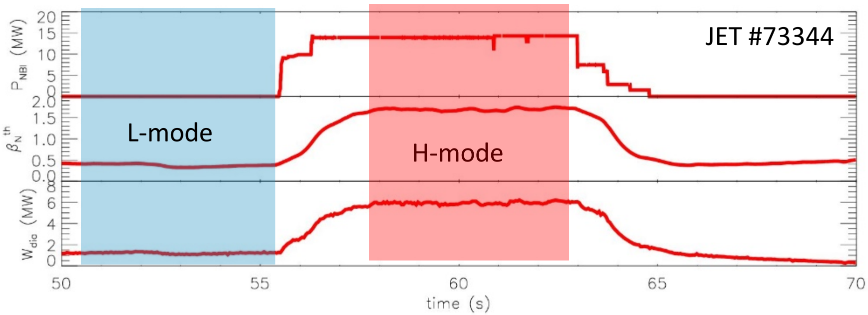
PEDESTAL PHYSICS
a phenomenological introduction

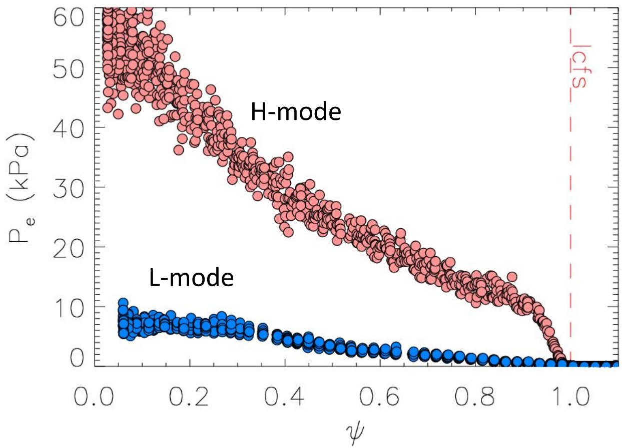
L. Frassinetti

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).



- 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:
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- Some of the most active research areas in pedestal physics

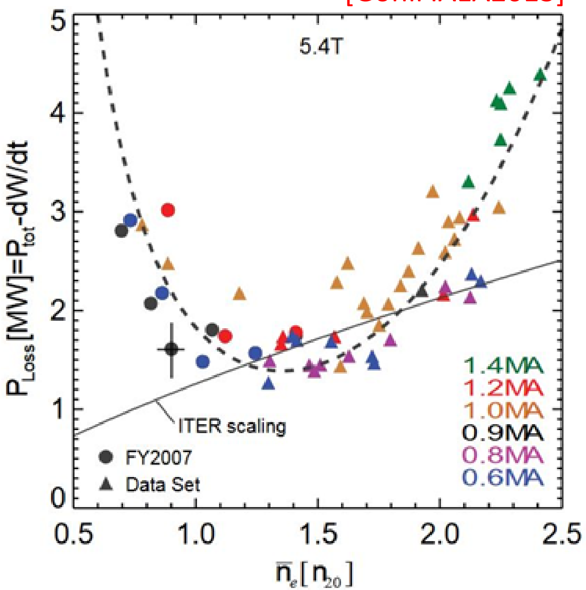
L-H transition

- 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]

- 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 0.2-0.4nGW
    - Non-monotonic behavior seem related to edge ion heating [Ryter NF2014]

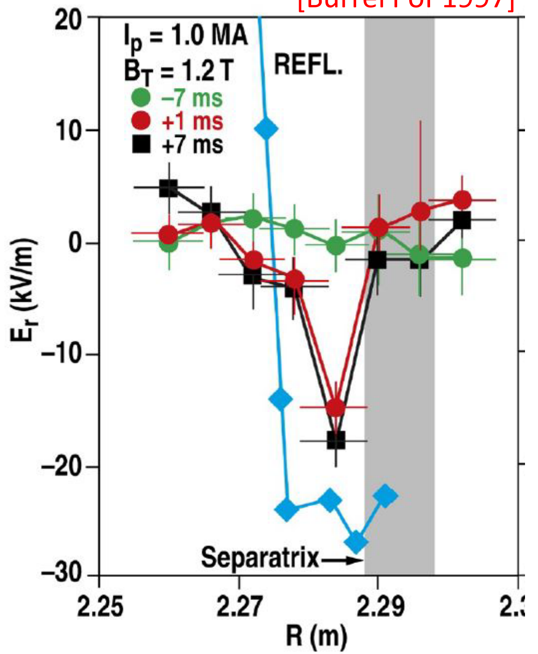
[Gohil IAEA2013]



L-H transition

- The physics of L-H transition is not yet fully understood
  - several models have been proposed to explain the experimental results
  - but a physics based model of the L-H transition with full predictive capabilities has not been developed yet.
- 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]
  - $\vec{E} \times \vec{B}$ 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]

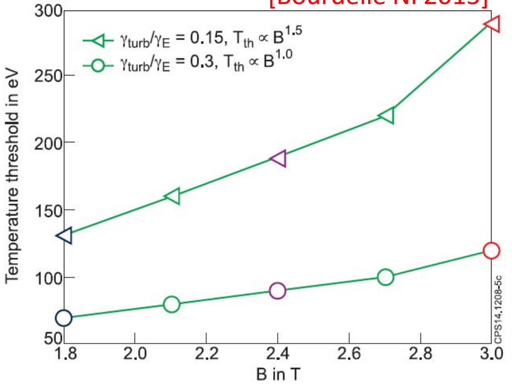


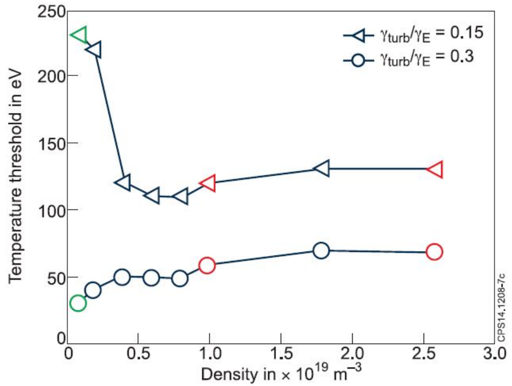
L-H transition

- 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: [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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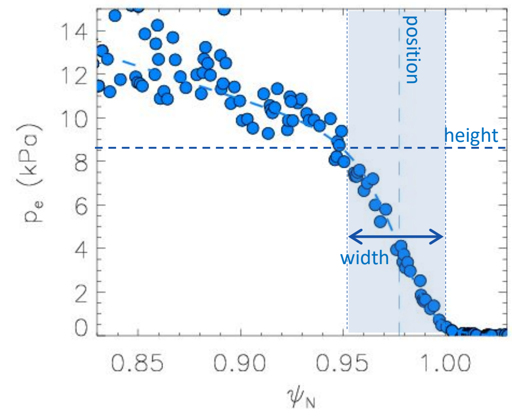
Pedestal structure

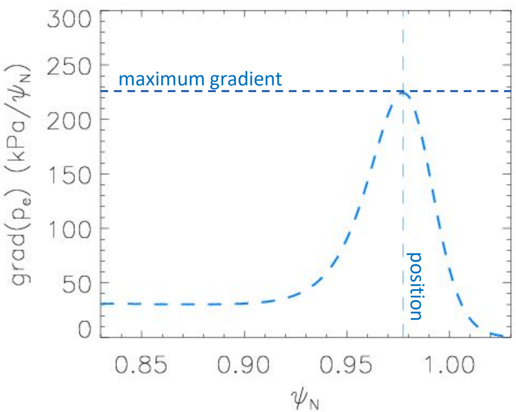
- To study the pedestal, it is necessary to quantify the parameters that identify its structure.

