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PEDESTAL PHYSICS
a phenomenological introduction

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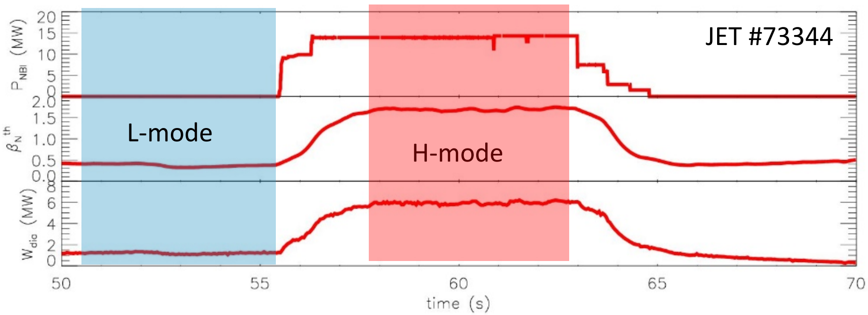
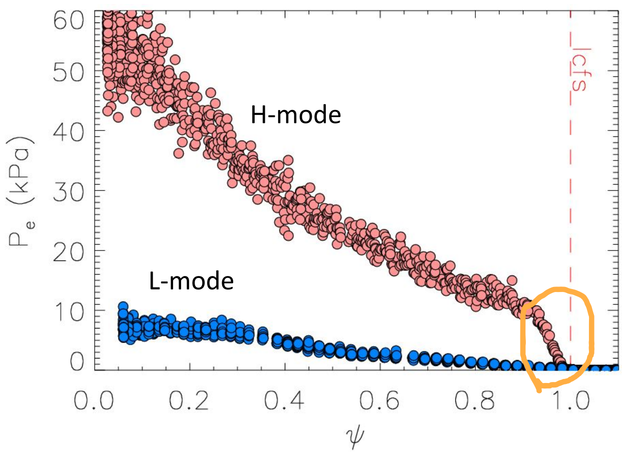
H-mode plasma

Pedestal requires an L-H transition

- 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:
    - The PB constraint
    - The KBM constraint
  - Non-linear MHD modelling
- 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:

Turbulence prevents H-mode

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

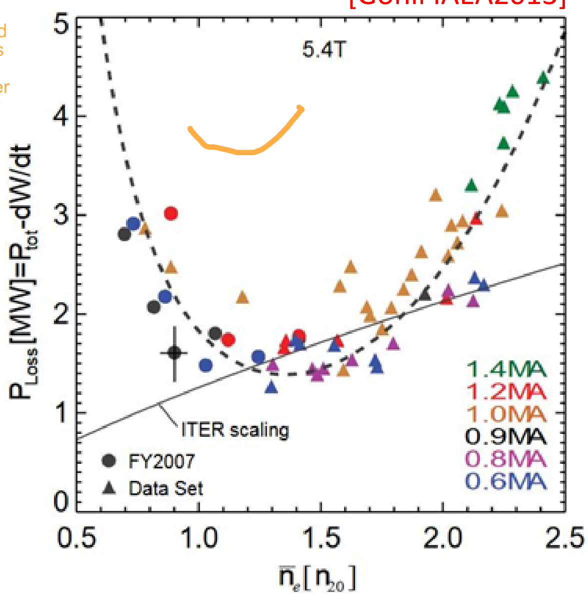
inaccurate

Physics not yet understood

- 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]

To enter H-mode one must suppress turbulence, and the instabilities that generate turbulence differ baed on density

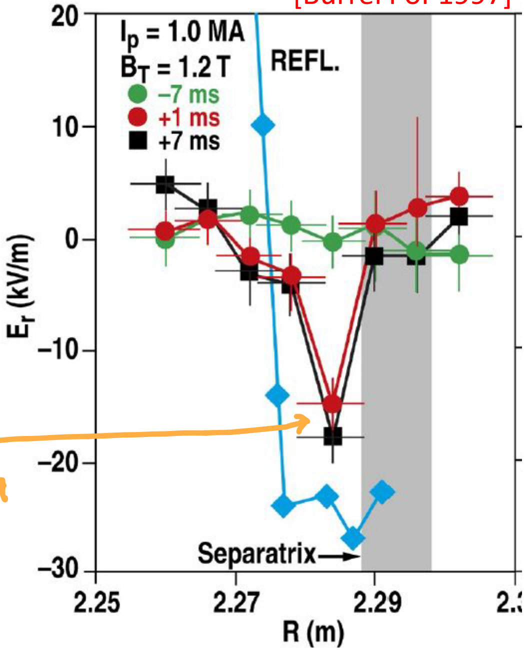
[Gohil IAEA2013]



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]



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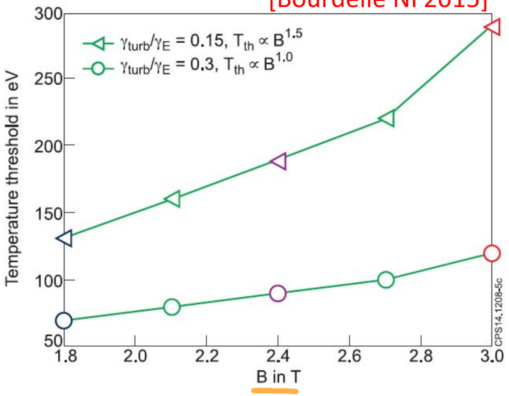
L-H transition

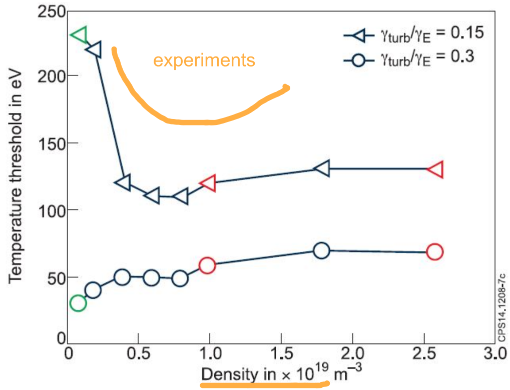
- Many of the theoretical works are based on the interplay between the L-mode turbulence and E_r shearing. [Connor PPCF2000]
- A large part of other theoretical works are based on the stabilization of RBM via increased pressure gradient. [Rogers PRL1997]

- 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. Stabilizing effect
  - $\gamma_{turb}/\ \gamma_E$ 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]

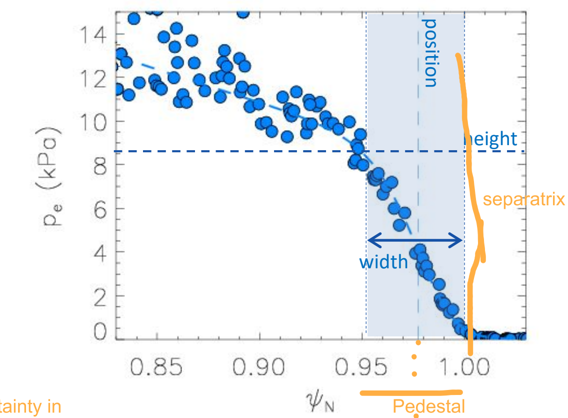
Pedestal structure

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

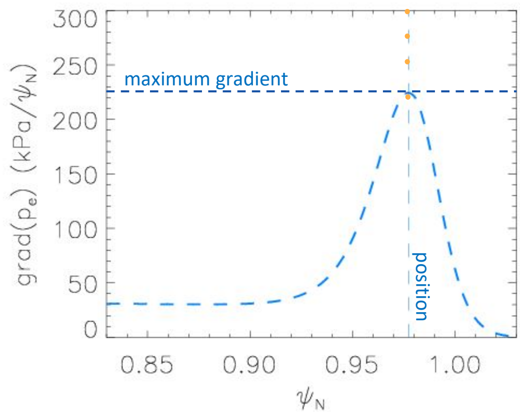
- The key parameters are
  - pedestal heigth
  - pedestal width
  - pedestal position (often defined as the position of the maximum gradient).
  - maximum gradient

- 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.



Uncertainty in ion/electron density near separatrix: issue



Edge Localized Modes (ELMs)

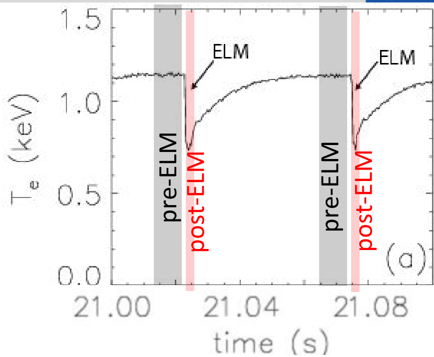
- The pedestal is characterized by sudden events, triggered by MHD instabilities, called edge localized modes (ELMs).
- The ELM triggers the collapse of the pedestal temperature and density, which in turn leads to the release of energy and particles to the divertor.
- The ELM collapse affects the kinetic profiles only in the pedestal region.
- The ELM losses can be calculated by integrating the profiles just before and soon after the ELMs:

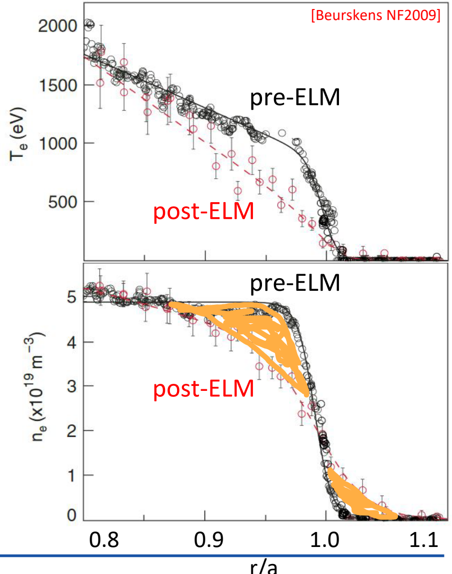
[Beurskens NF2009]

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

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

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

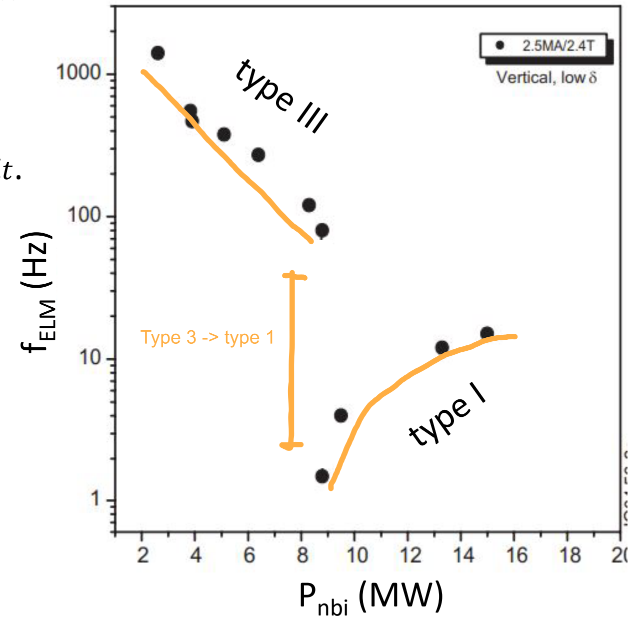




ELM types: definitions

- 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.** Most common ones Freq increases with power 3
    - 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. Supposedly
    - they appear as sharp burst on the D_α.
  - **Type III ELMs.**
    - f_{ELM} decreases with P_{sep}. Negative correlation with power
    - 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]



