PEELING LIMITED PEDESTALS IN JET-ILW, MAST-U AND TCV: EFFECT OF DENSITY AND ISOTOPE MASS IN DEUTERIUM AND TRITIUM-RICH PLASMA ON PEDESTAL STRUCTURE AND STABILITY AND VALIDATION OF PEDESTAL PREDICTIONS FOR ITER.

L. Frassinetti

KTH Royal Institute of Technology

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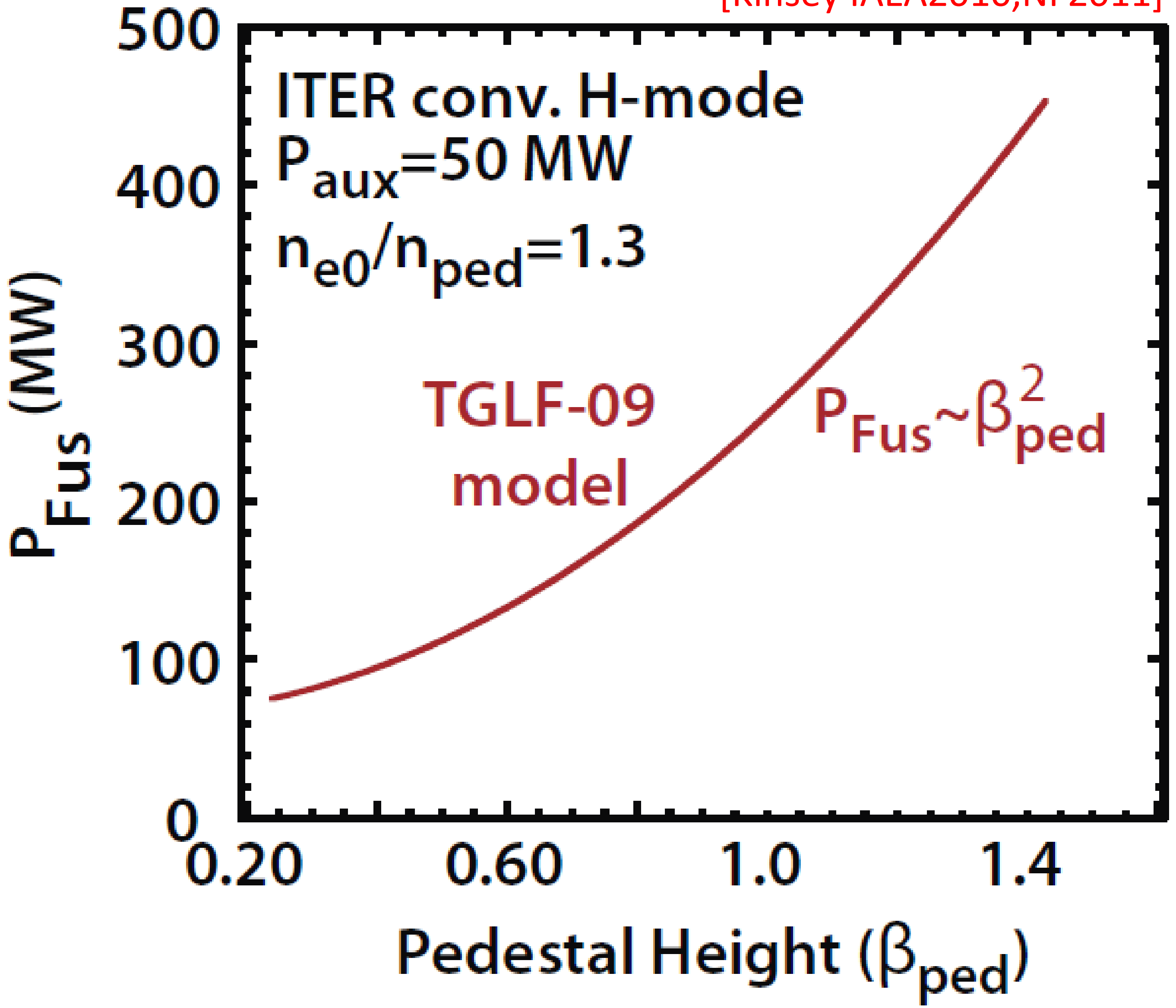
MOTIVATION

- The pedestal plays a major role for ITER:
  - fusion power will scale as

$$P_{fus} \sim \left(p^{ped}\right)^2$$

- Assessing and predicting the pedestal behavior in ITER-relevant conditions is essential

[Kinsey IAEA2010,NF2011]



MOTIVATION AND GOALS

- ITER will operate:
  - relatively high n^{ped} [Garzotti NF2019]
  - high n^{sep}/n^{ped} [Garzotti NF2019]
  - in mixed deuterium/tritium plasmas
  - with a metal wall

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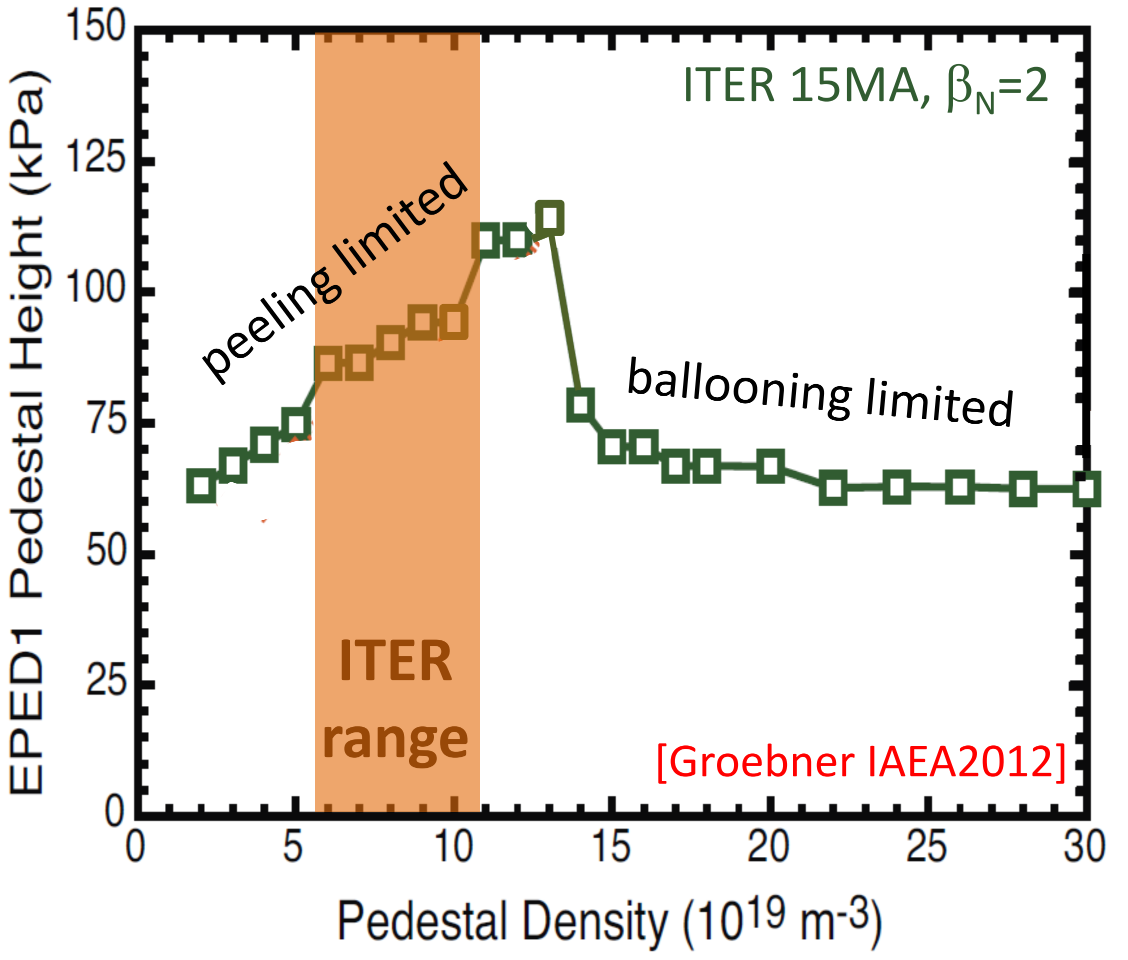

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- Earlier modelling suggests that ITER will be limited by peeling instabilities
- More recent modelling [Luda NF2025] suggests that ITER will be limited by ballooning modes
- **Goals**:
  - → reach peeling limited plasmas
  - → assess the role of density, isotope and wall material in the peeling limited pedestals
  - → validate the Europed pedestal predictions at ITER relevant ν_{ee}^{*ped}, ρ_i^{*ped}, n^{sep}/n^{ped}
  - → understand if ITER will be limited by peeling or ballooning instabilities

OUTLINE

1. Reaching peeling limited pedestals in JET-ILW, MAST-U and TCV
2. The datasets
3. Effect in peeling limited pedestals of
   - n_e^{ped} on p_e^{ped} in JET-ILW, MAST-U and TCV
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   plus corresponding pedestal predictions validation
4. Pedestal predictions in ITER
   - will ITER be limited by peeling or ballooning instabilites?
   - Is a transition from peeling to ballooning limited pedestals a problem?

   Type I ELMs are assumed→the predictions are an upper bound of ITER pedestals.

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REACHING PEELING LIMITED PEDESTALS

- Key ingredient: low ν^{*ped} → low n^{ped} and high T^{ped}

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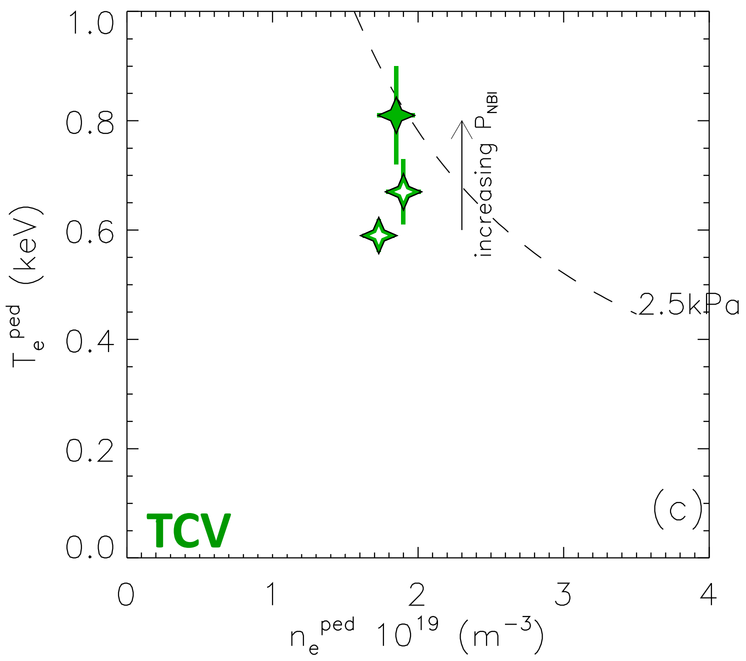

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TCV:

- high-δ (ITER relevant)
- 155kA/1.4T
- Increase power for high T^{ped}

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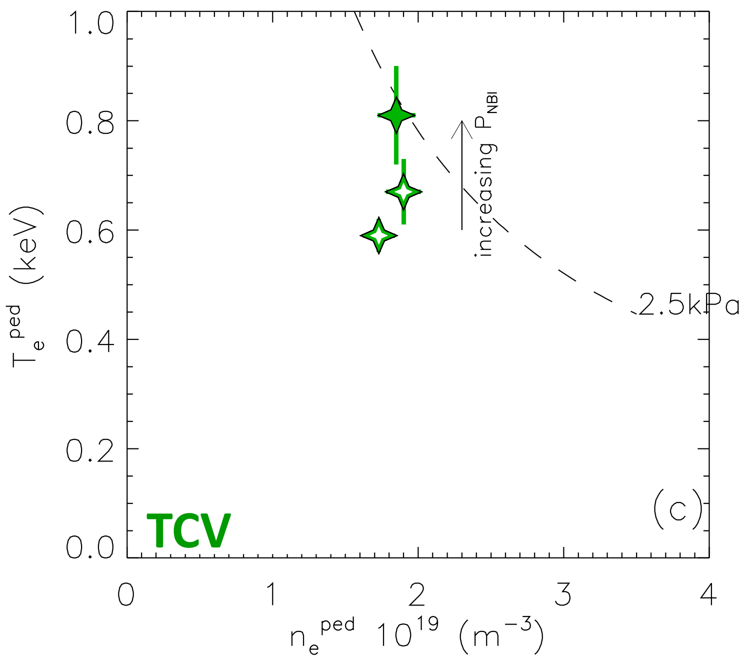

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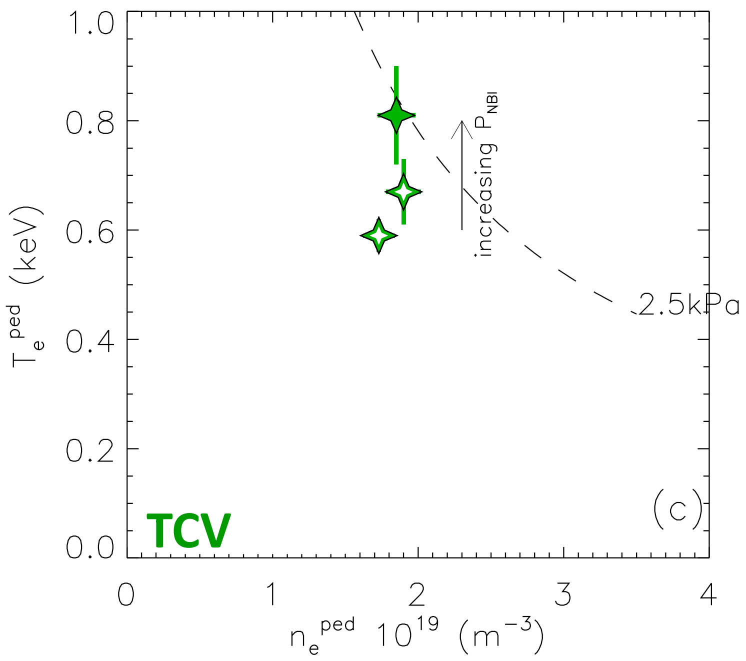

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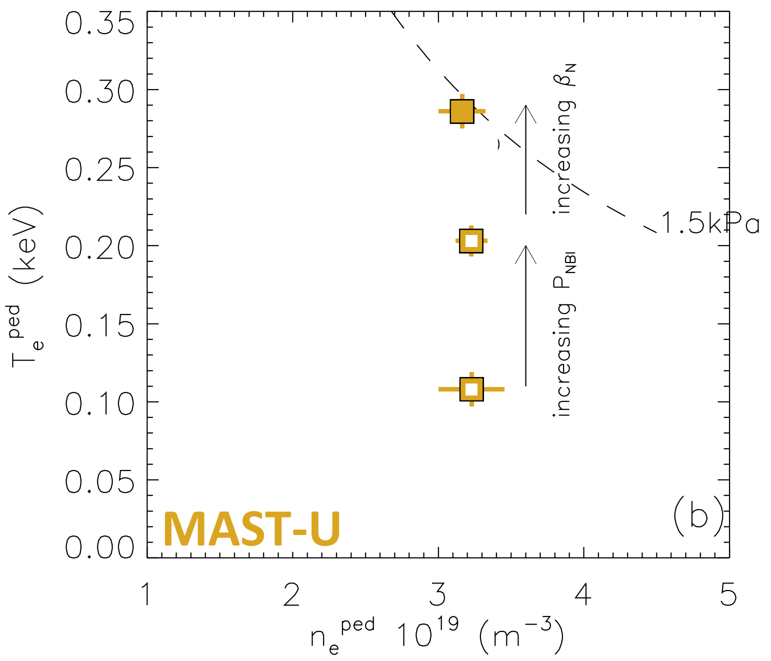

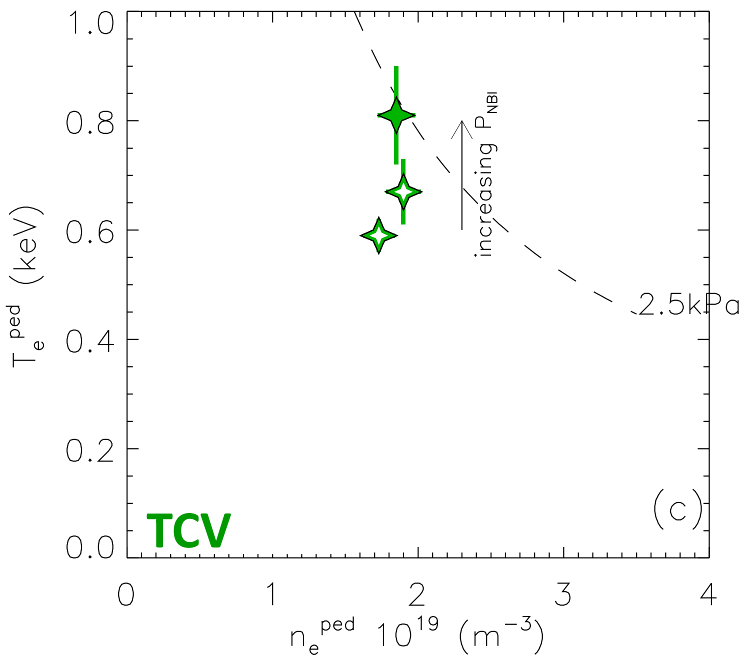

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MAST-U:
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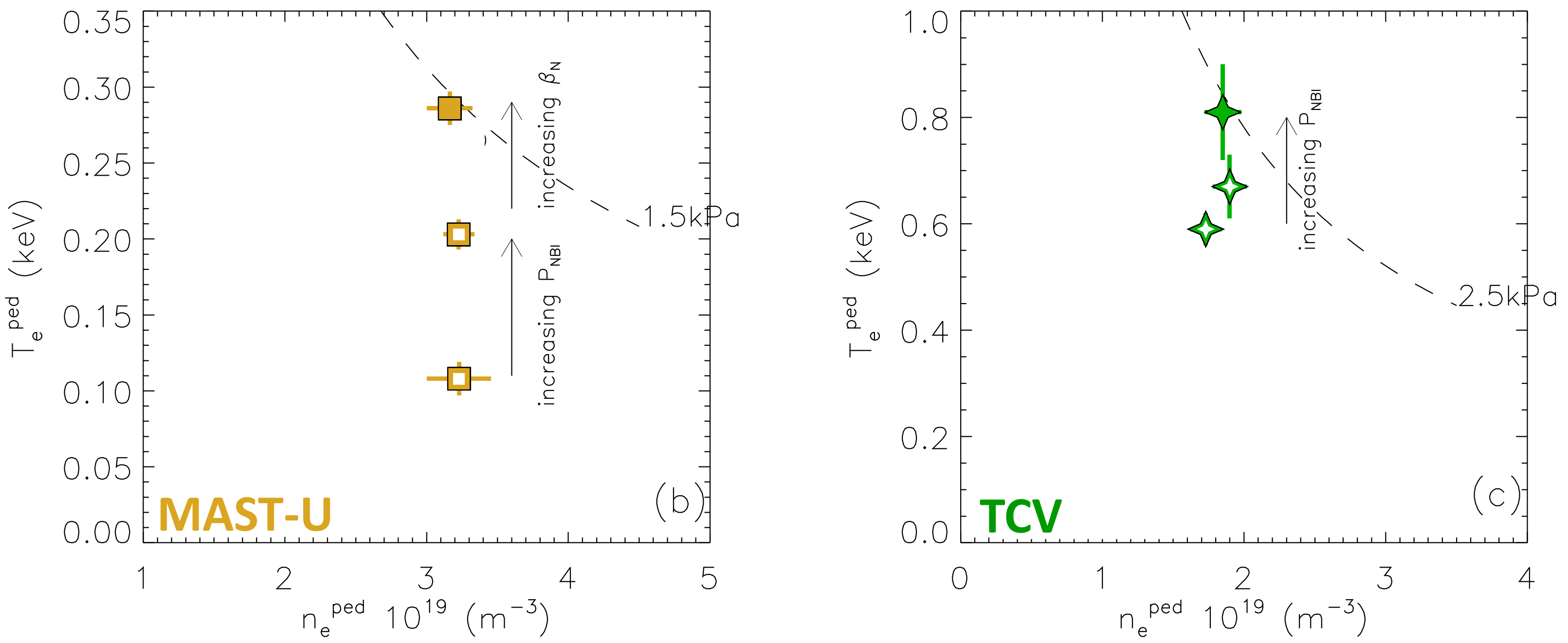

