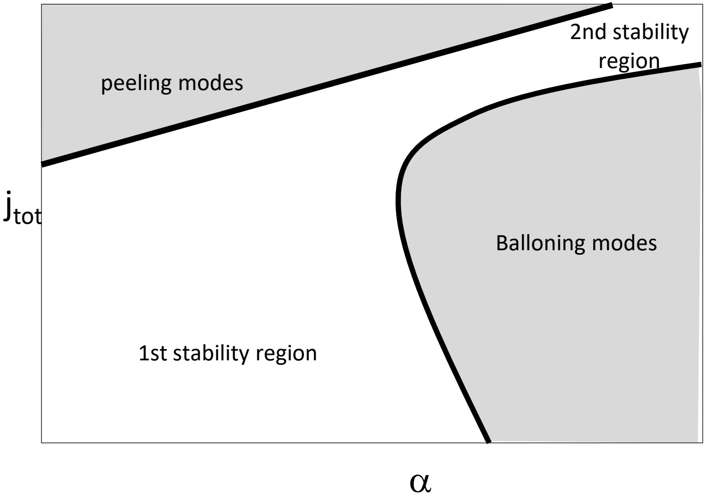

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[Connor PoP1998]

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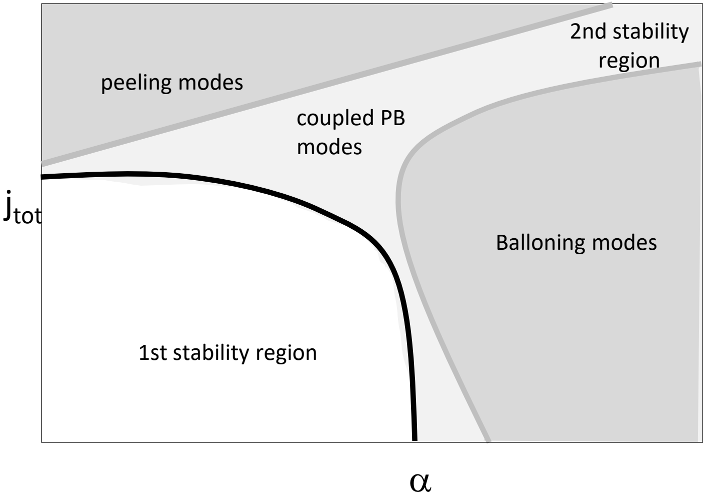

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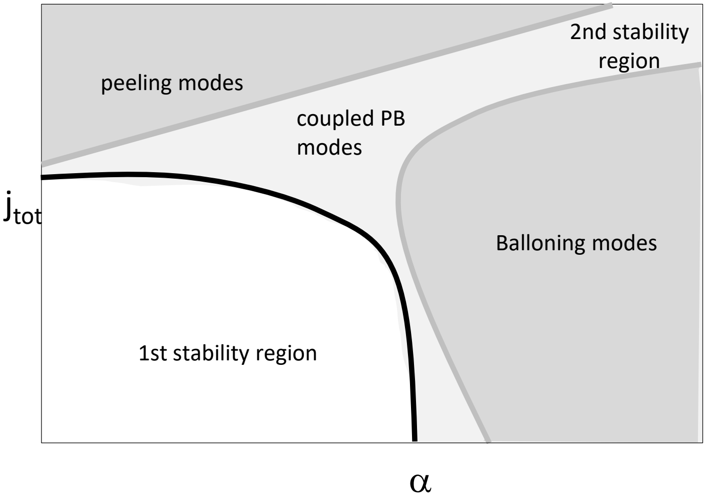
- The PB stability are driven by both pressure gradient and current density.
- The PB stability is the leading theory to explain the pedestal behvaior in type I ELMy H-modes. [Snyder PoP2002] [Wilson PoP2002]
- The PB modes strongly limit the stable region.
- The access to the 2nd stability region is closed (most of the times).



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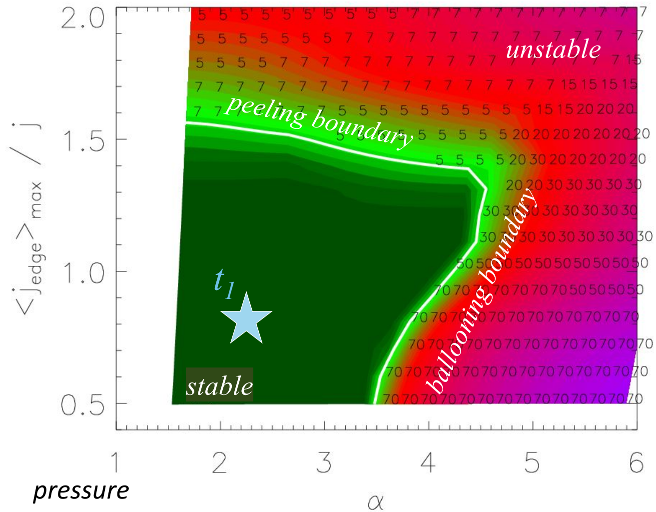
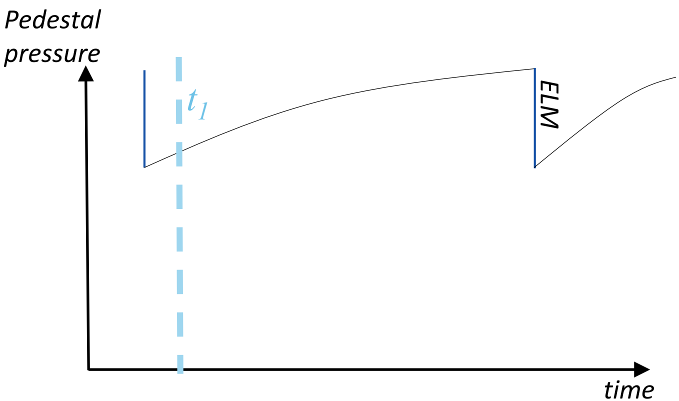
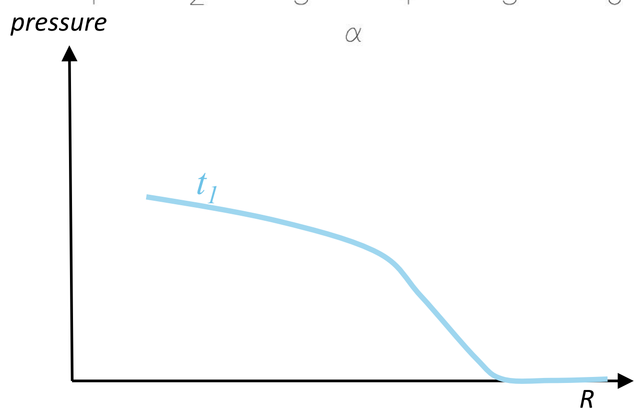
The PB model for the ELM cycle

1 Just after an ELM, the pedestal has low gradient and low j_{bs}.







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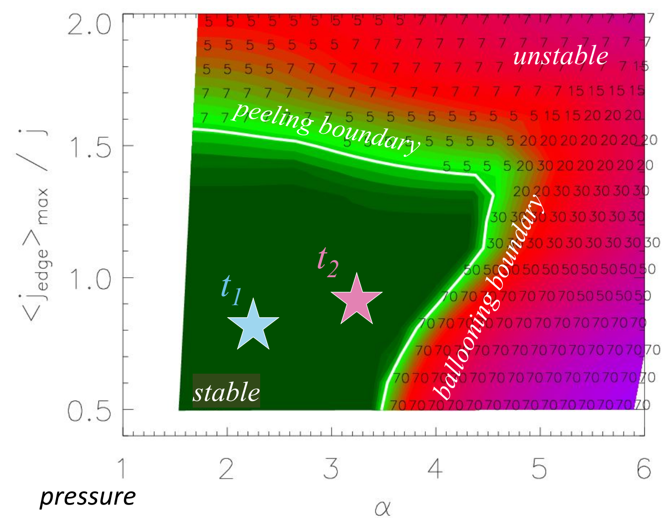

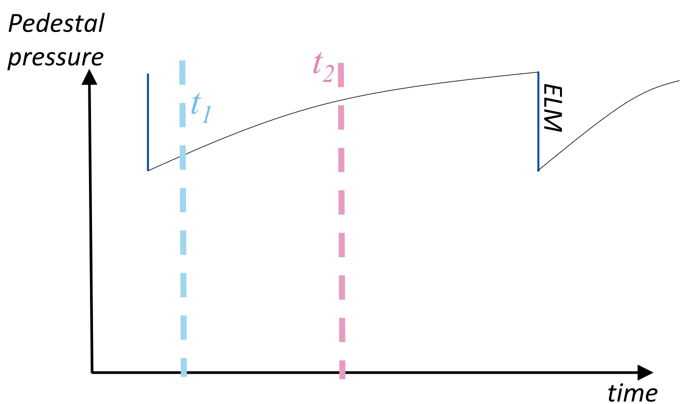

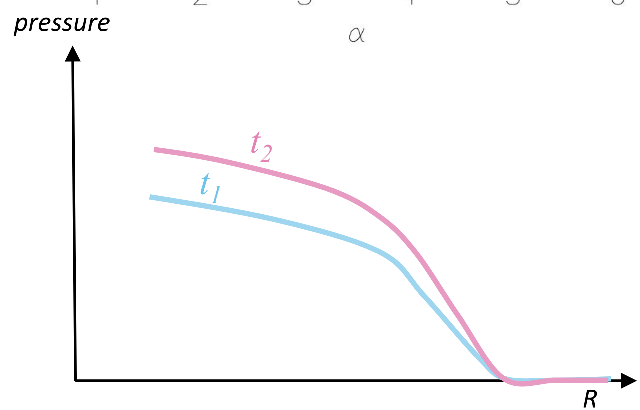

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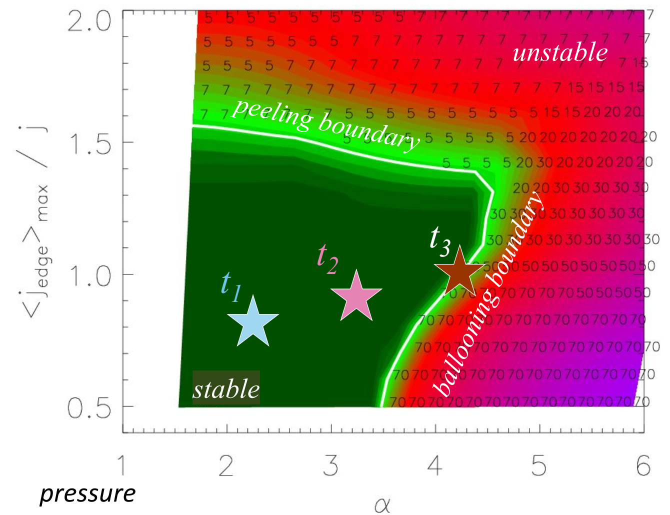