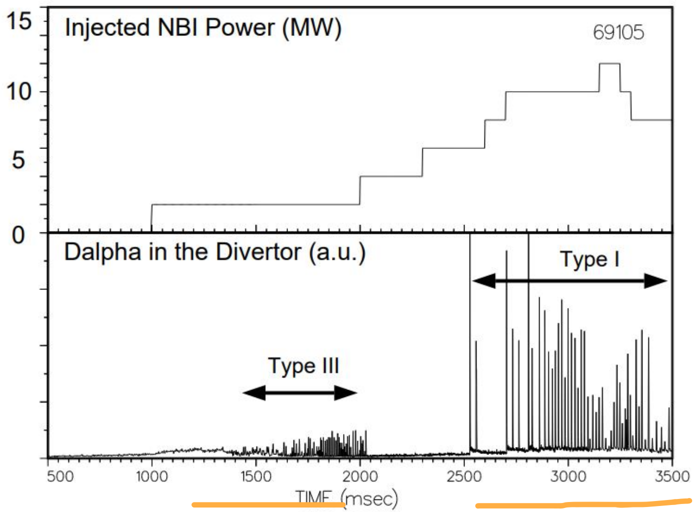
Power scan

1 and 3 most common

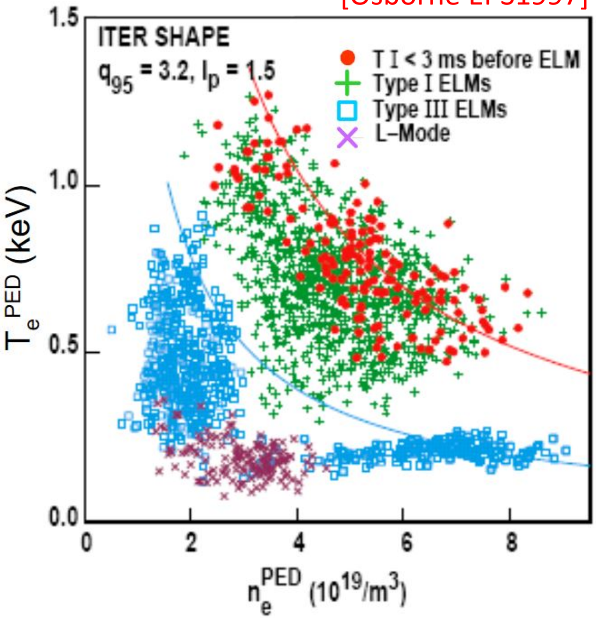
4 5 exist but not important

ELM types: examples

[Zohm PPCF1996]



[Osborne EPS1997]



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  - typically occurs $P_{sep} \approx P_{LH}$.

Type one less
freq but more
power loss

For reviews of ELM types:

- [Zohm PPCF1996]
- [Leonard PoP2014]

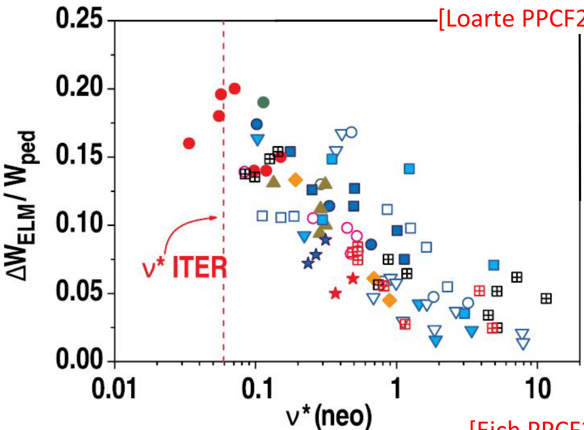
ELMs: energy losses and heat loads

- ELM losses tend to increase with decreasing collisionality. Several machines
- 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]

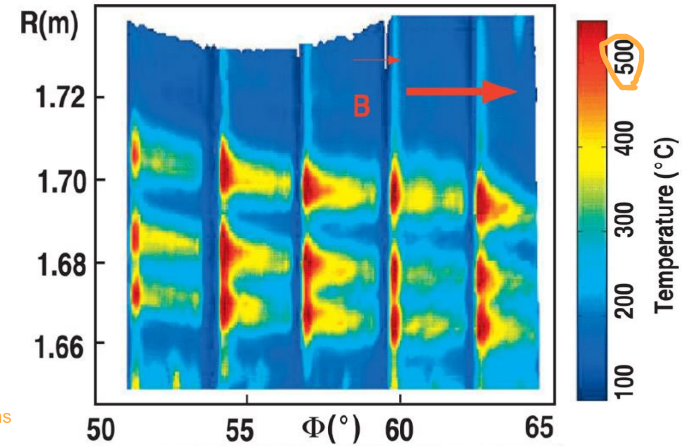
→ It is essential to understand ELM pedestal physics to:
  - Minimize ELM energy losses
  - Develop techniques for ELM mitigation/suppressions. Some of the most developed techniques are: 3
  - RMPs for a review: [Evans JNM2013]
  - ELM pacing with pellets [Baylor NF2009]

+ small elms regimes
+ vertical kicks: Moving plasma up-down with the control systems triggers elms

[Loarte PPCF2003]



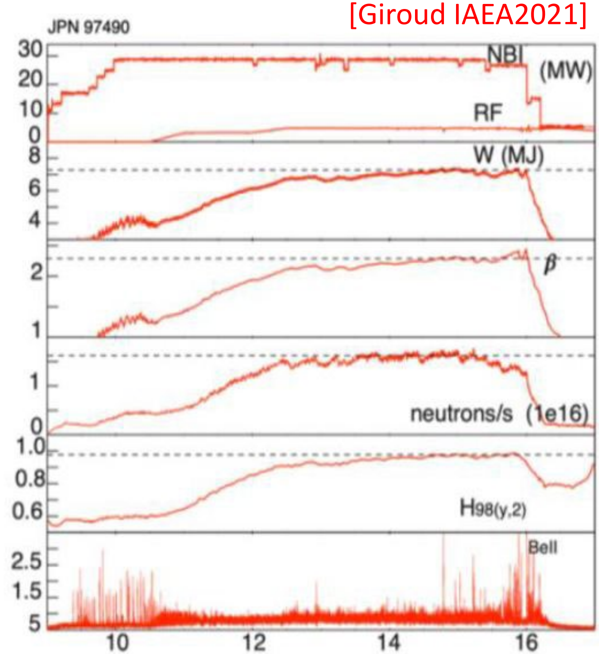
[Eich PPCF2005]



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

MHD stability and transport

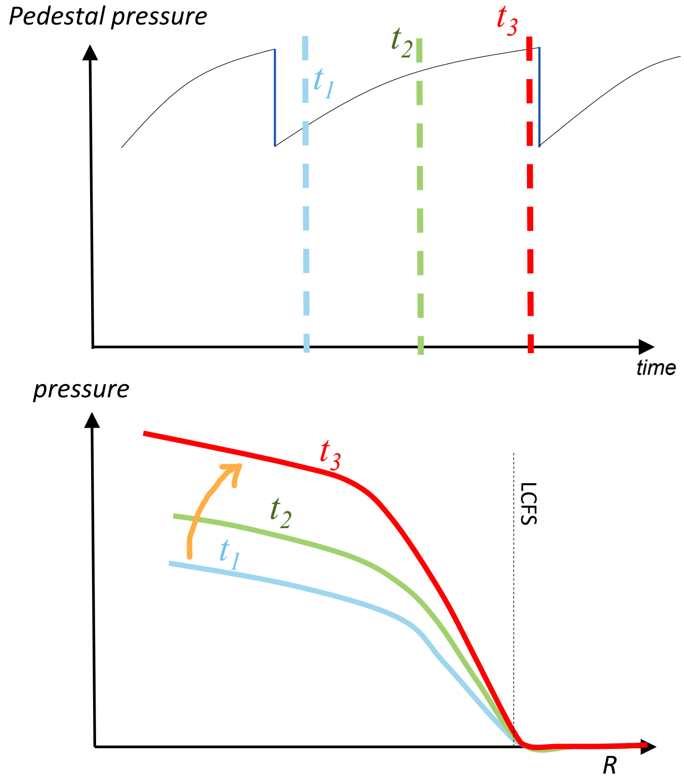
- What are the physical mechanisms that determines the pedestal structure and trigger the ELMs?
- Two main concepts
  - MHD stability
  - Heat and particle transport
- The time evolution is set by transport
  - Transport determines time evolution of
    - pedestal gradients
    - pedestal heights
- The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

Gradient pressure triggers the mhd instability

Transport control elm freq

Turbulent transport in pedestal

3



The ballooning modes

[Freidberg, ”Ideal MHD”]

- 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 Low field side (?)

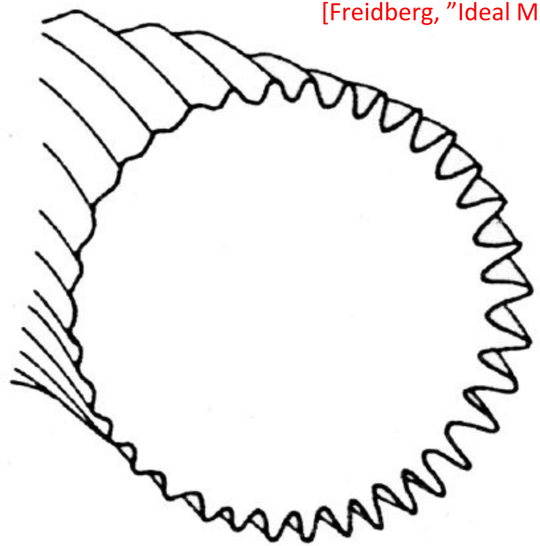
- Two key parameters define the ballooning stability
  - **the normalized pressure gradient α**

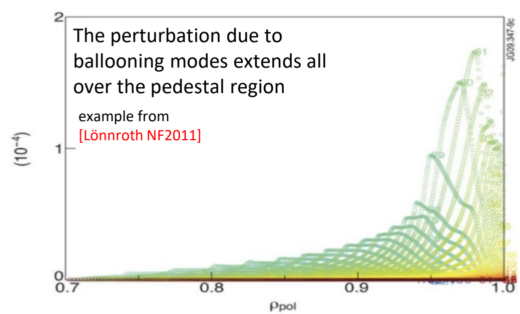
    $$\alpha = -\frac{2\mu_0 R q^2}{B^2}\frac{dp}{dr}$$

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

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

    s has a stabilizing effect.





