Role of the separatrix density in the pedestal performance in JET-ILW and comparison with JET-C

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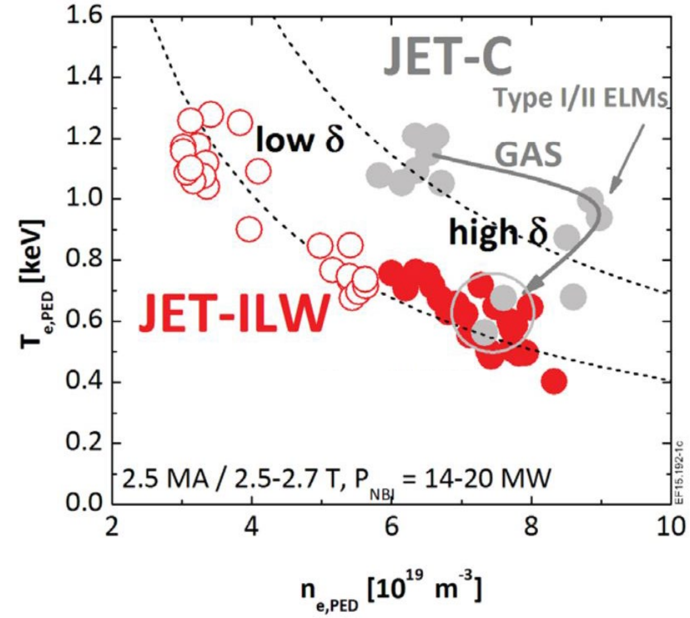
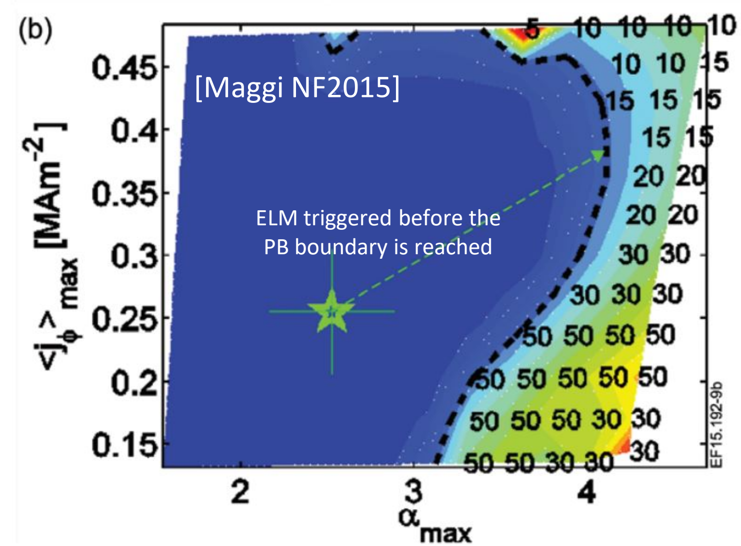
INTRODUCTION

- JET has changed wall from carbon (JET-C) to metal (JET-ILW) in 2011
- The initial results have shown a lower p^{ped} in JET-ILW plasma *[Giroud NF 2013, Beurskens NF2014]*
- In recent years, confinement comparable to JET-C has been obtained *[Mailloux IAEA2020]*
- However,
  - the origin of the low pedestal is still unclear
  - the understanding the pedestal behavior is essential to improve pedestal predictions.
- Hints:
  - low Z impurities play a role *[Giroud NF2013]*
  - high gas rates are typical in JET-ILW,
    - they play an important role
  - n_e^{sep}/n_e^{ped} is a relevant parameter in AUG and Alcator C-mod *[Dunne PPCF2017, IAEA2018]*
- Problems:
  - at high gas rates and power, Type I ELMy H-modes are not limited by ideal MHD *[Maggi NF2015]*

[Maggi NF2015]

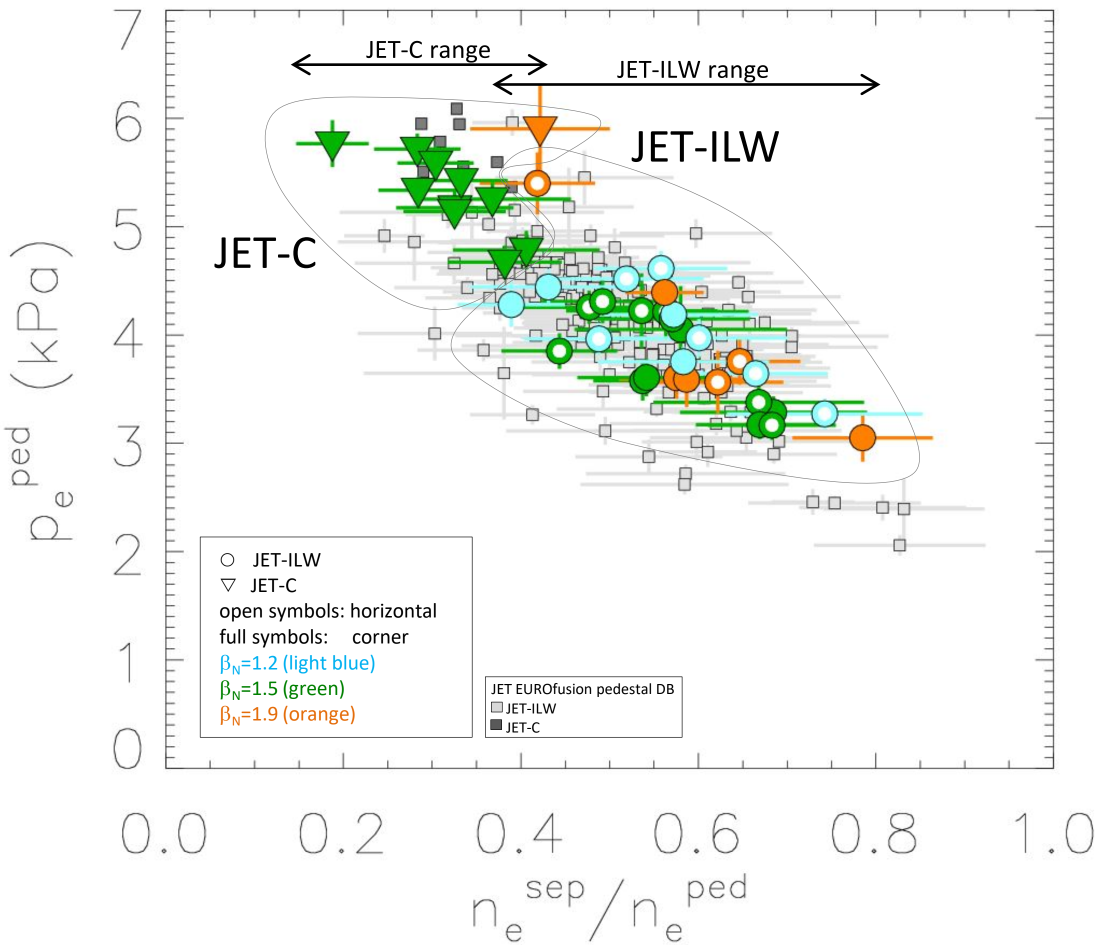




OUTLINE

- Datasets used
- p_e^{ped} and n_e^{sep}/n_e^{ped} : the empirical correlation in JET
- Understanding the correlation:
    - **Role of the pedestal position** in the pedestal stability (**Europed** modelling), relevant at **low n_e^{sep}/n_e^{ped}**
    - **Role of the turbulent transport** in the pedestal (**GENE** modelling), relevant **at high n_e^{sep}/n_e^{ped}**
    - Discussion on the **MHD pedestal stability at high n_e^{sep}/n_e^{ped}** (preliminary **CASTOR** modelling, for resisitive MHD)
- Next steps: towards an improved predictive modelling for JET
- Conclusion

THE DATASETS



JET-ILW dataset: (circles)