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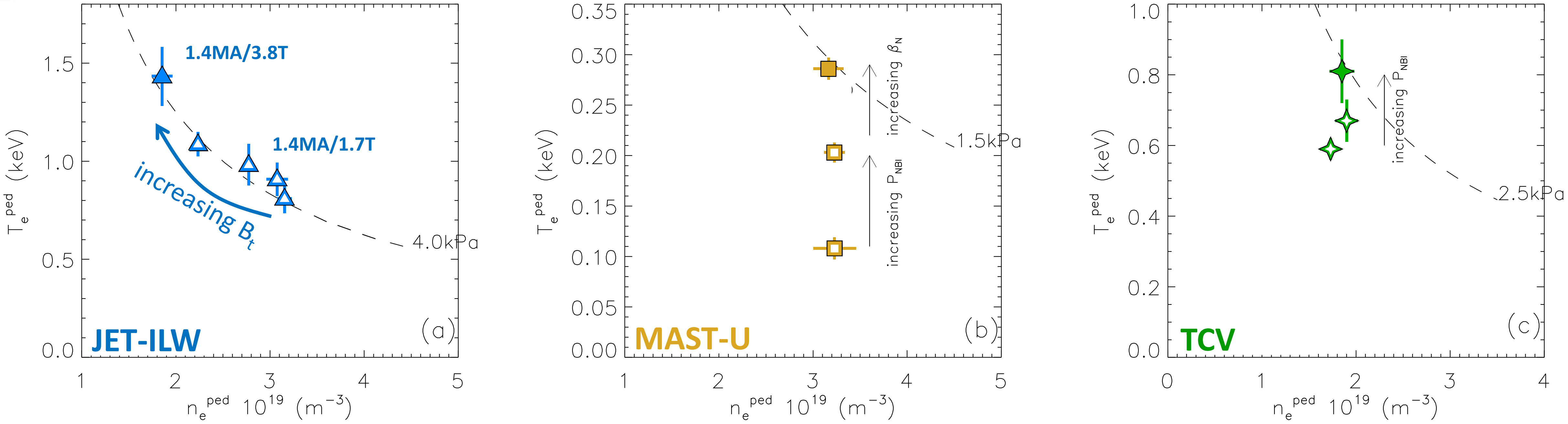

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JET-ILW:
- high-δ (ITER relevant)
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- $P_{tot} = 25MW$ (max possible power in this scenario)

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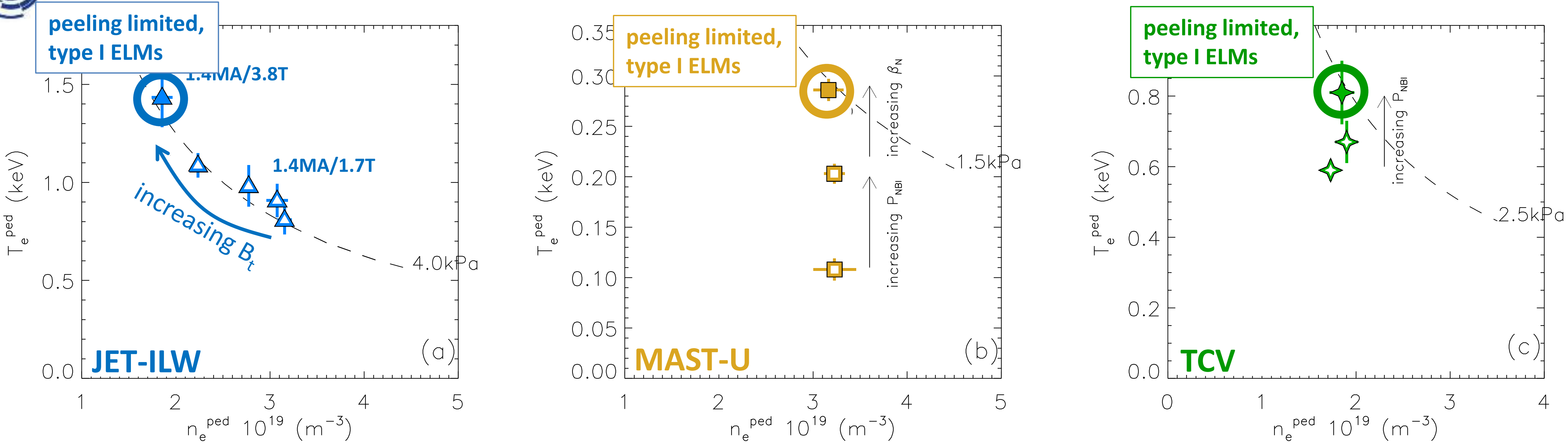

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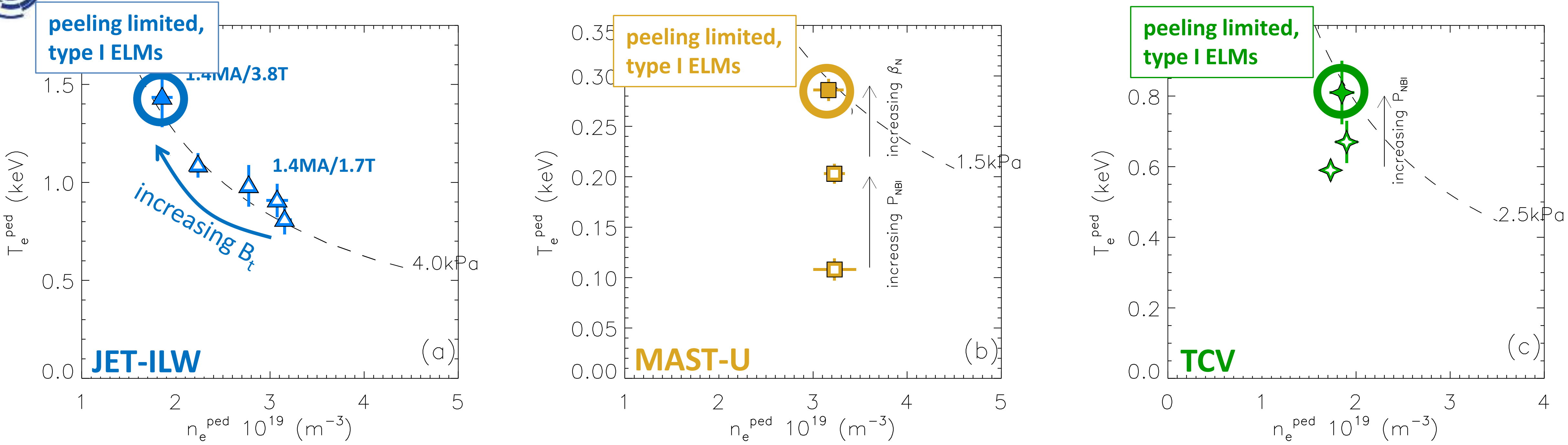

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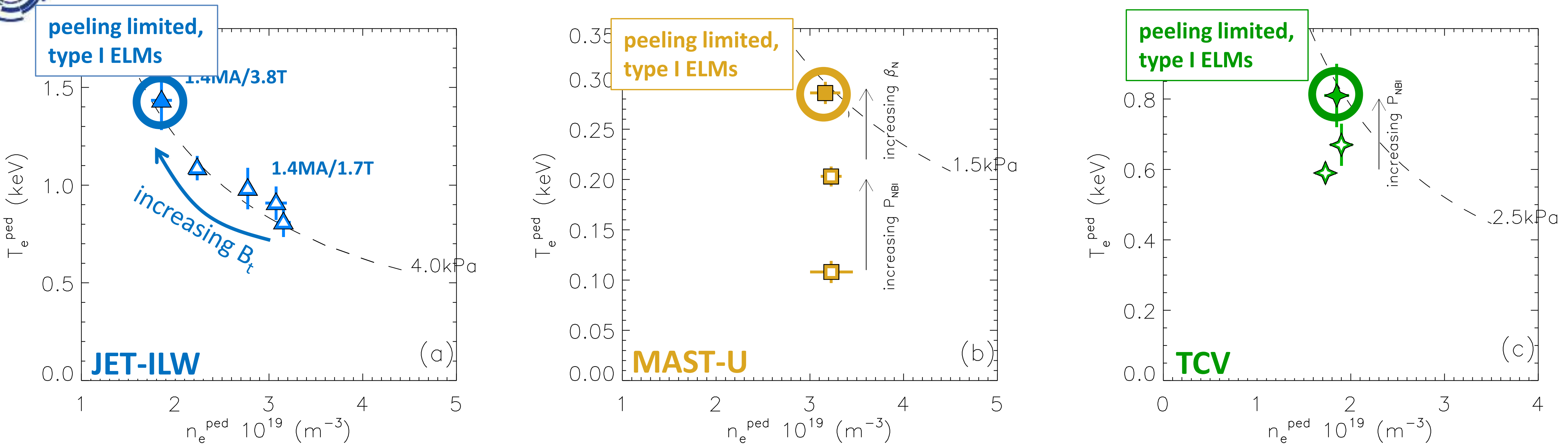

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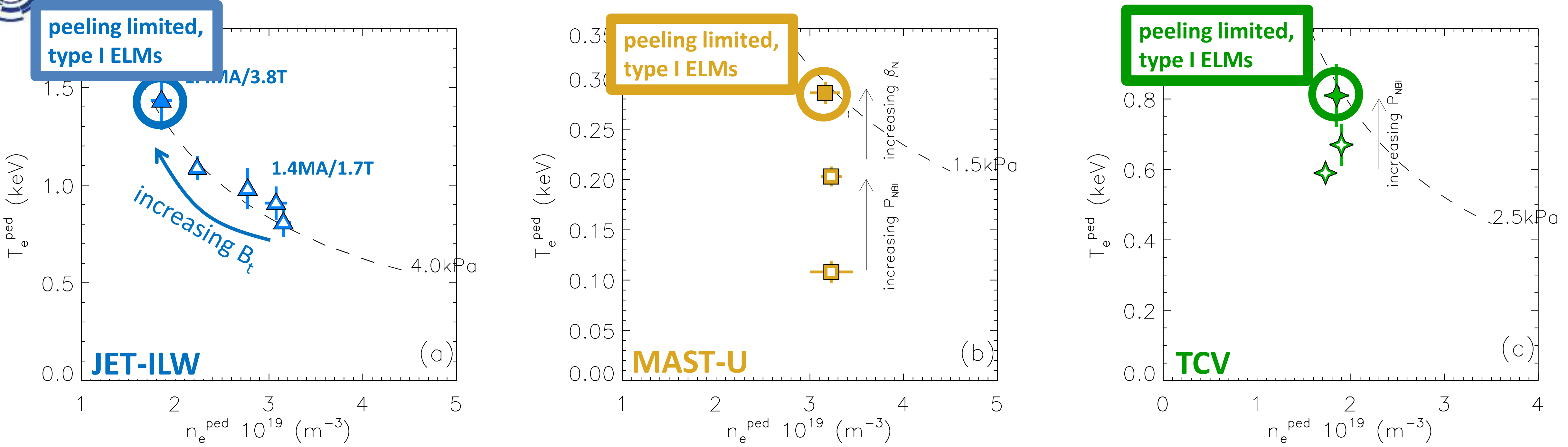

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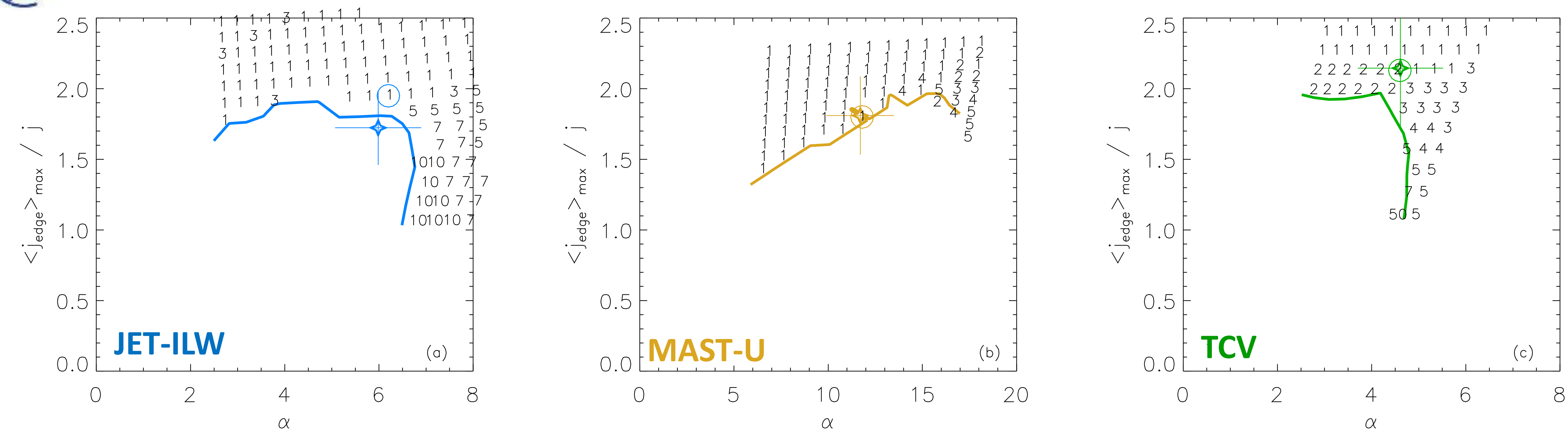
PEELING LIMITED PEDESTALS REACHED IN JET-ILW, MAST-U AND TCV



JET-ILW:

- Pedestal:
  - near the peeling boundary
  - limited by low-n modes

MAST-U:

- Pedestal:
  - at the peeling boundary
  - limited by low-n modes

TCV:

- Pedestal:
  - at the corner
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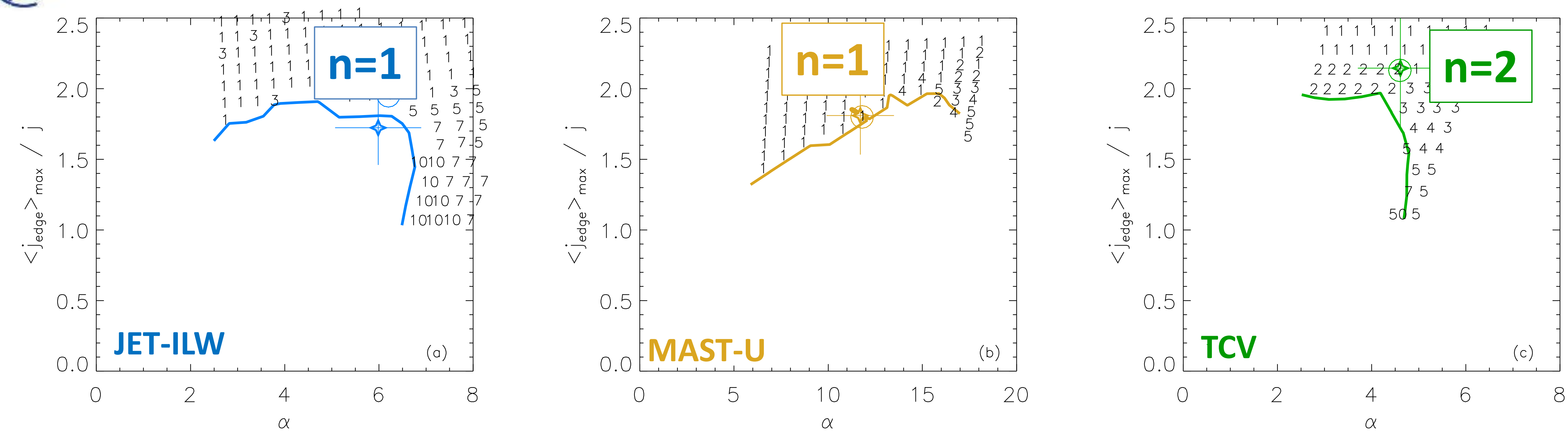
HELENA for equilibrium and MISHKA for the stability (with diamagnetic criterion)

PEELING LIMITED PEDESTALS REACHED IN JET-ILW, MAST-U AND TCV



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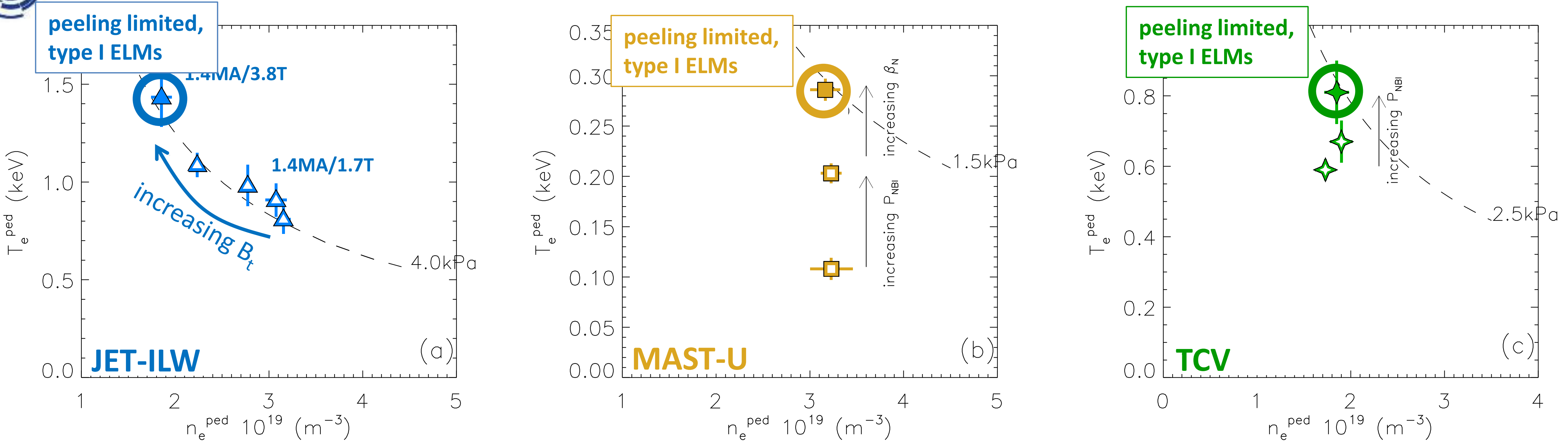

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   - n_e^{sep}/n_e^{ped} on p_e^{ped} in peeling limited pedestals in JET-ILW, MAST-U and TCV
   - the isotope mass in peeling limited pedestals in JET-ILW
   - and corresponding pedestal predictions with Europed
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   - Is a transition from peeling to ballooning limited pedestals a problem?