The ballooning modes

[Wesson "tokamaks"]

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

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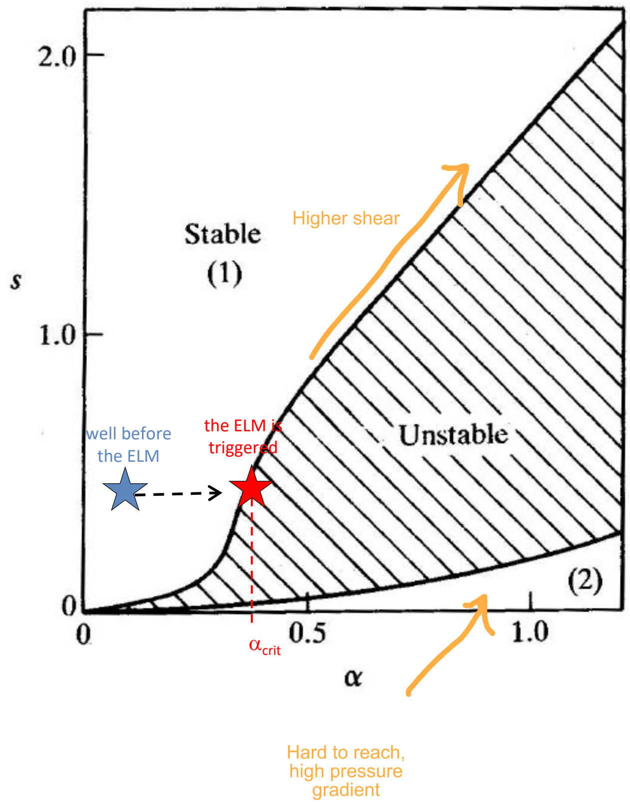

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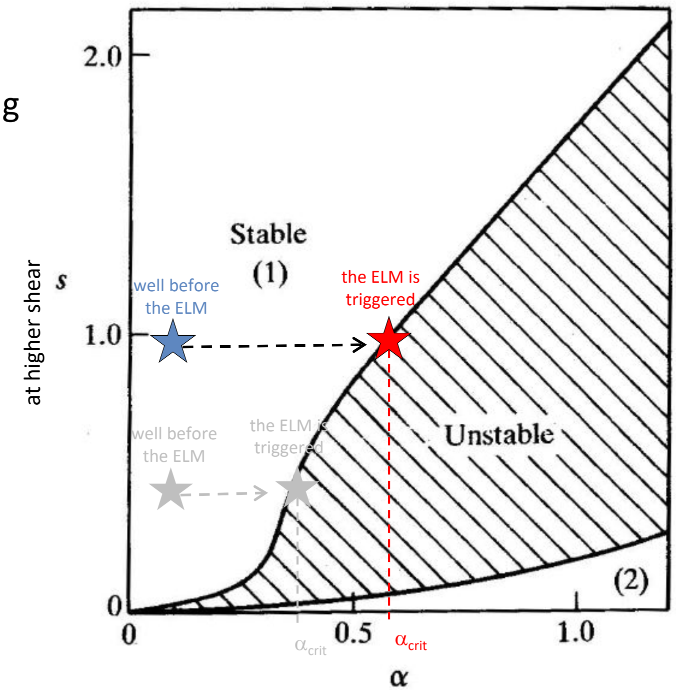
- However, theory predicts a second stability region, at high α and low shear



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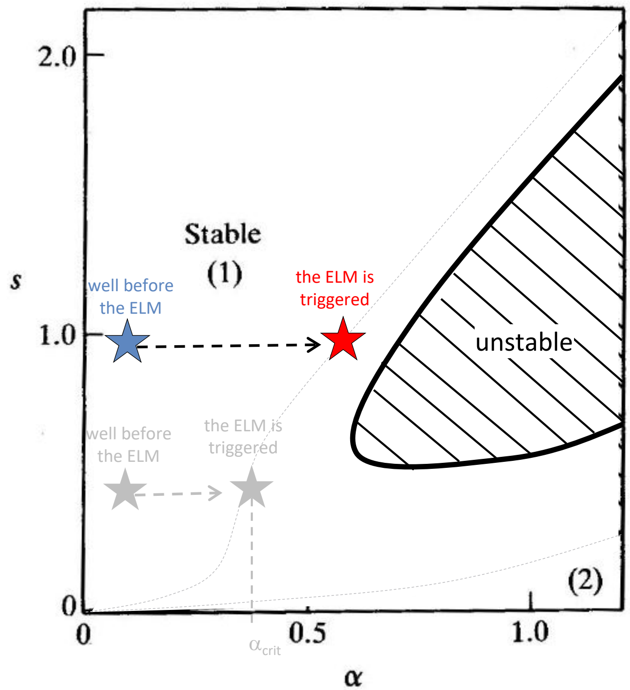

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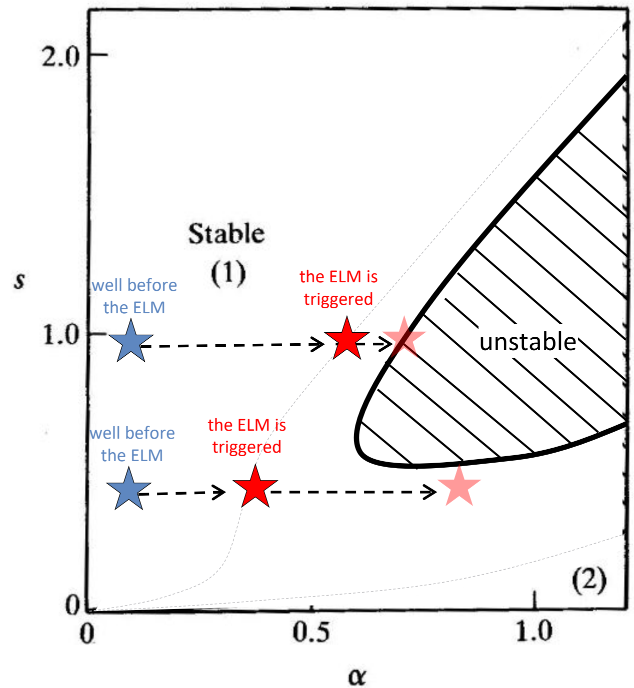

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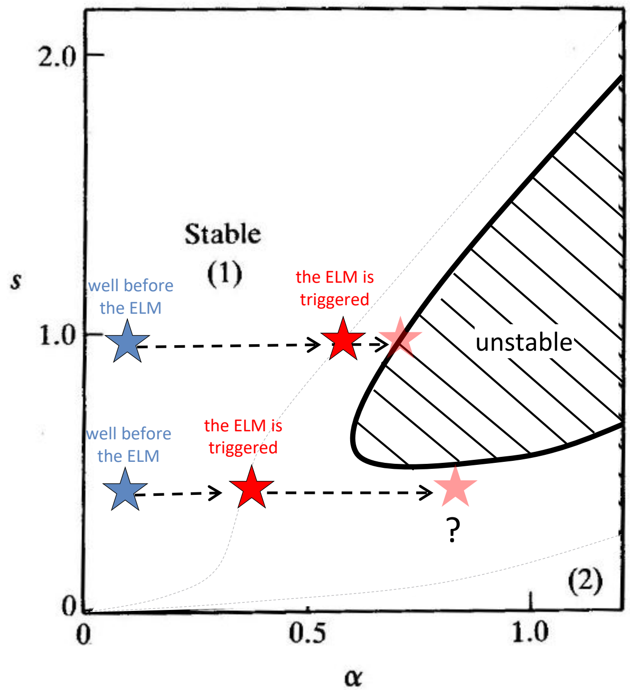


No!
There are further instabilities→see later.
But first…

The bootstrap current

Related to
pedestal stability

- 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]

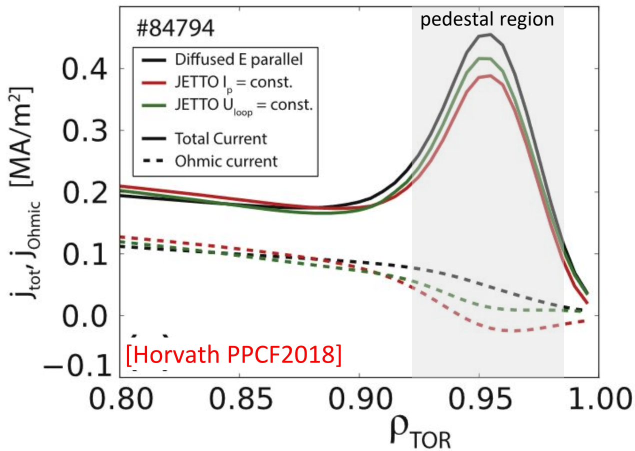
→ j_{bs} has an effect on the pedestal stability.

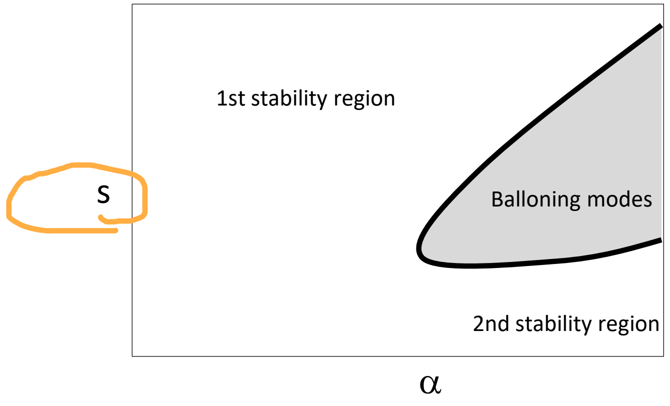
[Snyder PoP2002]

→ 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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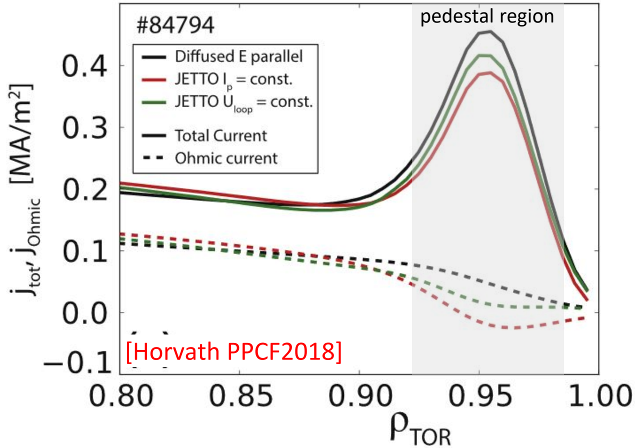
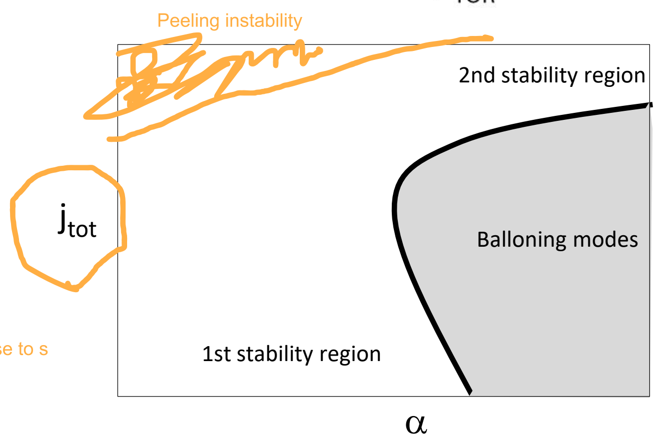
Jtot inverse to s