- Type I ELMs

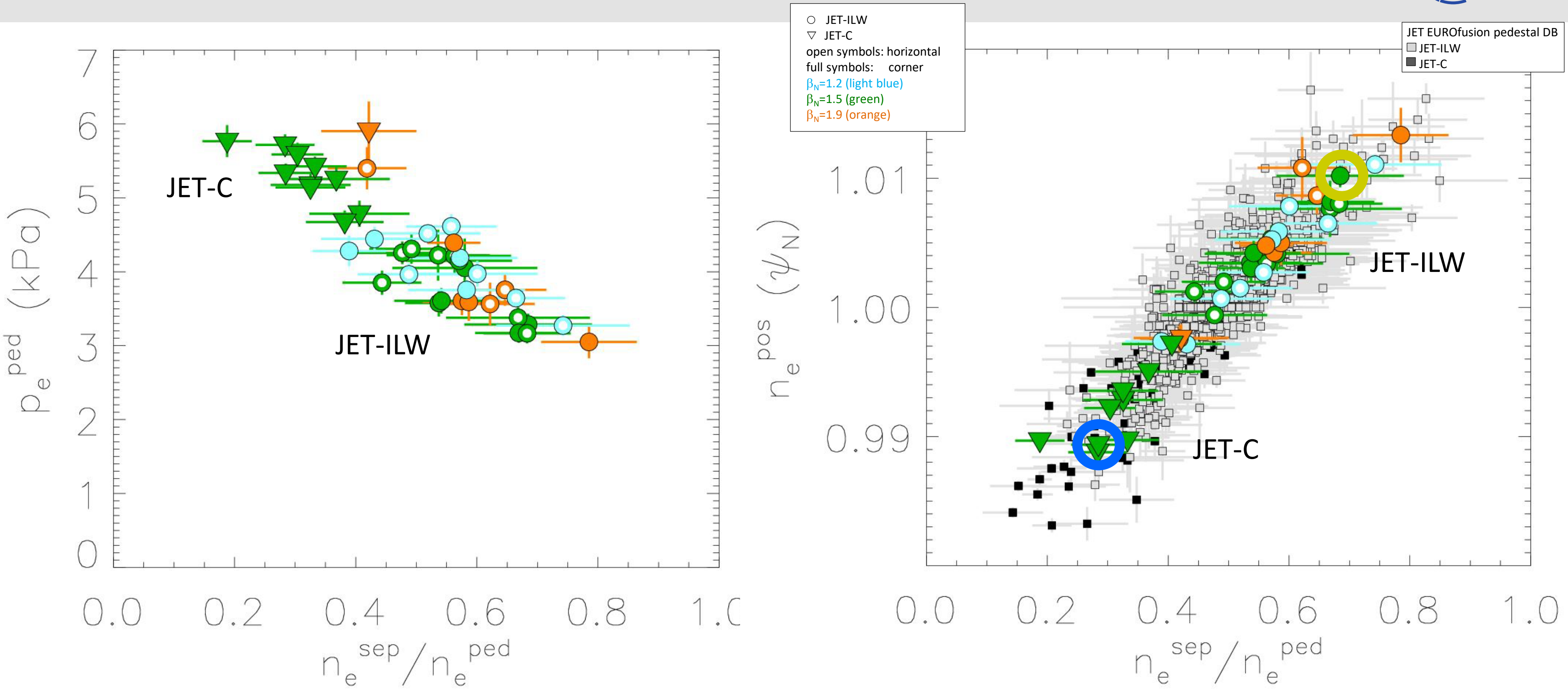
  (f_{ELM} increases with P_{sep} at constant Γ_{D2})
- 2MA / 2.3T / low-δ / deuterium
- Gas scans at constant β_N.
  - Three subsets:
    - β_N=1.2 (light blue)
    - β_N=1.5 (green)
    - β_N=1.9 (orange)
  - $\Gamma_{D2}=0.4\cdot10^{22}$ - $6.0\cdot10^{22}$ e/s
  - P_{NBI}=8-22MW
  - **$T_i=T_e$ (within 10%)** — physics mechansims for pedestals with T_i^{ped}>>T_e^{ped} not discussed here. See : **[Garcia EX/1-2, de la Luna EX/3]**
  - For each subset, two divertor configurations: horizontal and corner.

JET-C dataset: (triangles)

- 11 type I ELMy H-modes,2MA/2.3T, low-δ
- $\Gamma_{D2} < 0.4\cdot10^{22}$ e/s

Larger datasets also used to strengthen the conclusions
- data in grey (JET-ILW) and black (JET-C)
- data from the EUROfusion pedestal database
- selections in Ip and Bt when looking at dimensional parameters

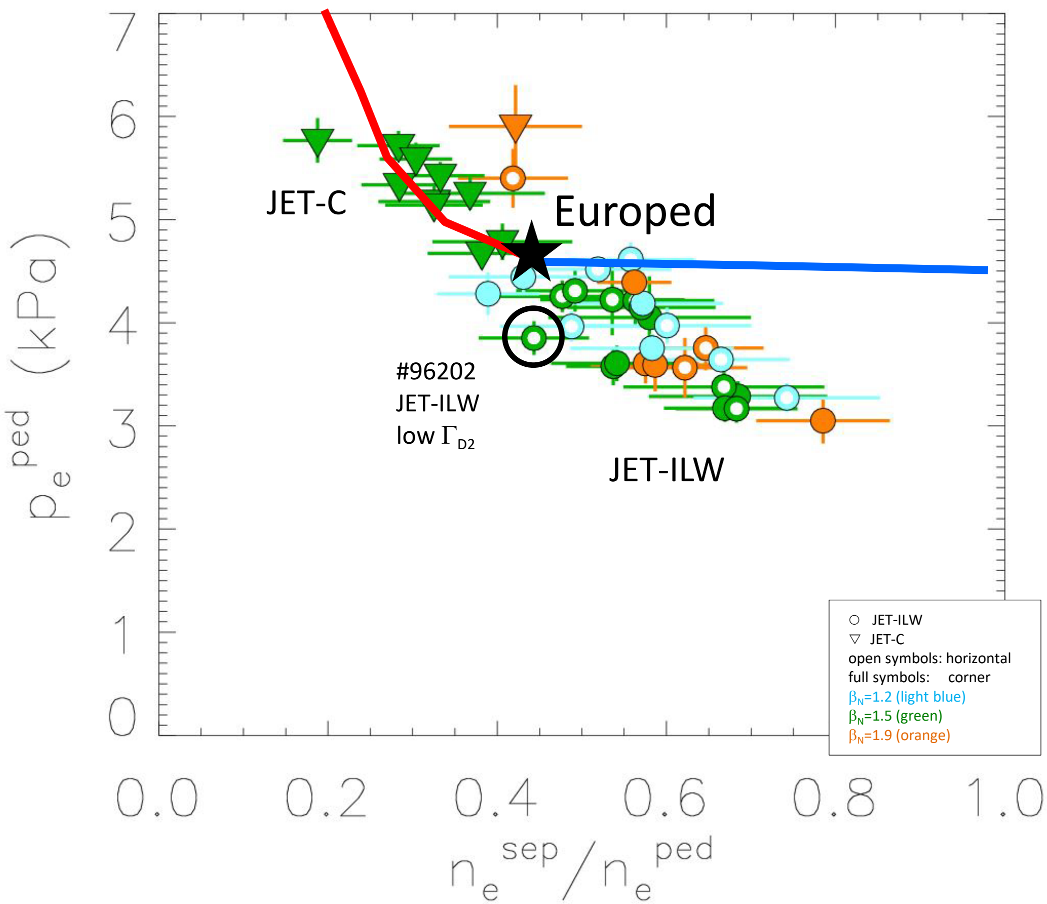
n_e^{sep}/n_e^{ped} AND DENSITY PROFILES



- p_e^{ped} increase with decreasing n_e^{sep}/n_e^{ped}
- JET-C data tend to have lower n_e^{sep}/n_e^{ped} than JET-ILW data

- The decrease of n_e^{sep}/n_e^{ped} is correlated with a change in the pedestal n_e radial position
- The n_e^{sep}/n_e^{ped} vs n_e^{pos} correlation is very robust.