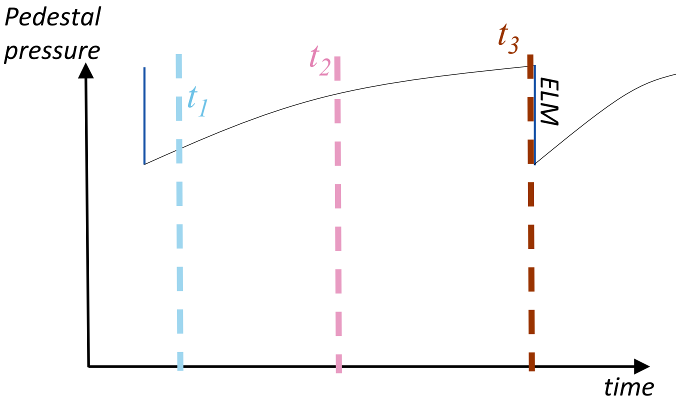

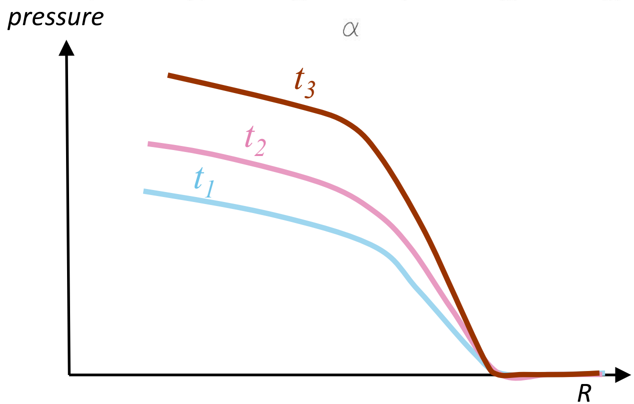

The PB model for the ELM cycle

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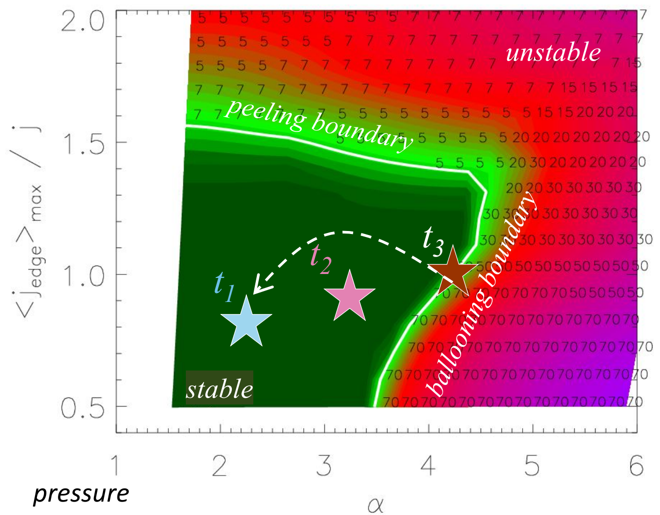
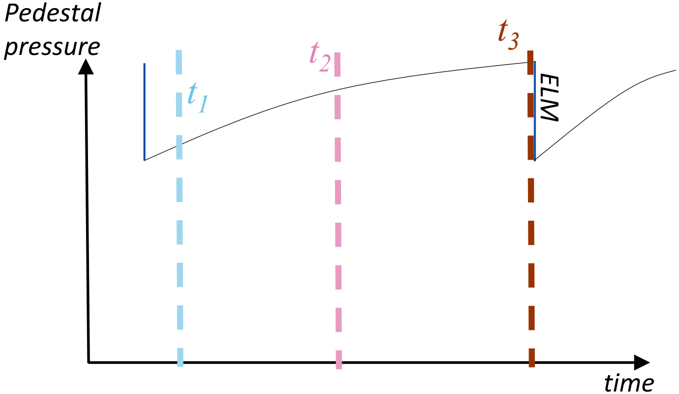
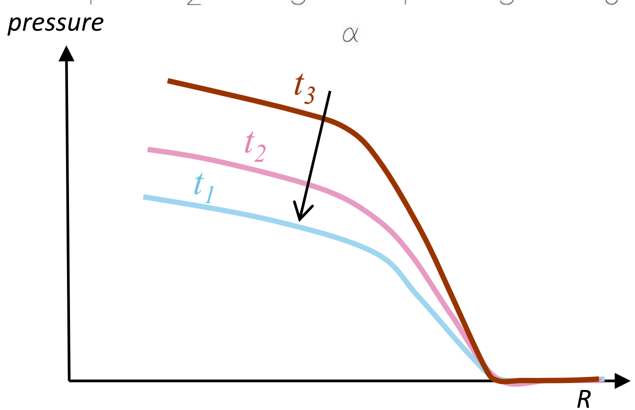
2. During the ELM cycle, the pressure gradient (and hence j_{bs}) increases
3. The process continues till the PB boundary is reached.
4. Then an ELM is triggered:
   - the pressure gradient and the j_{bs} collapse.
   - the process starts again.







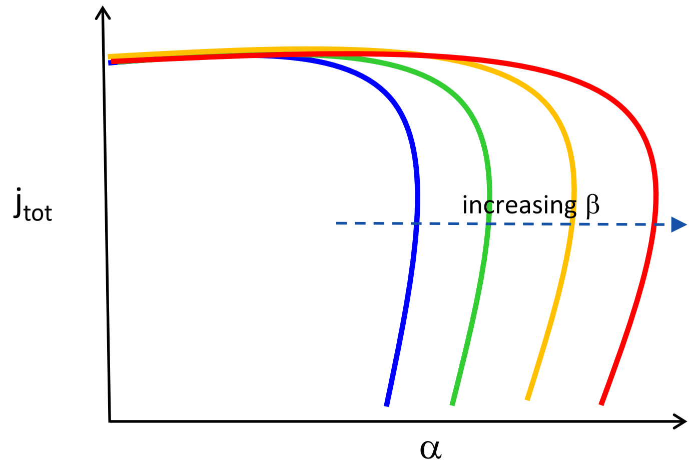
OUTLINE

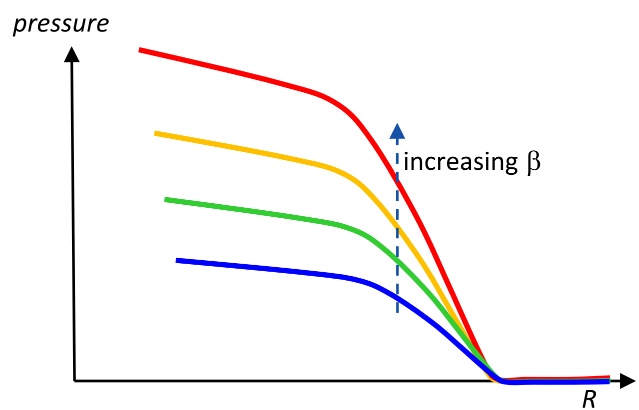
- L-H transition
- Pedestal structure
- Edge localized modes (ELMs)
  - ELM energy losses
  - ELM types
- **MHD stability of the pedestal**
  - **Role of MHD stability (and few words on transport)**
  - **The peeling-ballooning (PB) model**
  - **The ELM cycle within the PB model**
  - **Parameters that influences the pedestal**
- Pedestal predictions
  - The EPED model:
    - The PB constraint
    - The KBM constraint
  - Non-linear MHD modelling
- Some of the most active research areas in pedestal physics

Parameters that affect the pedestal: β

- $\beta = \frac{\langle p \rangle}{B^2/(2\mu_0)}$
- the increase of β leads to the increases of the Shafranov shift.
  - the Shafranov shift has a stabilizing effect on the ballooning modes.
  - the ballooning modes boundary moves to higher α
  - the pre-ELM pedestal pressure gradient increases

→ p^{ped} increases with increasing β.