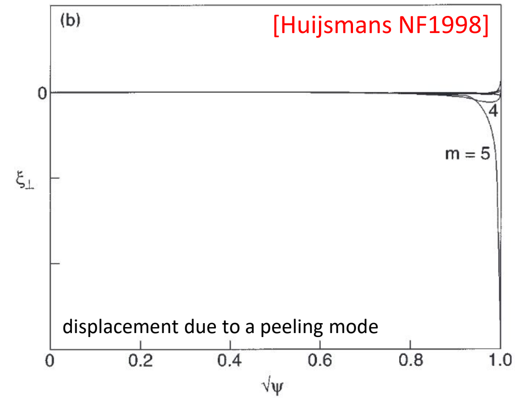


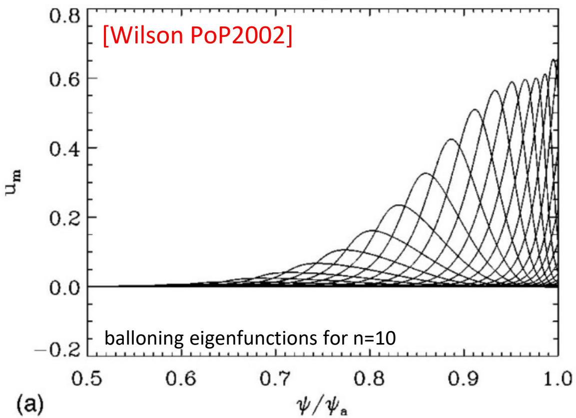
[Horvath PPCF2018]



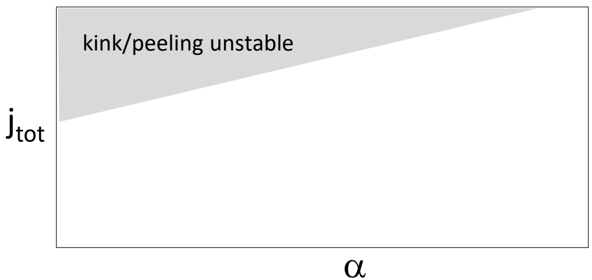
The external kink / peeling mode

- 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



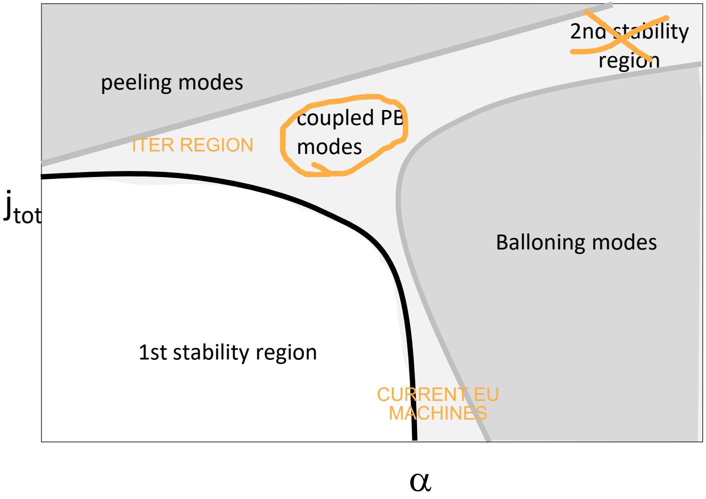


[Huijsmans NF1998]



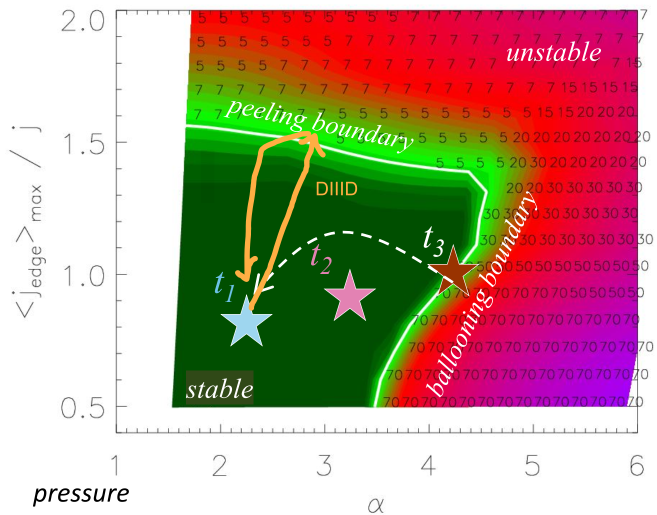
The peeling-ballooning (PB) modes

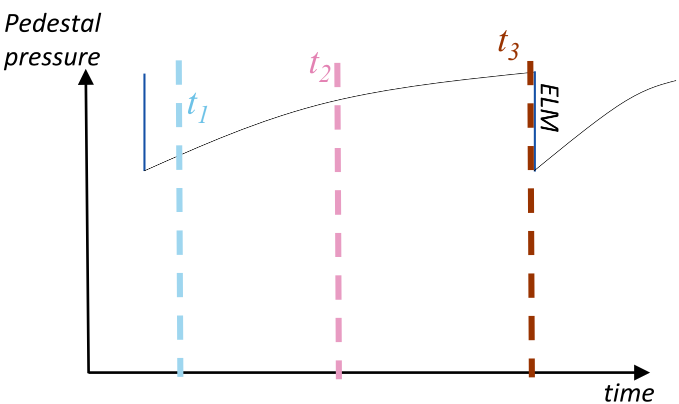
- Toroidicity and shaping effects can couple peeling and ballooning (PB) modes.
- The coupled PB modes can be destabilized even if the single peeling mode and ballooning are stable.
  [Connor PoP1998]
- The PB stability are driven by both pressure gradient and current density.
- The PB stability is the 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).

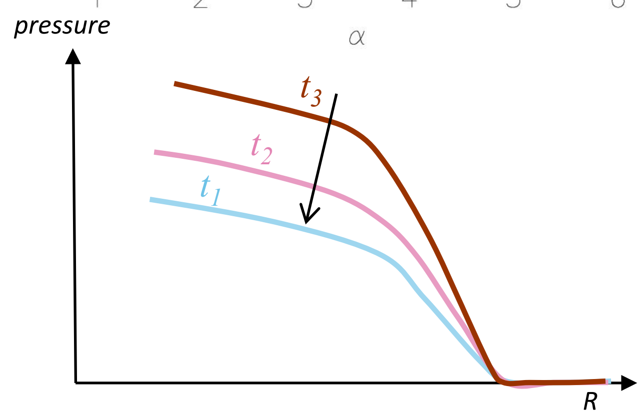


The PB model for the ELM cycle

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.







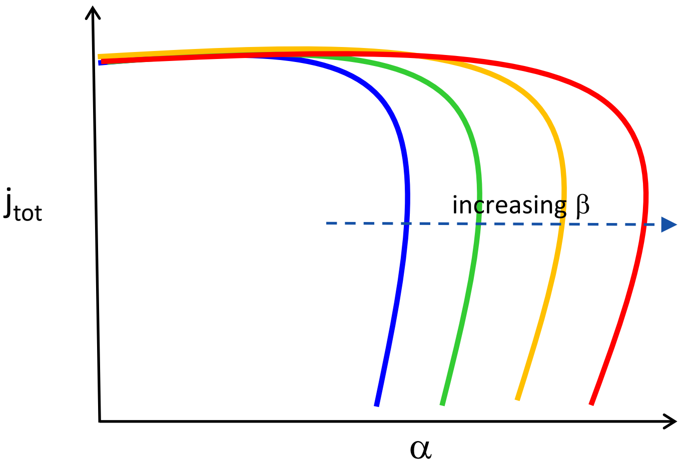
Parameters that affect the pedestal: $\boxed{\beta}$

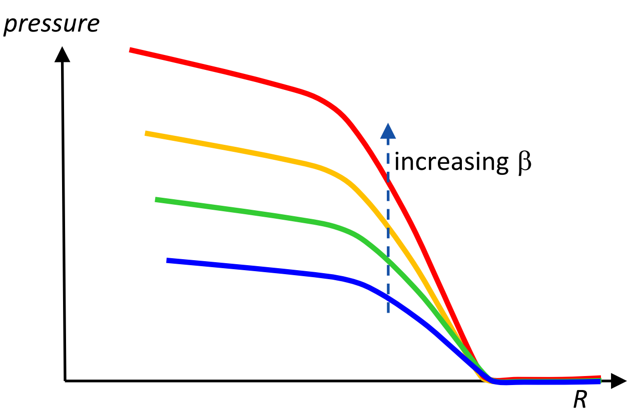
- $\beta = \frac{\langle p \rangle}{B^2/(2\mu_0)}$ Volume averaged pressure
- the increase of β leads to the increases of the Shafranov shift.
  - the Shafranov shift has a stabilizing effect on the ballooning modes.
  - the ballooning modes boundary moves to higher α
  - the pre-ELM pedestal pressure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

→ p^{ped} increases with increasing β.