EUROPED MODELLING

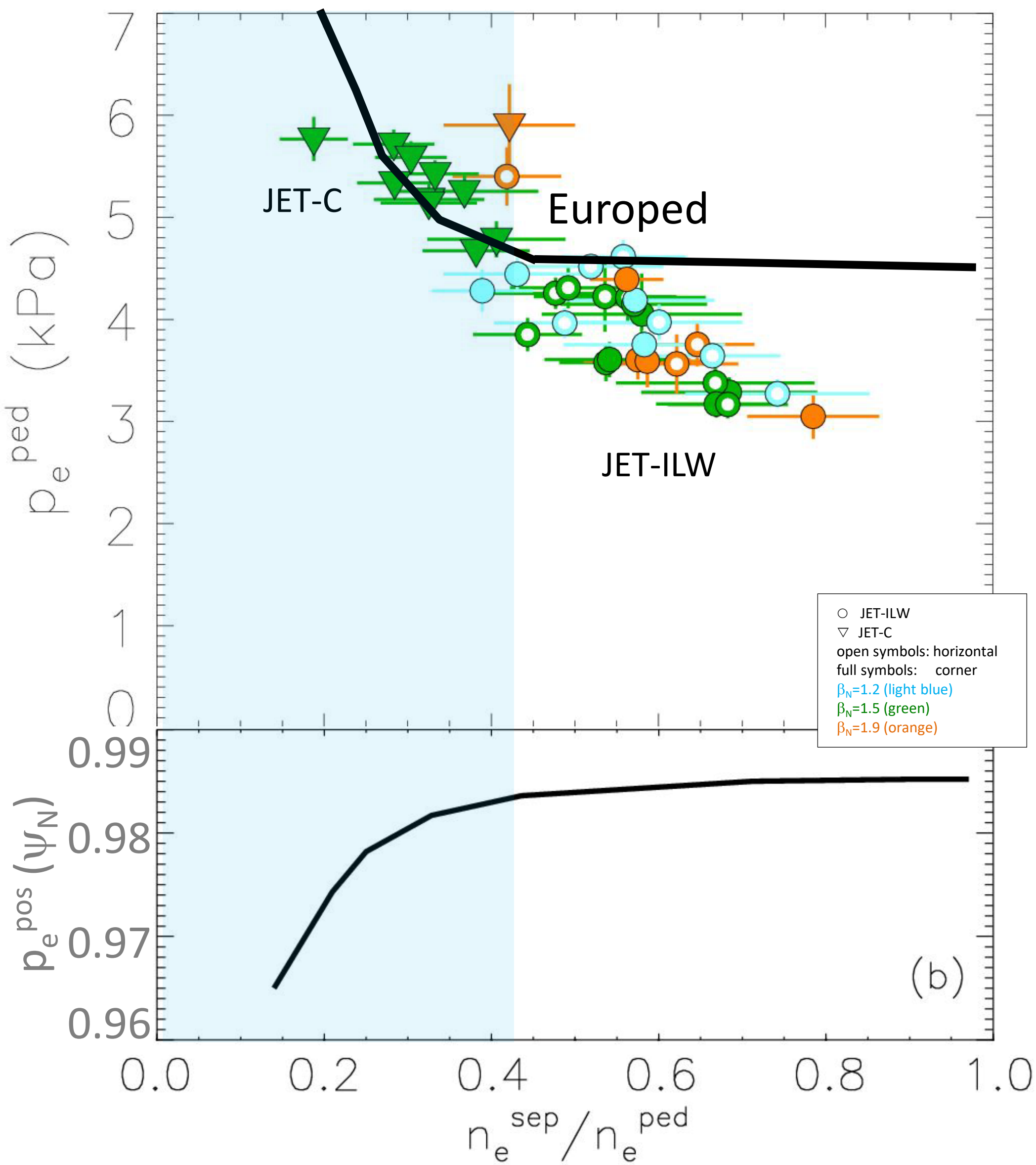


- Variation of n_e^{pos} affects p_e^{pos}
- Radial inward shift of p_e^{pos} stabilizes ballooning modes and increase pedestal

  [Dunne PPCF2017, Frassinetti NF2019]
  [Maingi PRL2009, Osborne NF2015]

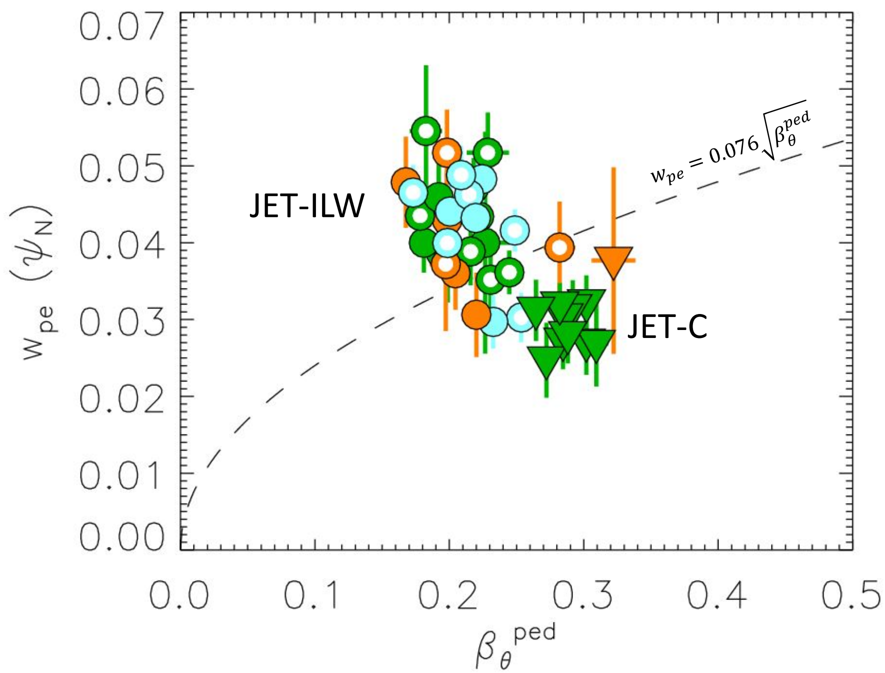
- Europed (based on EPED1) *[Saarelma PPCF2018] [Snyder PoP2009]*
  - PB stability
  - KBM constraint: $w_{pe} = 0.076\sqrt{\beta_\theta^{ped}}$
- Reference case reasonably predicted (within 20%)
- n_e^{sep}/n_e^{ped} variation modeled via the change in n_e^{pos} (input parameter)
  - Reduction of n_e^{sep}/n_e^{ped}:
    - increase of p_e^{ped}
    - quantitative agreement with JET-C
  - Increase of n_e^{sep}/n_e^{ped}:
    - no effect on p_e^{ped}
    - disagreement with JET-ILW

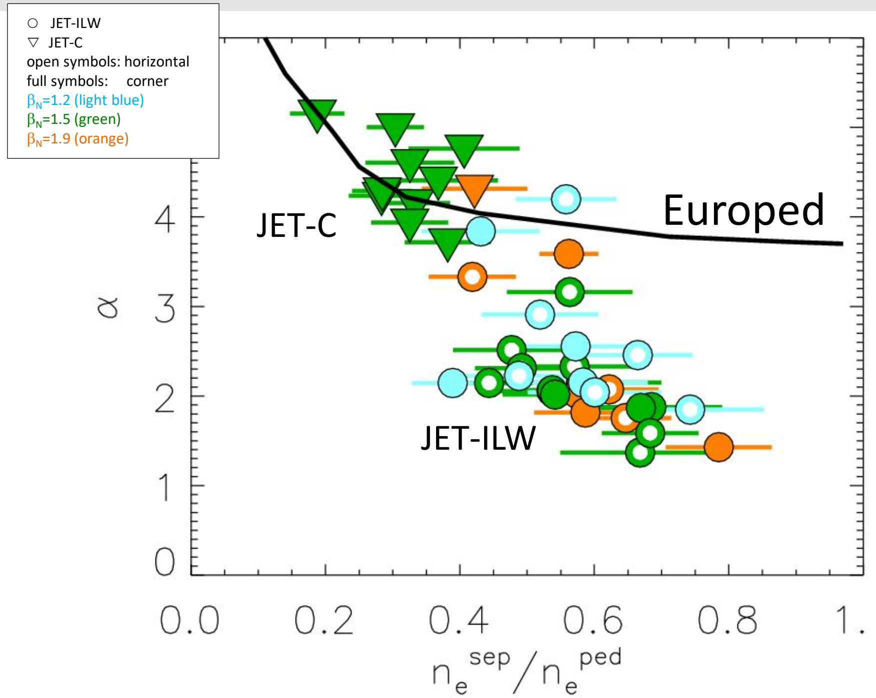
Effect of p_e^{pos} only for n_e^{sep}/n_e^{ped} <0.4



- **n_e^{sep}/n_e^{ped}<0.4**
  - The increase of n_e^{sep}/n_e^{ped} leads to a radial outward shift of the pressure
  - This destabilizes the ballooning modes, reduces the stability and leads to the decrease of the pedestal pressure
- **n_e^{sep}/n_e^{ped}>0.4**
  - the effect saturates
  - p_e^{pos} is not related anymore with n_e^{sep}/n_e^{ped}
  - no pressure reduction is predicted