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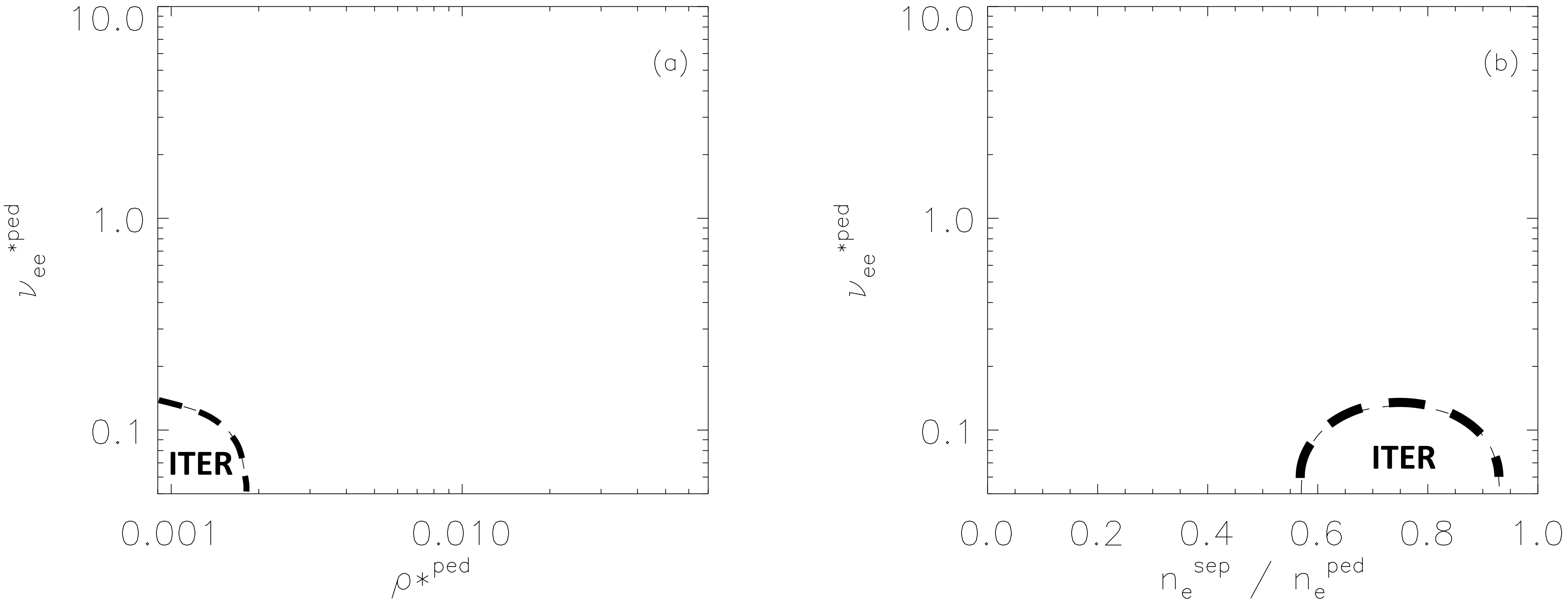

JET-ILW:

- $\langle\delta\rangle$=0.4
- 1.4MA/3.8T, $q_{95} = 8.5$
- $P_{NBI} = 25MW$

MAST-U:

- $\langle\delta\rangle$=0.5
- 750kA/0.5T, $q_{95} = 6.7$
- $P_{NBI} = 3.2MW$

TCV:

- $\langle\delta\rangle$=0.5
- 155kA/1.4T , $q_{95} = 5.0$
- $P_{NBI} + P_{ECRH} = 1.0 + 1.1MW$

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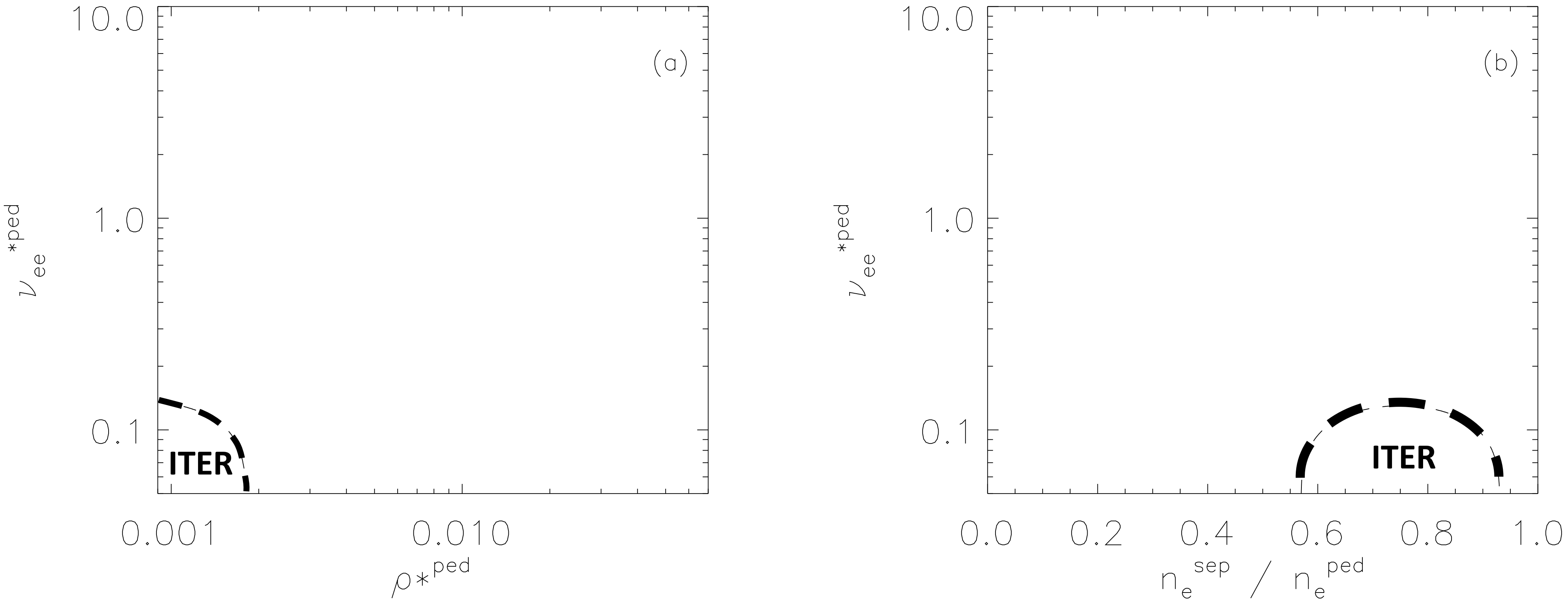

JET-ILW:
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- **Gas scan**

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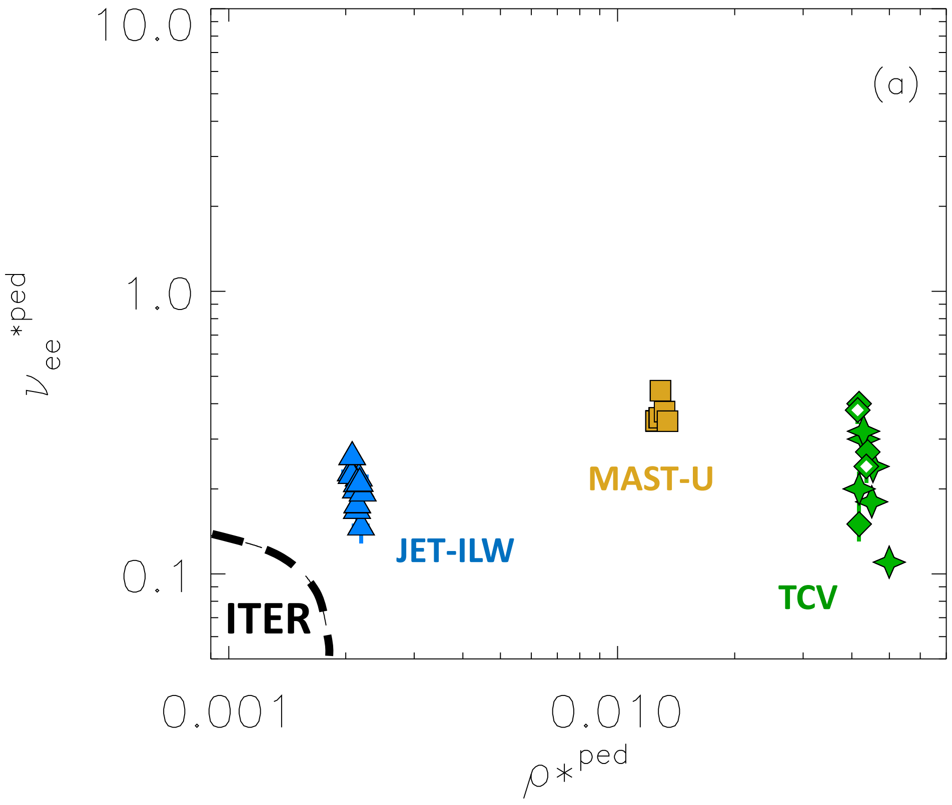
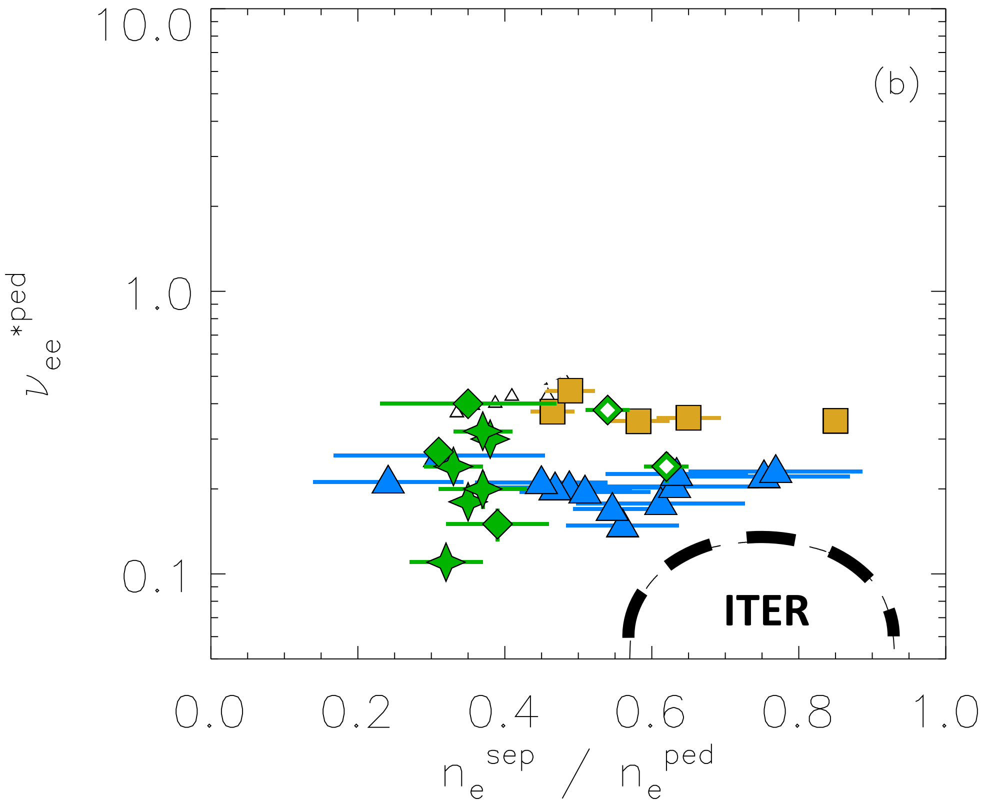
THE DATASETS: ITER ranges approached for JET-ILW





JET-ILW:

- $\langle\delta\rangle$=0.4
- 1.4MA/3.8T, $q_{95} = 8.5$
- $P_{NBI} = 25MW$
- Gas scan

MAST-U:

- $\langle\delta\rangle$=0.5
- 750kA/0.5T, $q_{95} = 6.7$
- $P_{NBI} = 3.2MW$
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TCV:

- $\langle\delta\rangle$=0.5
- 155kA/1.4T
- $P_{NBI} + P_{ECRH} = 1.0 + 1.1MW$
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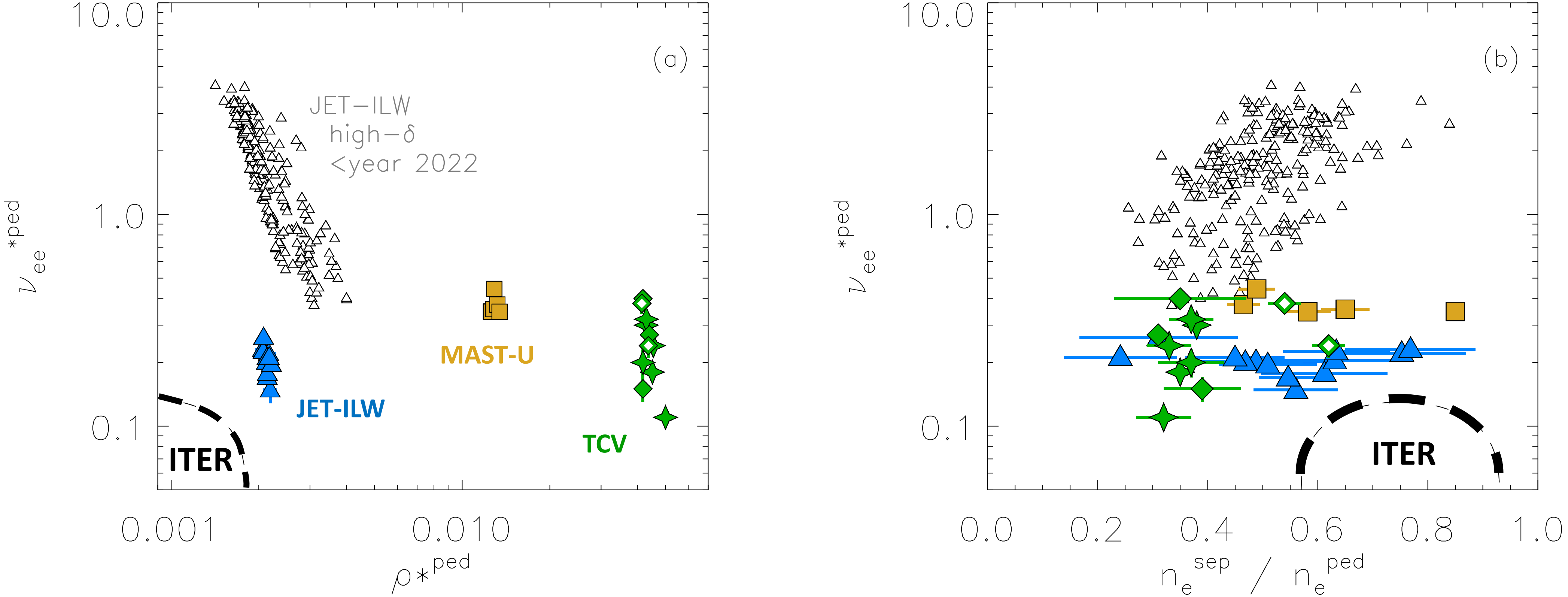
→ **approached ITER ν_{ee}^{*ped}, ρ_i^{*ped}, n^{sep}/n^{ped}**

THE DATASETS: ITER ranges approached for JET-ILW



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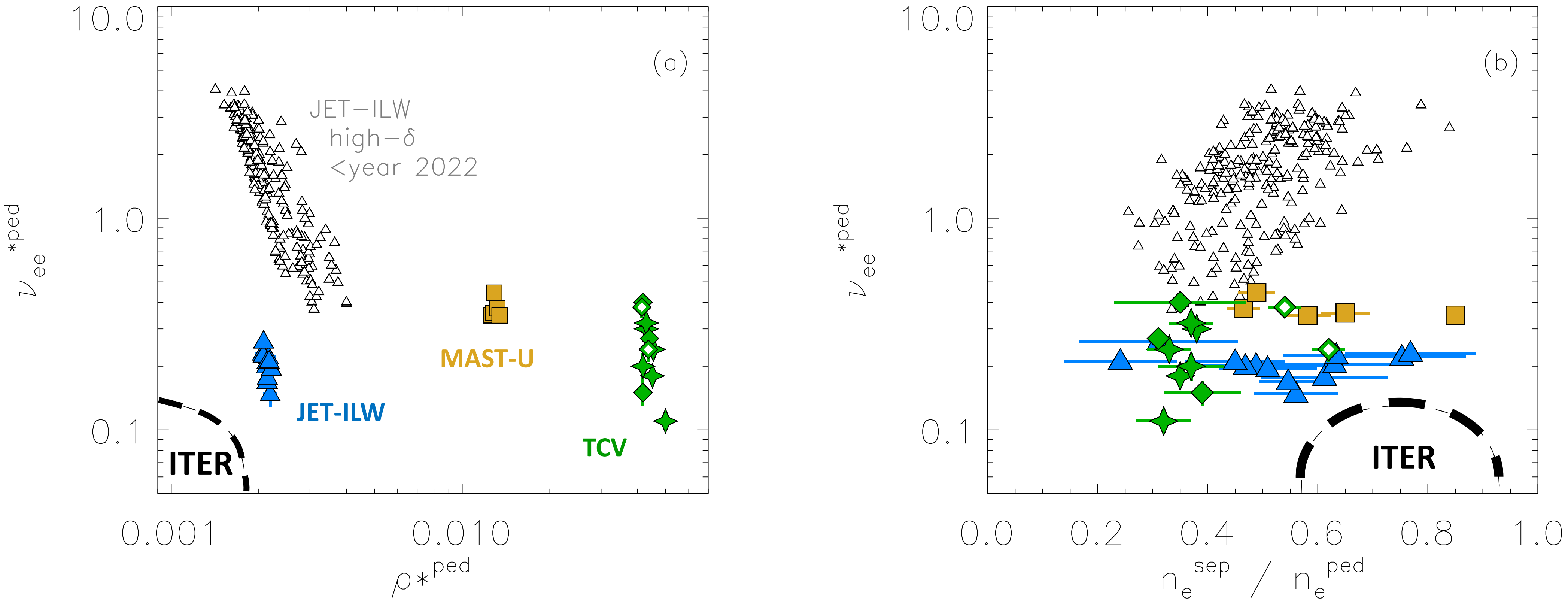

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approaching ITER ν_{ee}^{*ped}, ρ_i^{*ped}

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OUTLINE

1. Reaching peeling limited pedestals in JET-ILW, MAST-U and TCV
2. The datasets
3. **Effect of**
   - $\boldsymbol{n_e^{ped}}$ **on** $\boldsymbol{p_e^{ped}}$ **in peeling limited pedestals in JET-ILW, MAST-U and TCV**
   - n_e^{sep}/n_e^{ped} on p_e^{ped} in peeling limited pedestals in JET-ILW, MAST-U and TCV
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   - **and corresponding pedestal predictions with Europed**
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   - will ITER be limited by peeling or ballooning instabilites?
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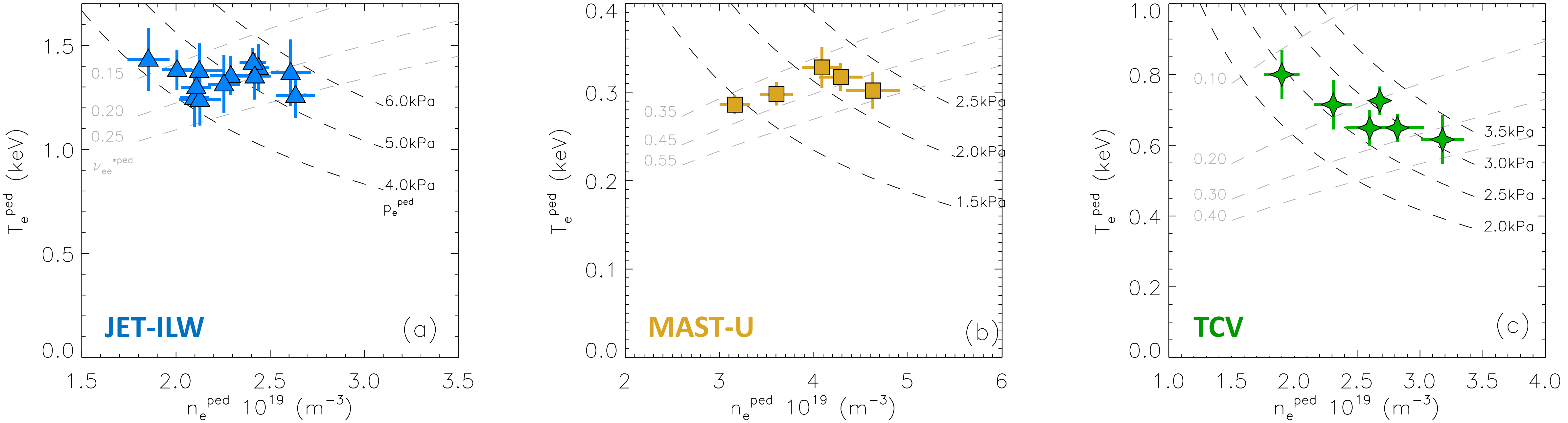
Pedestal pressure increases with increasing n_e^{ped}



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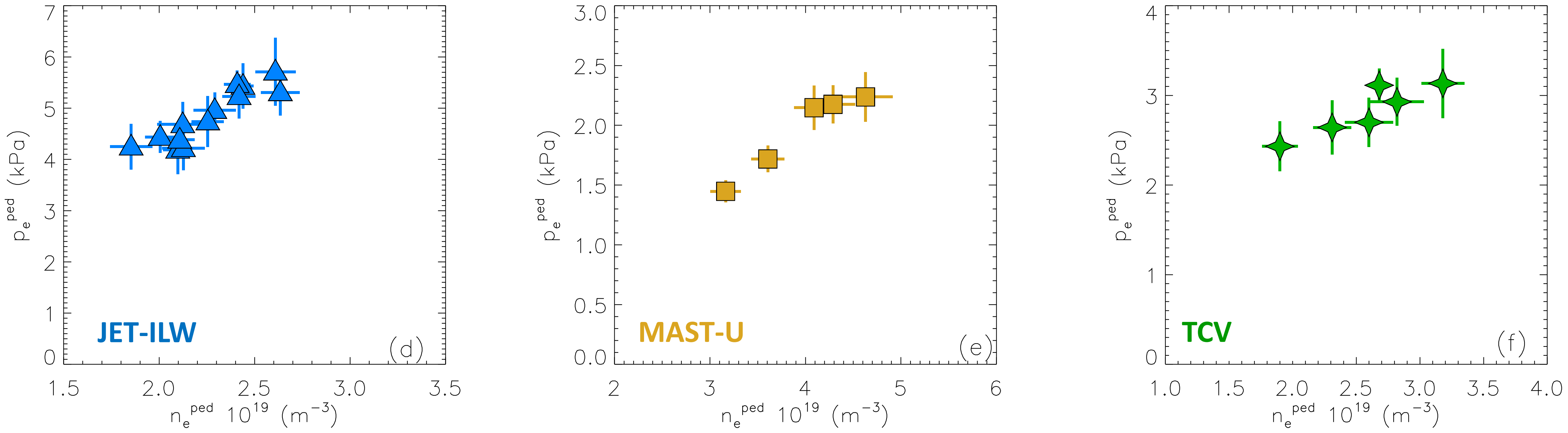