Pedestal pressure

To increase beta we increase power





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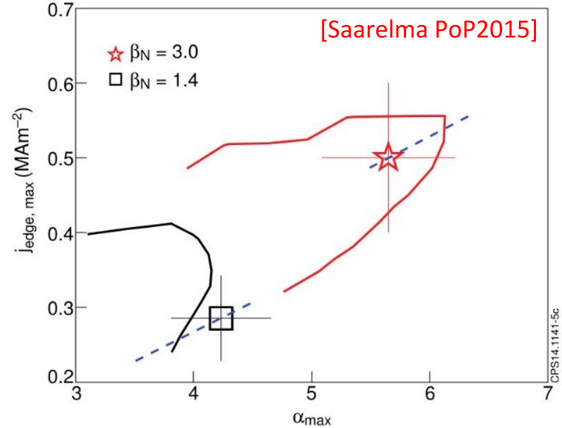
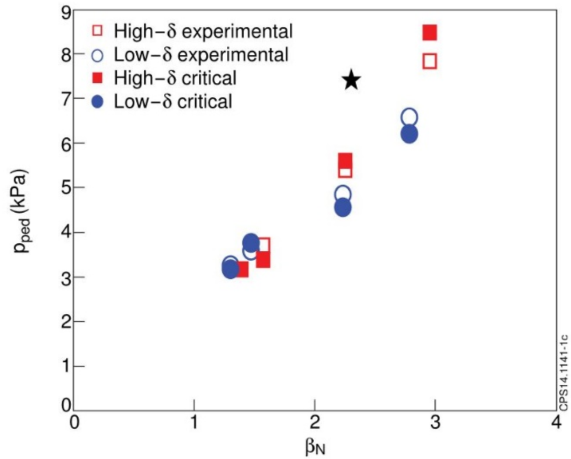




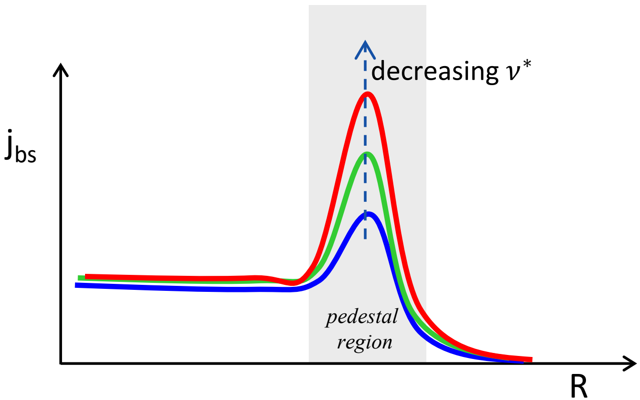
Parameters that affect the pedestal: ν

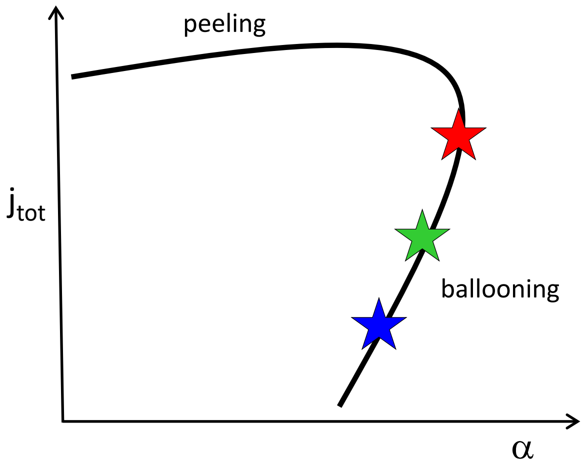
- Collisionality

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

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

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

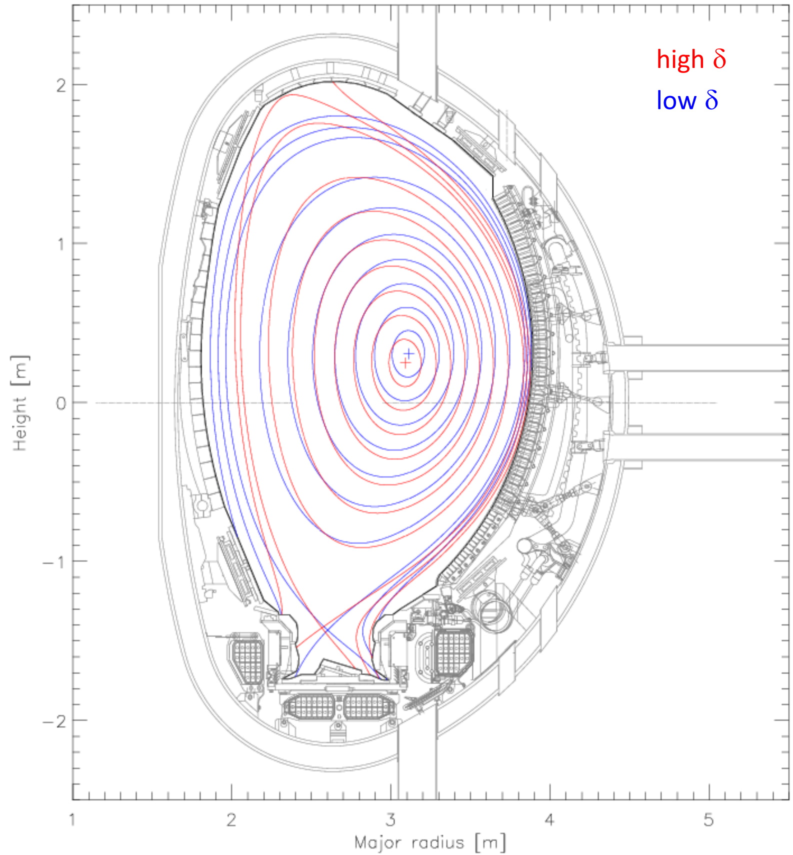




- The reduction of collisionality tends to increase ∇p, if the pedestal is near the ballooning boundary

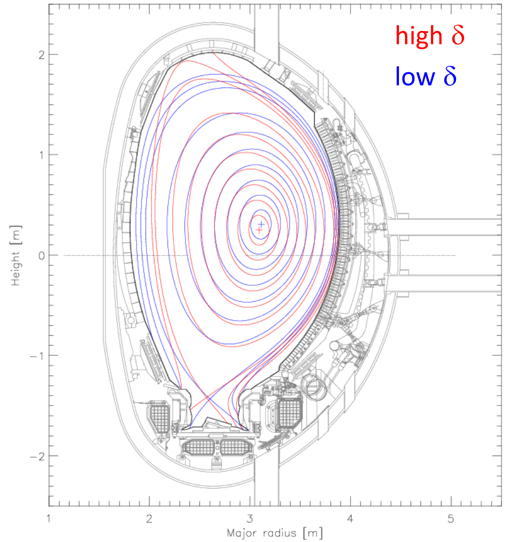
Parameters that affect the pedestal: δ

- δ: plasma triangularity

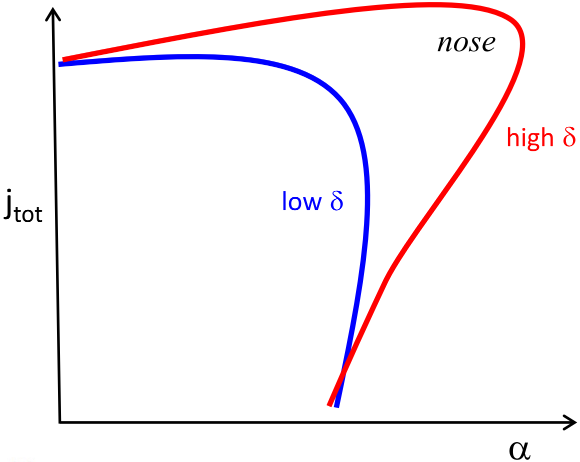


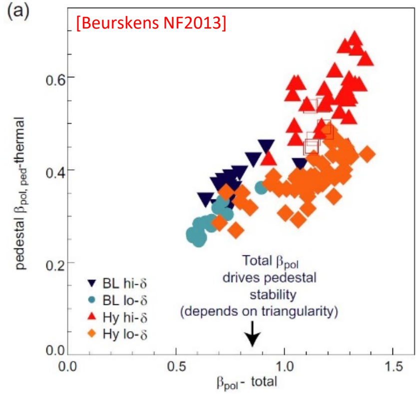
Parameters that affect the pedestal: δ

- 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.



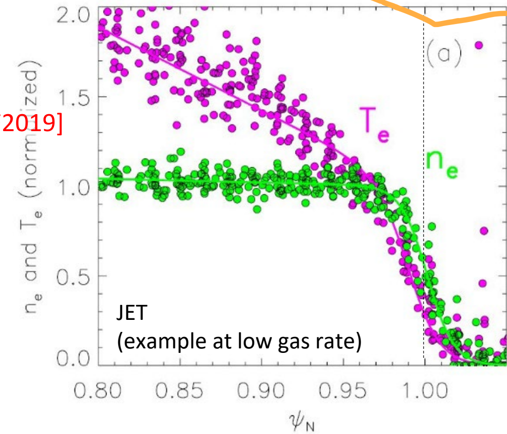
[Saibene PPCF2002]
[Beurskens NF2013]
[Urano NF2014]



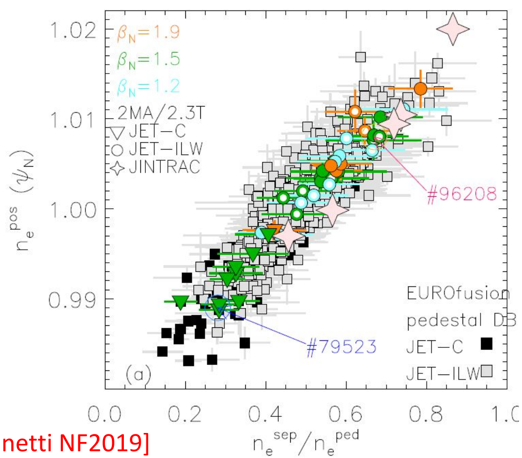


Parameters that affect the pedestal: n_e^{sep}/n_e^{ped}

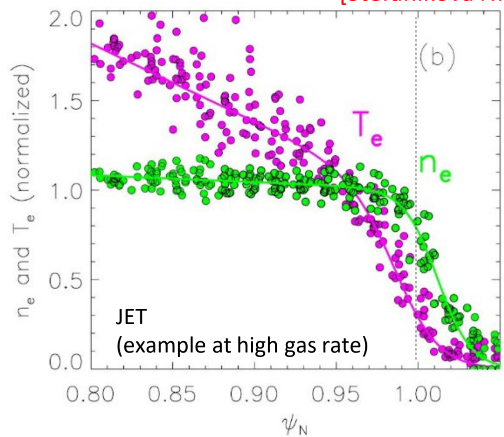
- Separatrix density and pedestal position:
  - The pedestal position can vary signifantly depending on enginnering parameters [Stefanikova NF2019]
  - n_e pedestal position and separatrix density are strongly correlated. [Frassinetti NF2021]



[Stefanikova NF2019]



[Frassinetti NF2019]



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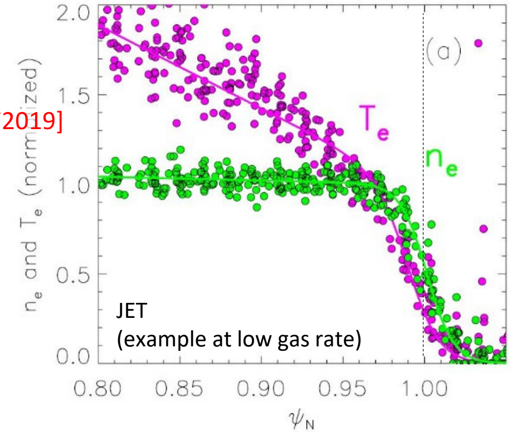
  - The increase of $\mathbf{n_e^{sep}/n_e^{ped}}$ and the outward shift of the pedestal position destabilizes balloning modes and reduces the pedestal height [Dunne PPCF2017[Frassinetti NF2019]