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

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

- These parameters are determined by fitting an analytical function (typically, a modified hyperbolic tangent) to the experimental data.





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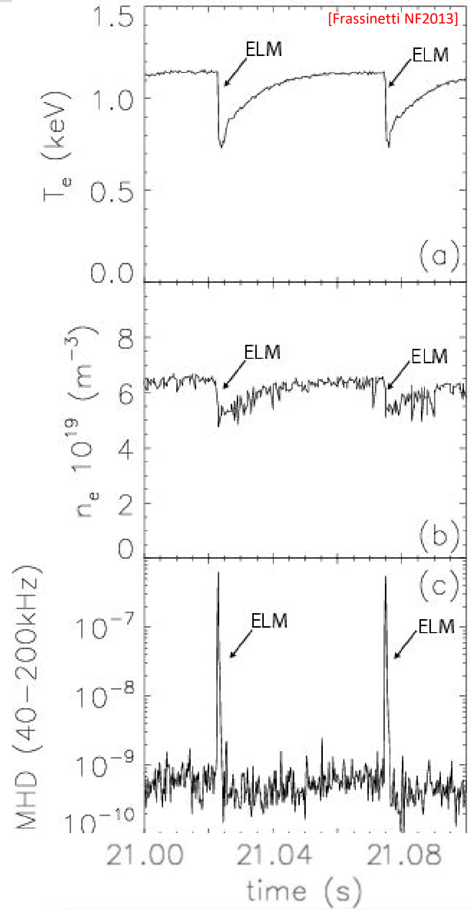
Edge Localized Modes (ELMs)

- The pedestal is characterized by sudden events, triggered by MHD instabilities, called edge localized modes (ELMs).
- The ELM triggers the collapse of the pedestal temperature and density, which in turn leads to the release of energy and particles to the divertor.



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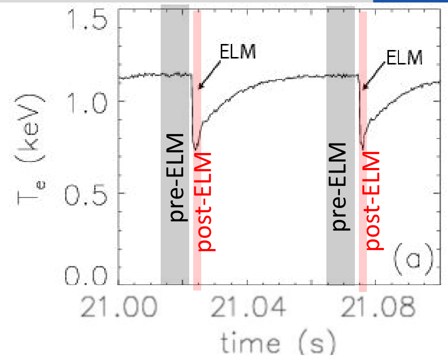
- The ELM triggers the collapse of the pedestal temperature and density, which in turn leads to the release of energy and particles to the divertor.
- The ELM collapse affects the kinetic profiles only in the pedestal region.
- The ELM losses can be calculated by integrating the profiles just before and soon after the ELMs:

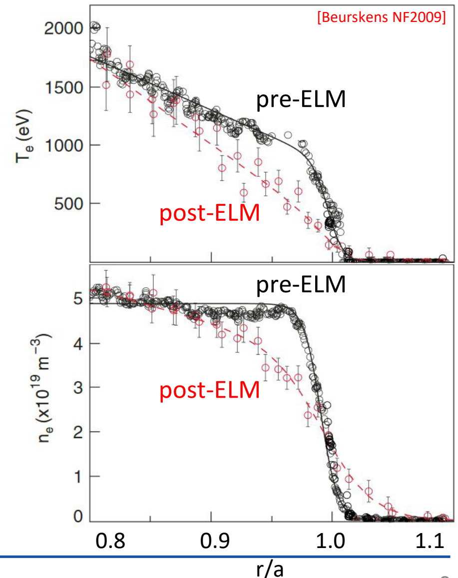
[Beurskens NF2009]

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

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

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

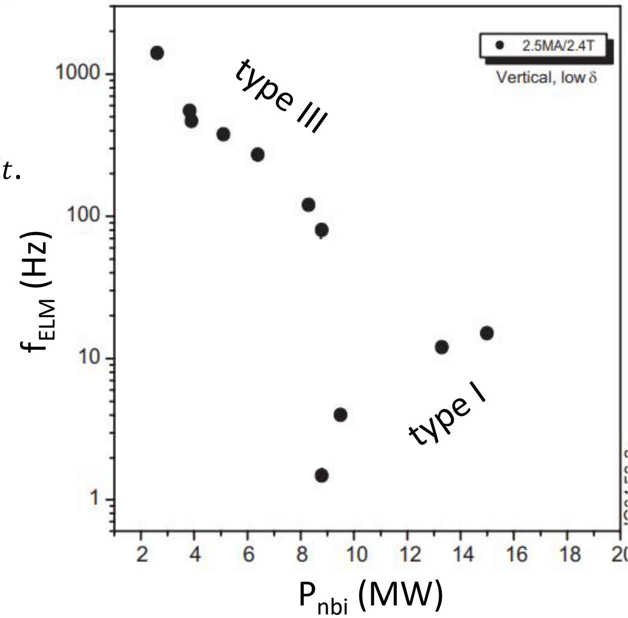




ELM types: definitions

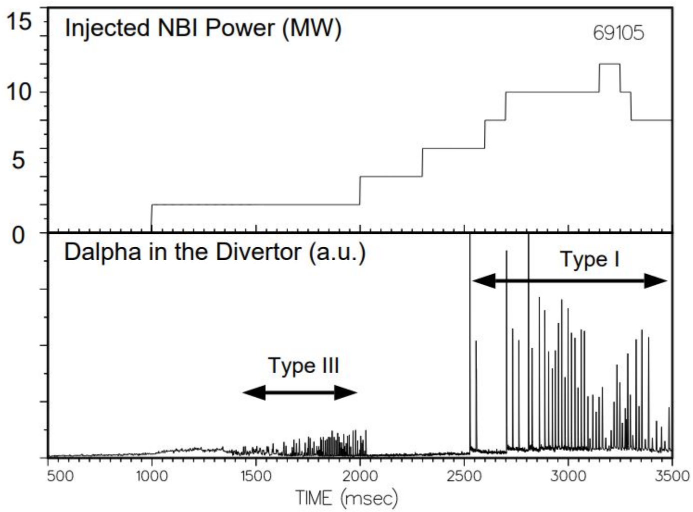
- H-mode plasma can be characterized by several types of ELMs. The ELM frequency (f_{ELM}) is often used to identify the most common ELMs.
- The most common are:
  - **Type I ELMs.**
    - f_{ELM} increases with $P_{sep} = P_{in} - P_{rad} - dW/dt$.
    - typically occurs at $P_{sep} \gg P_{LH}$.
    - they are triggered by ideal MHD.
    - they appear as sharp burst on the D_α.
  - **Type III ELMs.**
    - f_{ELM} decreases with P_{sep}.
    - typically occurs $P_{sep} \approx P_{LH}$.
    - they are not triggered by ideal MHD.
  - **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]