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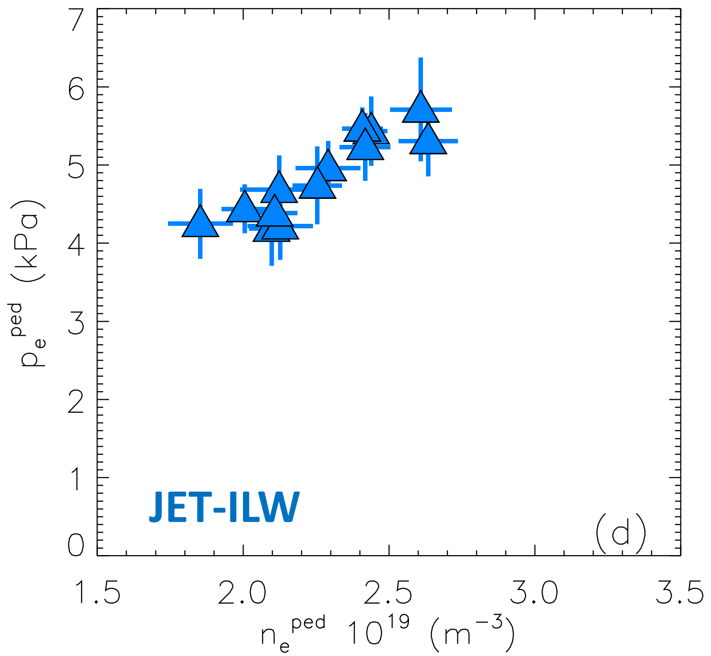

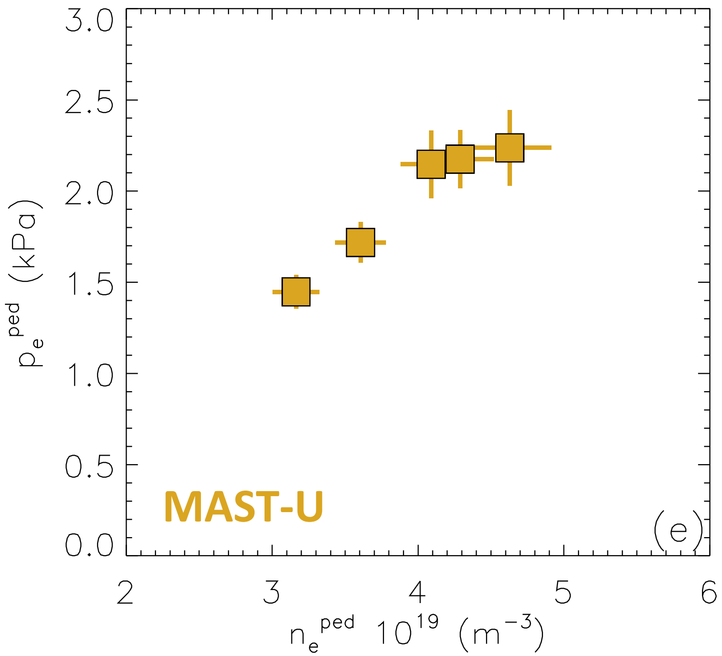

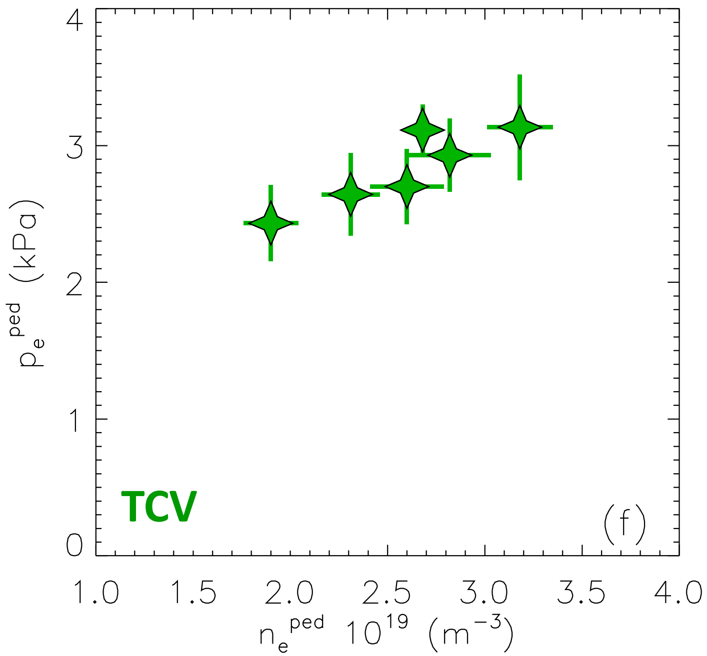

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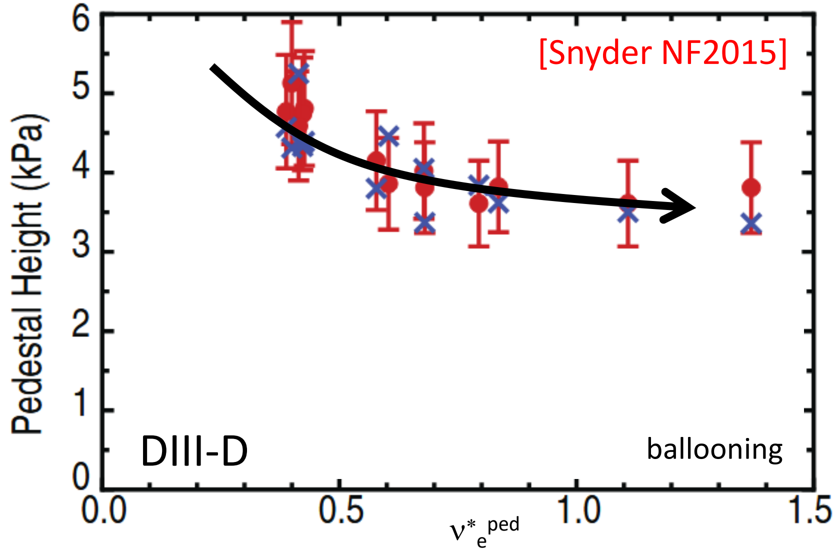

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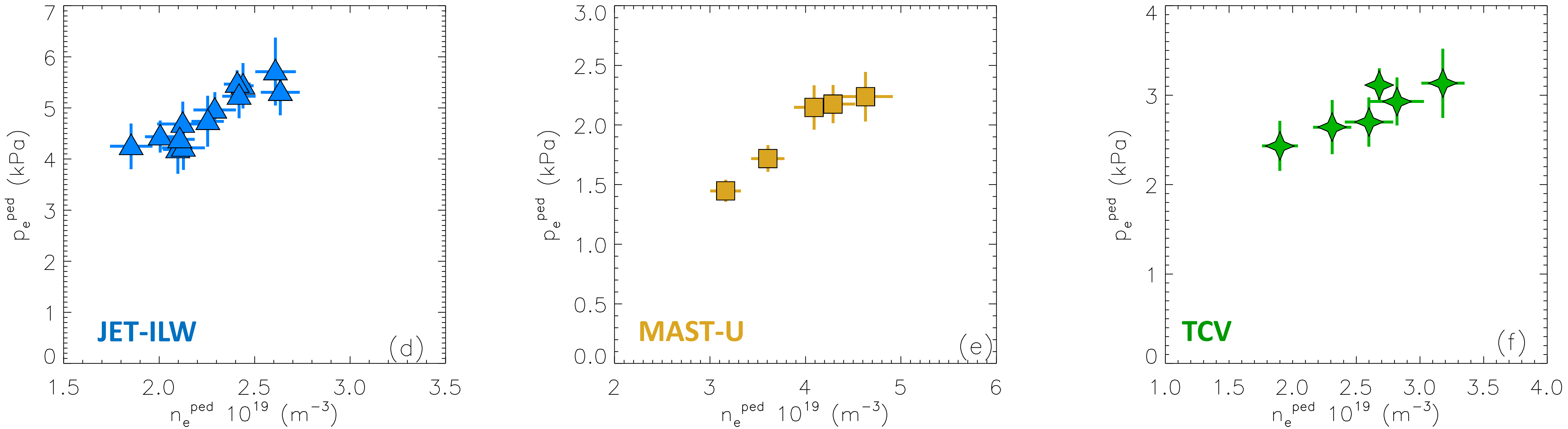

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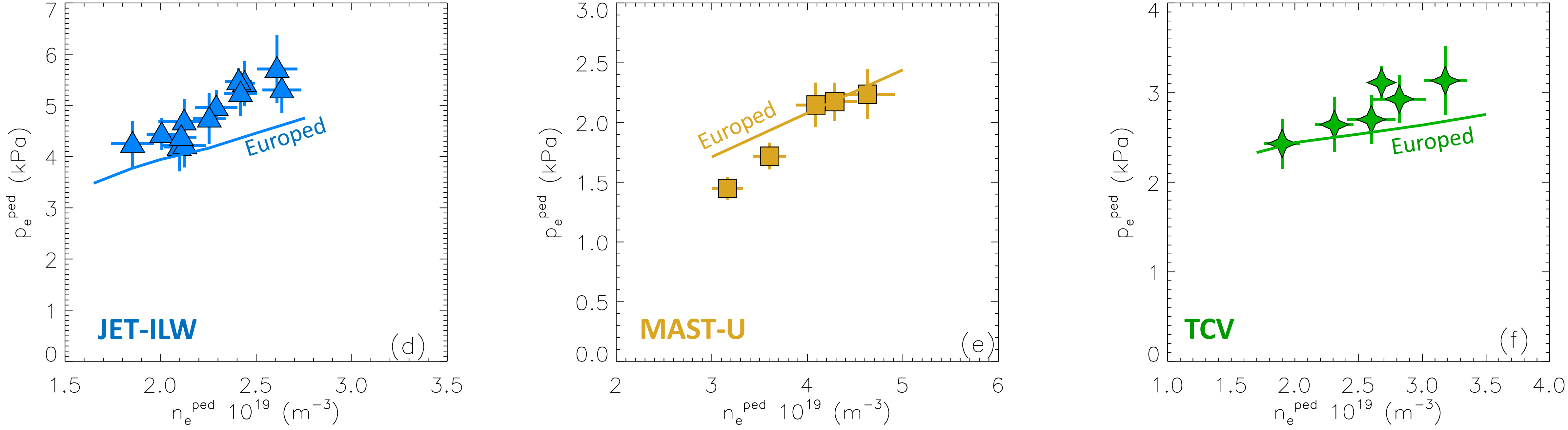

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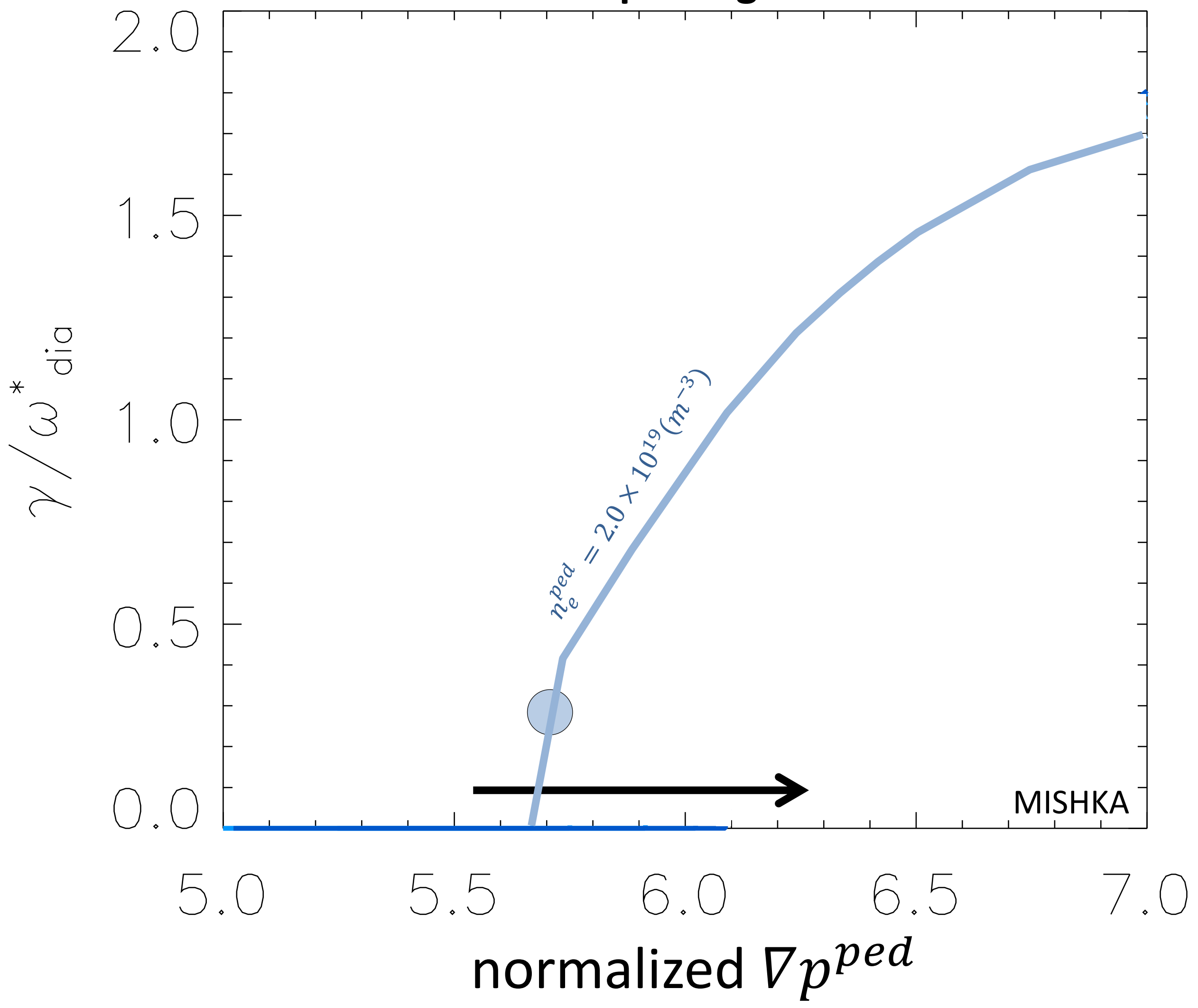
  - Good qualitative agreement in all three machines

Increasing n_e^{ped} stabilizes peeling modes

- The increase of density stabilizes peeling modes

  [Snyder PPCF2004], [Frassinetti NF2025]

JET-ILW example
n=2 peeling mode



Increasing n_e^{ped} stabilizes peeling modes

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  → ∇p^{ped} that triggers the peeling instability increases with increasing n_e^{ped}

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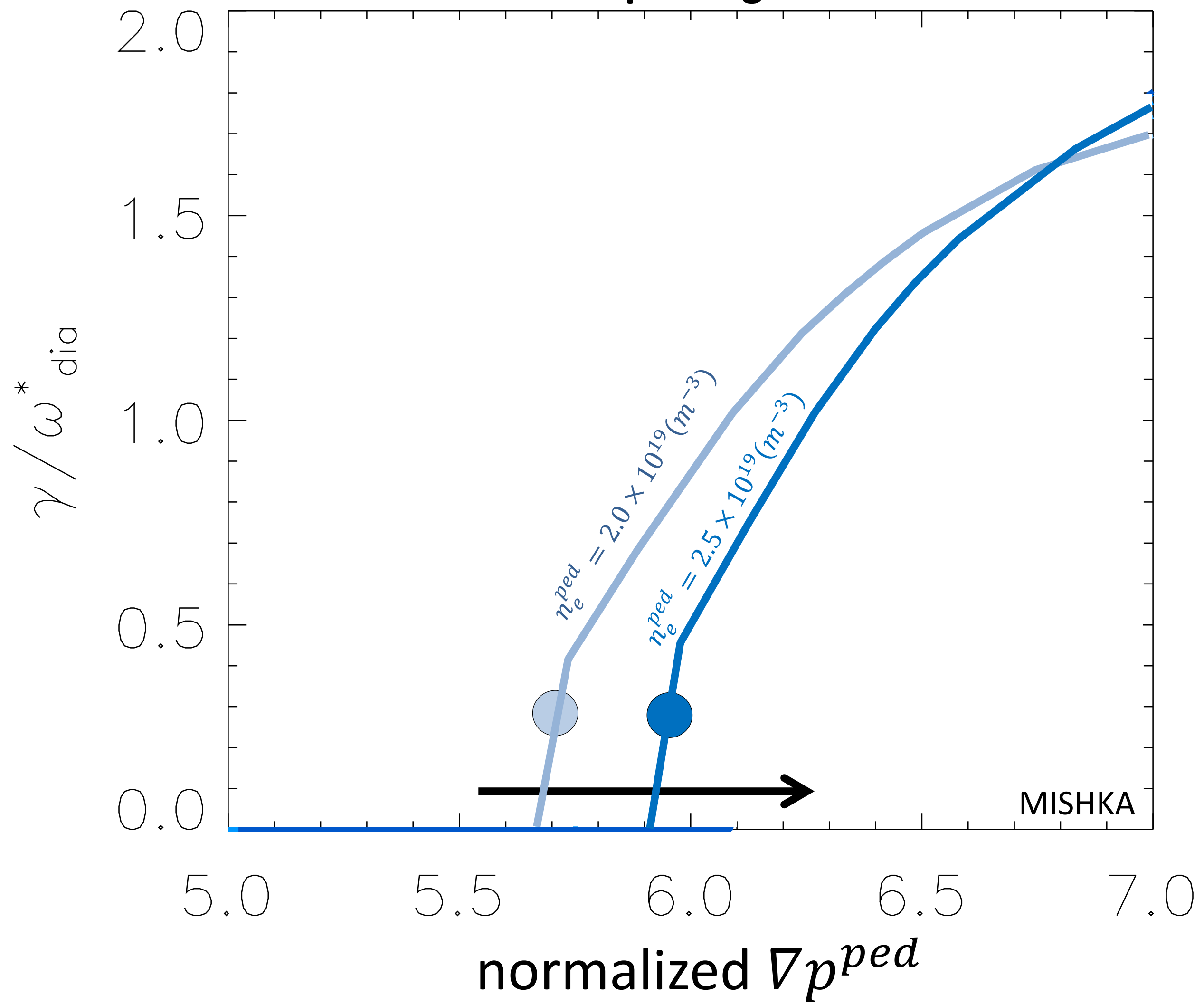