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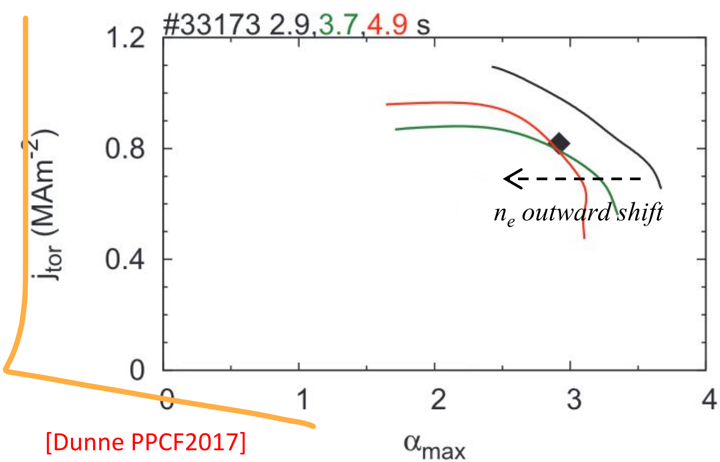
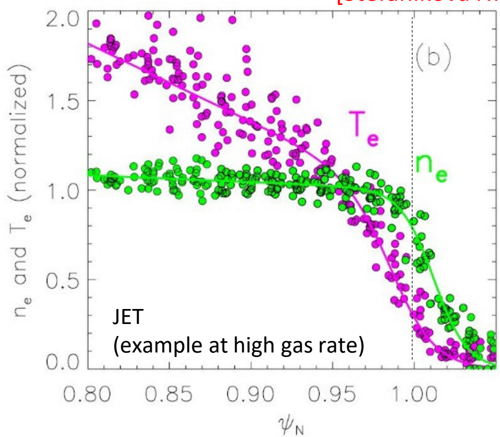


[Dunne PPCF2017]



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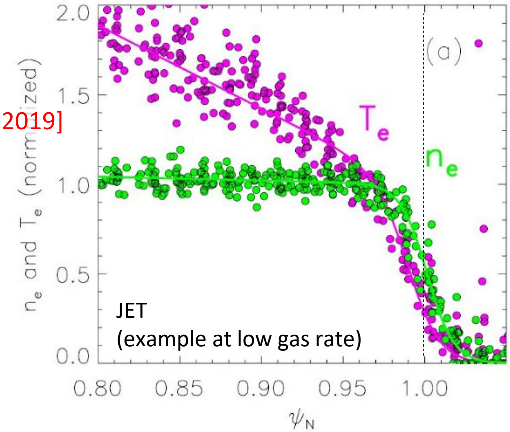

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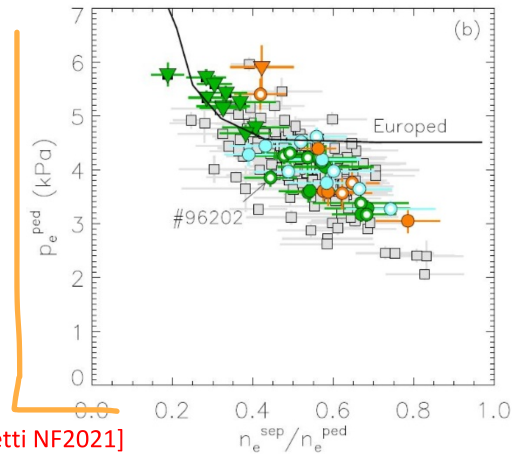
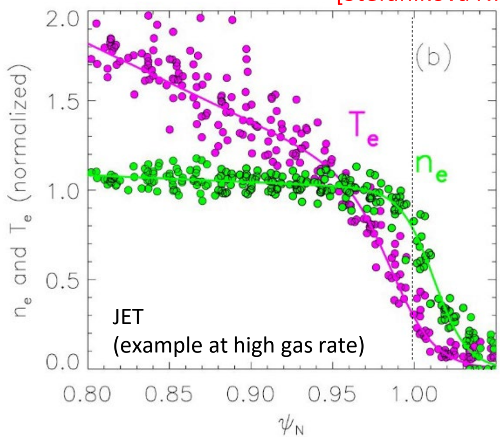


[Frassinetti NF2021]



Parameters that affect the pedestal: isotope

- Isotope mass (A) can affect the pedestal:
  - pedestal density
    - n_e^{ped} increases with increasing A (JET, DIII-D, AUG, JT60-U…)
    - Effect observed both from H→D and from D→T

[Urano NF2013]
[Gohill IAEA2008]
[Maggi PPCF2018]
[Horvath NF2021]
[Schneider PPCF2021]
[Schneider NF2022]
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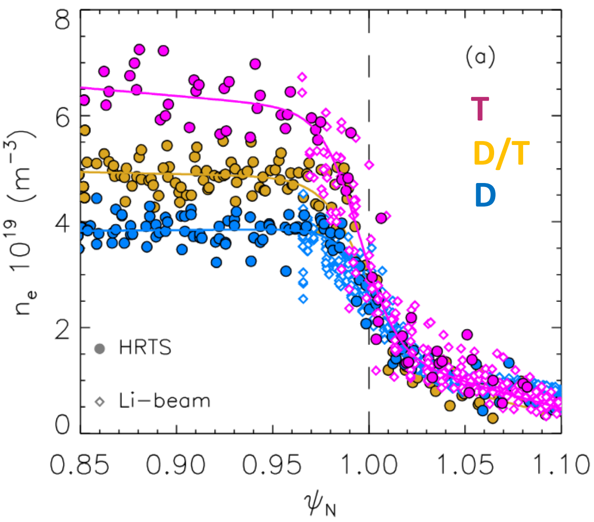

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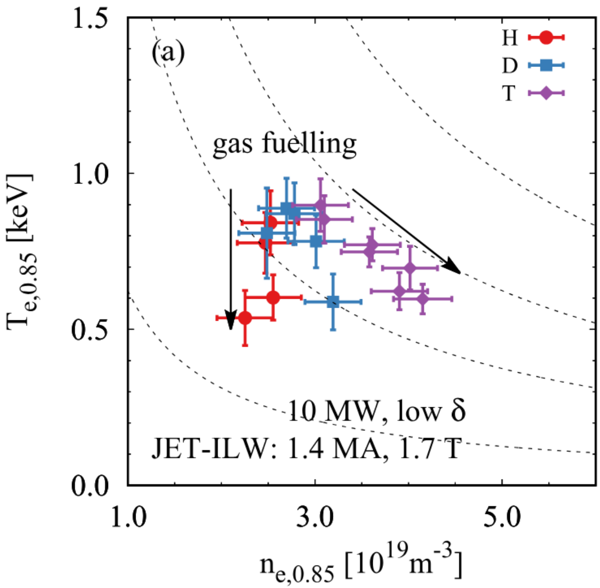

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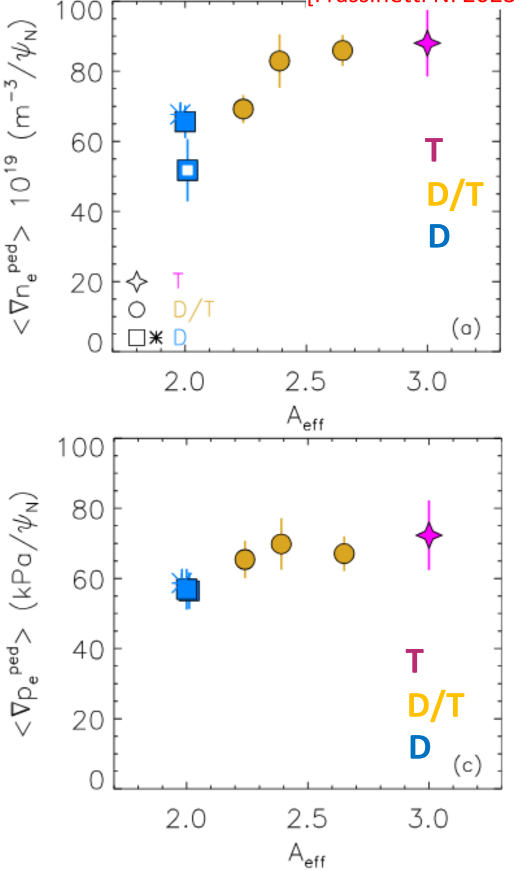
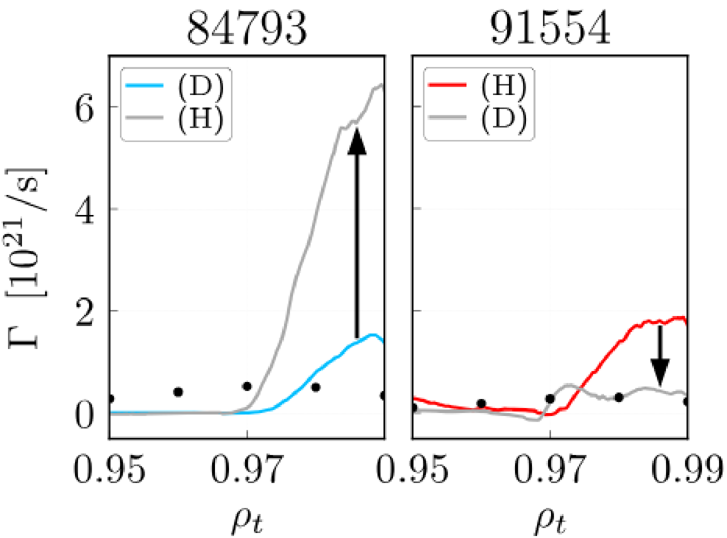
  - Pedestal gradients:
    - The increase in n_e^{ped} is due to an increase in ∇n_e → likely, A affects the transport (but other reasons cannot be excluded yet) [Frassinetti NF2023]
    - The increase in p_e^{ped} is due to an increase in ∇p_e → A can affects the stability [Frassinetti NF2023]
  - Pedestal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

[Frassinetti NF2023]



Parameters that affect the pedestal: isotope

- Understandings of the effects of A
  - pedestal density
    - Sources: experimental estimate very challenging
    - GK results show in H vs D plasmas in JET-ILW show reduction of particle transport with increasing mass [Predebon NF2023]
      (due to reduced ITG turbulence)
    - Further work on-going before conclusive claims



[Predebon NF2023]

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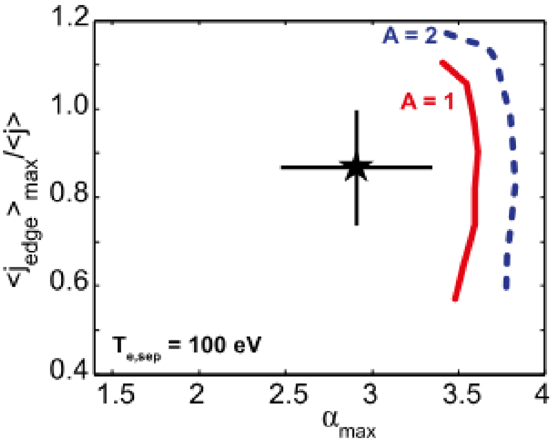

[Horvath NF2021]