Width and gradient: comparison Europed / experiment

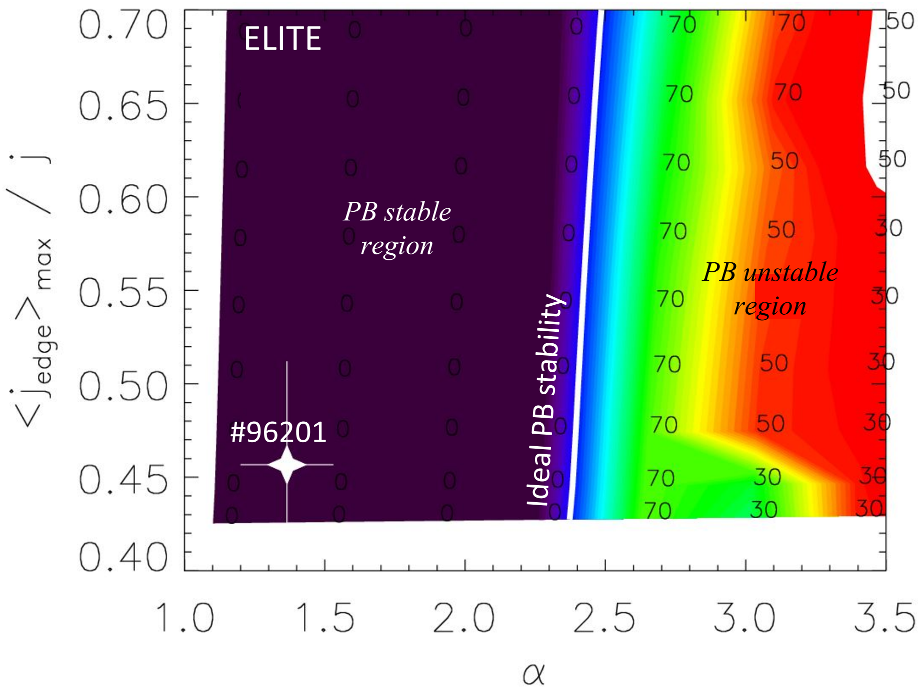


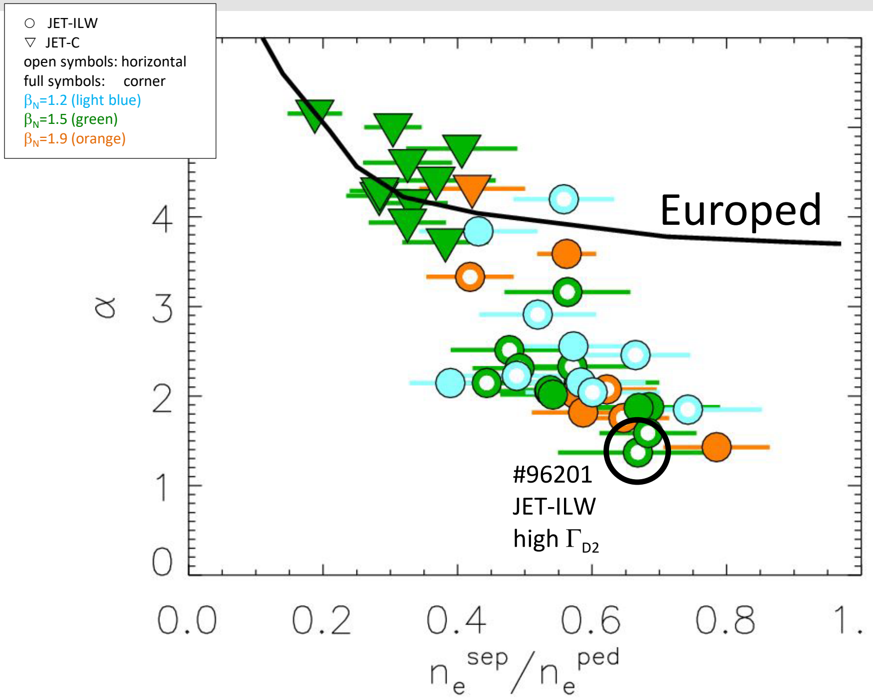


- **Pedestal width**
  - No reasonable agreement with the model

- **Experimental normalized pressure gradient (α_{exp})**
  - agreememnt with the model at $n_e^{sep}/n_e^{ped} < 0.4$
  - disagreement for $n_e^{sep}/n_e^{ped} > 0.4$

Ideal MHD stability





- **Pedestal width**
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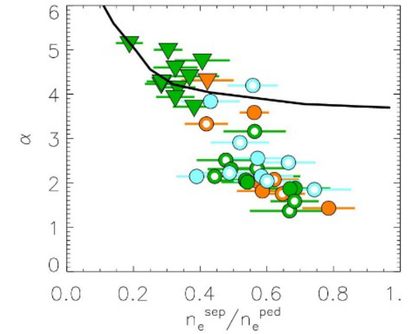
- **Experimental normalized pressure gradient (α_{exp})**
  - agreememnt with the model at $n_e^{sep}/n_e^{ped} < 0.4$
  - disagreement for $n_e^{sep}/n_e^{ped} > 0.4$
    - → at $n_e^{sep}/n_e^{ped} > 0.4$, the pre-ELM pedestal does not reach the ideal PB stability boundary
    - → #96201: $\alpha_{crit}/\alpha_{exp} \approx 1.8$ (from ELITE)

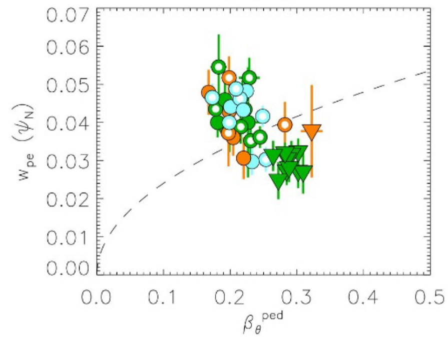
What must we explain at high n_e^{sep}/n_e^{ped}?

- The mechanisms that describe the pedestal at high n_e^{sep}/n_e^{ped} need to explain:

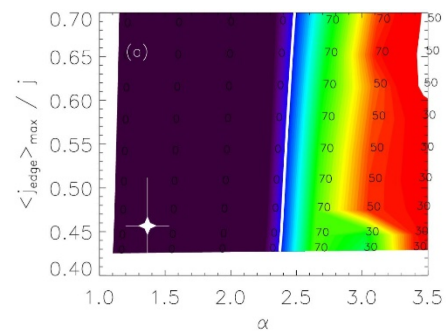
1. The reduction of ∇p_e with increasing n_e^{sep}/n_e^{ped}



2. The behavior of the pedestal width w_{pe}



3. The ELM triggering mechanism



- Working hypothesis:
  - n_e^{sep}/n_e^{ped} can affect the turbulent transport

JET KTH

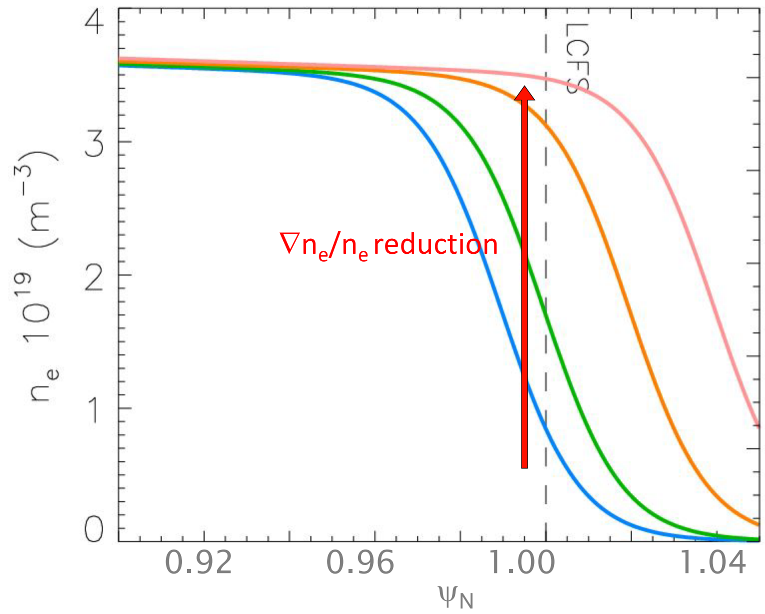
[Hatch, Kotschenreuther NF2017]

Why n_e^{sep}/n_e^{ped} can affect the transport?

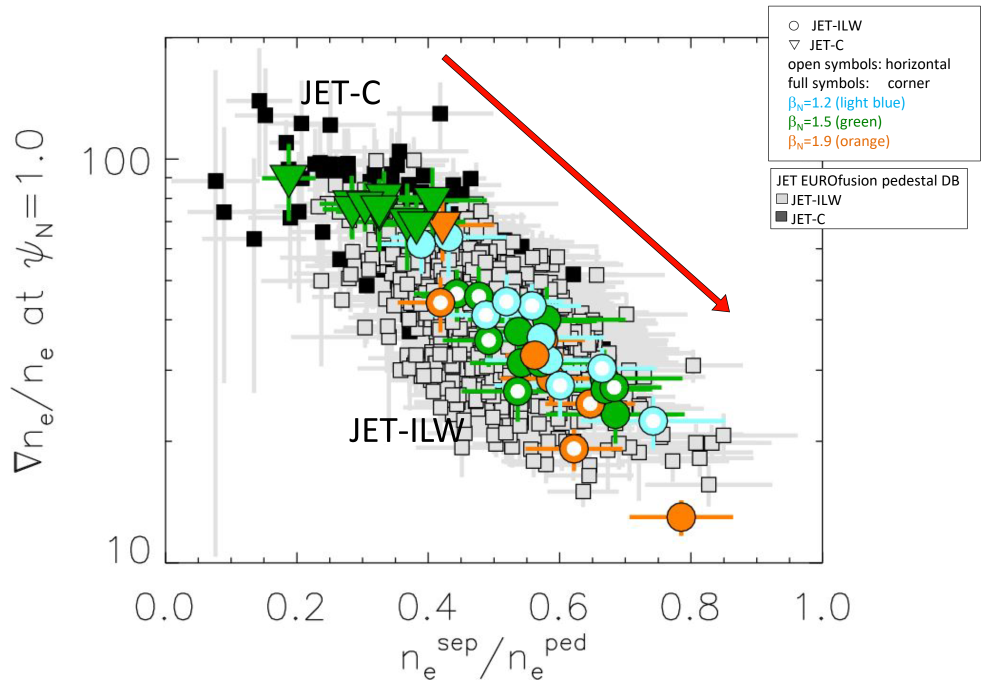
- n_e^{sep}/n_e^{ped} can affect the turbulent transport