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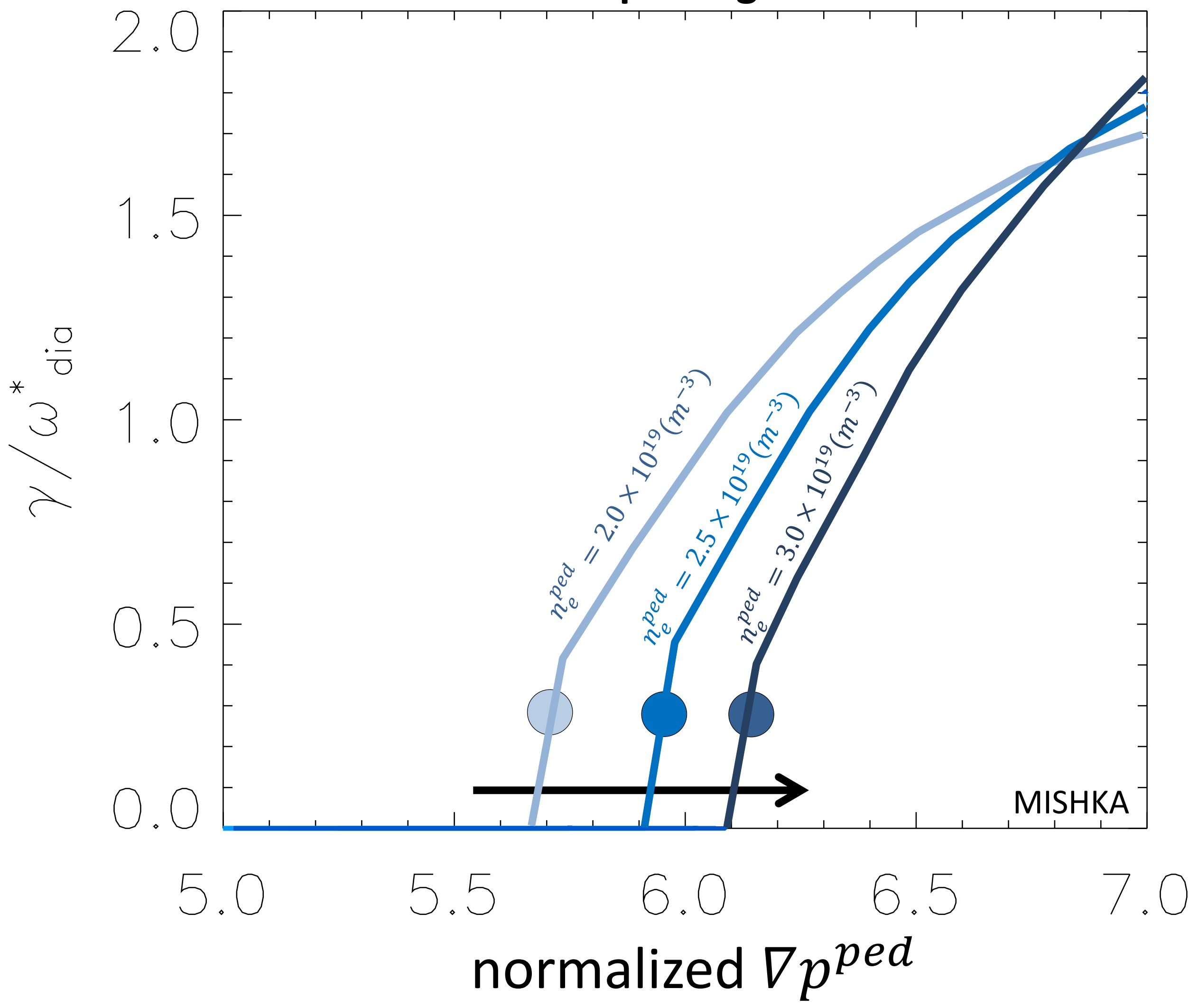
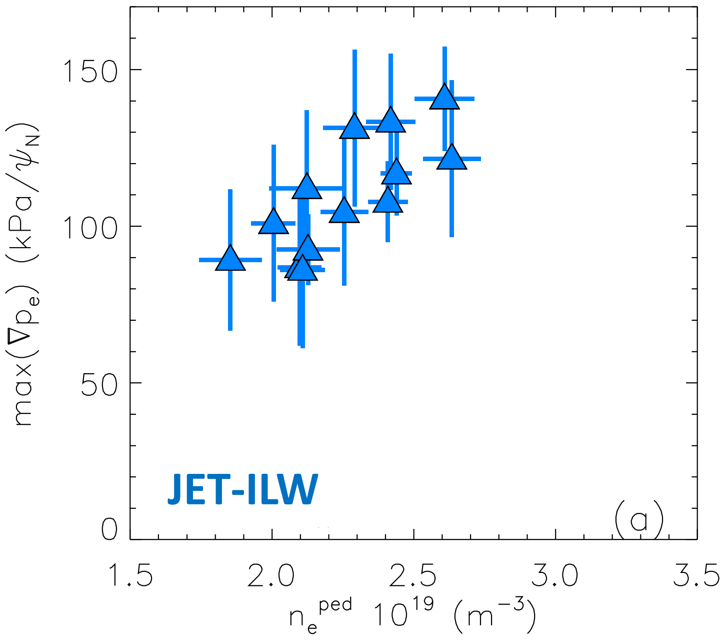
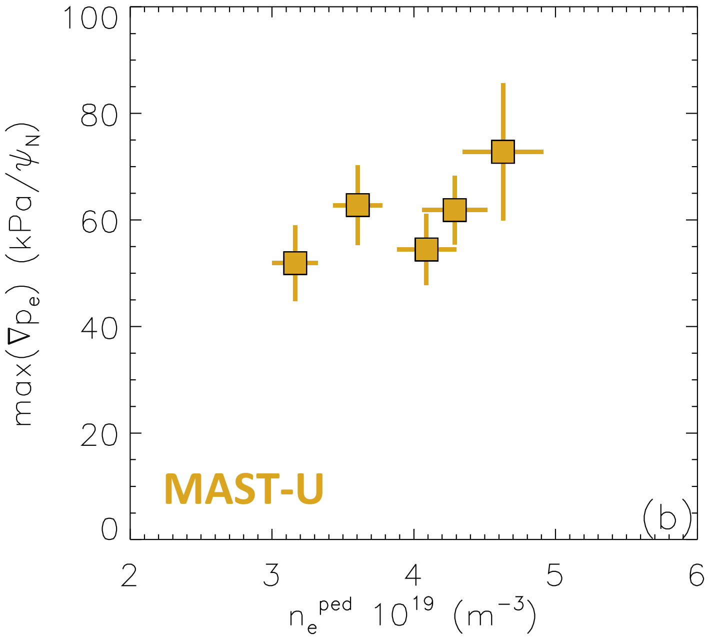


Reasonable predictions approaching ITER ν^{*ped}, ρ^{*ped}





JET-ILW:

The increase in p_e^{ped} is due to:

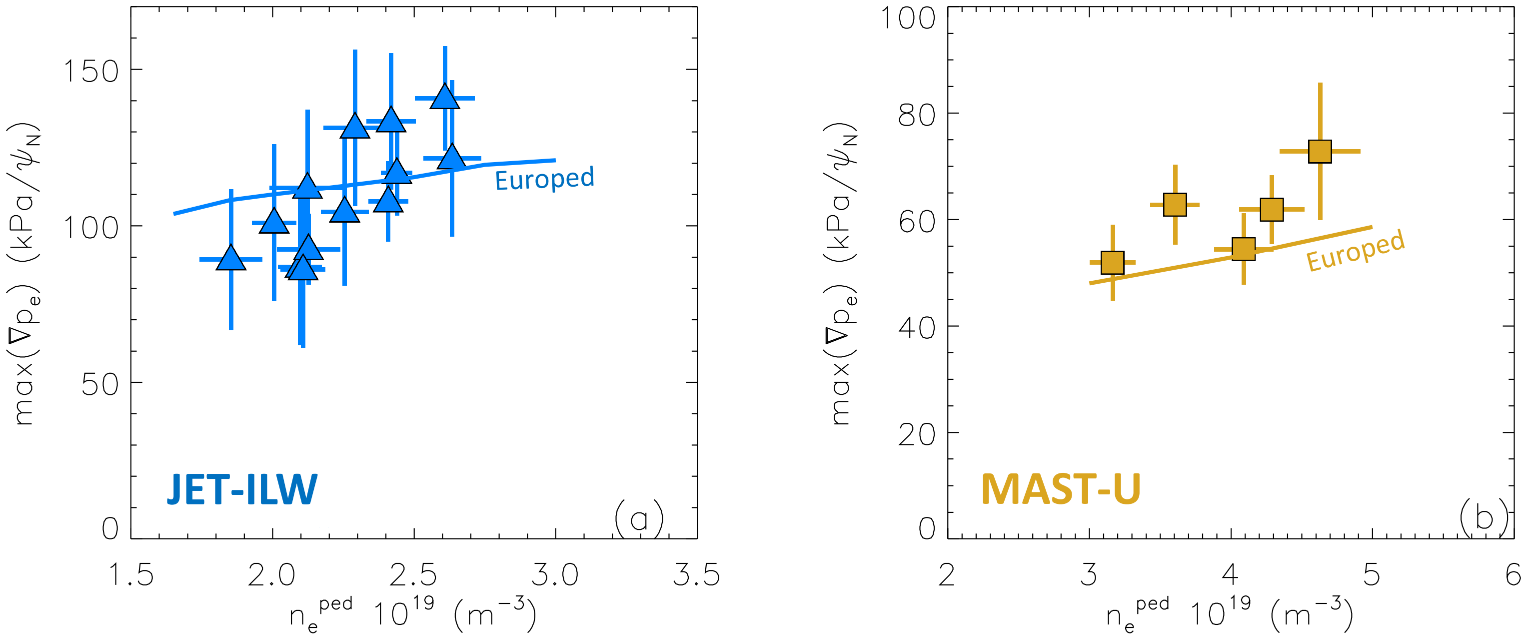
- the increase in the gradient

MAST-U:

The increase in p_e^{ped} is due to:

- the increase in the gradient

Reasonable predictions approaching ITER ν^{*ped}, ρ^{*ped}



JET-ILW:

The increase in p_e^{ped} is due to:

- the increase in the gradient
  - effect due to the stabilization of peeling modes

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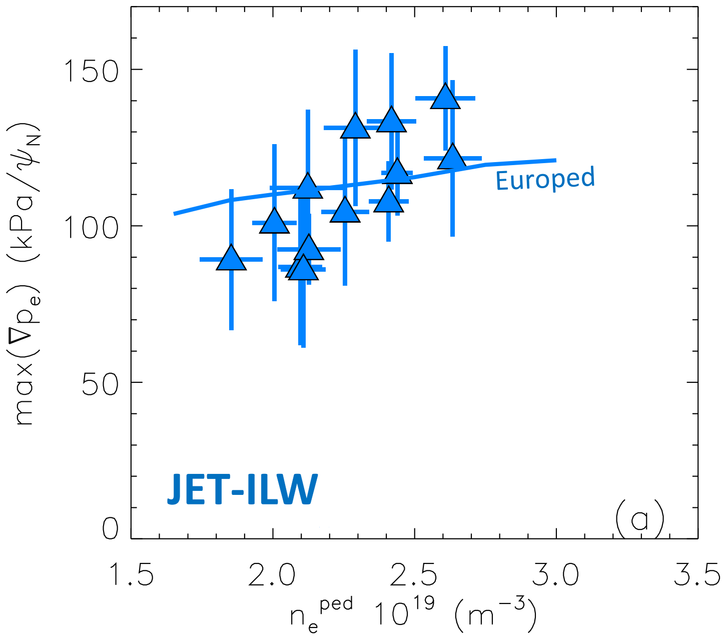

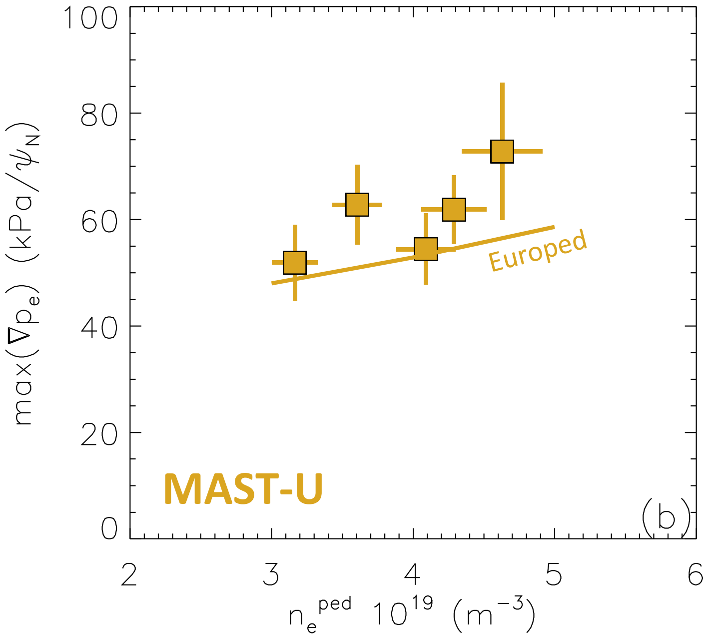

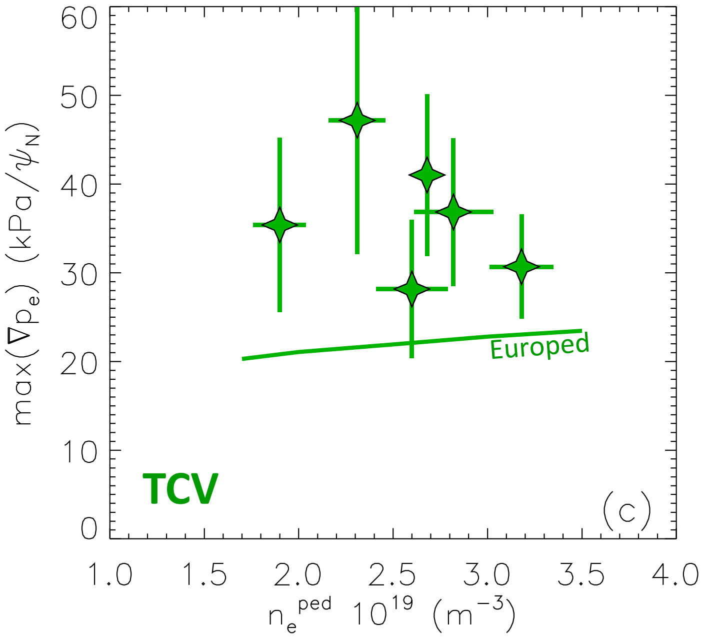

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TCV:

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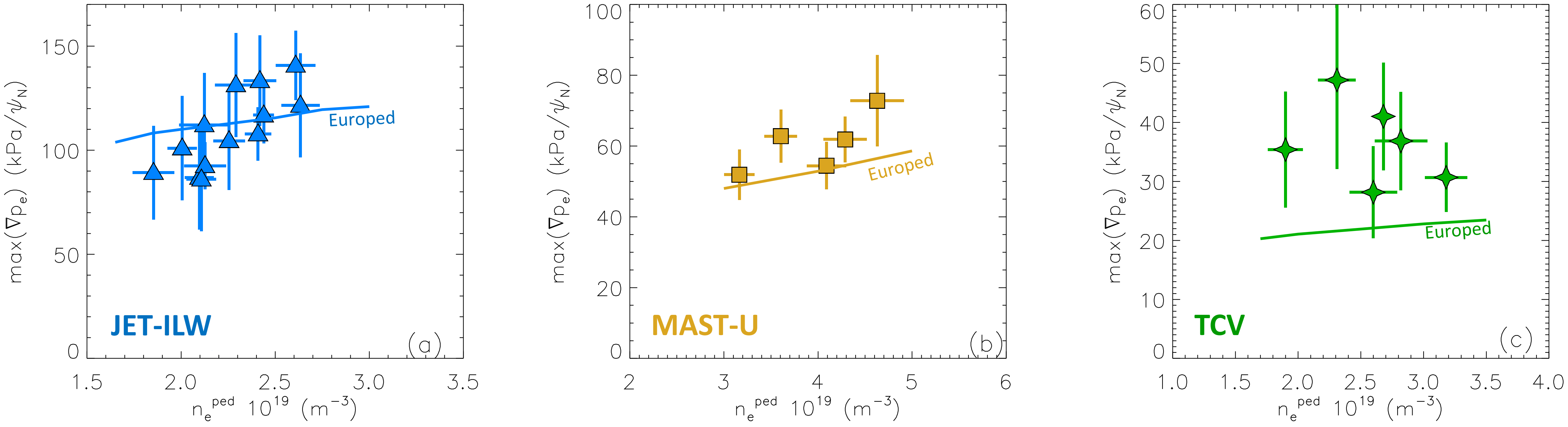

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approaching ITER ν_{ee}^{*ped}, ρ_i^{*ped}

JET-ILW:

- Good qualitative agreement with Europed
- Good understanding

MAST-U:

- Good qualitative agreement with Europed
- Good understanding

TCV:

- No reasonable agreement with Europed
- No good understanding yet

OUTLINE

1. Reaching peeling limited pedestals in JET-ILW, MAST-U and TCV
2. The datasets
3. **Effect of**
   - n_e^{ped} on p_e^{ped} in peeling limited pedestals in JET-ILW, MAST-U and TCV
   - **n_e^{sep}/n_e^{ped} on p_e^{ped} in peeling limited pedestals in JET-ILW, MAST-U and TCV**
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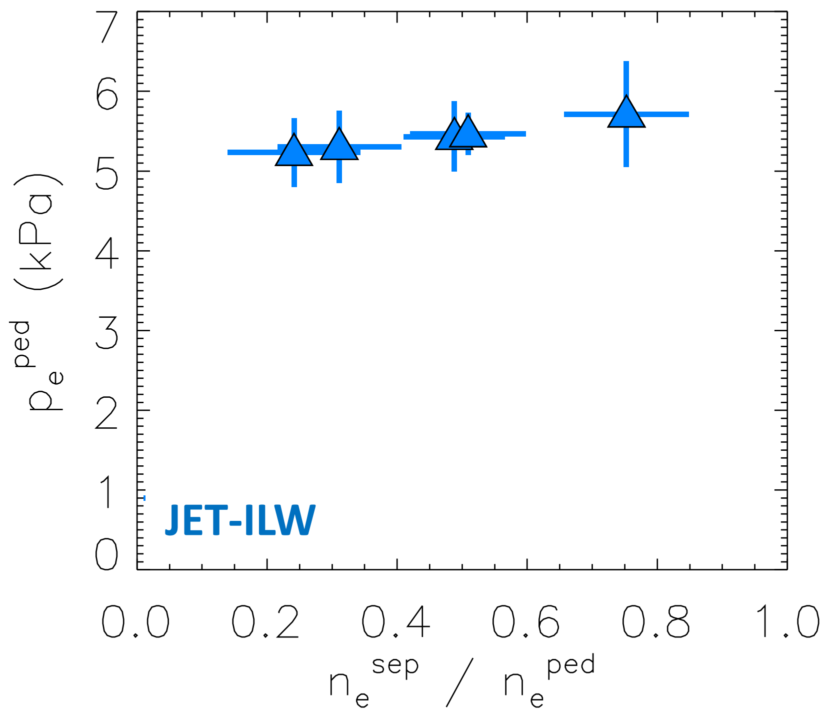
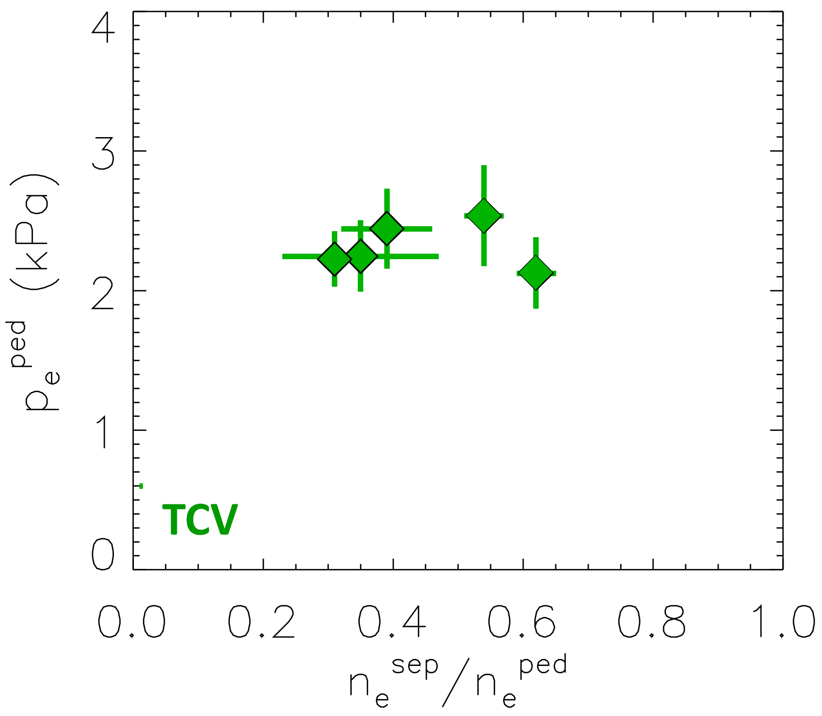
Effect of n_e^{sep}/n_e^{ped} on pedestal pressure

MAST-U dataset:
n_e^{sep}/n_e^{ped} variation achieved only via n_e^{ped} variation→not discussed here