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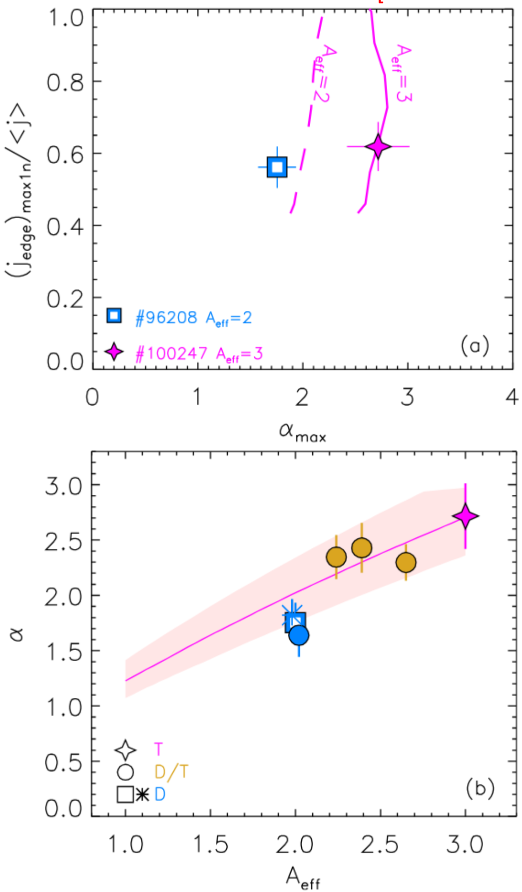
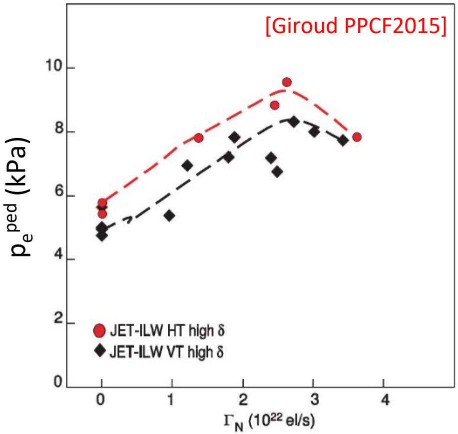
    - Resistive MHD shows a reasonable agreement with experimental results [Frassinetti NF2023]

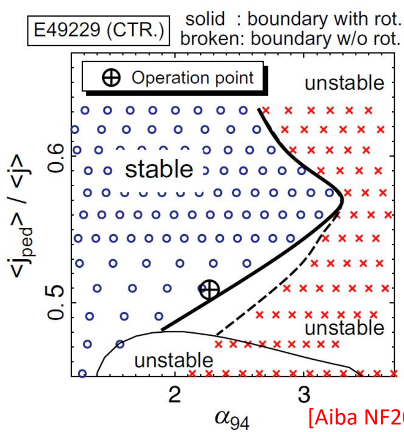
[Frassinetti NF2023]



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]

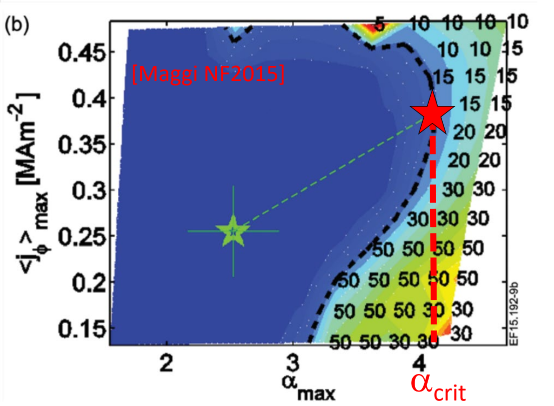
Pedestal predictions: the PB constraint

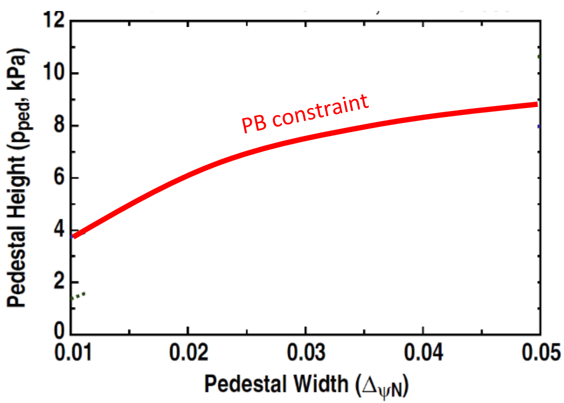
- Can we use the PB model to predict the pedestal pressure height before the ELM?

- 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.





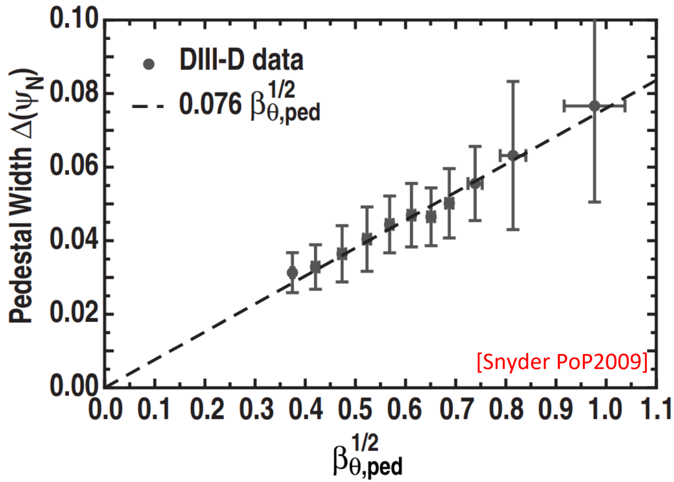
Pedestal predictions: the KBM constraint

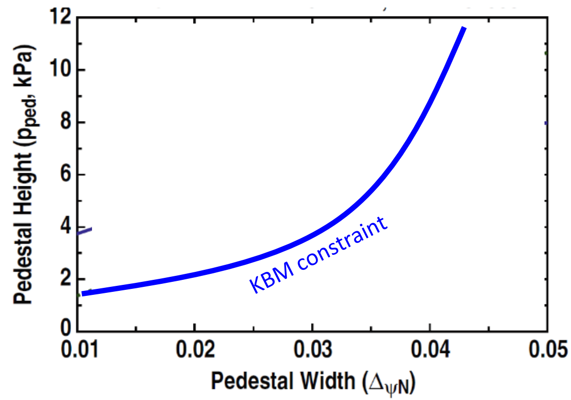
- The other constraint can come from pedestal transport
- The problem is that the pedestal transport is (often) driven by turbulence. Turbulence studies are not trivial and very time consuming
- The most succesfull approach, so far, has been developed in DIII-D [Snyder PoP2009]
  - experimental results 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





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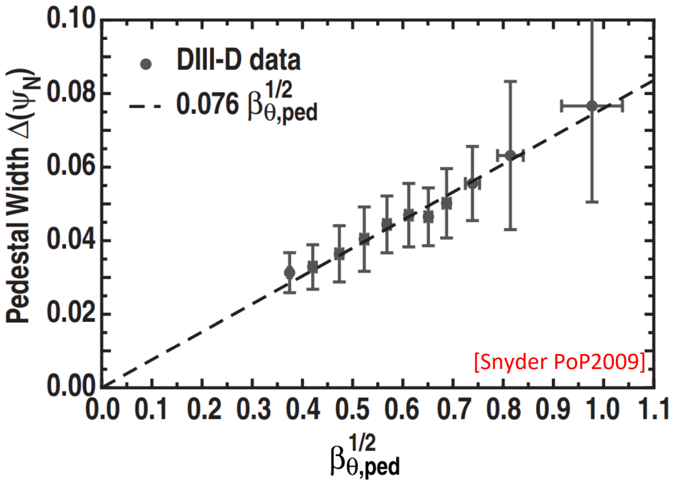
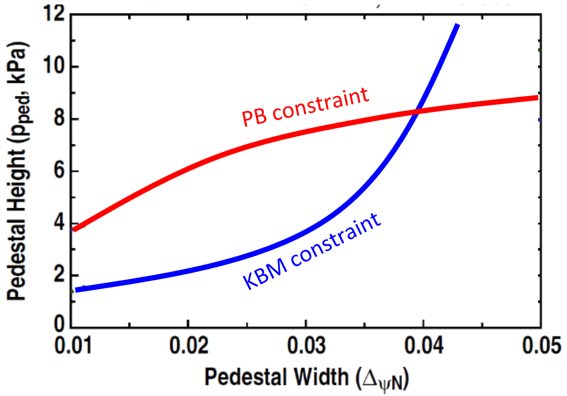
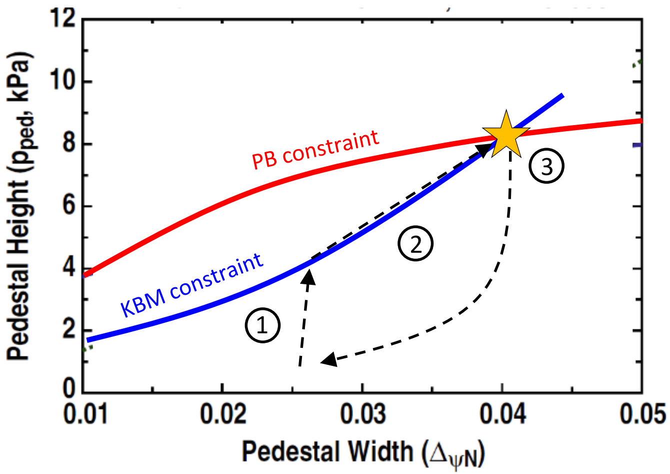




The EPED1 model

- 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:

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

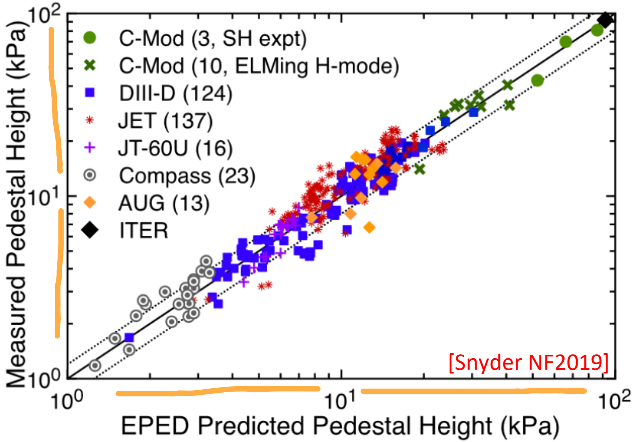
3. PB boundary is reached
   - ELM triggered