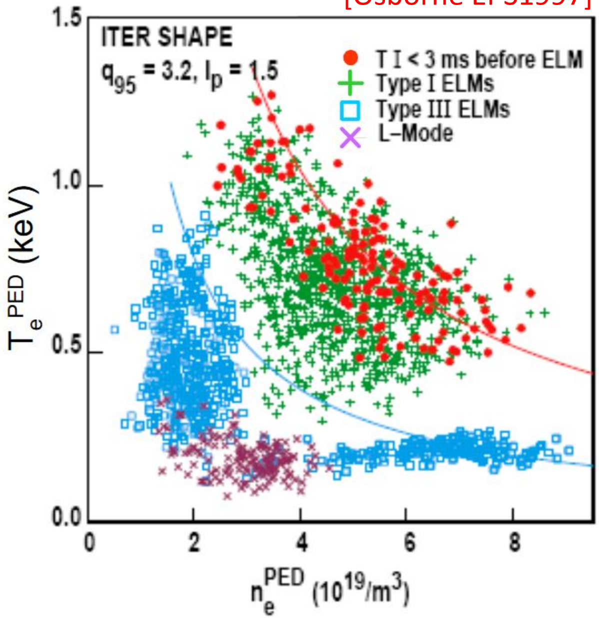


ELM types: examples

[Zohm PPCF1996]



[Osborne EPS1997]



- **Type I ELMs.**
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  - typically occurs at $P_{sep} \gg P_{LH}$.
- **Type III ELMs.**
  - f_{ELM} decreases with P_{sep}.
  - typically occurs $P_{sep} \approx P_{LH}$.

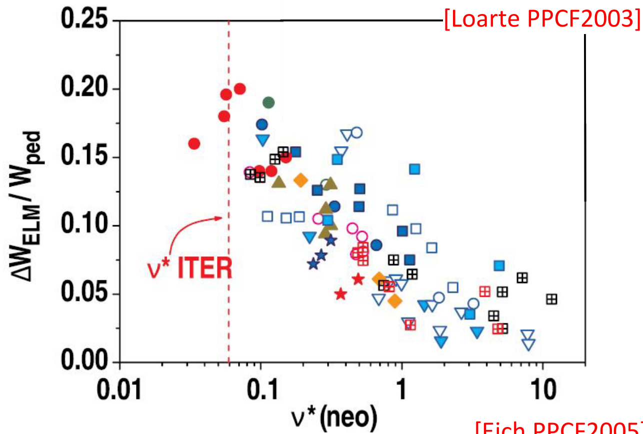
For reviews of ELM types:

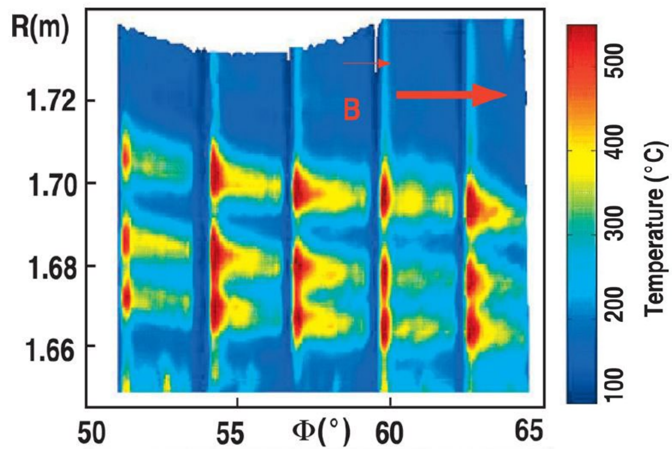
- [Zohm PPCF1996]
- [Leonard PoP2014]

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.
- 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]





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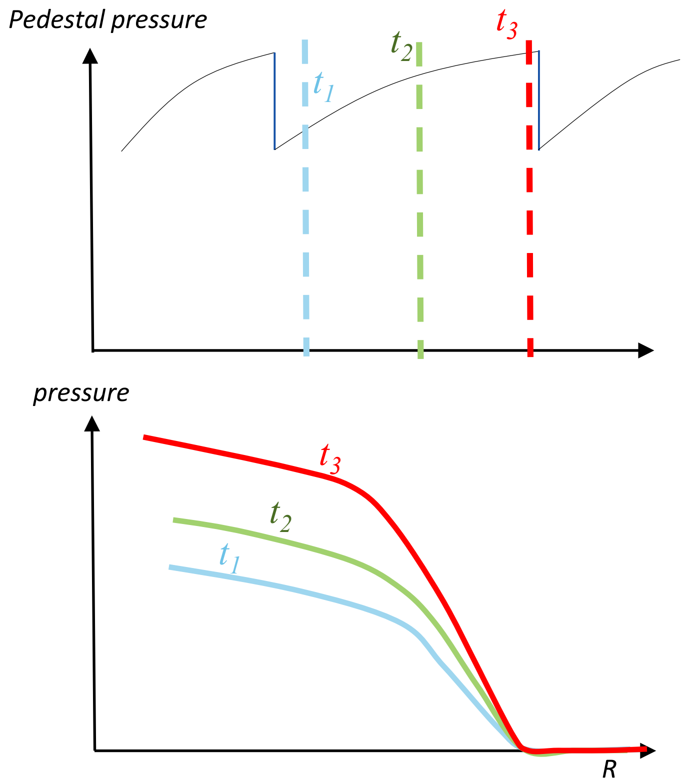
MHD stability and transport

- What are the physical mechanisms that determines the pedestal structure and trigger the ELMs?
- Two main concepts
  - MHD stability
  - Heat and particle transport
- The time evolution is set by transport
  - Transport determines time evolution of
    - 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

- Two key parameters define the ballooning stability
  - **the normalized pressure gradient α**

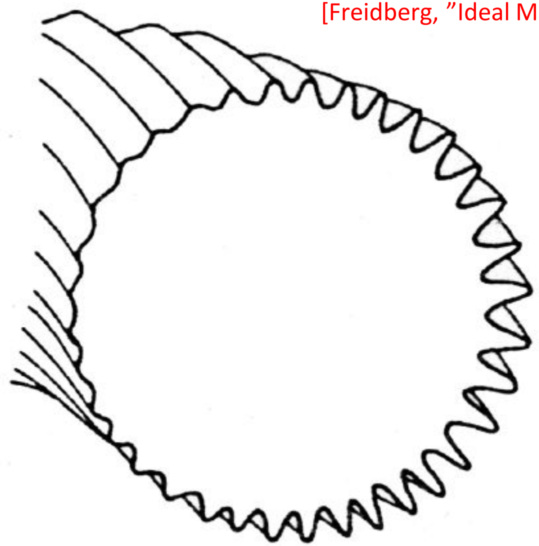
    $$\alpha = -\frac{2\mu_0 R q^2}{B^2}\frac{dp}{dr}$$

    has a destabilizing effect.
  - **the magnetic shear**

    $$s = -\frac{r}{q}\frac{dq}{dr}$$

    s has a stabilizing effect.