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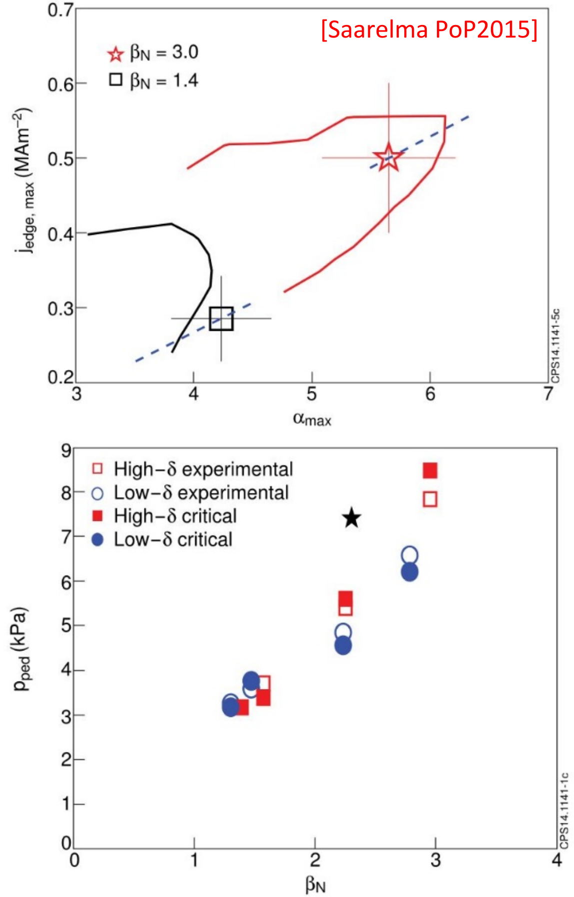


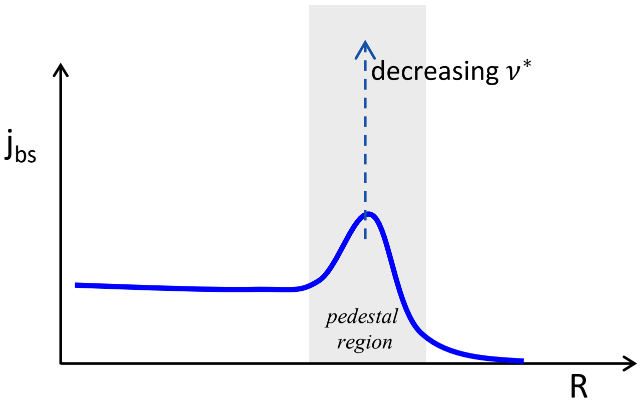
Parameters that affect the pedestal: ν

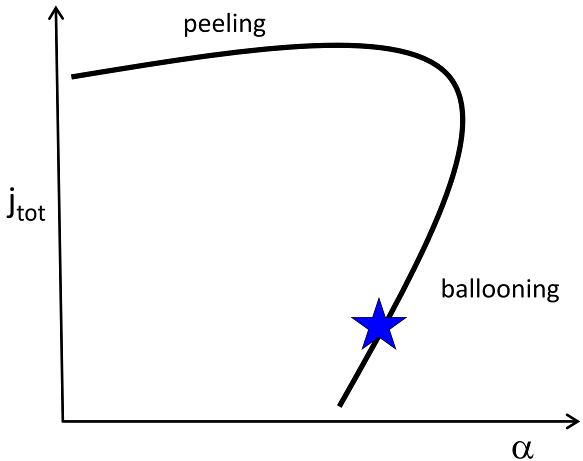
- Collisionality

$$\nu^* = c ln\Lambda \frac{Rq\,n_e}{\varepsilon^{3/2}(T_e)^2}$$

- the collisionality has a major effect on j_{bs}.
  [Sauter PoP1999] [Redl PoP2021]
- Approximately:

$$j_{bs} \approx \nu^{*\,-1}$$





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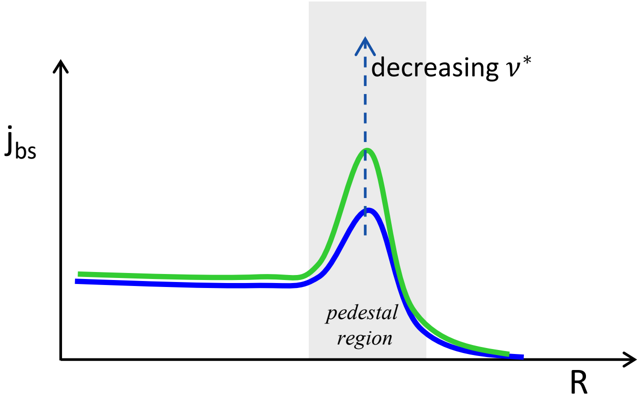

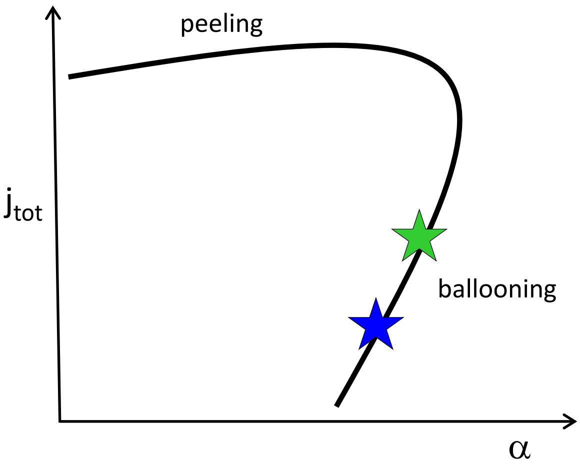

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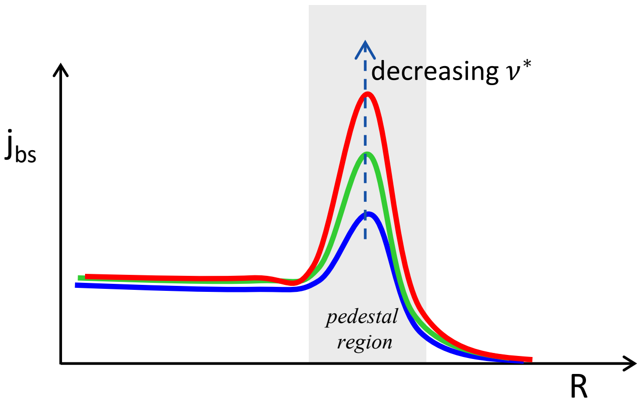

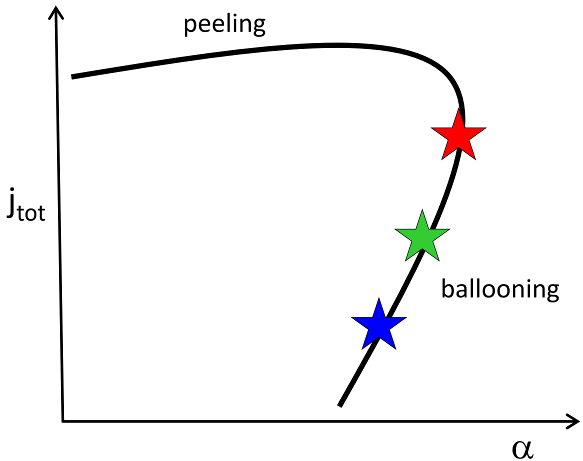

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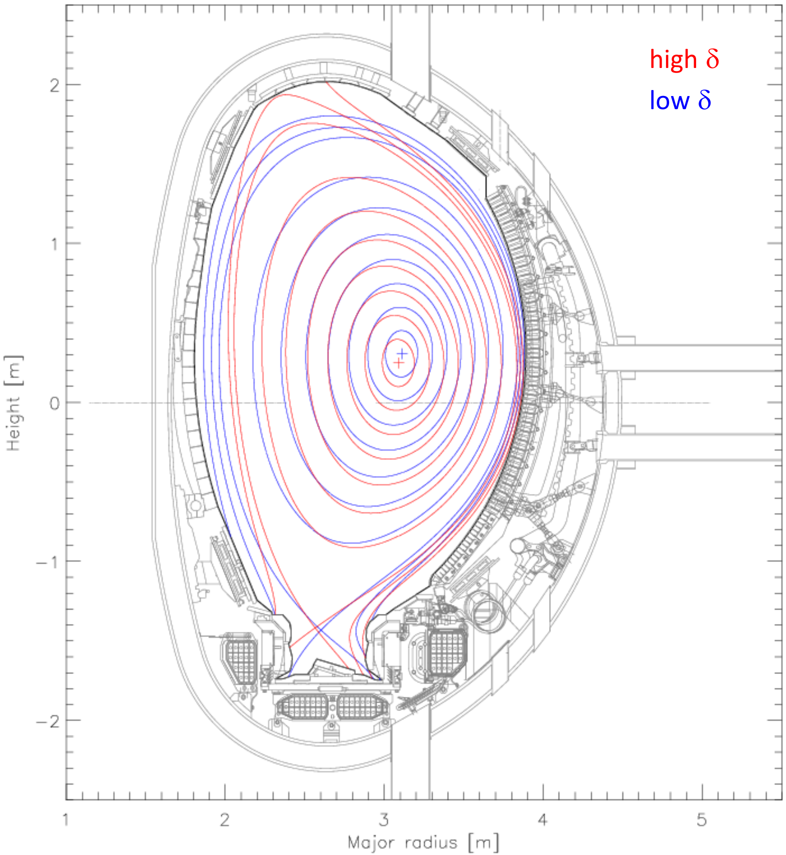

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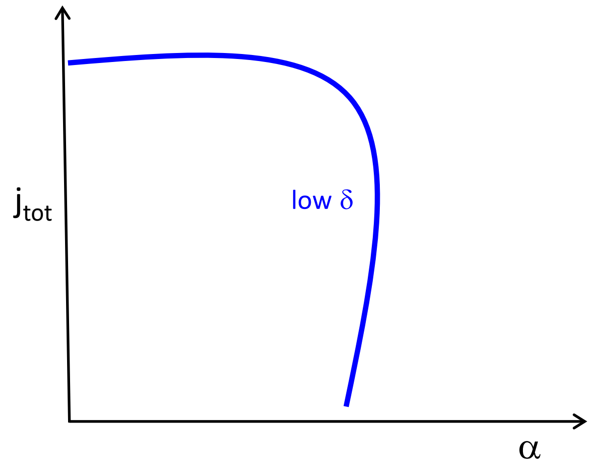