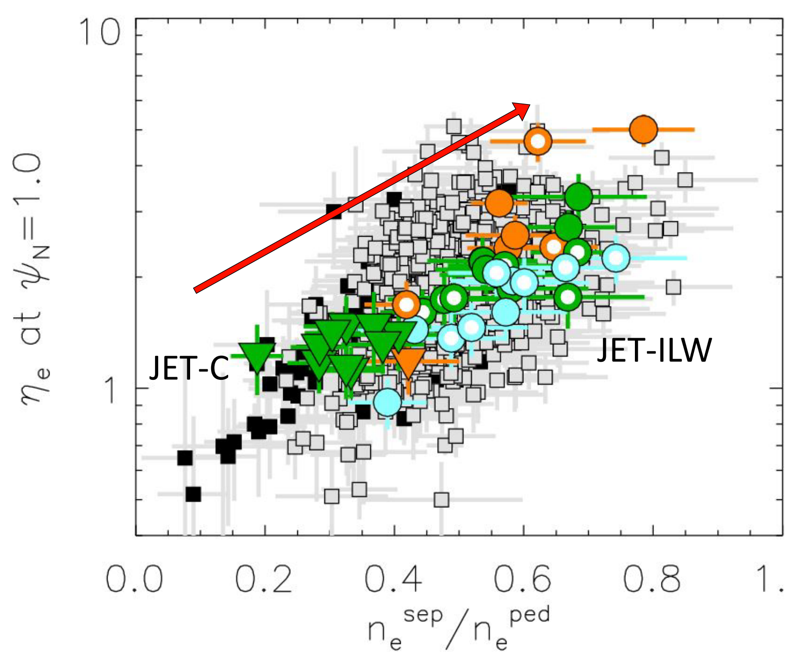
  [Hatch, Kotschenreuther NF2017]

- Increase of n_e^{sep}/n_e^{ped} leads to
  - $\nabla n_e/n_e$ reduction, which leads to:
    - η_e increase $\quad \eta_e = \frac{(n_e/\nabla n_e)}{(T_e/\nabla T_e)}$
      - turbulent transport increase



Also $\nabla T_e/T_e$ can affect turbuent transport *[Maggi NF2017]*
but this effect is not directly studied here.





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2. **the behavior of the pedestal width w_{pe}**
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[Hatch, Kotschenreuther NF2017]

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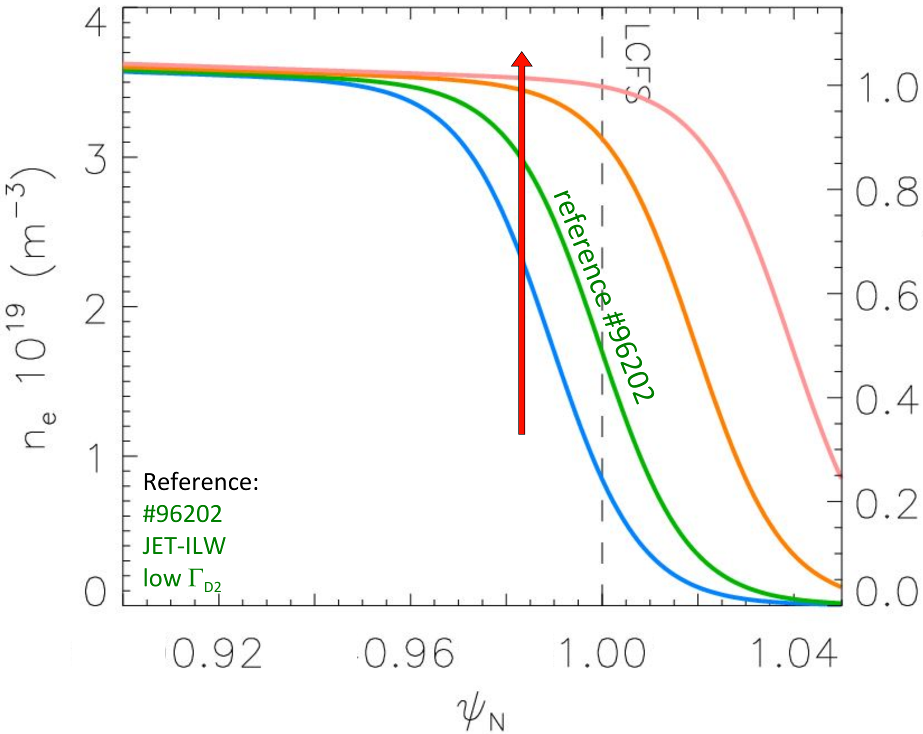
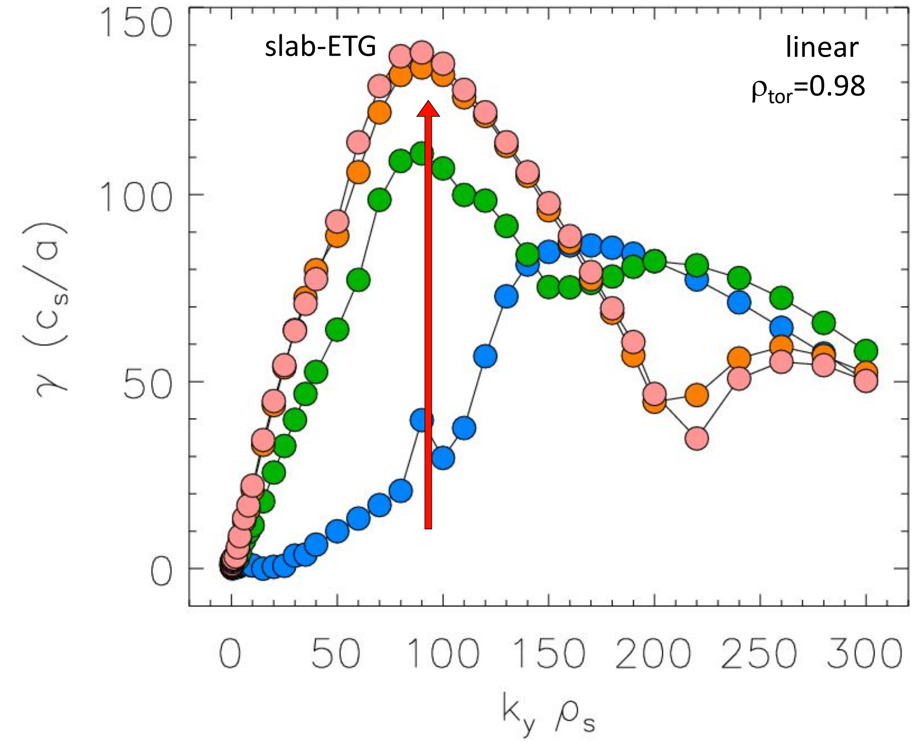
[Hatch, Kotschenreuther NF2017]