[Freidberg, "Ideal MHD"]



The ballooning modes

[Wesson "tokamaks"]

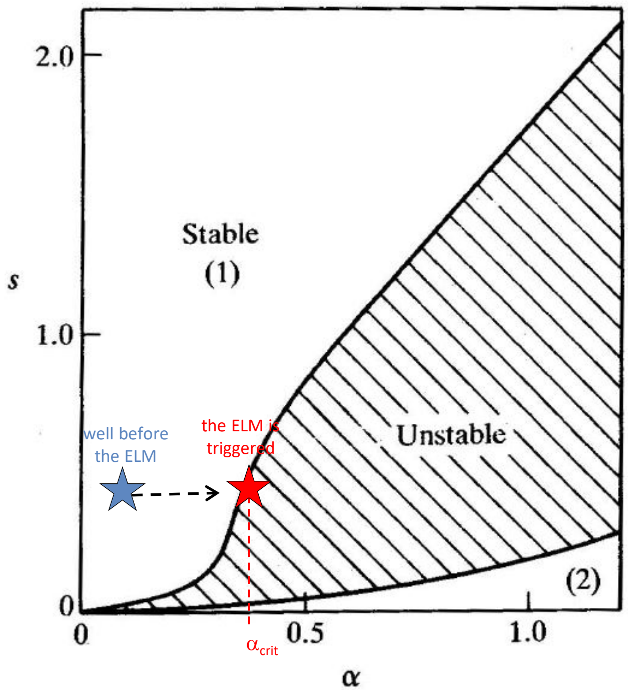
- **the normalized pressure gradient α**

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

  - the increase of α destabilizes balloning modes
  - at a certain threshold in α (α_{crit}) , the mode is unstable
- **the magnetic shear**

$$s = -\frac{r}{q}\frac{dq}{dr}$$

  - the shear has a stabilizing effect
  - Increasing the shear leads to an increase in α_{crit}.
- Most of the machines have a pedestal in region (1): the first stability region
- However, theory predicts a second stability region, at high α and low shear



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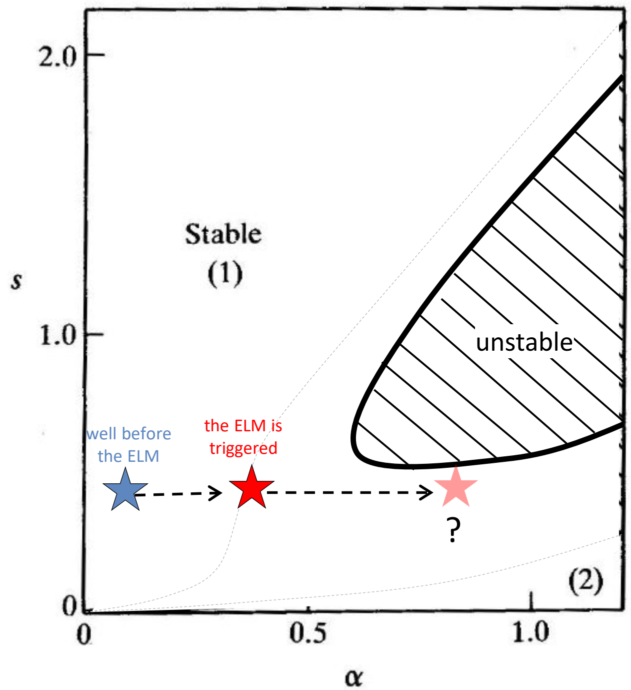
- Most of the machines have a pedestal in region (1): the first stability region
- However, theory predicts a second stability region, at high α and low shear
- Finite Larmor radius effects have a stabilzing effects and reduce the unstable region



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

The bootstrap current

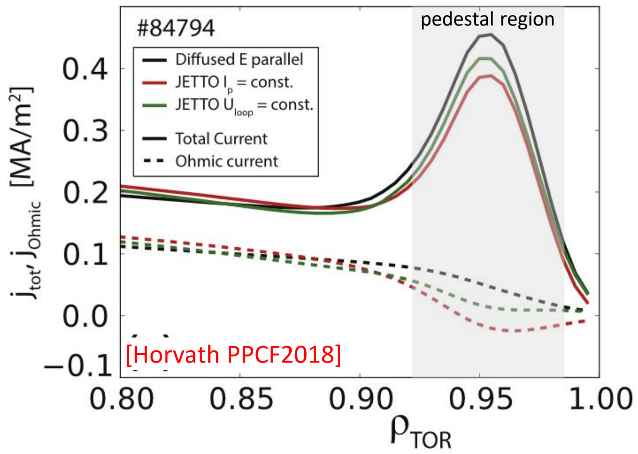
- Due to the steep gradients in the pedestal region, the bootstrap current (j_{bs}) can give a significant contribution to the total current density.
- For an expression of j_{bs}: [Sauter PoP1999]
- The increase in the current density affects the shear [Miller PoP1999]

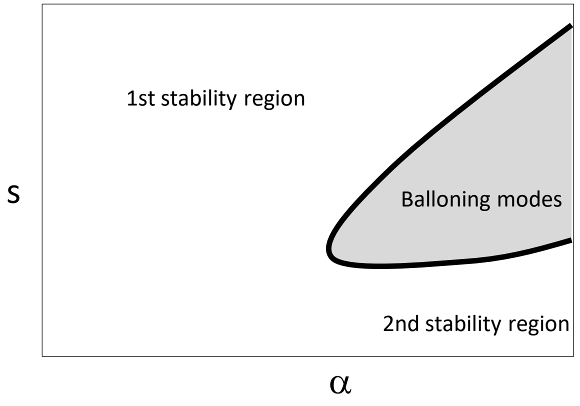
  → j_{bs} has an effect on the ballooning stability.

  [Snyder PoP2002]

  → the parameters that affects j_{bs} will affect also the balloning stability:
    - collisionality
    - plasma shape

- It is common to use j_{tot} instead of the shear in the stability diagram





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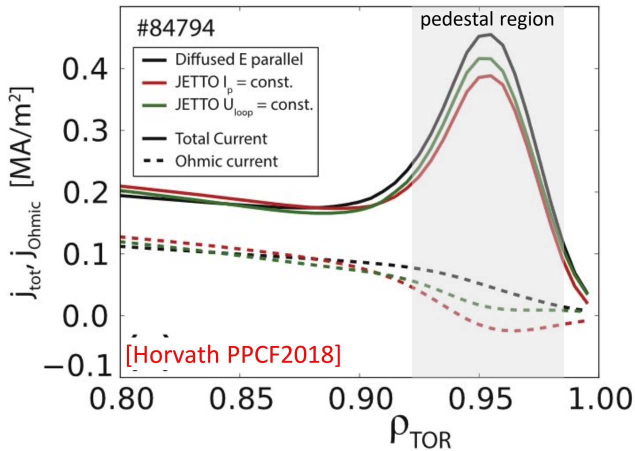
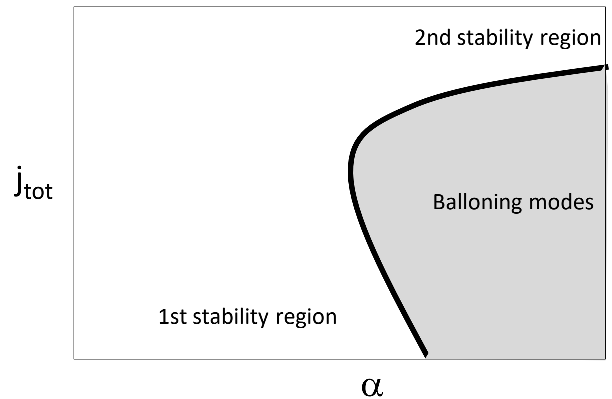
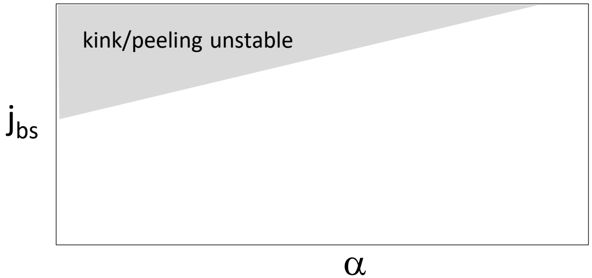