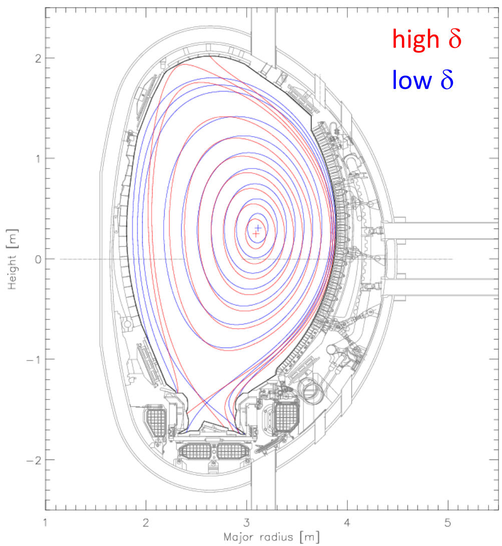

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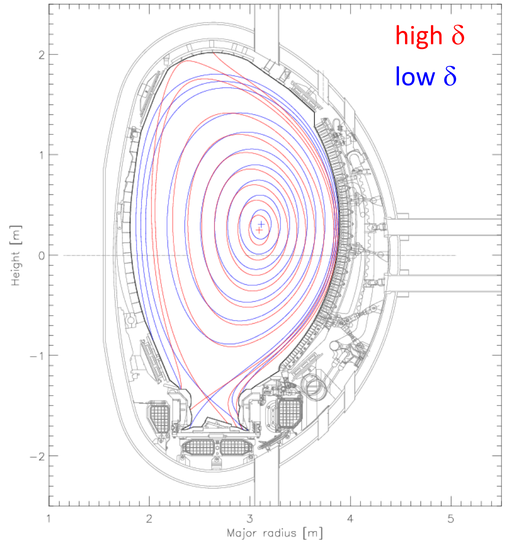

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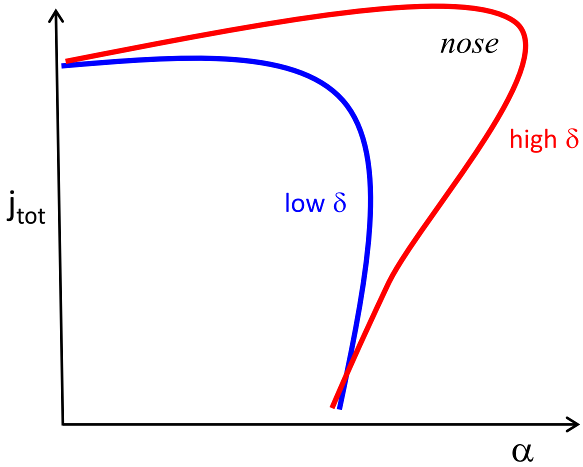

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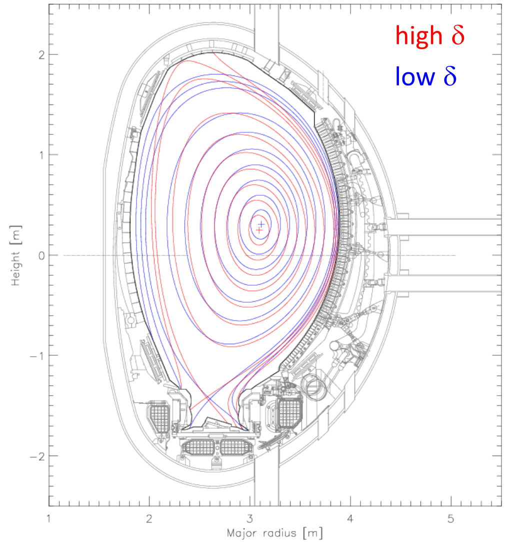

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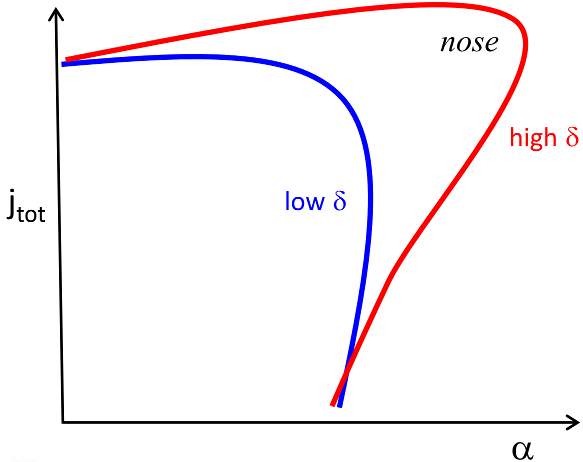

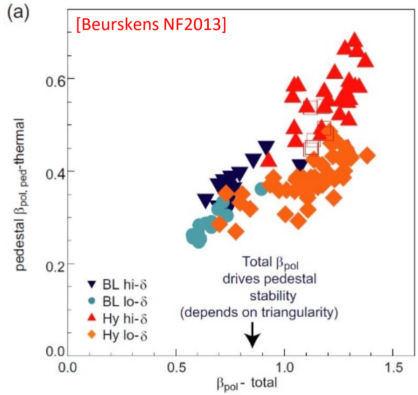

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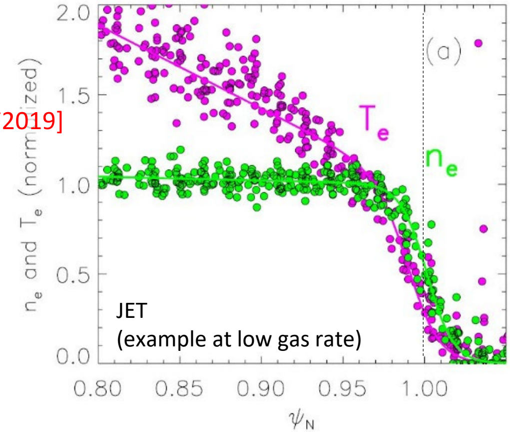

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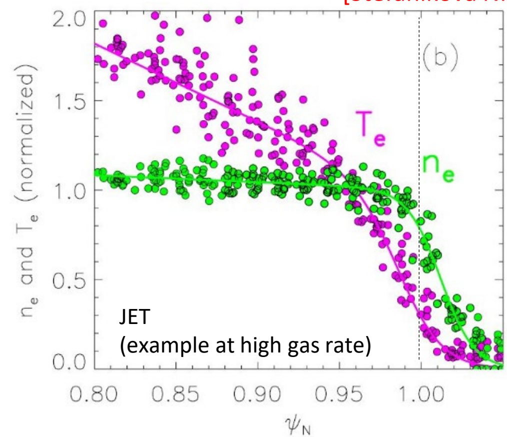

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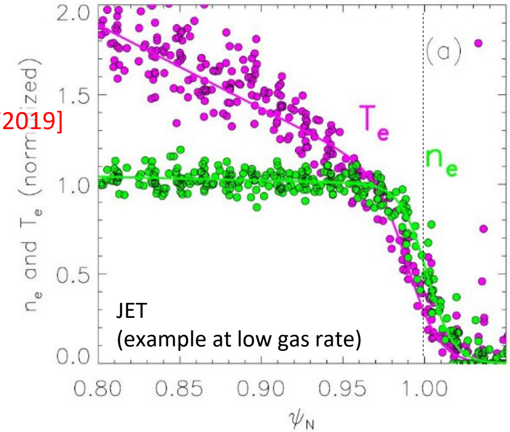

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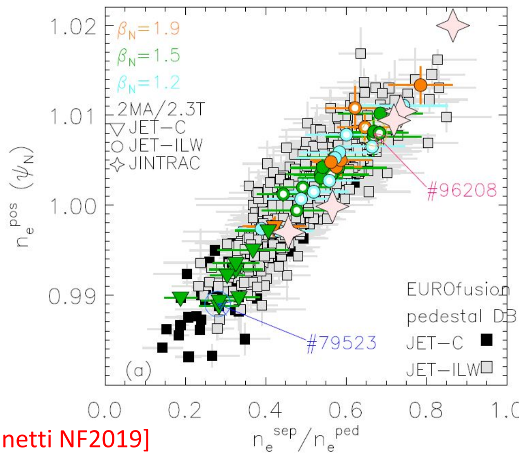

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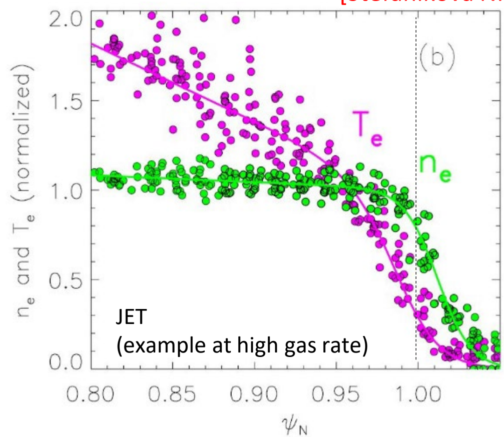

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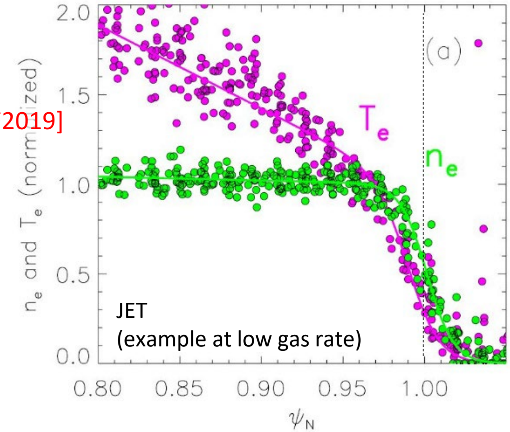

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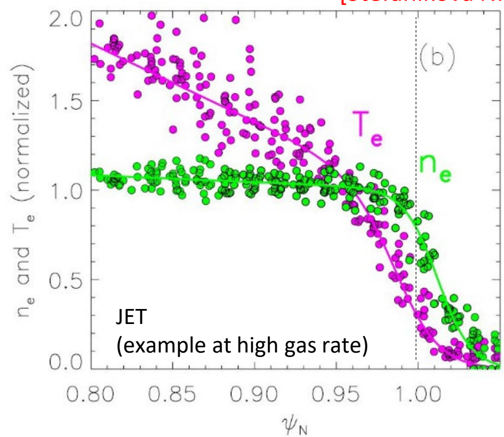