Turbulent transport in the pedestal



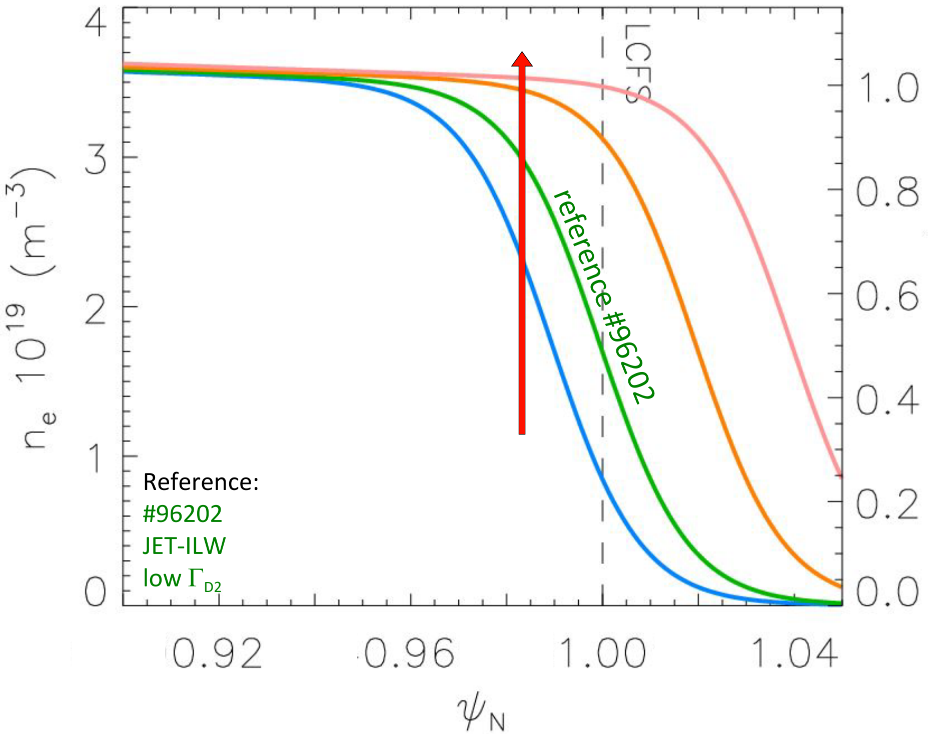


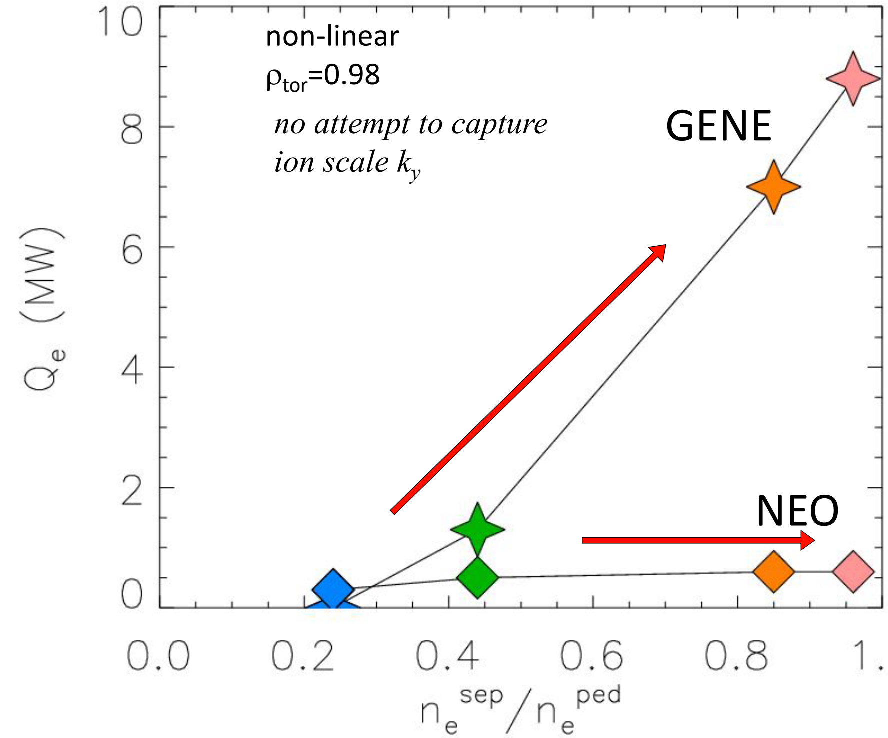
- Linear and non-linear local GENE modelling for
  - JET-ILW reference case (low Γ_{D2})
  - n_e profile shifted inwards (to n_e^{sep}/n_e^{ped} JET-C range)
  - n_e profile shifted outwards (to n_e^{sep}/n_e^{ped} high Γ_{D2} JET-ILW range)
- **Slab-ETG** observed at the peak *[Chapman EPS2021], [Hatch NF2016], [Parisi NF2020]*
- Growth rates increase with increasing n_e^{sep}/n_e^{ped}

Simulation details:

- *fully electro-magnetic,*
- *include collisions and parallel magnetic fluctuations*
- *tested a range of ballooning angles.*
- *$T_i=T_e$ has been assumed*
- *no ExB flow shear has been included.*
- *No attempt to capture ion scale k_y*

Turbulent transport in the pedestal





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- **Slab-ETG** observed at the peak *[Chapman EPS2021], [Hatch NF2016], [Parisi NF2020]*
- Growth rates increase with increasing n_e^{sep}/n_e^{ped}
- Heat flux increases with increasing n_e^{sep}/n_e^{ped}
- At high n_e^{sep}/n_e^{ped} , turbulent electron heat flux >> total neoclassical heat flux

Simulation details:

- *fully electro-magnetic,*
- *include collisions and parallel magnetic fluctuations*
- *tested a range of ballooning angles.*
- *T_i=T_e has been assumed*
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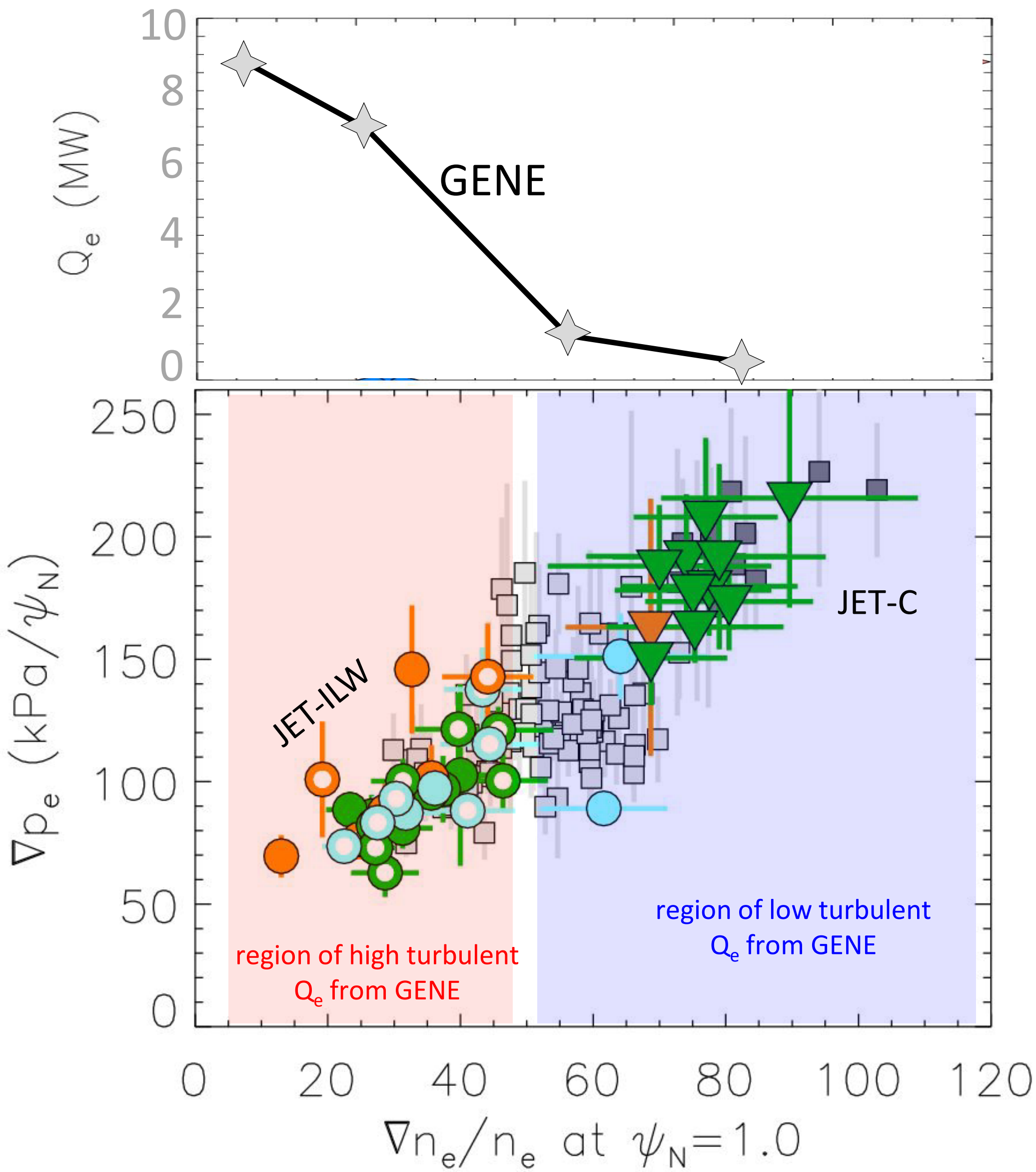
∇p_e vs $\nabla n_e/n_e$: experimental correlation

- Good experimental correlation between ∇p_e and $\nabla n_e/n_e$.
- At high n_e^{sep}/n_e^{ped} : experimental data are consistent with a reduced ∇p_e driven by increased turbulent transport



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- Working hypothesis:
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[Hatch, Kotschenreuther NF2017]