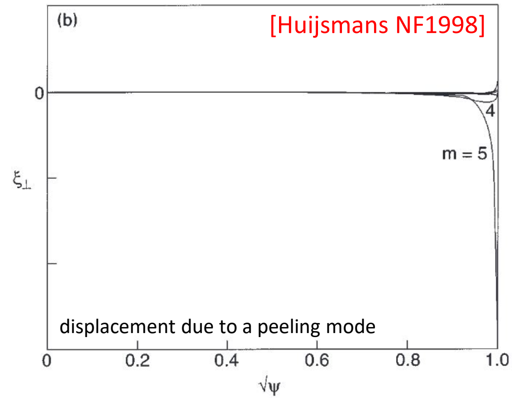


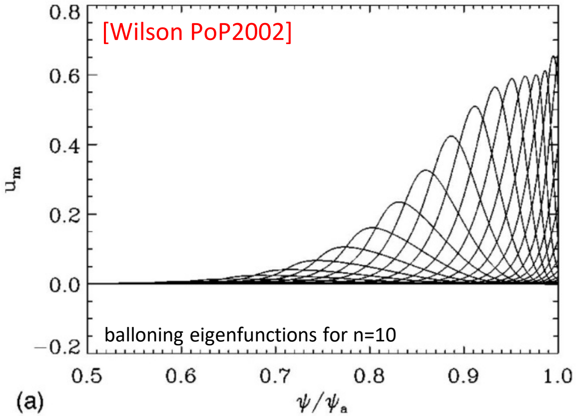
The external kink / peeling mode

- 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.
    For comparison, the ballooning modes have a more global structure.
- The kink mode depends on the edge current
  → j_{bs} has a strong role

[Huijsmans NF1998]

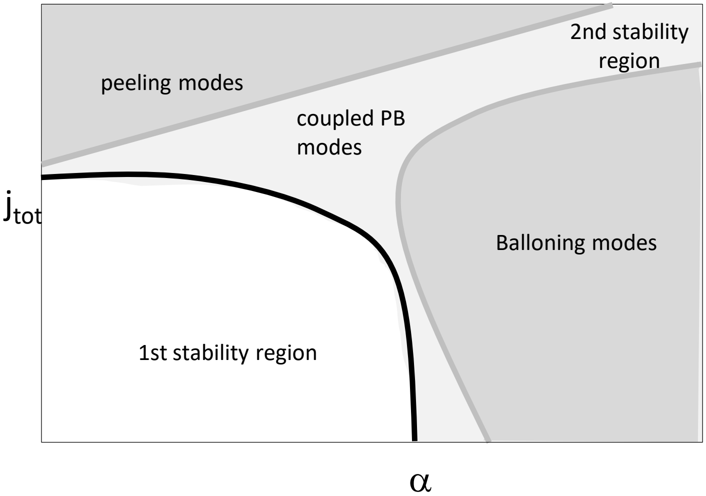






The peeling-ballooning (PB) modes

- Toroidicity and shaping effects can couple peeling and ballooning (PB) modes.
- The coupleds PB modes can be destabilized even if the single peeling mode and ballooning are stable. [Connor PoP1998]
- 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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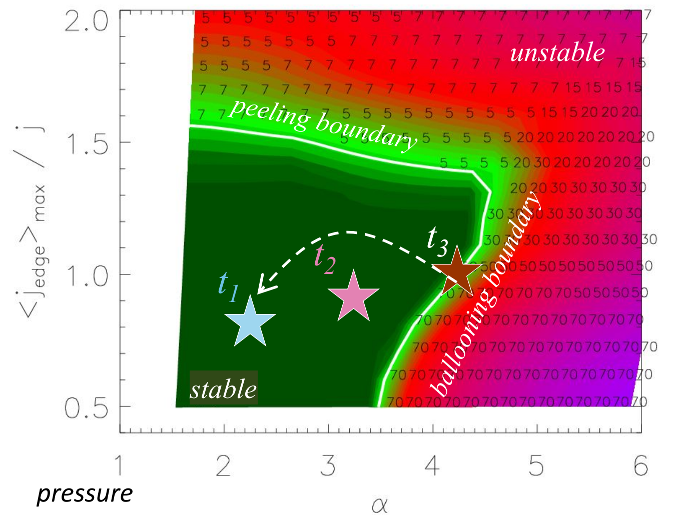
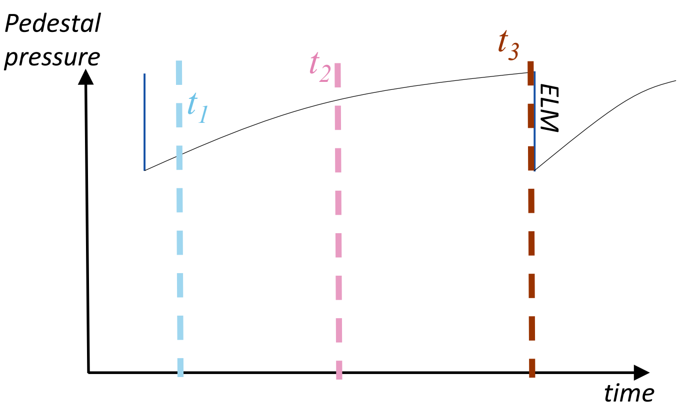
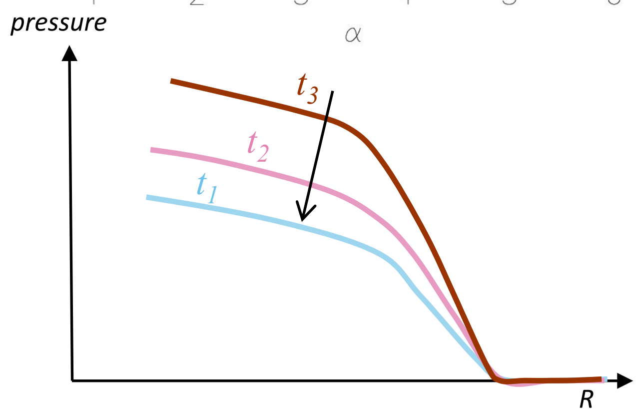
The PB model for the ELM cycle

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







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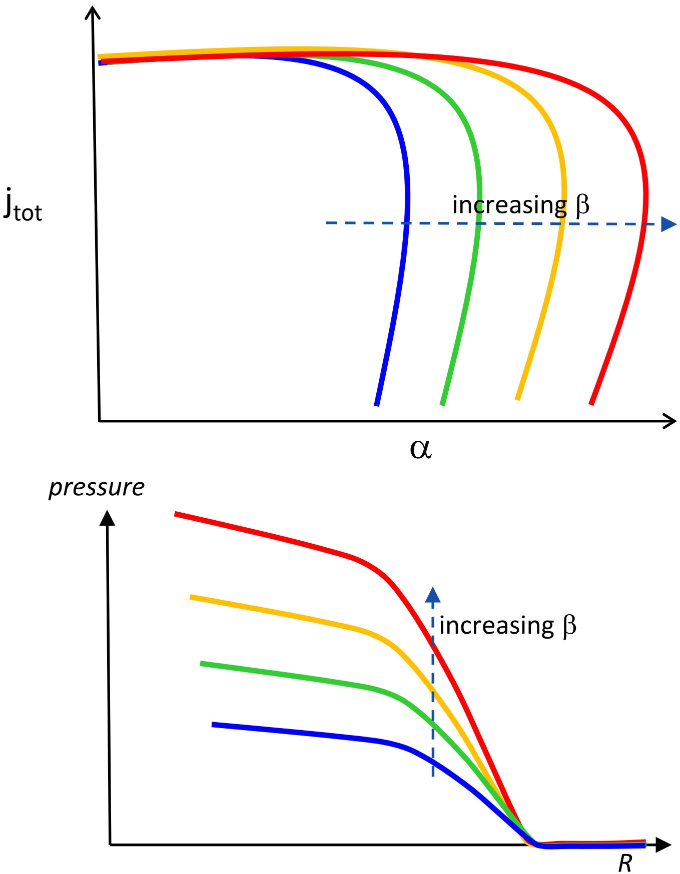
Parameters that affect the pedestal: β