The EPED1 model

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

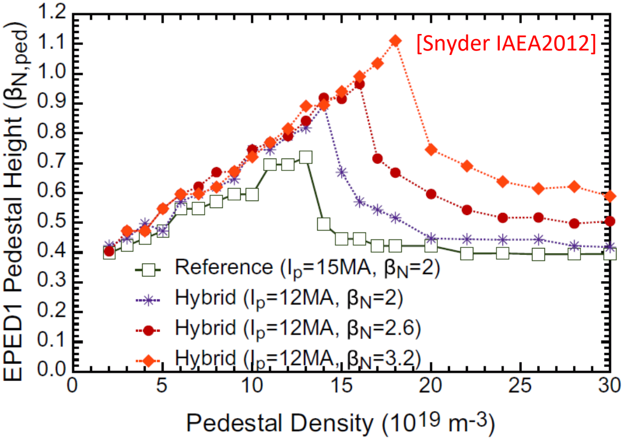
[Snyder NF2019]

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



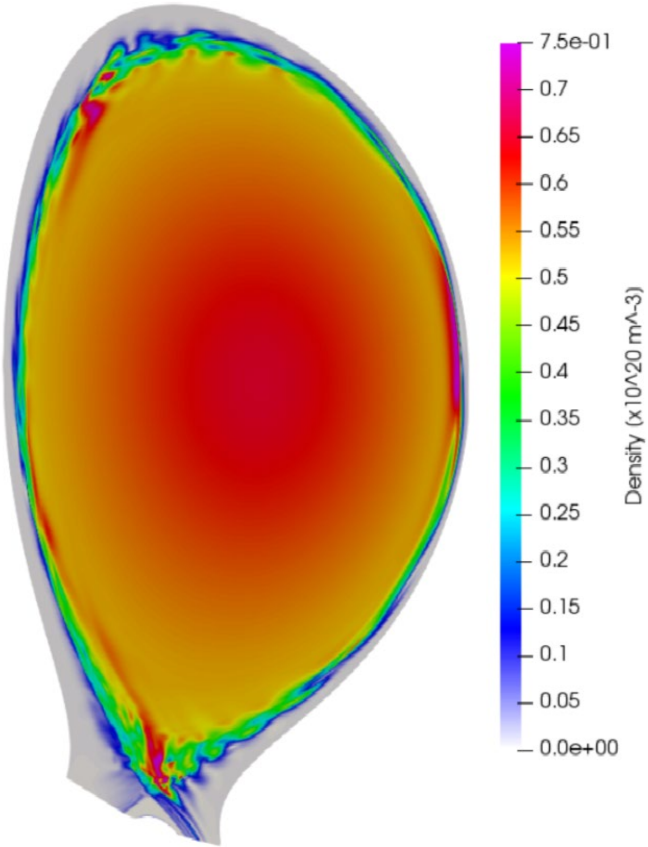
- EPED1 is widely used to predict the pedestal height (also in ITER).

- 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]



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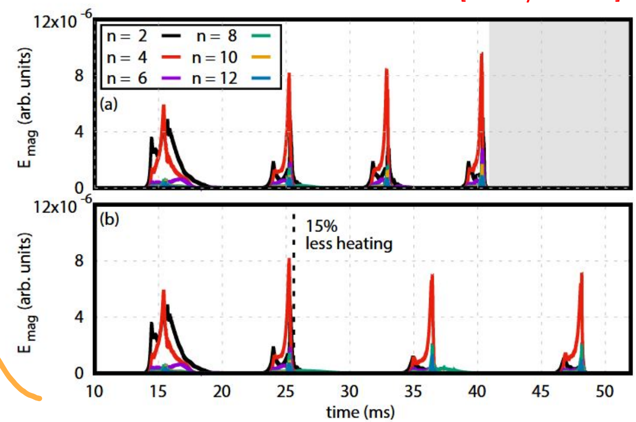
  - type I ELMs start to be modeled rather well

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

ELM cycle simulations with JOREK

[Cathey NF2020]



Some active research areas

- Discrepancies between PB stability and experimental results, especially in JET-ILW, have been observed.
  [Frassinetti NF2019], [Frassinetti NF2021], [Nyström NF2022]
  - Resitive MHD might play a role
- 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?
- Peeling limited pedestals
  - Reach peeling limited pedestals and validate pedestal predictions in view of ITER [Frassinetti, in preparation]
- Small ELMs
  - will operation with good pedestals and small ELMs be posible in ITER? [Viezzer NF2018] [Dunne NF2024]
- ELM mitigation
  - develop and test ELM mitigation techniques that can be used in ITER

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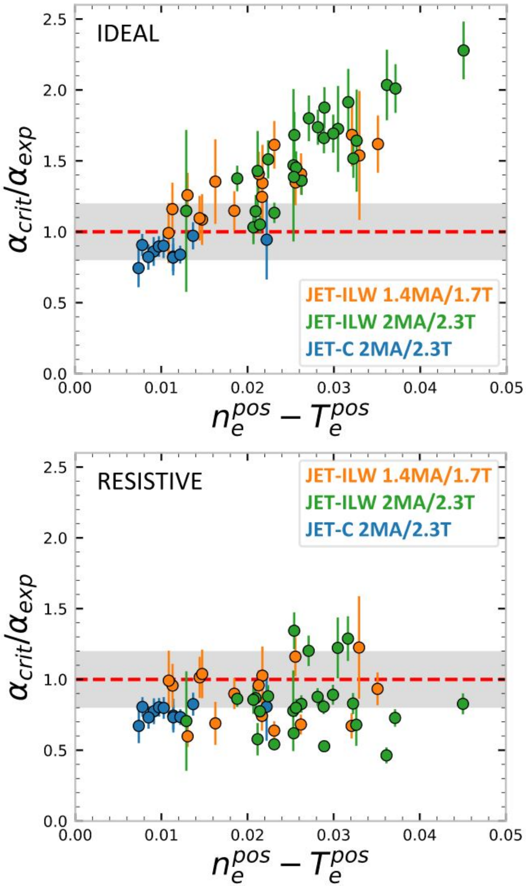
[Nyström NF2022]



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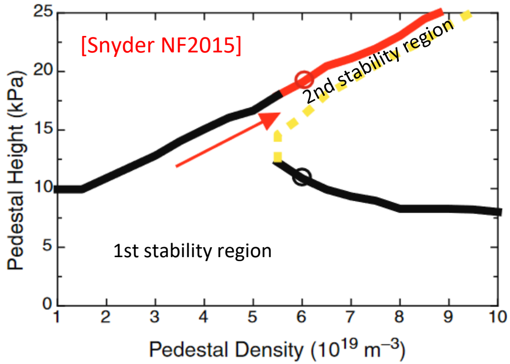

Some active research areas

- Discrepancies between PB stability and experimental results, especially in JET-ILW, have been observed.
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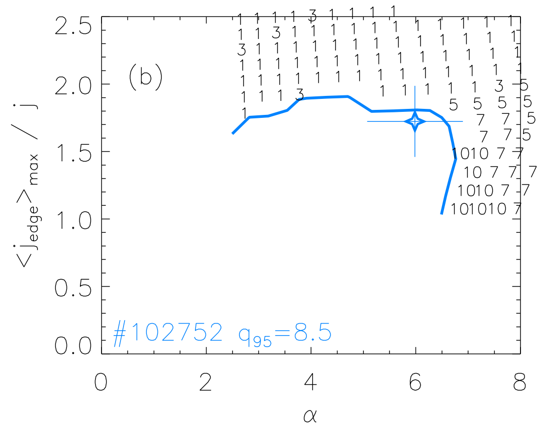

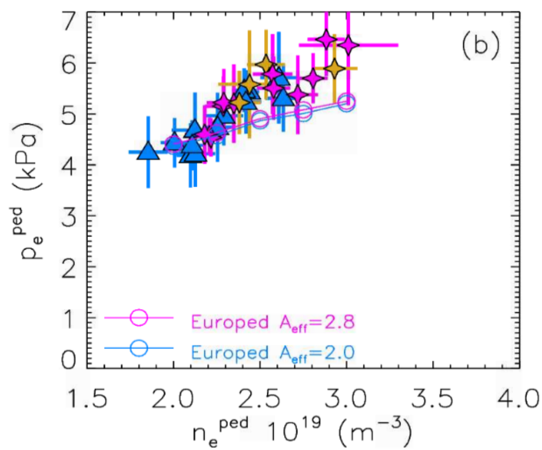

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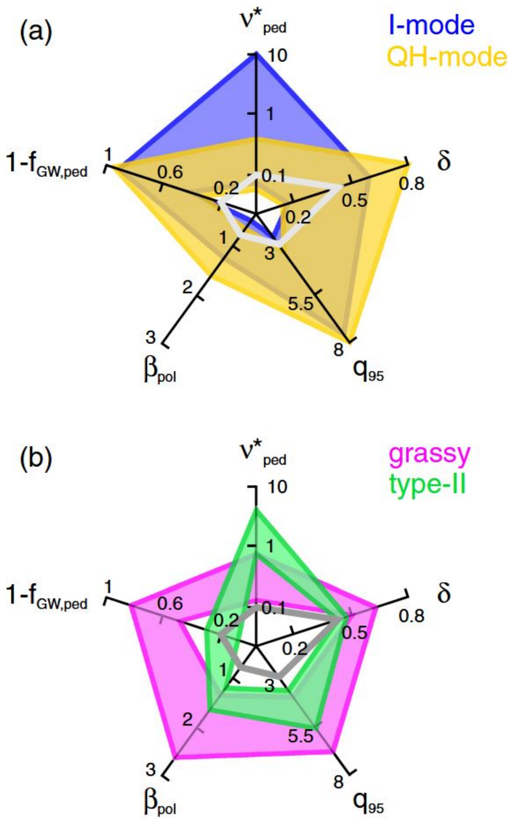

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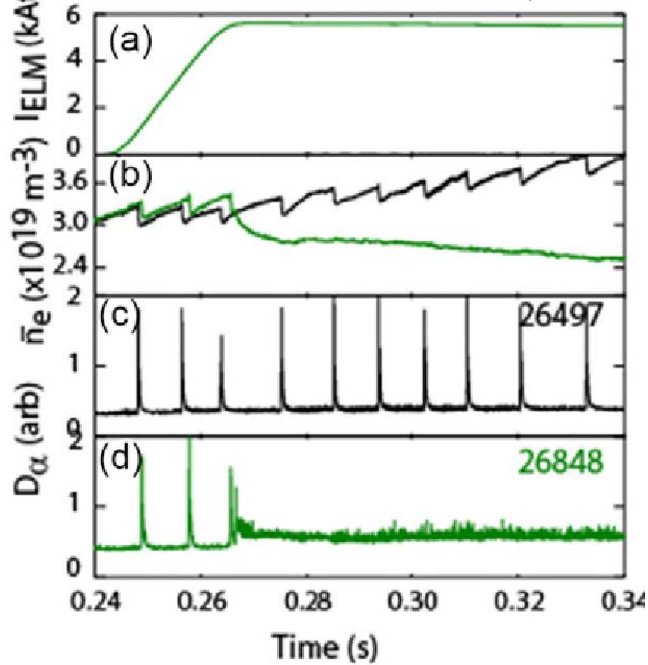
[Kirk, Suttrop NF2015]



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