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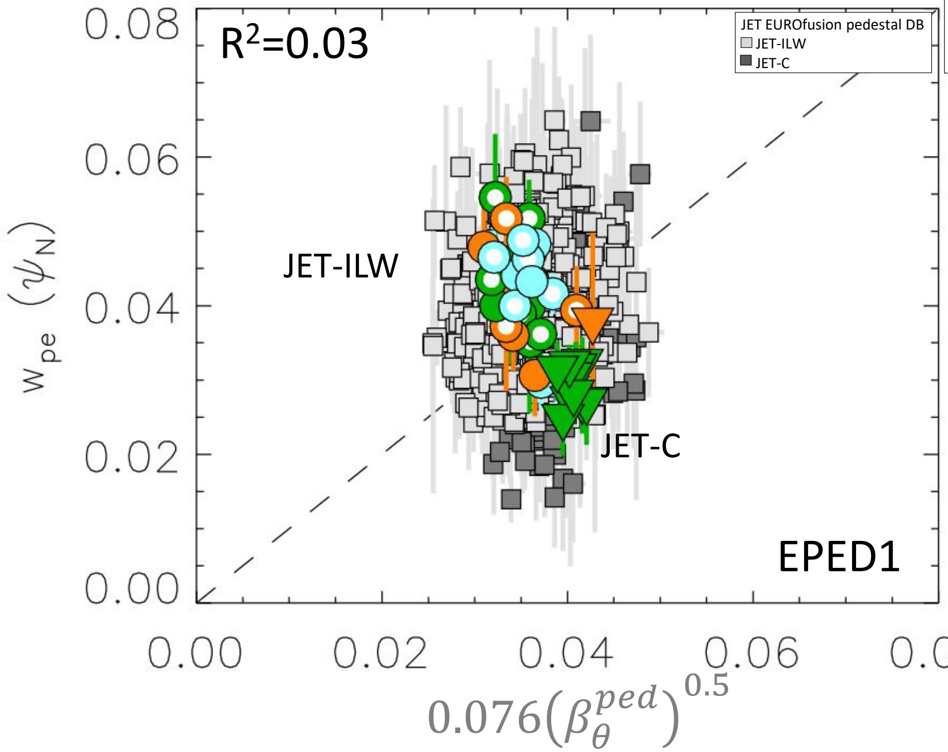
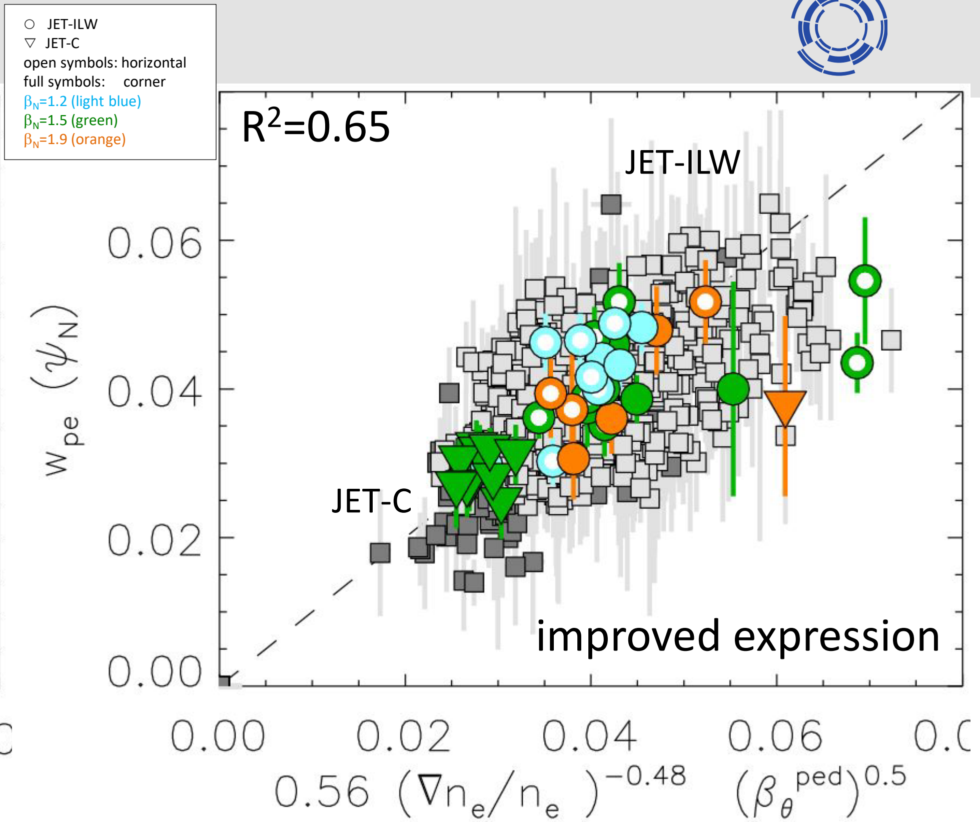
Pedestal width and transport





- w_{pe} EPED1 predictions in JET reliable only at low Γ_{D2}. *[Maggi NF2015]*
- Transport is supposed to affect the width.

→ Improved expression proposed: $$w_{pe} = 0.56\left(\frac{\nabla n_e}{n_e}\right)^{-0.48}\left(\beta_\theta^{ped}\right)^{0.5}$$

→ experimental data consistent with w_{pe} correlated with turbulent transport

- at low gas or for JET-C: $\frac{\nabla n_e}{n_e} \approx 50 - 100\ (\psi_N^{-1})$

$$\Rightarrow\ 0.56\left(\frac{\nabla n_e}{n_e}\right)^{-0.48} \approx 0.061 - 0.085$$ (consistent with 0.076, from EPED1)

What must we explain at high n_e^{sep}/n_e^{ped}?

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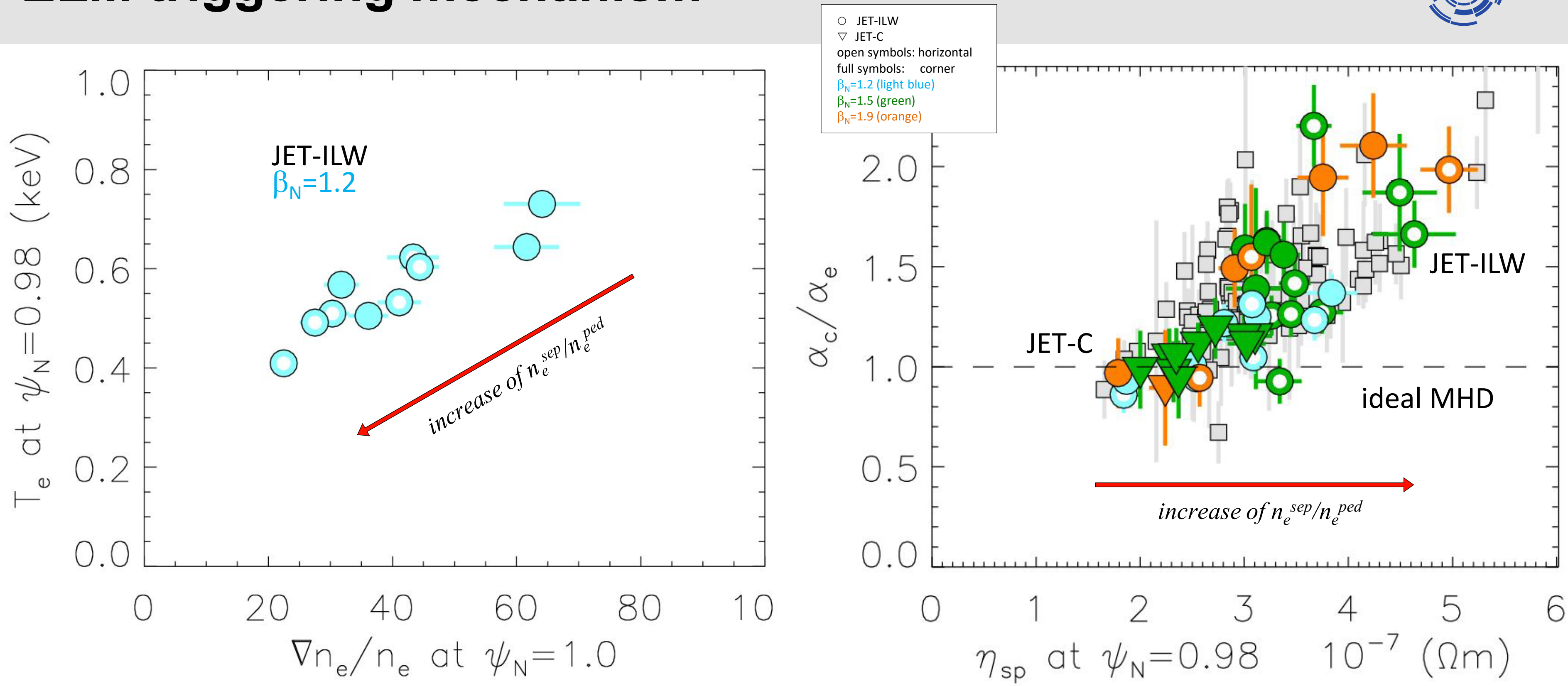
[Hatch, Kotschenreuther NF2017]

ELM triggering mechanism



- The increased transport reduces the temperature in the pedestal

→ The resistivity in the pedestal increases with increasing n_e^{sep}/n_e^{ped}

- Empirical correlation between:
  - $\alpha_{crit}/\alpha_{exp}$ (ratio between ideal MHD predicted α and experimental α)
  - resistivity

→ Resistivity MHD might be necessary to explain the ELMs trigger at high n_e^{sep}/n_e^{ped}.

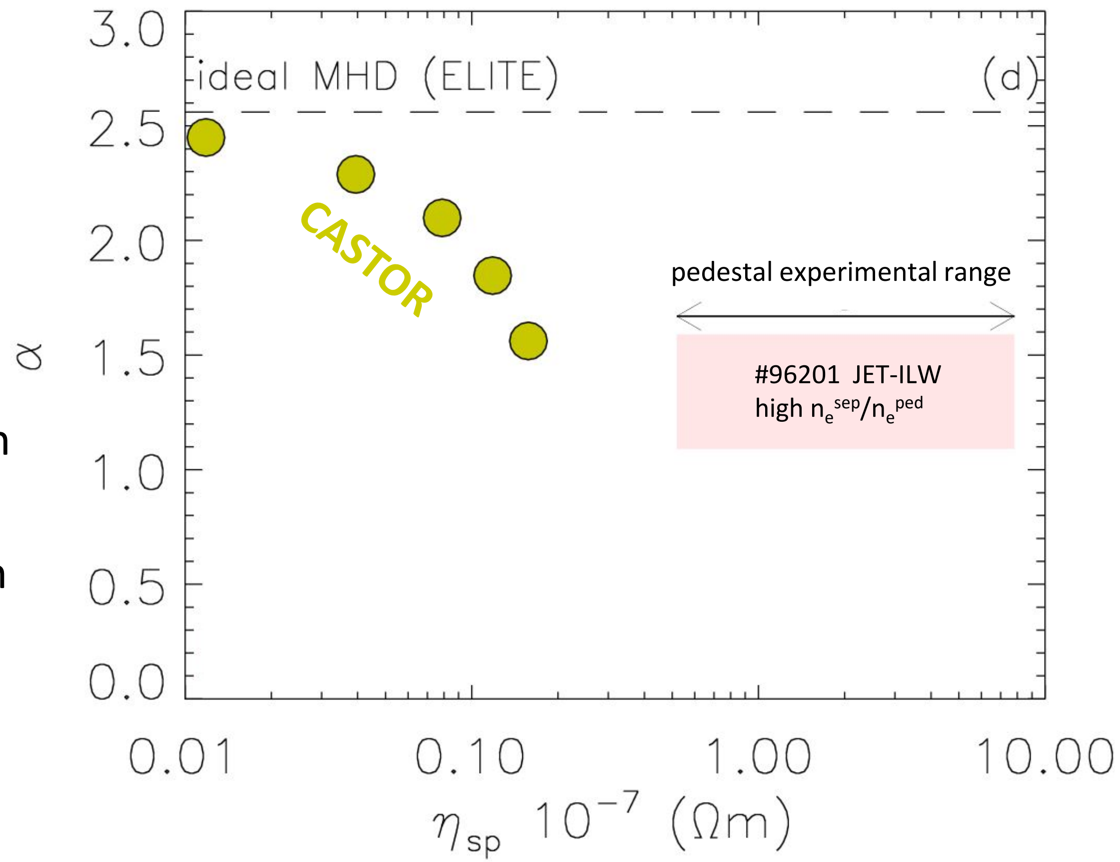
as also suggested in [*Pamela NF2017, Aiba NF2017*]