- $\beta = \frac{\langle p \rangle}{B^2/(2\mu_0)}$
- 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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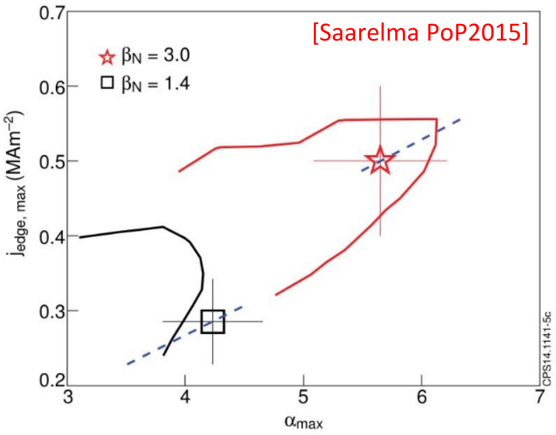
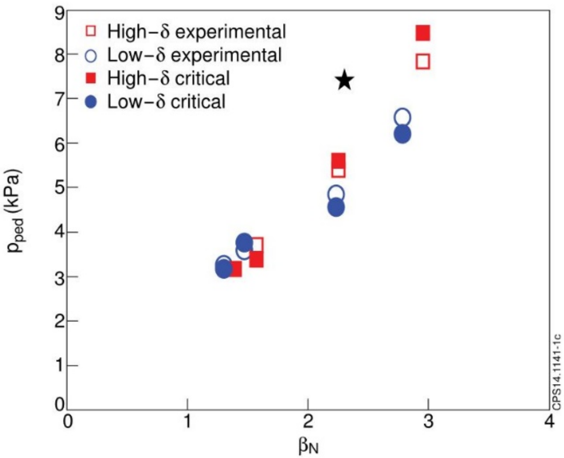
→ p^{ped} increases with increasing β.





Parameters that affect the pedestal: ν

- Collisionality

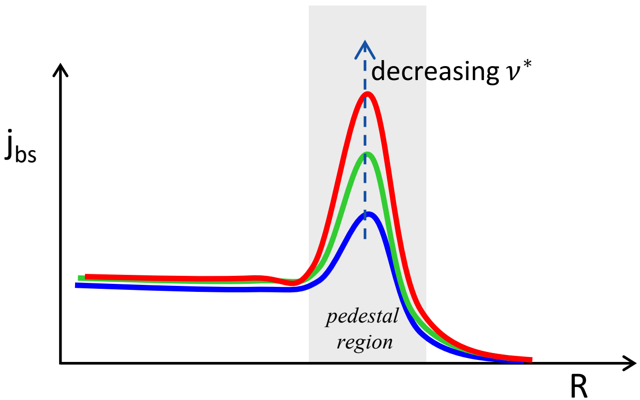
$$\nu^* = c ln\Lambda \frac{R q n_e}{\varepsilon^{3/2}(T_e)^2}$$

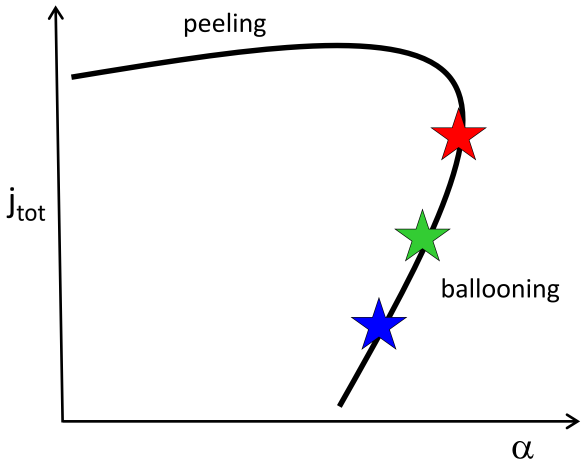
- the collisionality has a major effect on j_{bs}.

  [Sauter PoP1999]

- Approximately:

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

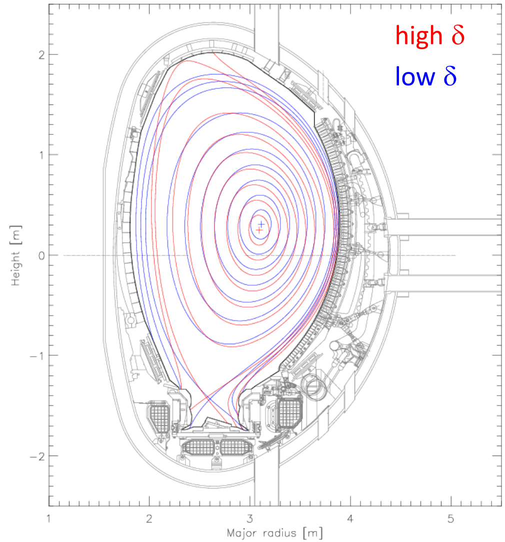




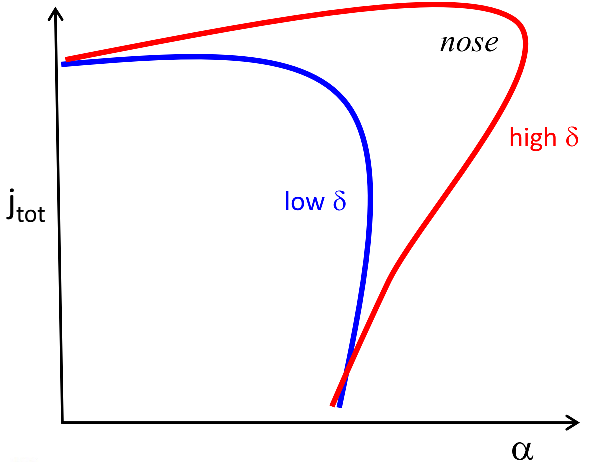
- The reduction of collisionality tends to increase ∇p, if the pedestal is near the ballooning boundary

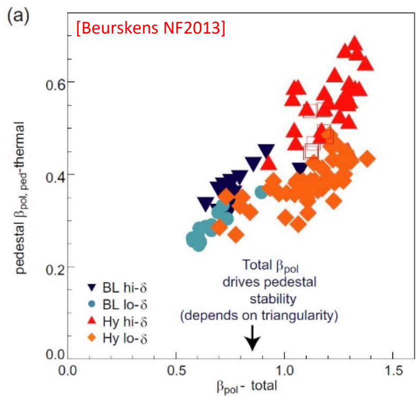
Parameters that affect the pedestal: δ

- δ: plasma triangularity
- the increase of δ stabilizes part of the ballooning modes.
- the PB is strongly shaped at high δ and a so called "nose" is formed:
  - high j_{bs} → ∇p increases with increasing δ.
  - low j_{bs} → ∇p does not change much with δ.