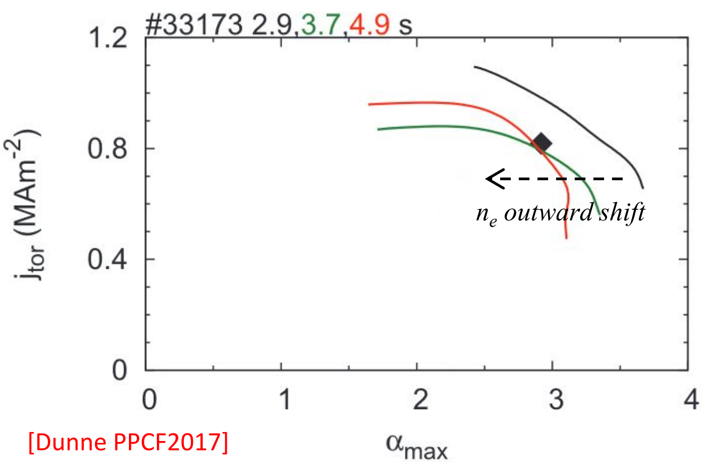

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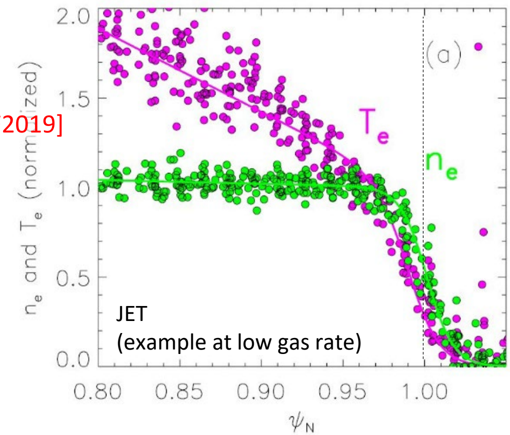

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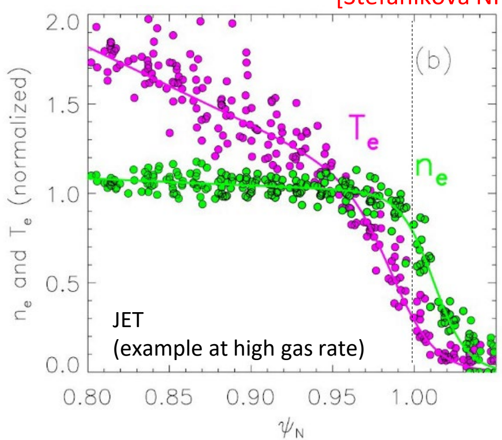

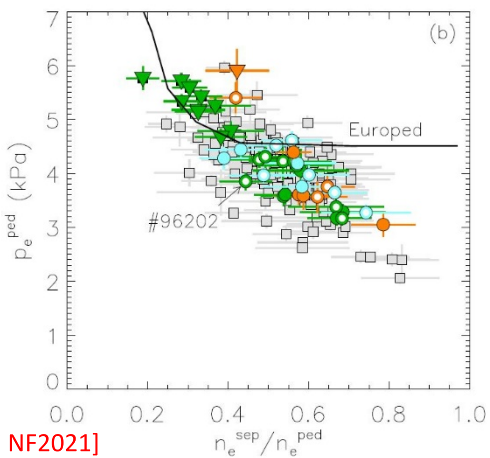

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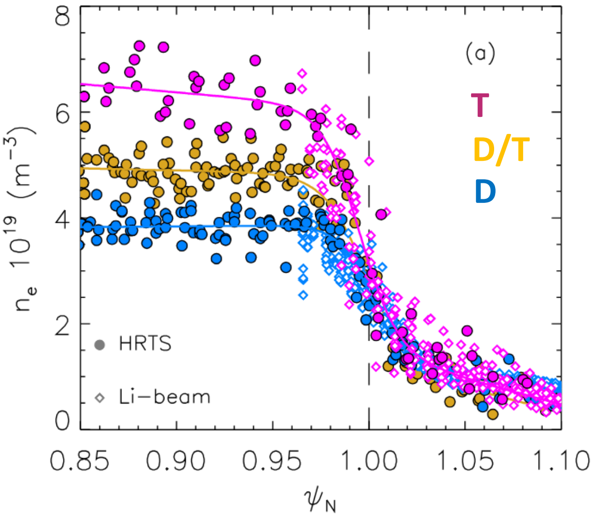

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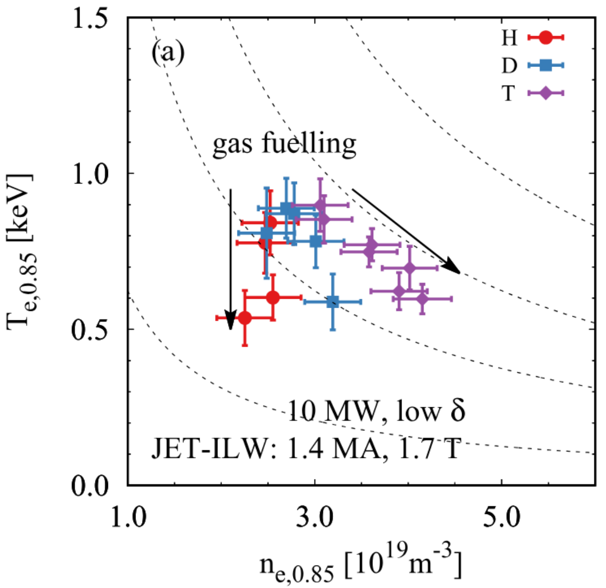

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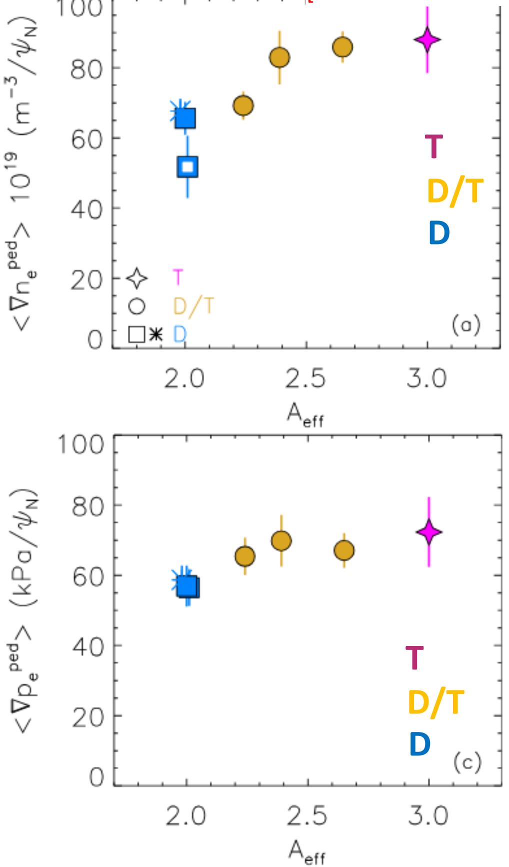
  - Pedestal gradients:
    - The increase in n_e^{ped} is due to an increase in ∇n_e → likely, A affects the transport (but other reasons cannot be excluded yet) [Frassinetti NF2023]
    - The increase in p_e^{ped} is due to an increase in ∇p_e → A can affects the stability [Frassinetti NF2023]
  - Pedestal width: no significant variation

[Frassinetti NF2023]



Parameters that affect the pedestal: isotope

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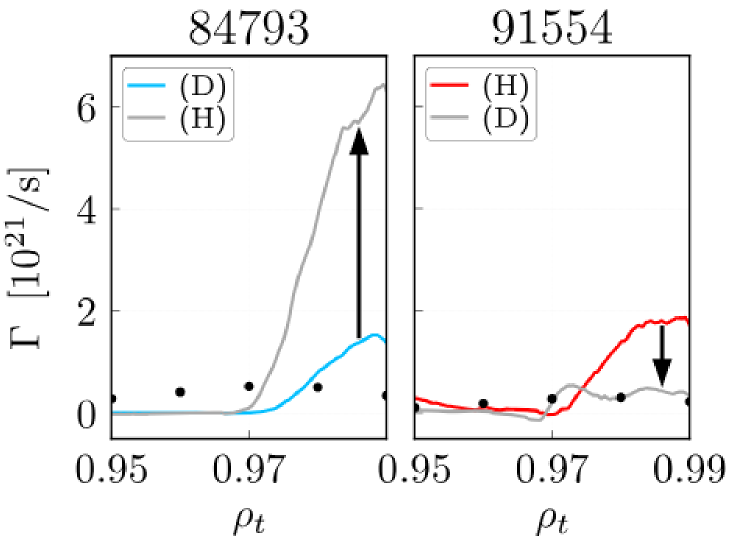

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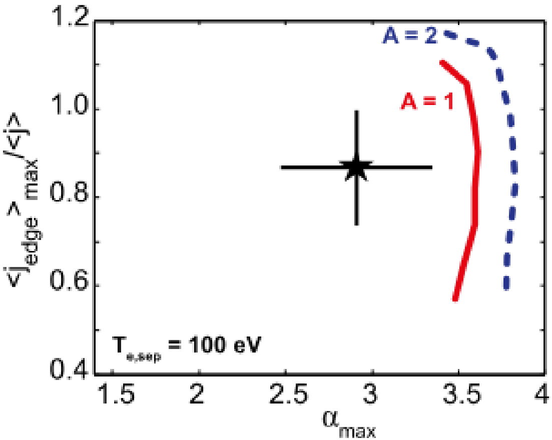