Resistive MHD: initial results

- Hypothesis tested with CASTOR

  (resisitve linear MHD code)   [Kerber JPC1998]
  - flat resistivity profile assumed
  - non-self consistent resisitivty yet
  - analysis is only at its initial stages

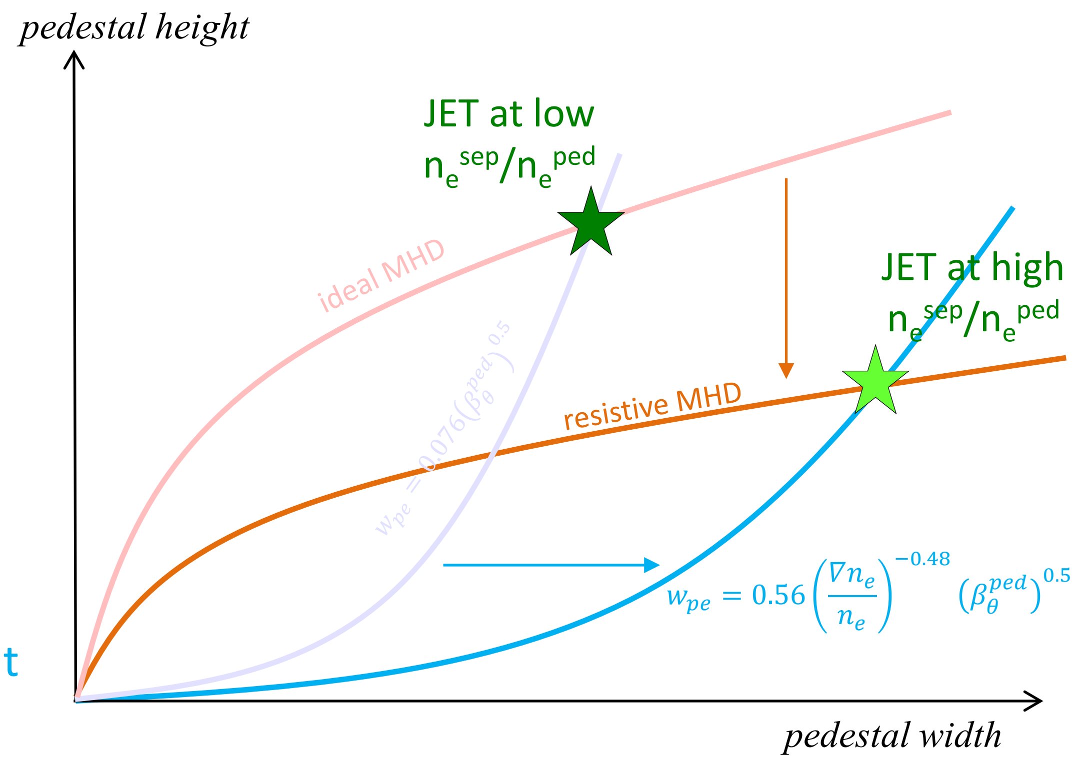
- Increasing resistivity → reduction in predicted α
- No quantitative agreement yet with experimental data



- Possible reasons for disagreement:
  - Non-realistic resisitivity profile used
  - Non self-consistent resistivity used
  - Modes destabilized by resistivity non investigated yet (are they ballooning modes? Can they trigger ELMs?)
  - Viscosity and diamagnetic term neglected

NEXT STEPS: towards improved pedestal predictions

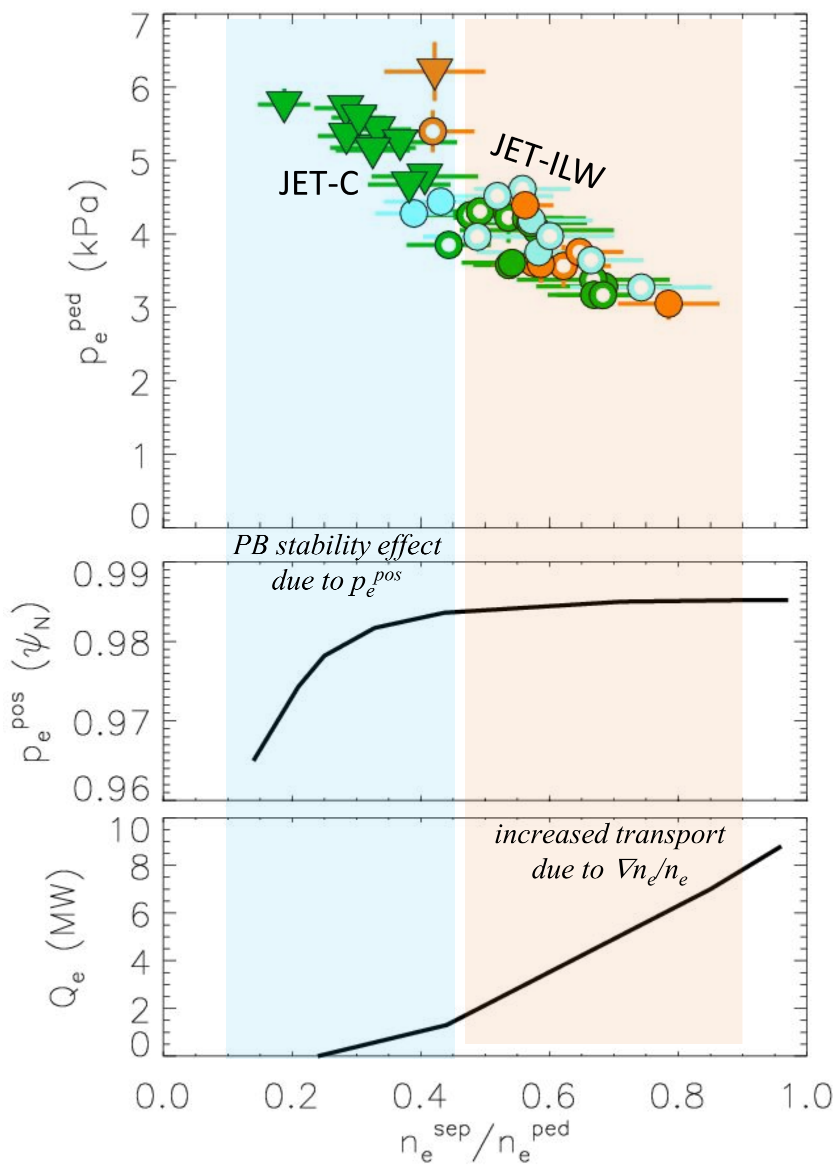
- Clarify if resistive MHD can explain the ELM triggering
  - CASTOR
  - JOREK
- Improve pedestal predictions at high n_e^{sep}/n_e^{ped}:
  - KBM transport constraint:
    $w_{pe} = 0.076(\beta_\theta^{ped})^{0.5}$
    → improved transport constraint
    $$w_{pe} = 0.56\left(\frac{\nabla n_e}{n_e}\right)^{-0.48}(\beta_\theta^{ped})^{0.5}$$
  - PB constraint
    ideal MHD
    → Resistive MHD



CONCLUSIONS

- The correlation between p_e^{ped} and n_e^{sep}/n_e^{ped} is due to two distinct mechansims:
  1. $n_e^{sep}/n_e^{ped}<0.4$
     - the increase of n_e^{sep}/n_e^{ped} shifts the pressure outwards
     - PB modes are destibilized and the p_e^{ped} decreases.
     - The effect saturates at $n_e^{sep}/n_e^{ped}\approx0.4$
  2. $n_e^{sep}/n_e^{ped}>0.4$
     - the increase of n_e^{sep}/n_e^{ped} reduces $\nabla n_e/n_e$
     - increase of turbulent transport
     - The pedestal gradients are reduced
     - Resistive MHD might be neccesary to explain the ELMs

- Extrapolation to ITER are not trivial: ITER will operate on the peeling boundary



Thank you to all co-authors

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* see J. Mailloux et al., Nuclear Fusion Special Issue IAEA 2021