- With increasing n_e^{sep}/n_e^{ped} (at constant n_e^{ped})
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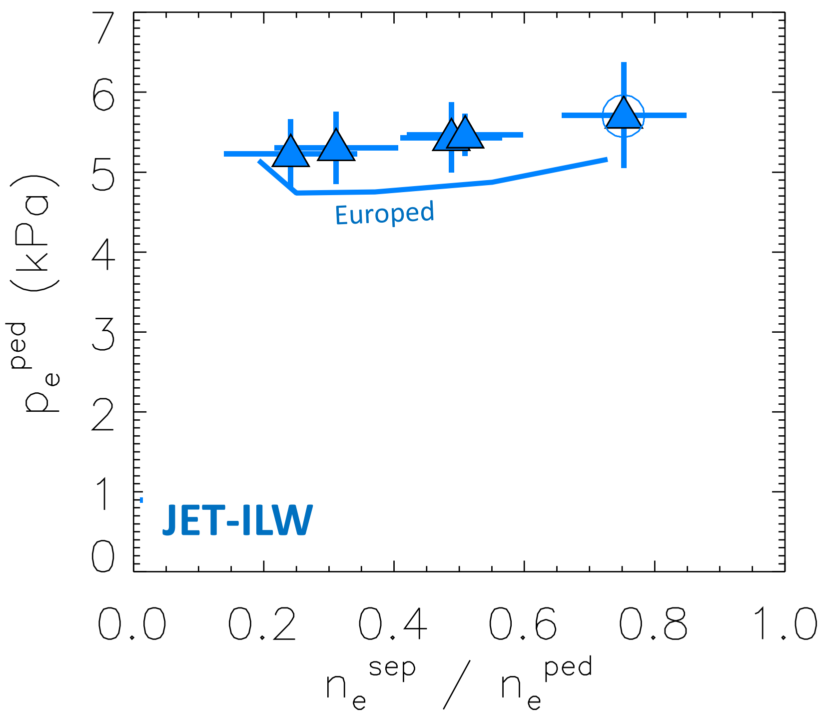

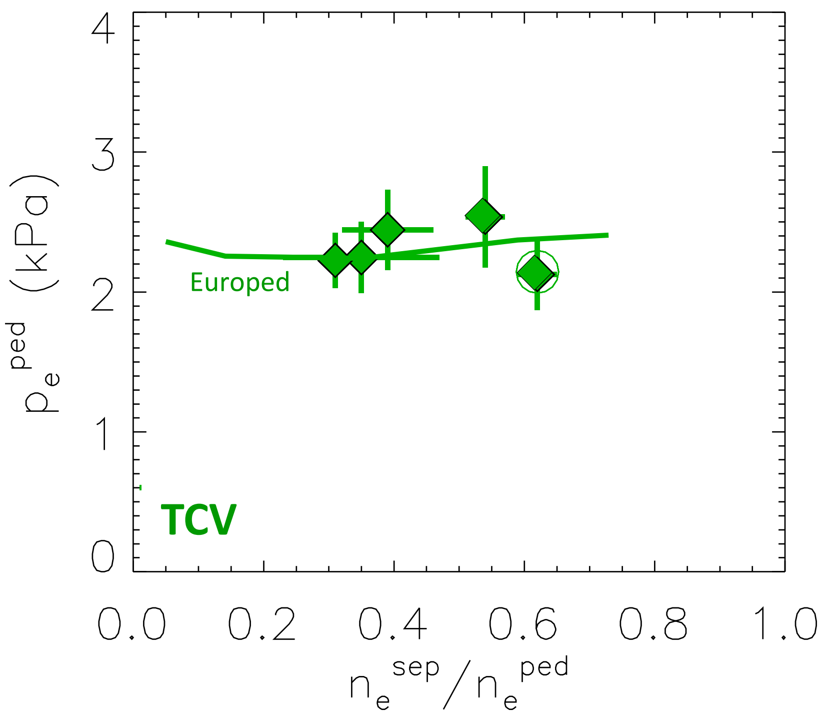

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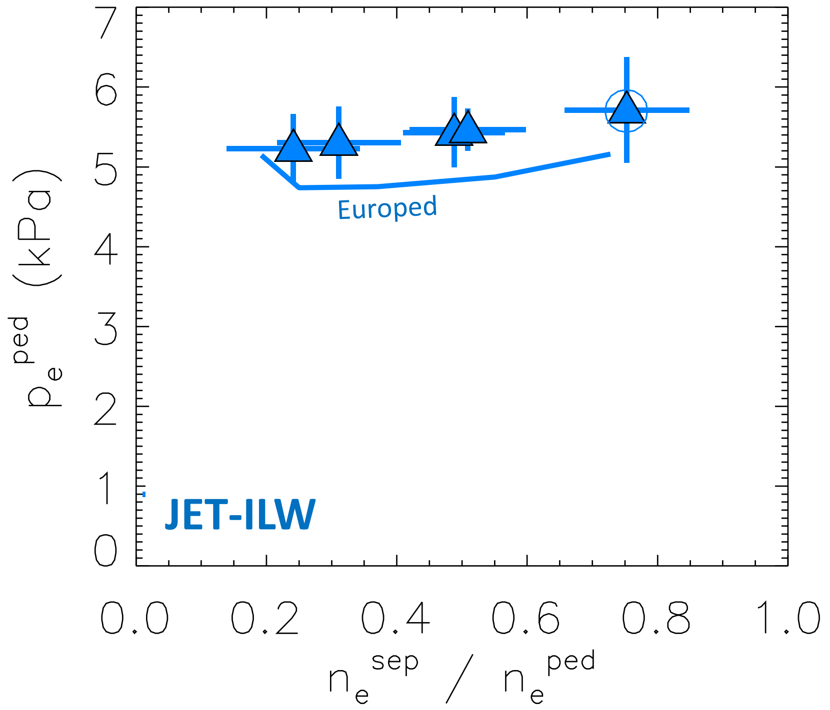
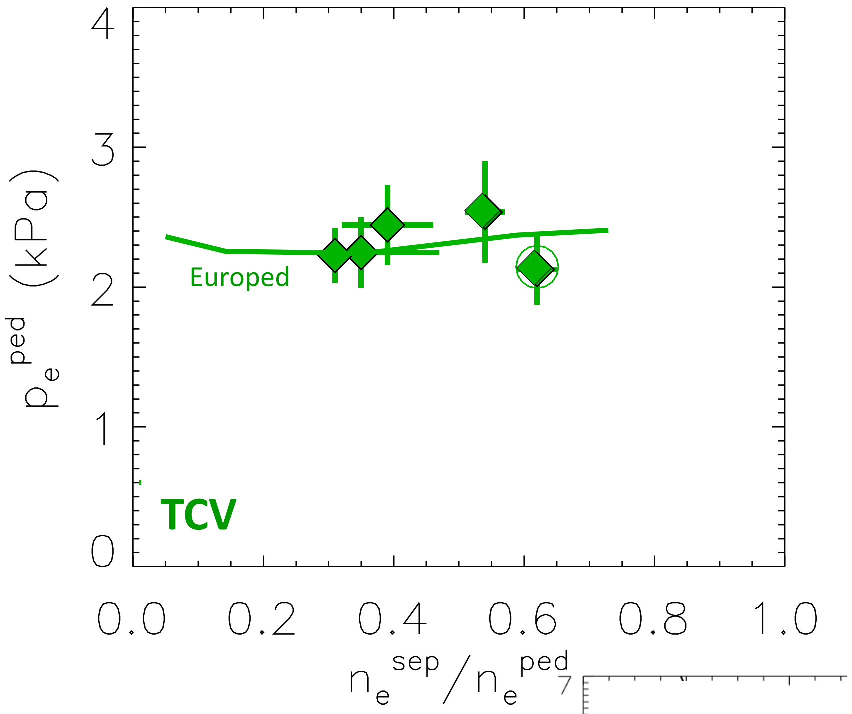
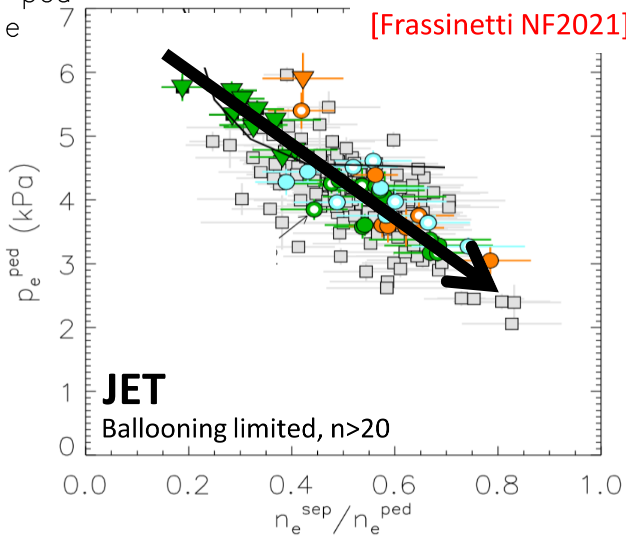




[Frassinetti NF2021]



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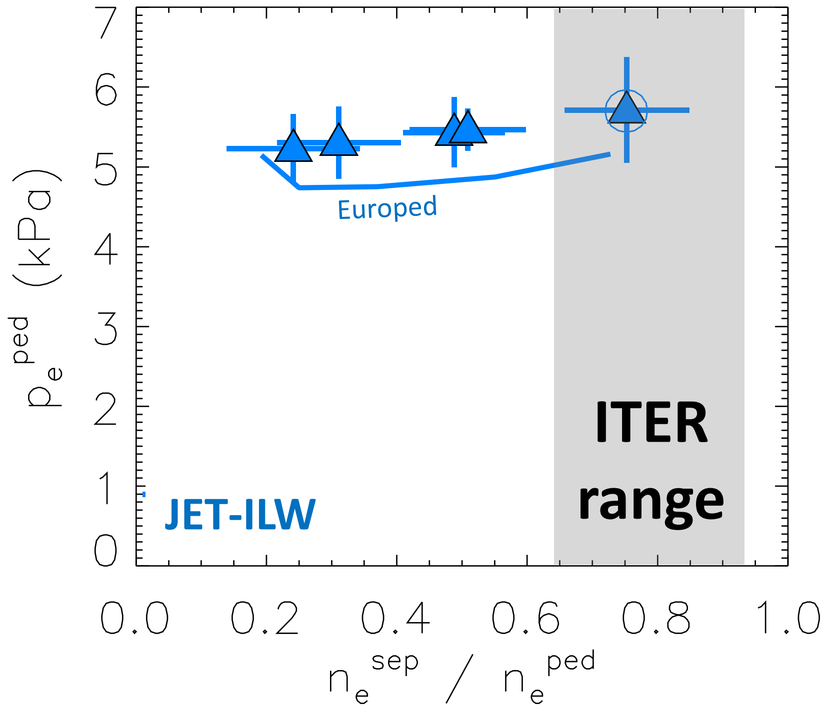

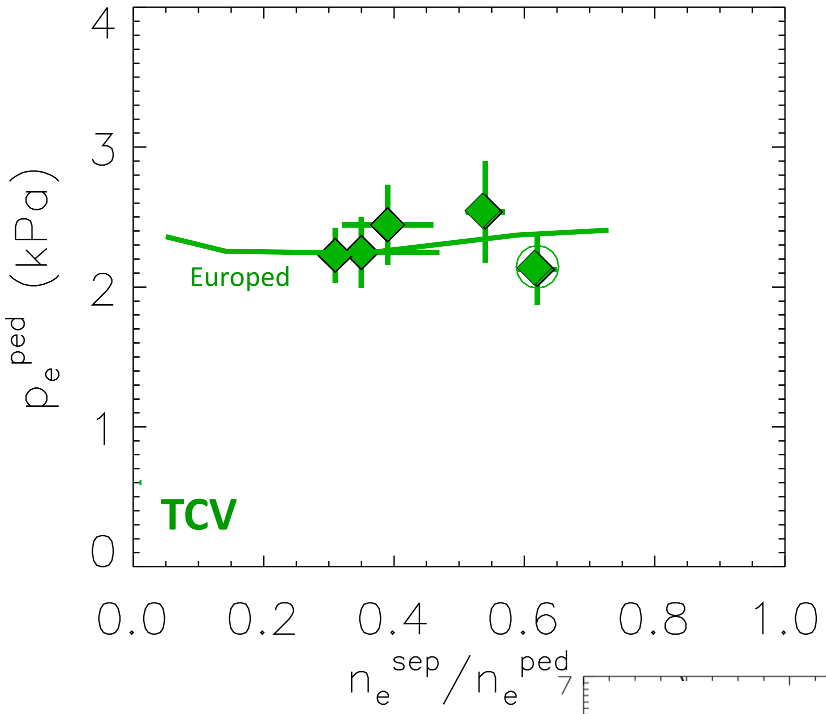

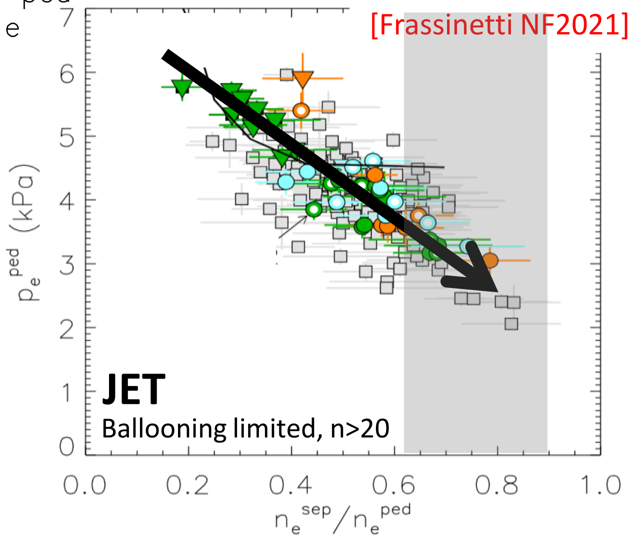

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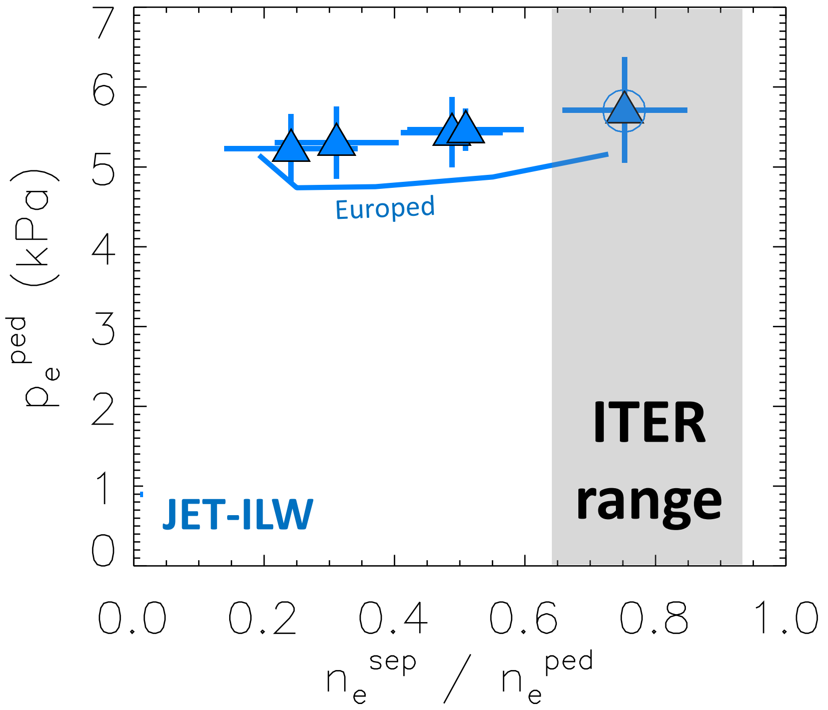
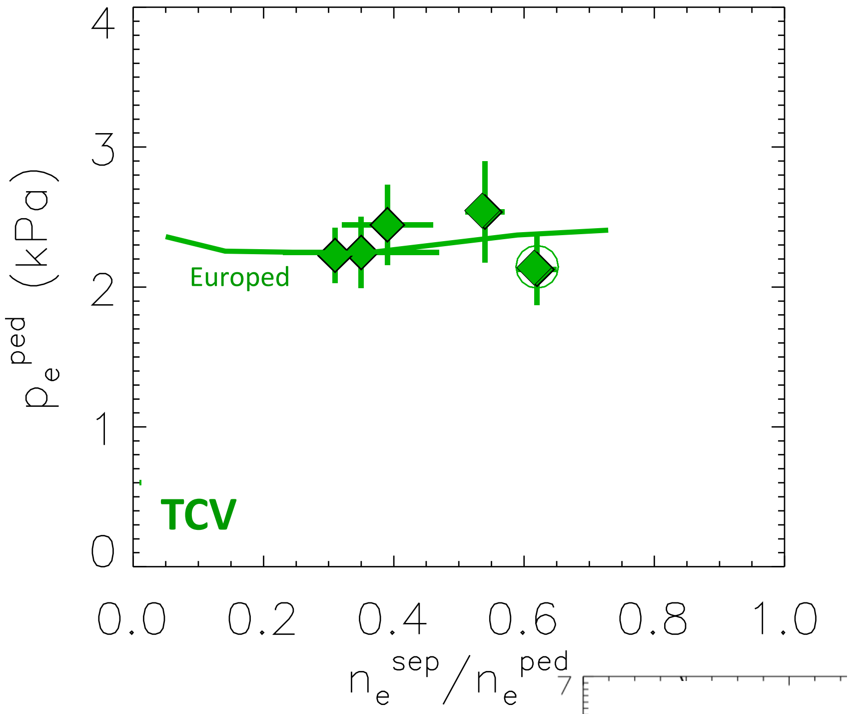
Effect of n_e^{sep}/n_e^{ped} on pedestal pressure

Good news for ITER





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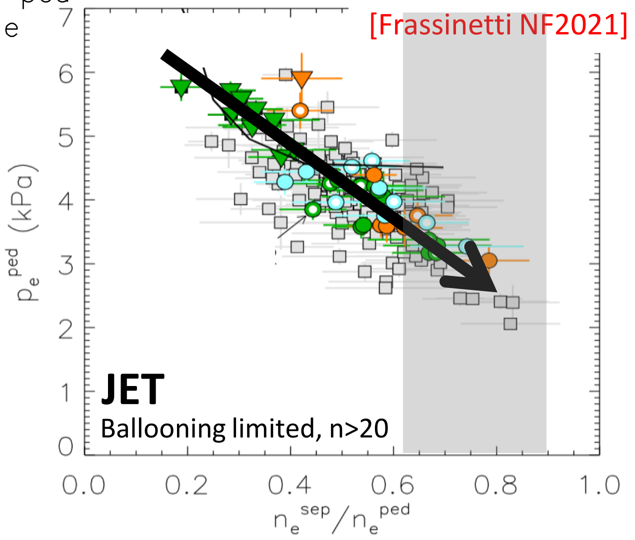

Increasing n_e^{sep}/n_e^{ped} can effects on the global pedestal stability

- Increasing n_e^{sep}/n_e^{ped} destabilizes ballooning modes [Dunne PPCF2017, Frassinetti NF2021]