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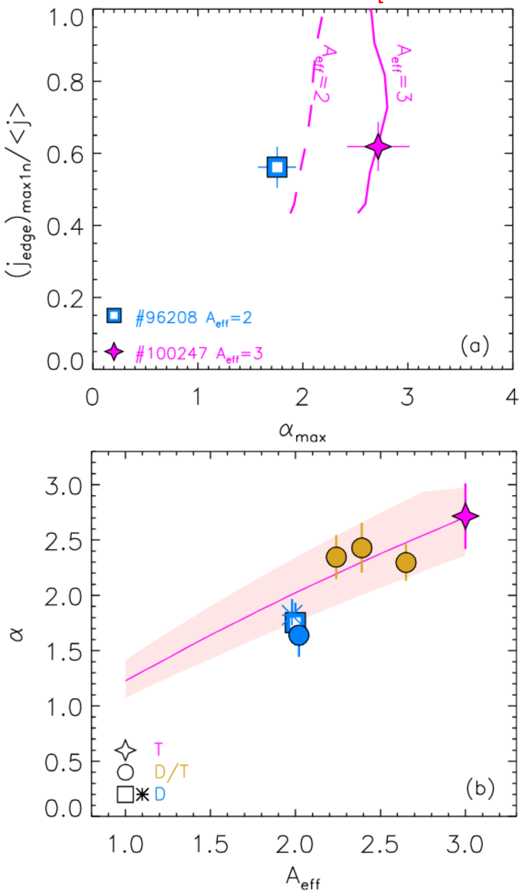
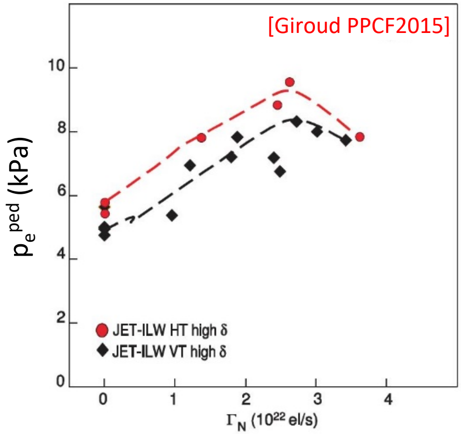
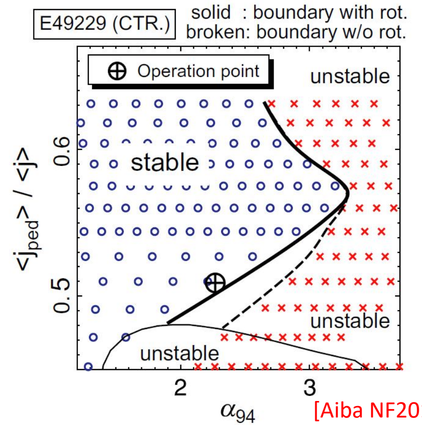


Parameters that affect the pedestal

- Other parameters that affect the pedestal stability are:
  - **Impurities and seeding**. Z_{eff} affects collisionality and j_{bs}. It affects the electron pressure via the dilution effect. It can affect turbulent trasnport. Not fully understood yet.
    [Giroud NF2013, PPCF2015, IAEA2018, Dunne PPCF2017] [Saarelma PoP2015]
  - **q-profile**. A change in q-profiles affects the shear. [Snyder PoP2002]
  - **Pedestal width**. A wider pedestal can contain more ballooning modes, so it is more unstable [Snyder PoP2002]
  - **Plasma rotation.** [Aiba NF2018]
  - **Density at the pedestal top**. Not trivial effects, see later [Snyder NF2011]





[Aiba NF2011]

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Pedestal predictions: the PB constraint

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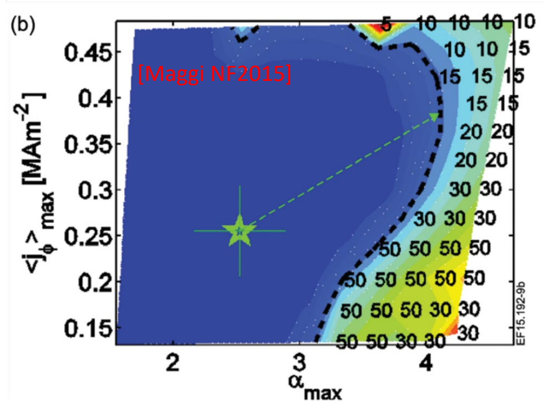

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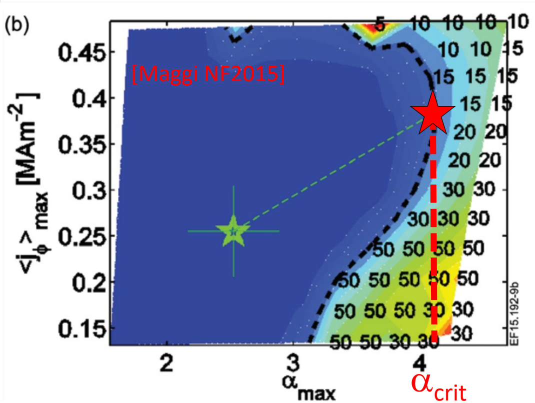

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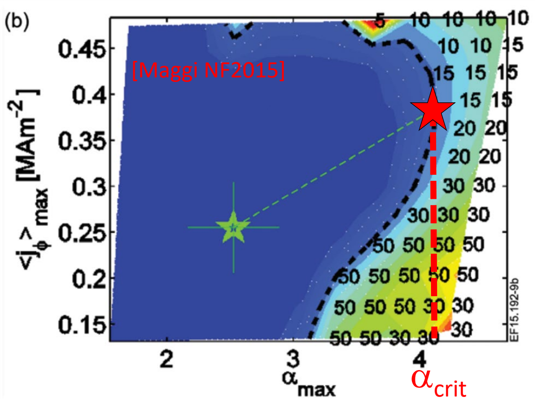

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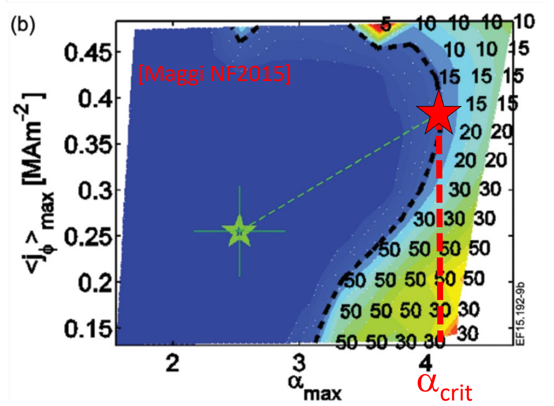
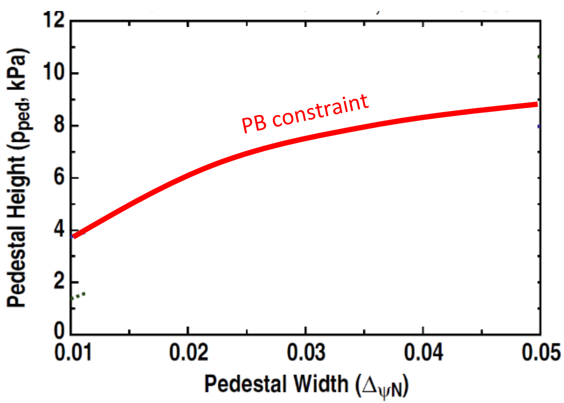
  - A correlation between width and critical pressure can be obtained. This is often called "PB constraint"
- More information is necessary to predict pedestal height and width.





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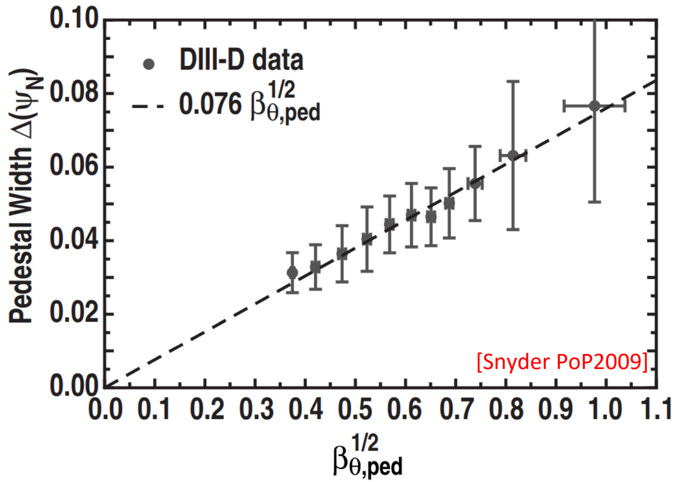

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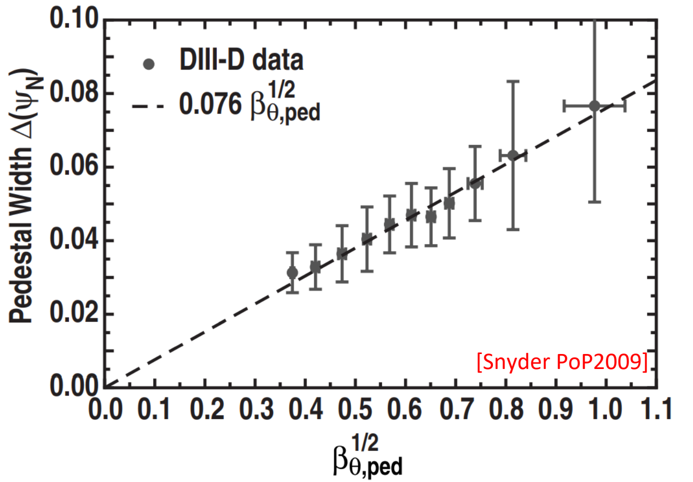

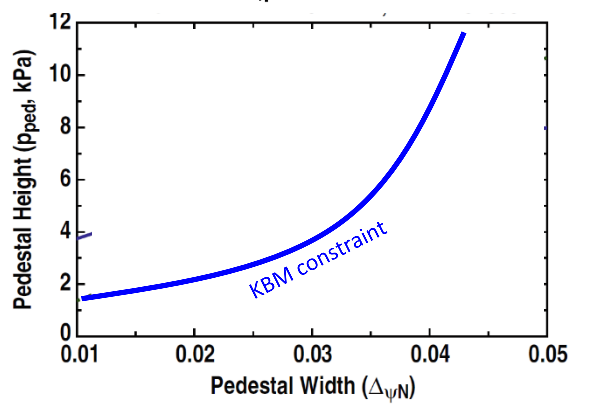

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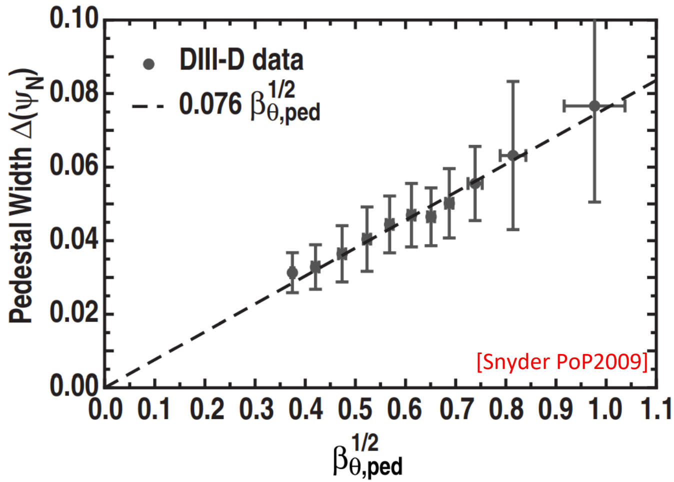