[Saibene PPCF2002]
[Beurskens NF2013]
[Urano NF2014]

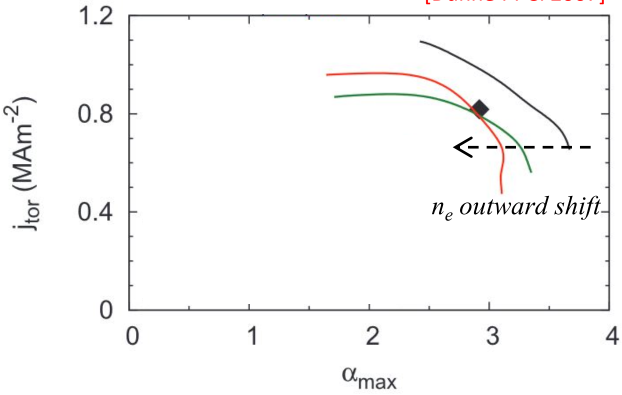


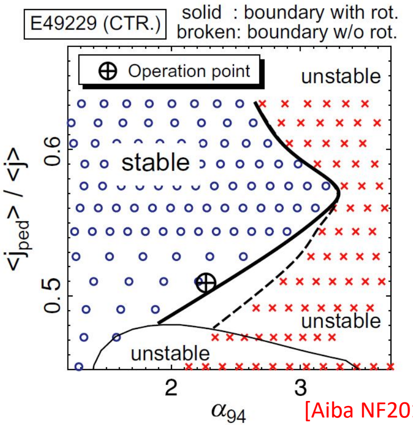


Parameters that affect the pedestal

- Other parameters that affect the pedestal stability are:
  - **Impurities**. Z_{eff} affects collisionality and j_{bs}. It affects the electron pressure via the dilution effect. [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]
  - **Position of the pedestal**. An outward shift of the pedestal destabilizes the ballooning modes→ pedestal reduction [Dunne PPCF2007]
  - **Density at the separatrix**. Only partially understood. [Snyder IAEA2018]
  - **Isotope mass**. Origin of the effect still unclear. [Maggi NF2019]

[Dunne PPCF2007]





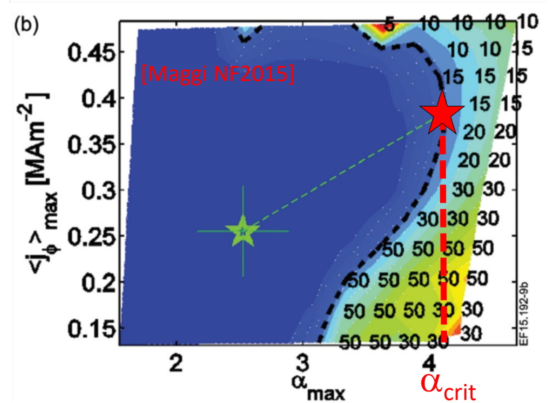
[Aiba NF2011]

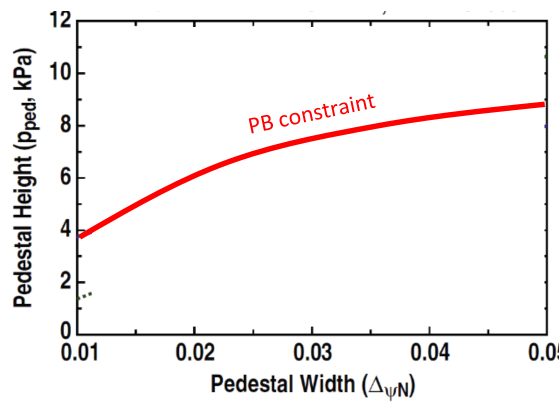
OUTLINE

- 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

Pedestal predictions: the PB constraint

- Can we use the PB model to predict the pedestal pressure height before the ELM?
- The PB model identify the critical normalized pressure gradient (α_{crit}) above which the PB modes are destibilized.
    - It can be used to determine ∇p.
- For a specific pedestal width, the PB model can determine the critical ∇p at which the PB modes are destabilized.
    - for this specific width, the critical pressure height can determined from $(\nabla p)_{crit}$.
    - 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.





Pedestal predictions: the KBM constraint

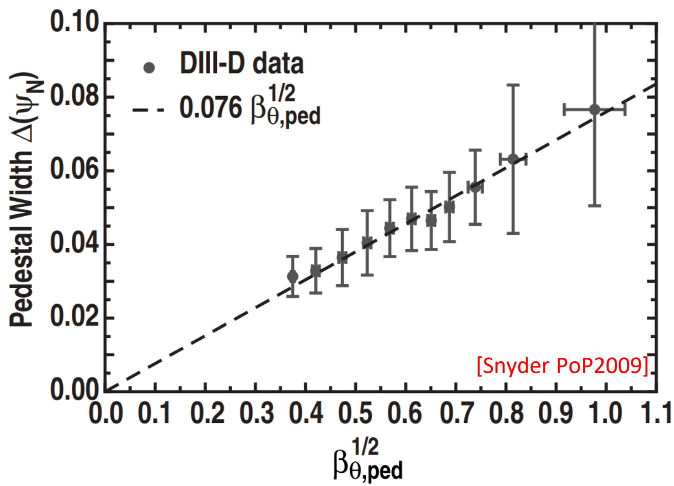
- The other constraint can come from pedestal transport
- The problem is that the pedestal transport is (often) driven by turbulence. Turbulence studies are not trivial and very time consuming
- The most succesfull approach, so far, has been developed in DIII-D [Snyder PoP2009]
  - experimental results suggest that DIII-D pedestal transport is driven by kinetic ballooning modes (KBMs)
  - from the theoretical arguments, it can be derived that for pedestals limited by the KBM turbulence:

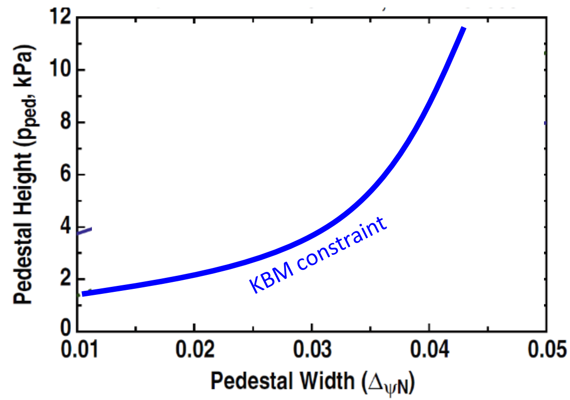
$$w_{ped} = c\sqrt{\beta_\theta^{ped}}$$

  - an experimental fit from DIII-D data gives:

$$w_{ped} = 0.076\sqrt{\beta_\theta^{ped}}$$

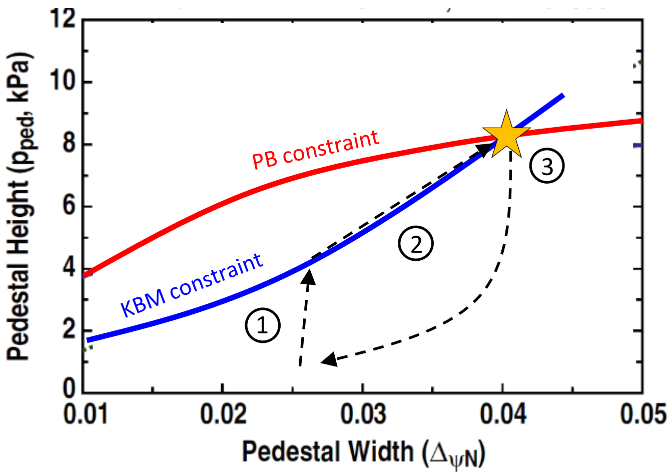
KBM constraint





The EPED1 model

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



THE ELM CYCLE ACCORDING TO EPED1:

1. ∇p grows unconstrained
2. KBM boundary is reached:
   - ∇p is "clamped"
   - The pedestal height grows via the increase of the pedestal width:

$$w_{ped} = 0.076\sqrt{\beta_\theta^{ped}}$$

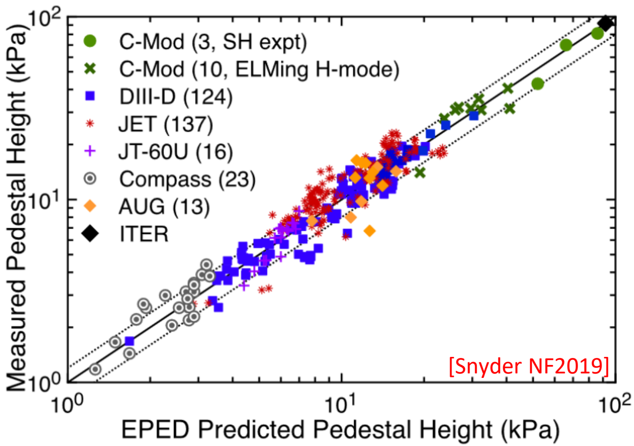
3. PB boundary is reached
   - ELM triggered

The EPED1 model

- EPED1 tends to predicts the pedestal pressure height rather well, for a large of parameters and in many machines.

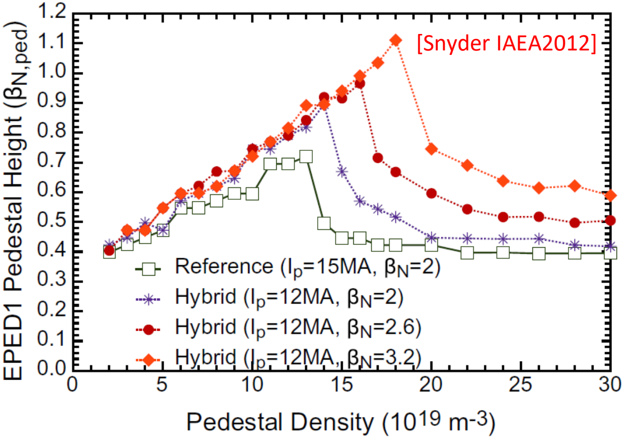
[Snyder NF2019]

- EPED1 is a useful tool to test the PB model.



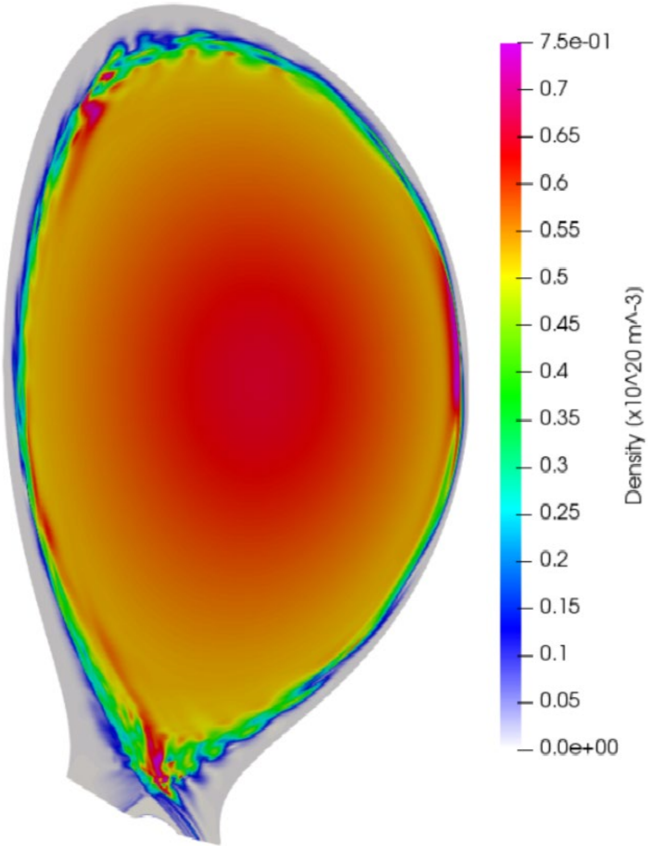
- EPED1 is widely used to predict the pedestal height (also in ITER).

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



Non-linear MHD modelling

- EPED1 works relatively well, but it is a linear model:
  - it does not predict time evolutions
  - cannot predict ELM energy losses
- Non-linear codes are necessary for modelling the details of the ELMs.
- Recent results with the JOREK code are very promising: [Huijsmans NF2007]
  - type I ELMs start to be modeled rather accurately [Cathey NF2021]
  - ELMs similar to type III have also been modelled.



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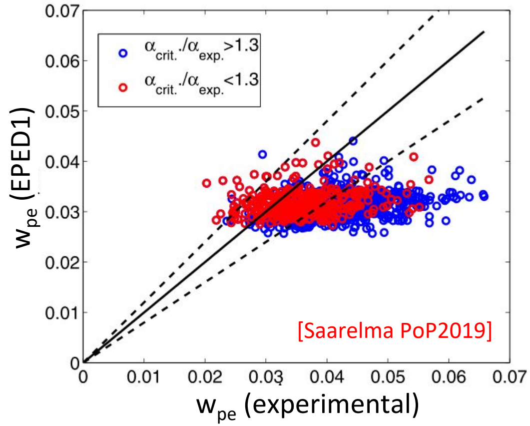
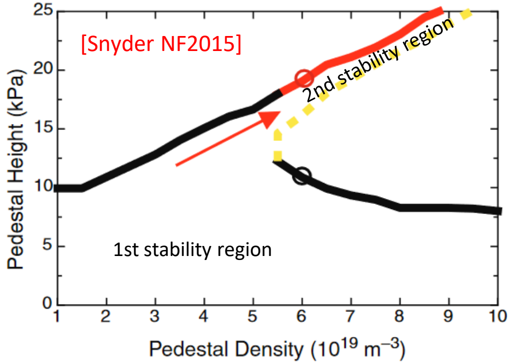
Some active research areas

- Discrepancies between EPED1 and experimental results, especially in JET-ILW, have been observed.
  [Frassinetti NF2019], [Saarelma PoP2019], [Frassinetti NF2021]
  - what physics is missing in EPED?
- Super H-mode: DIII-D results show that at high δ the 2nd stability region can be accessed. [Snyder NF2015]
  - can other experiments reach this region?
- Isotope effect
  - What is the physical mechanism that exlains the effect of isotope mass on the pedestal?
- Small ELMs
  - will operation with good pedestals and small ELMs be posible in ITER?
- ELM mitigation
  - develop and test ELM mitigation techniques that can be used in ITER





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: [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] [Snyder NF2004]
- EPED model: [Snyder PoP2009] [Snyder NF2011]