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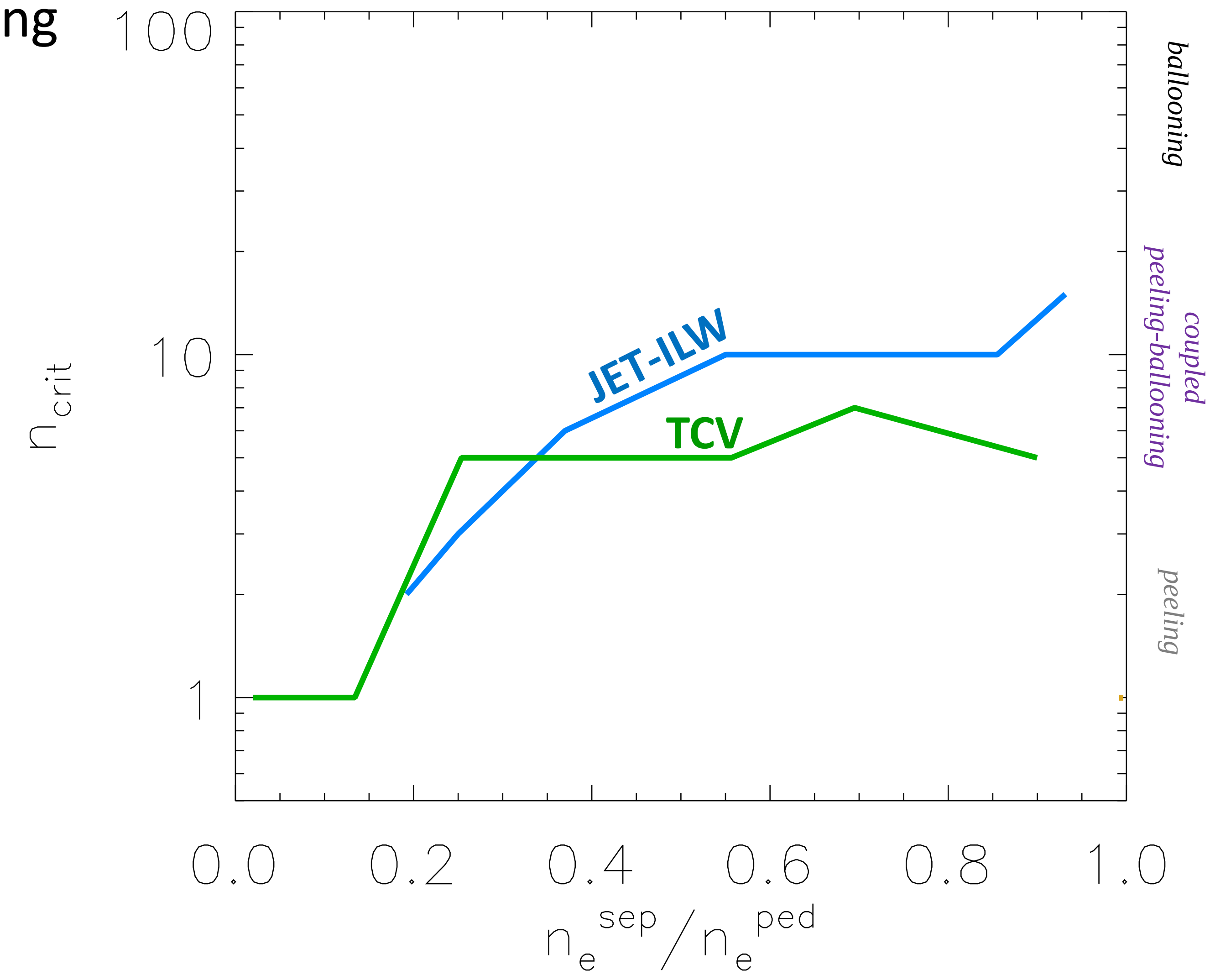

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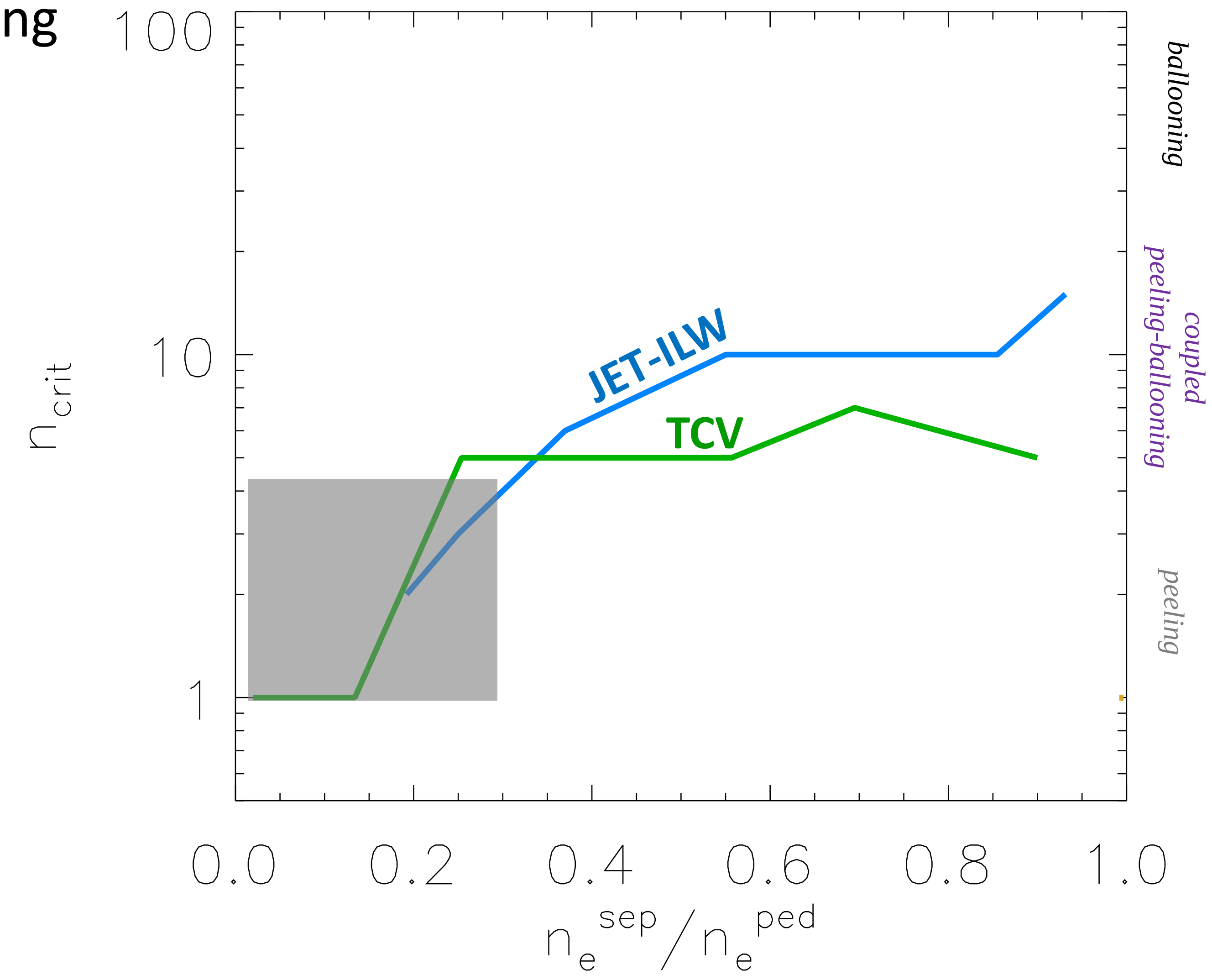

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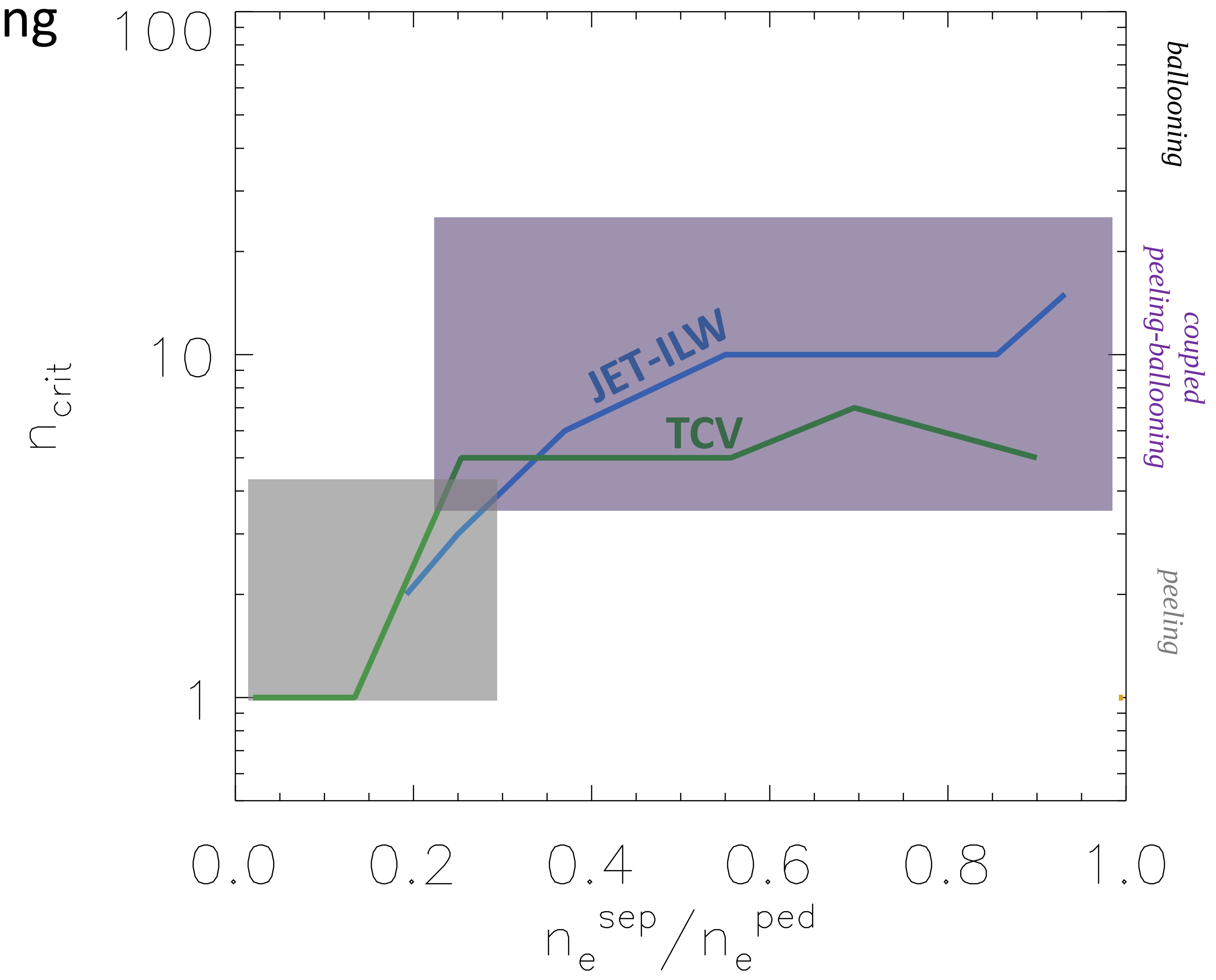

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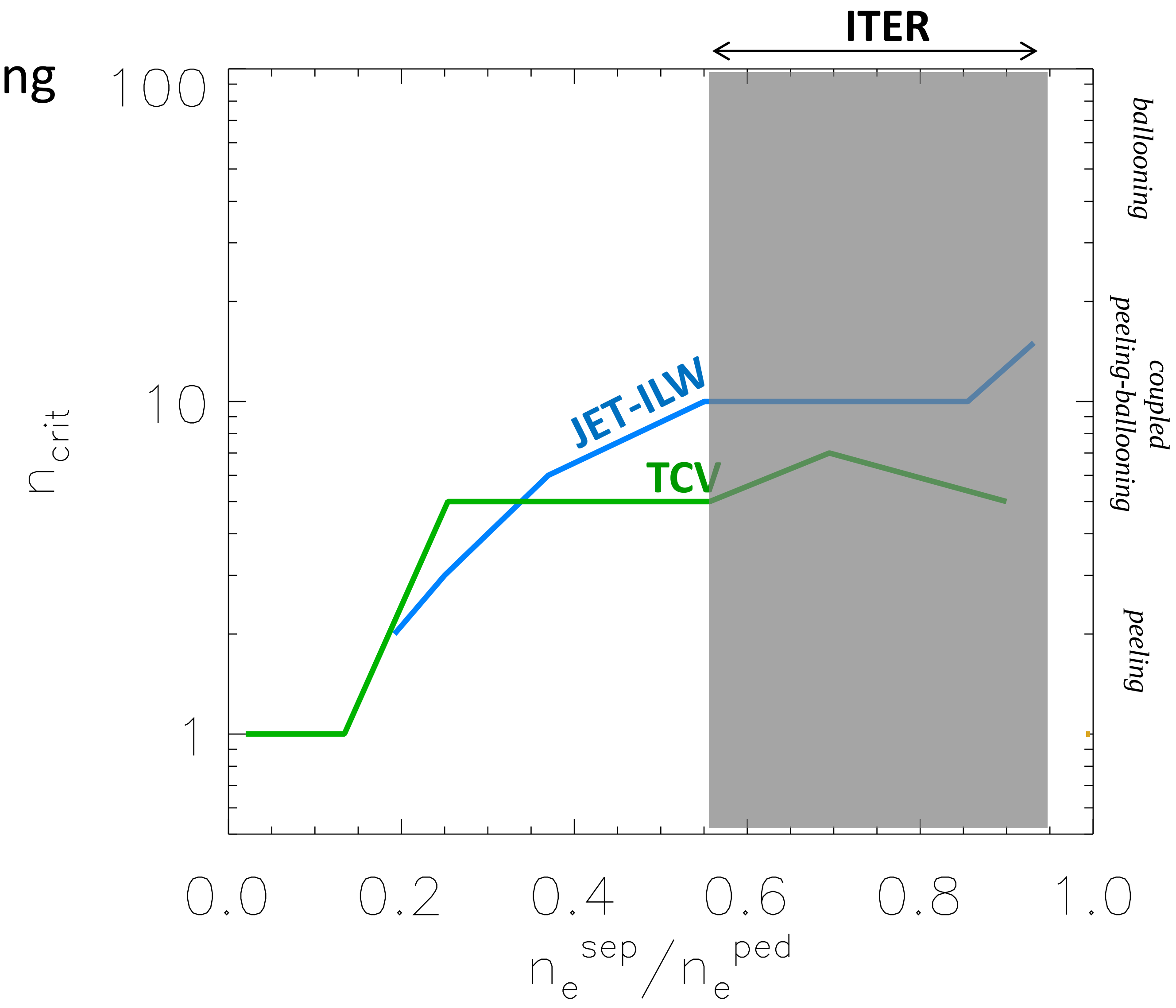
- ITER will operate at high n_e^{sep}/n_e^{ped}
  → this issue must be investigated



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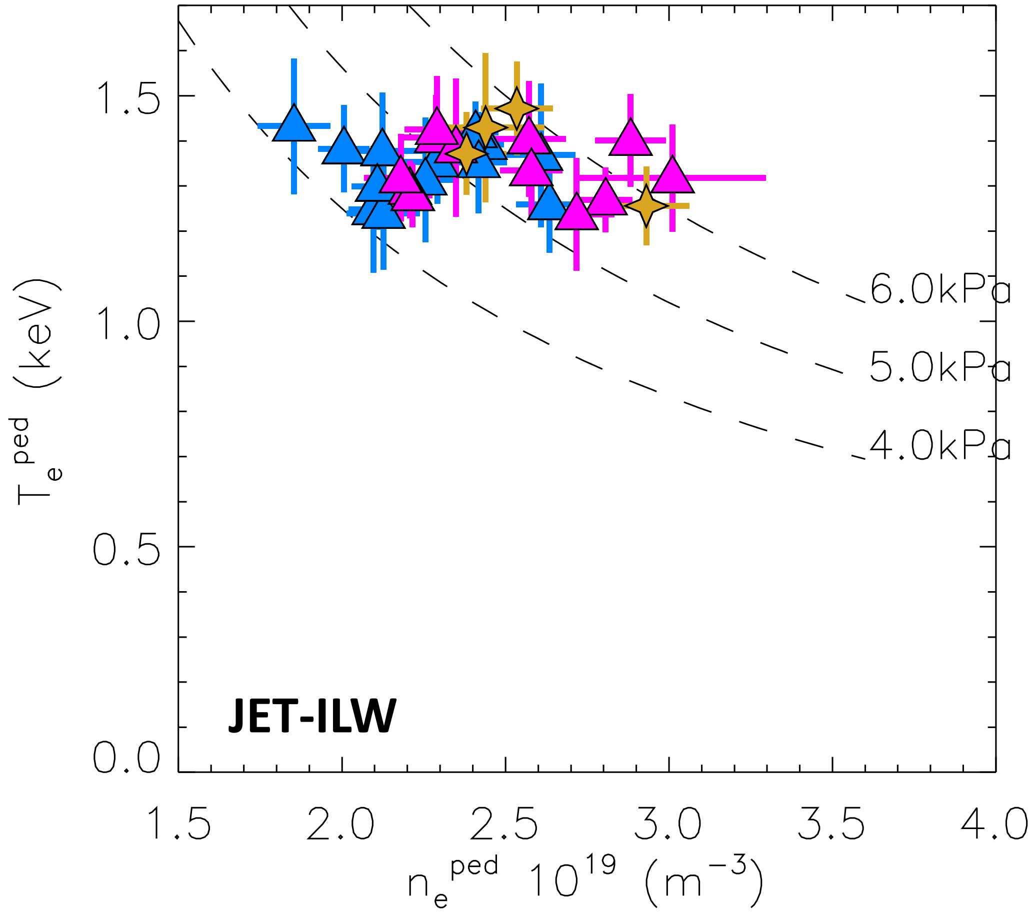
INCREASING THE ISOTOPE MASS INCREASES THE PEDESTAL PRESSURE

- A unique dataset in JET-ILW low ν_{ee}^{*ped}/peeling limited pedestal has been obtained:
  - **pure deuterium, $A_{eff} = 2.0$**
  - **mixed deuterium/tritium, $A_{eff} = 2.5$**
  - **tritium-rich, $A_{eff} = 2.9$**
- Key results:



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- Key results:
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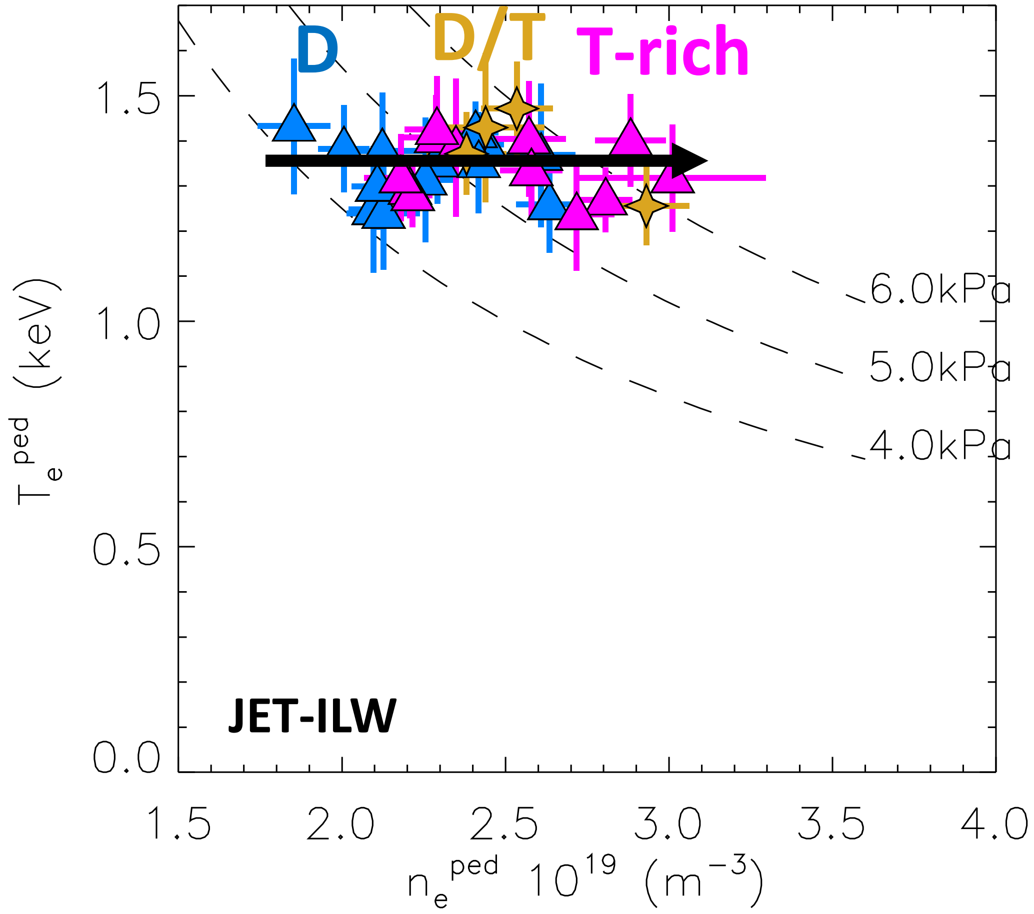