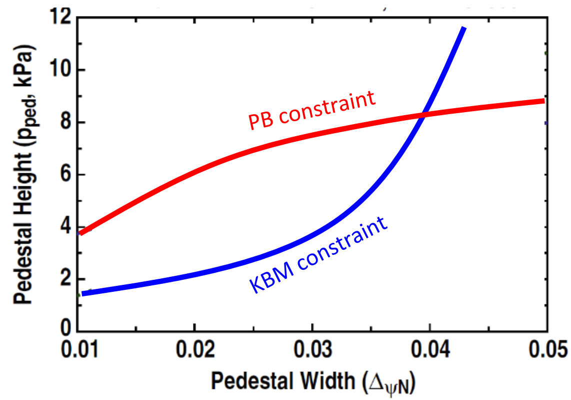

The EPED1 model

- The EPED1 model predicts pedestal pressure height and pedestal pressure width using the [Snyder PoP2009] [Snyder NF2011]
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    local KBM stability → "clamps" ∇p
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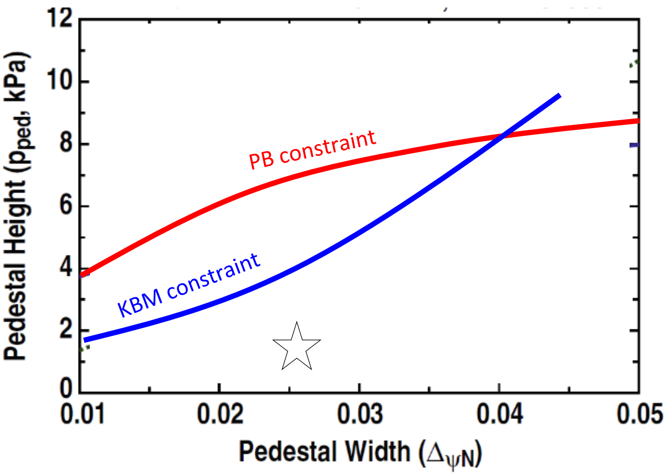

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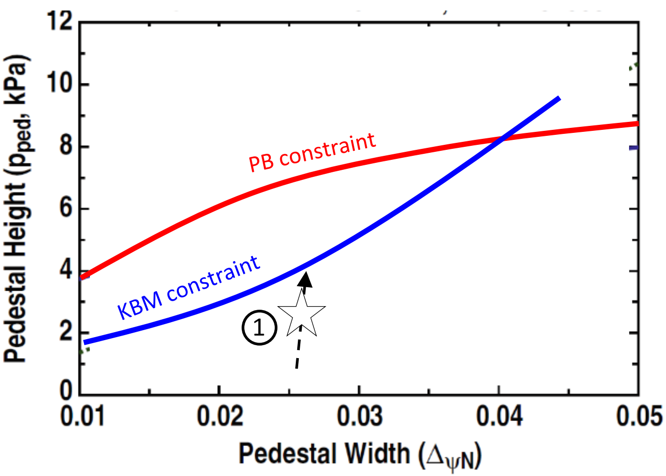

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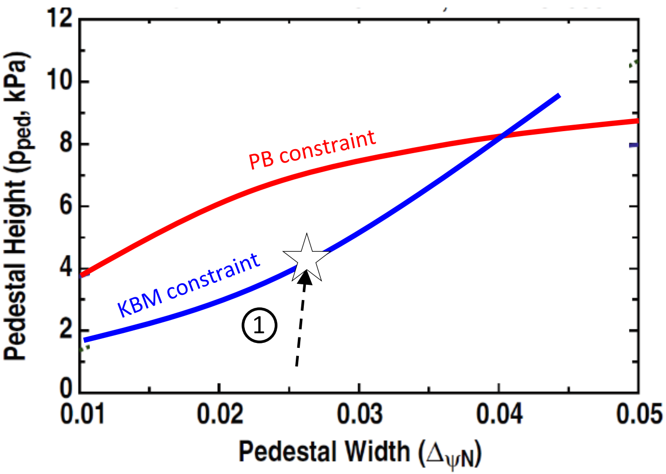

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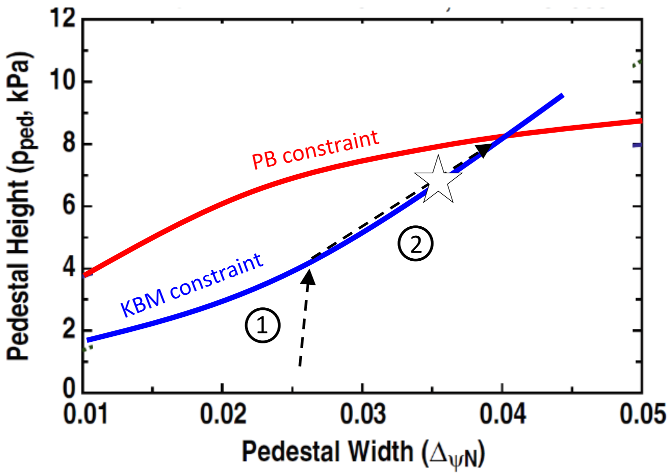

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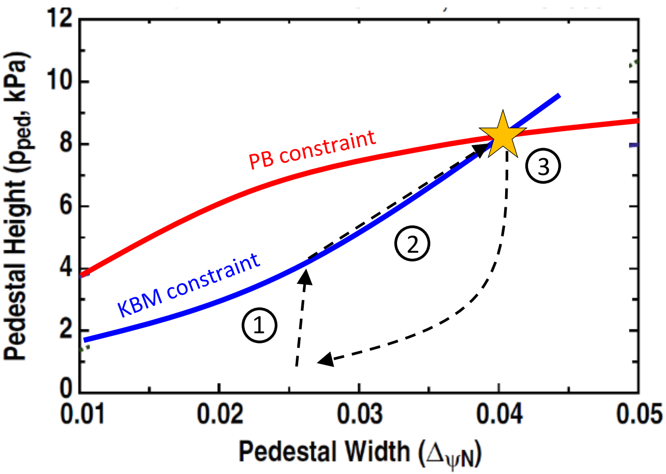

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[Snyder NF2019]

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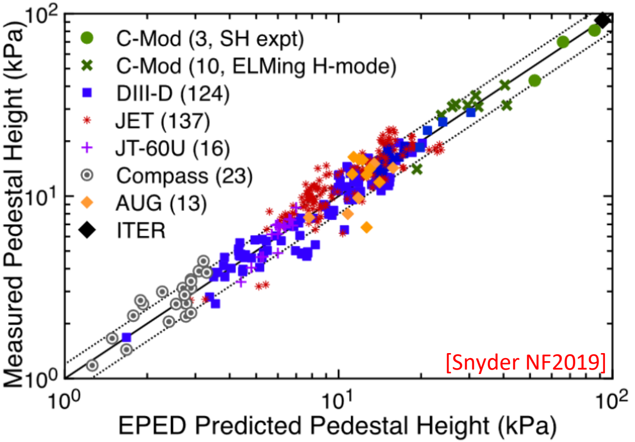

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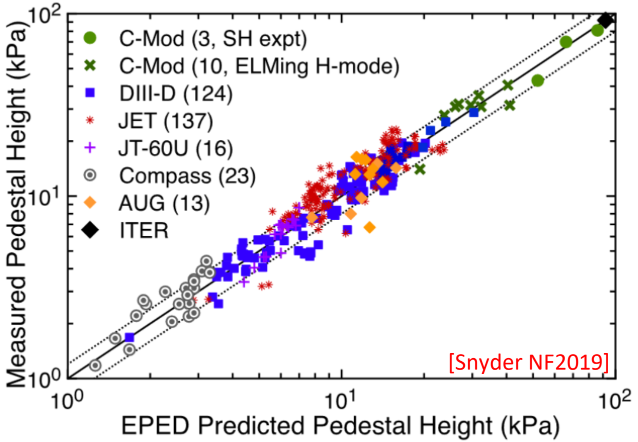
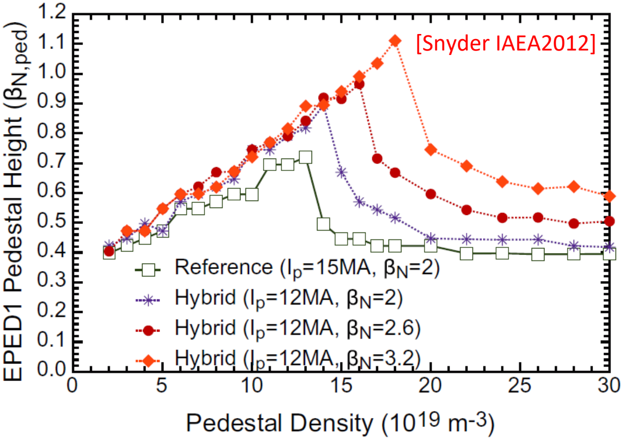


- EPED1 is widely used to predict the pedestal height (also in ITER).

- Example: prediction of pedestal pressure dependence with:
  - density
  - β



Non-linear MHD modelling

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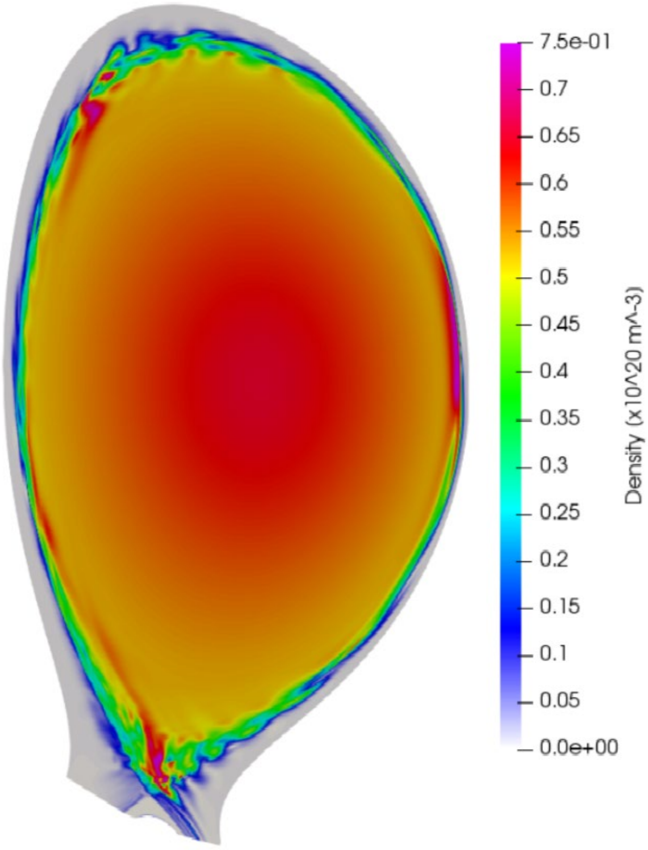

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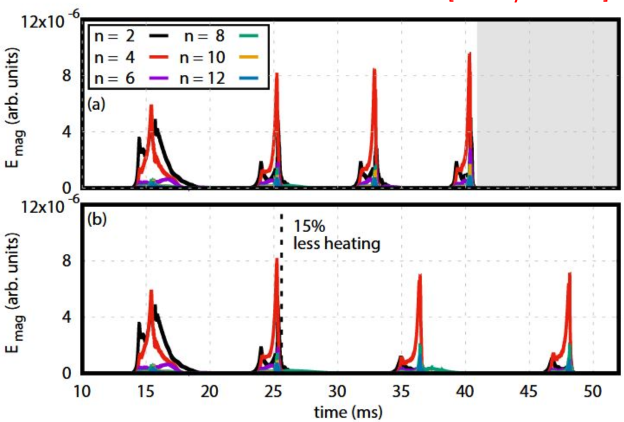
  - type I ELMs start to be modeled rather well

    [Cathey NF2021]
  - ELMs similar to those in small ELMs scenarios have also been modelled. [Cathey PPCF2022]

ELM cycle simulations with JOREK

[Cathey NF2020]



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Some active research areas

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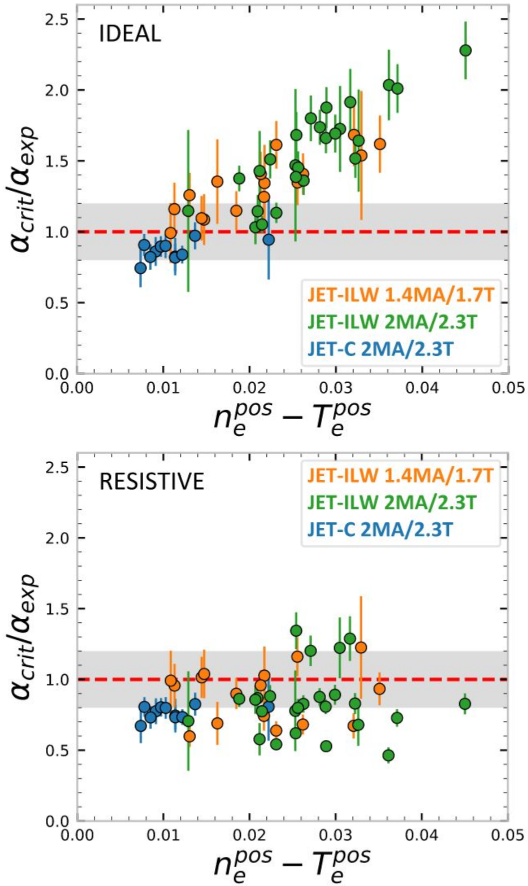

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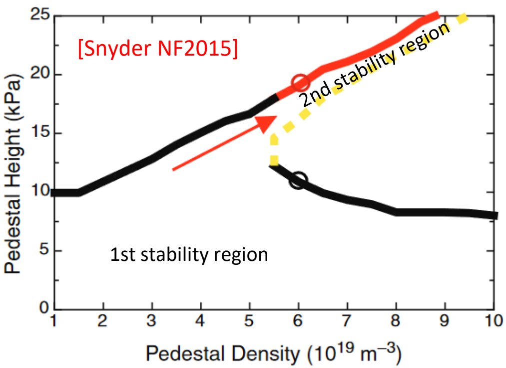

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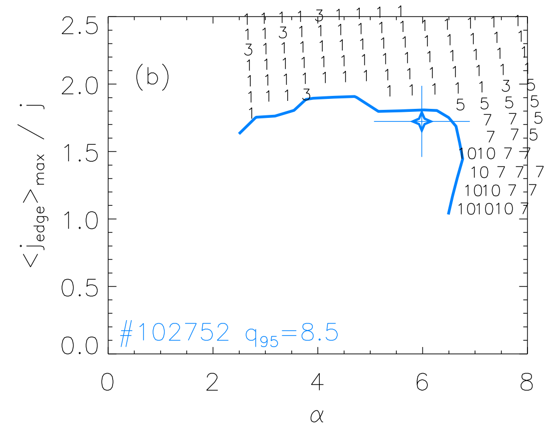

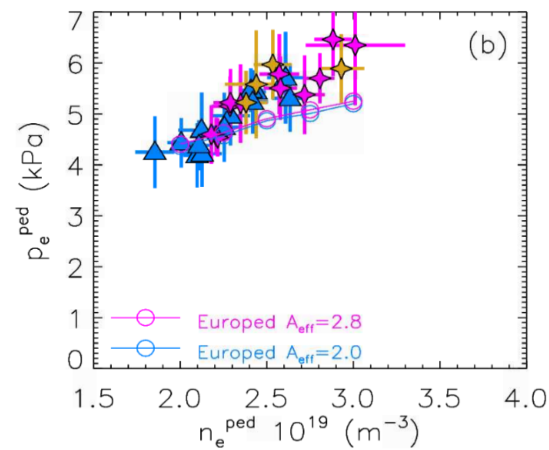

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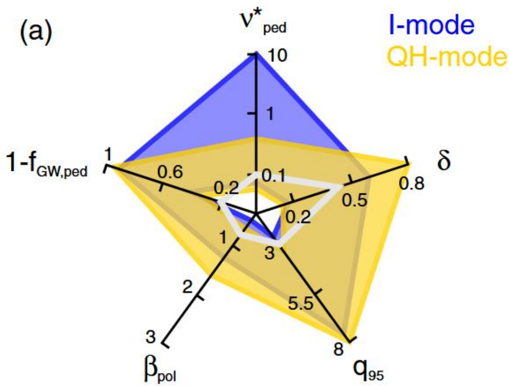

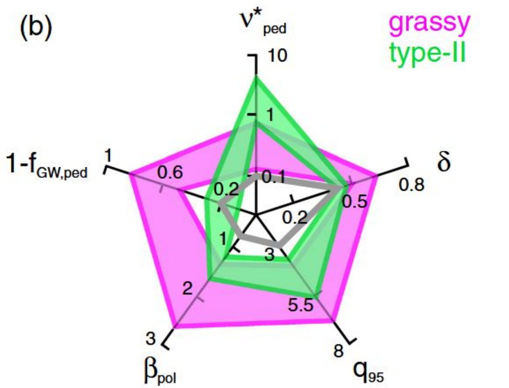

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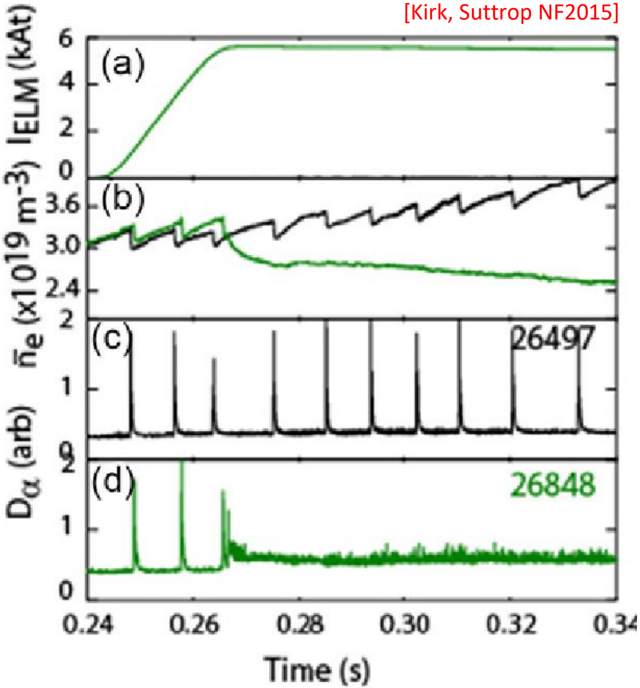
[Kirk, Suttrop NF2015]



Some useful references

The choice of the following papers is based on two criteria:
- overview papers, when possible.
- most recent papers.

This list does not necessarily cite the original papers on the topic.
Many excellent papers have not been included.

▪ Pedestal physics:	[Groebner PPCF2023]
	[Urano NF2014]
	[Leonard PoP2014]
▪ LH transition:	[Bourdelle NF2020]
▪ Pedestal structure:	[Frassinetti NF2021]
▪ Isotope effect:	[Maggi PPCF2018]
▪ ELMs:	[Zohm PPCF1996]
	[Leonard PoP2014]
▪ PB model:	[Wilson PoP1999]
	[Snyder PoP2002]
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▪ EPED model:	[Snyder PoP2009]
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