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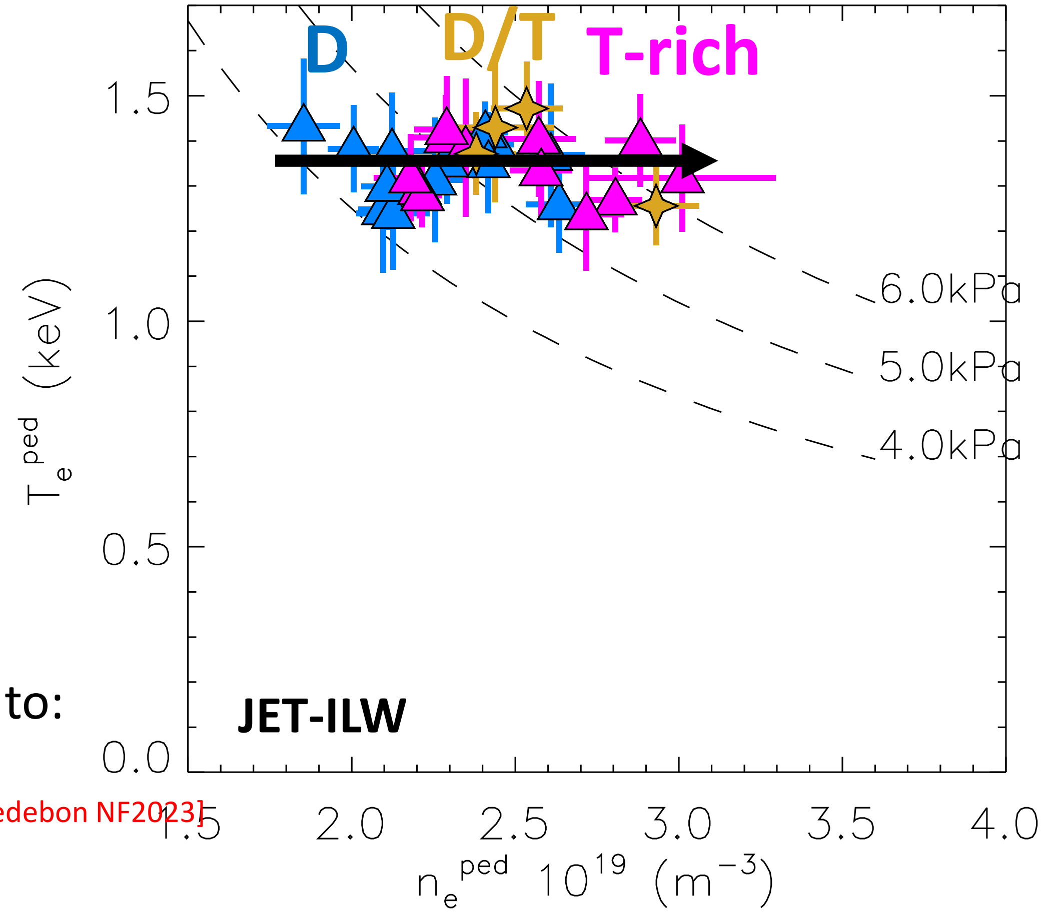

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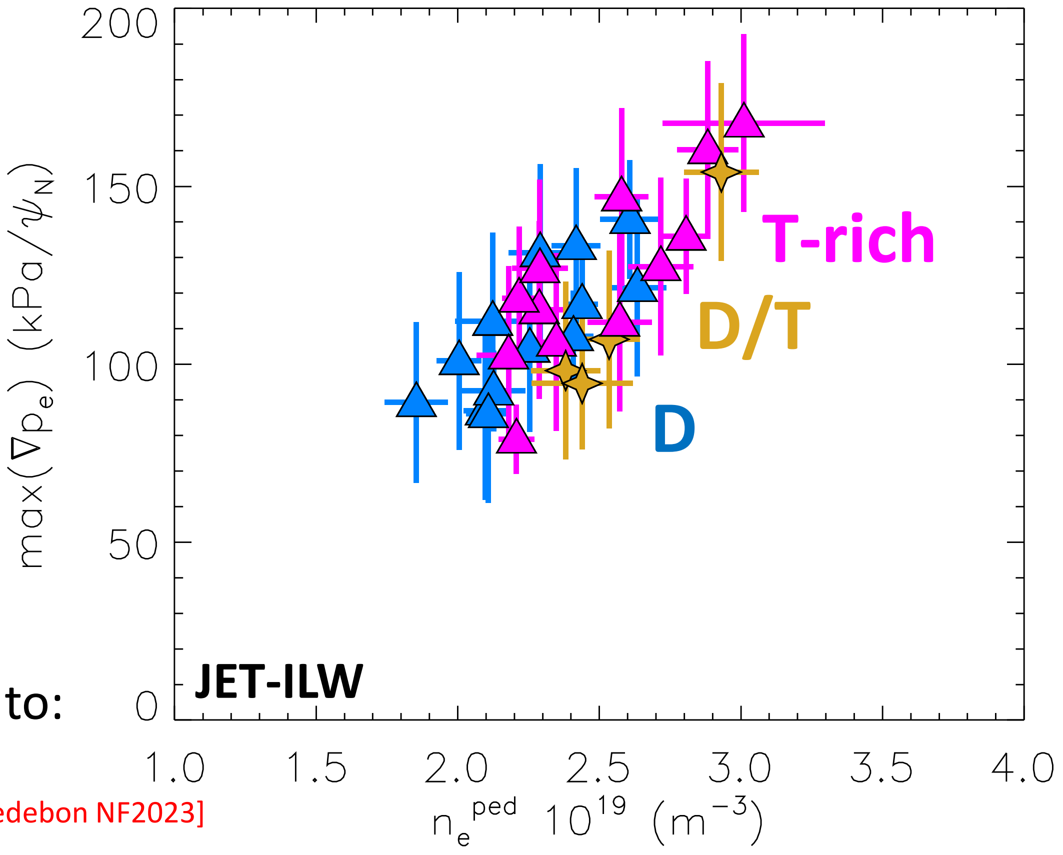

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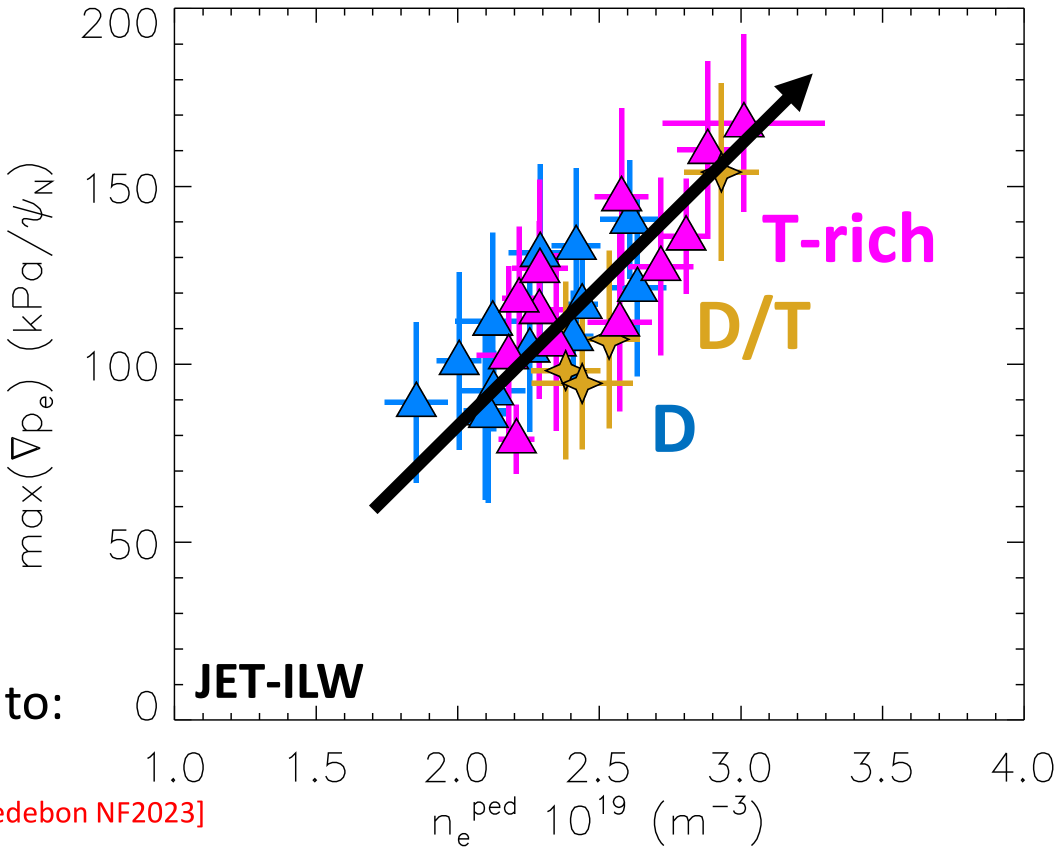

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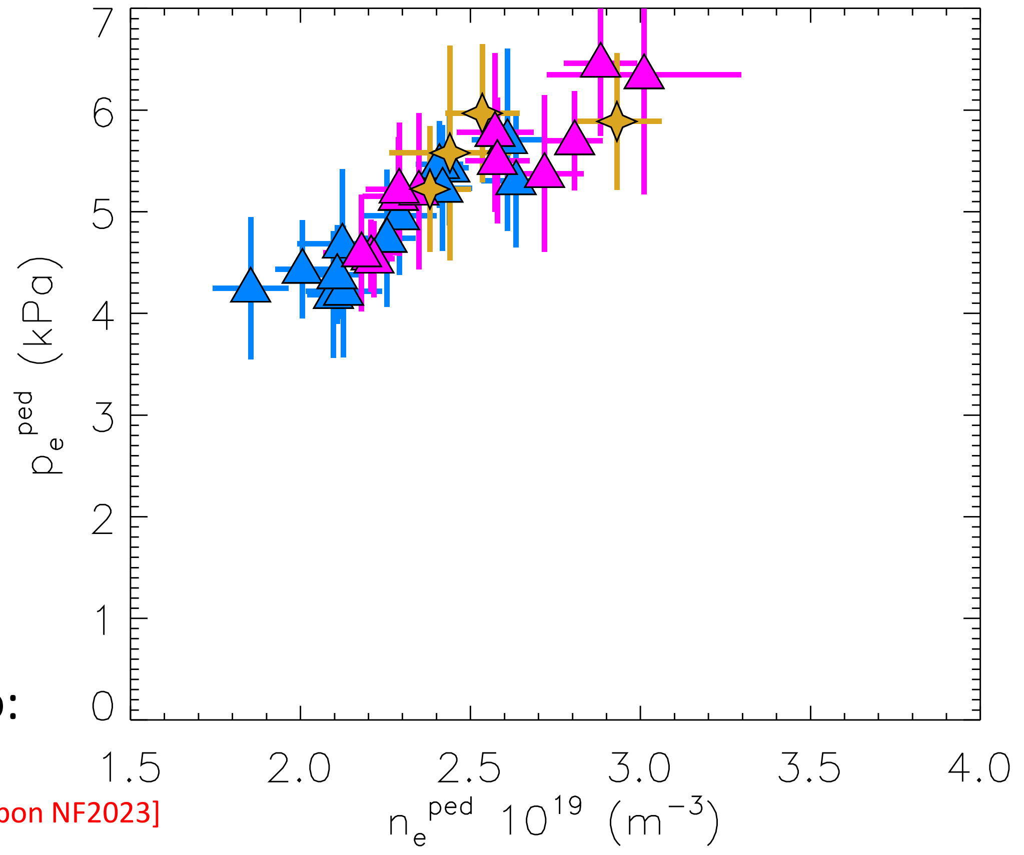

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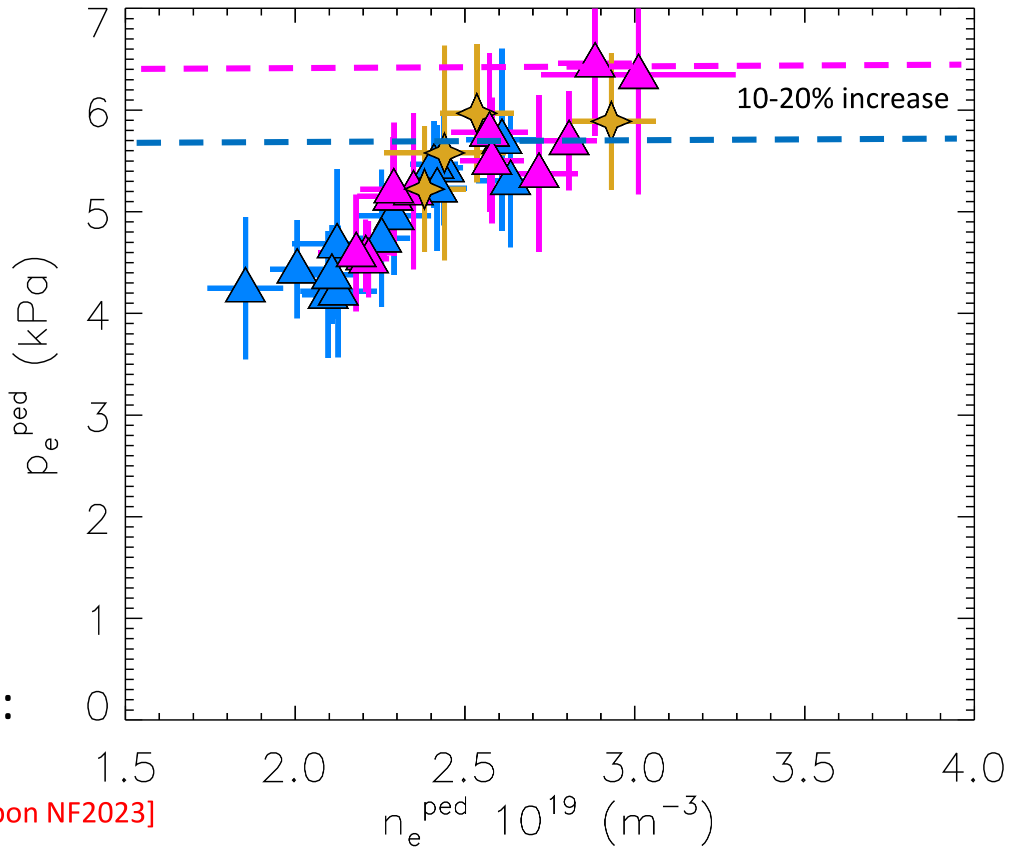

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Positive result in view of future ITER D/T operation

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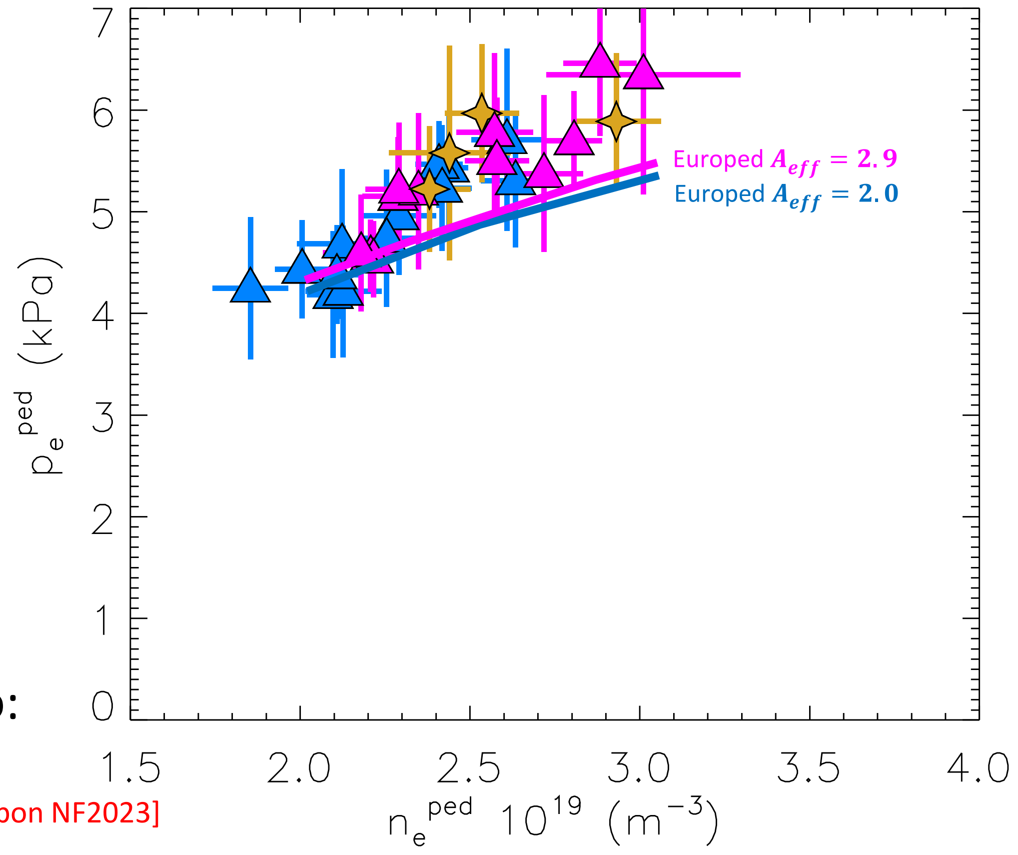

- Pedestal predictions:
  - Reasonable qualitative agreement
  - No direct effect of the isotope mass in this scenario

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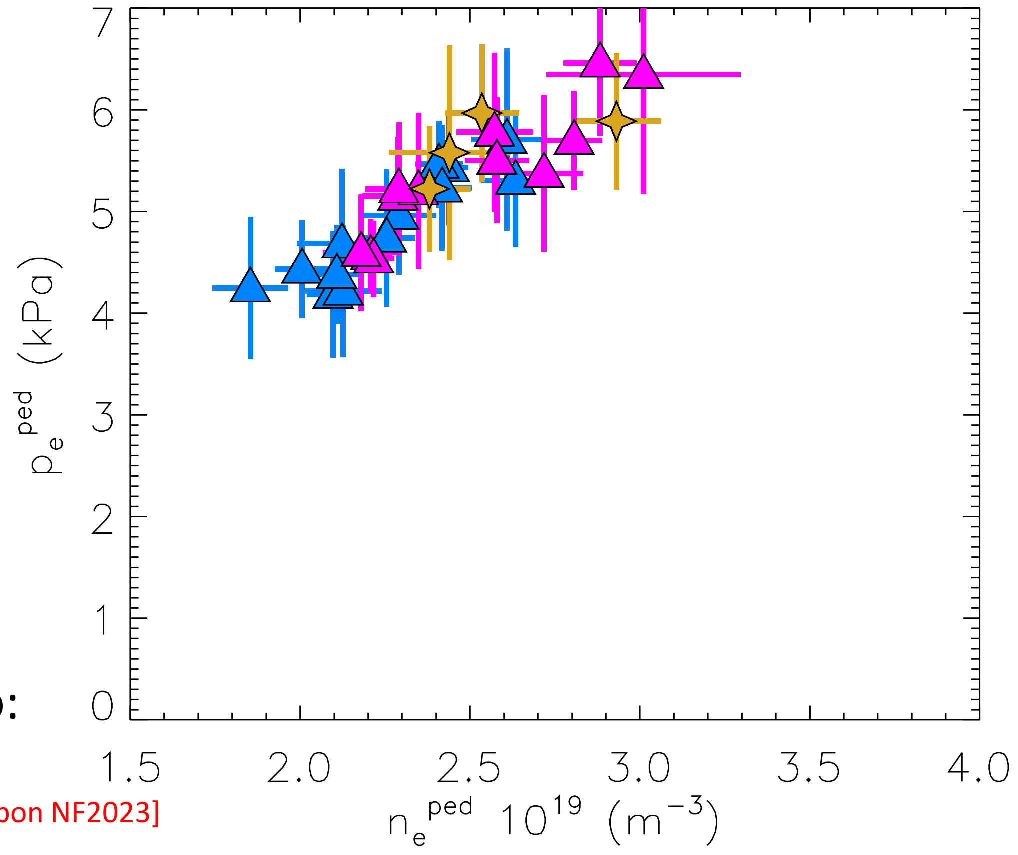

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similar to ballooning limited pedestal in JET-ILW [Schneider NF2023, Frassinetti NF2023]

OUTLINE

1. Reaching peeling limited pedestals in JET-ILW, MAST-U and TCV
2. The datasets
3. Effect of
   - n_e^{ped} on p_e^{ped} in peeling limited pedestals in JET-ILW, MAST-U and TCV
   - n_e^{sep}/n_e^{ped} on p_e^{ped} in peeling limited pedestals in JET-ILW, MAST-U and TCV
   - the isotope mass in peeling limited pedestals in JET-ILW
   - and corresponding pedestal predictions with Europed
4. **Pedestal predictions in ITER**
   - **will ITER be limited by peeling or ballooning instabilites?**
   - **is this an issue?**

ITER predictions

- Europed has been used to predict the limiting pedestal instability in the ITER Q=10 scenario at
  - $I_p = 15MA, B_t = 5.3T, \beta_N = 2$
  - shape before the new baseline

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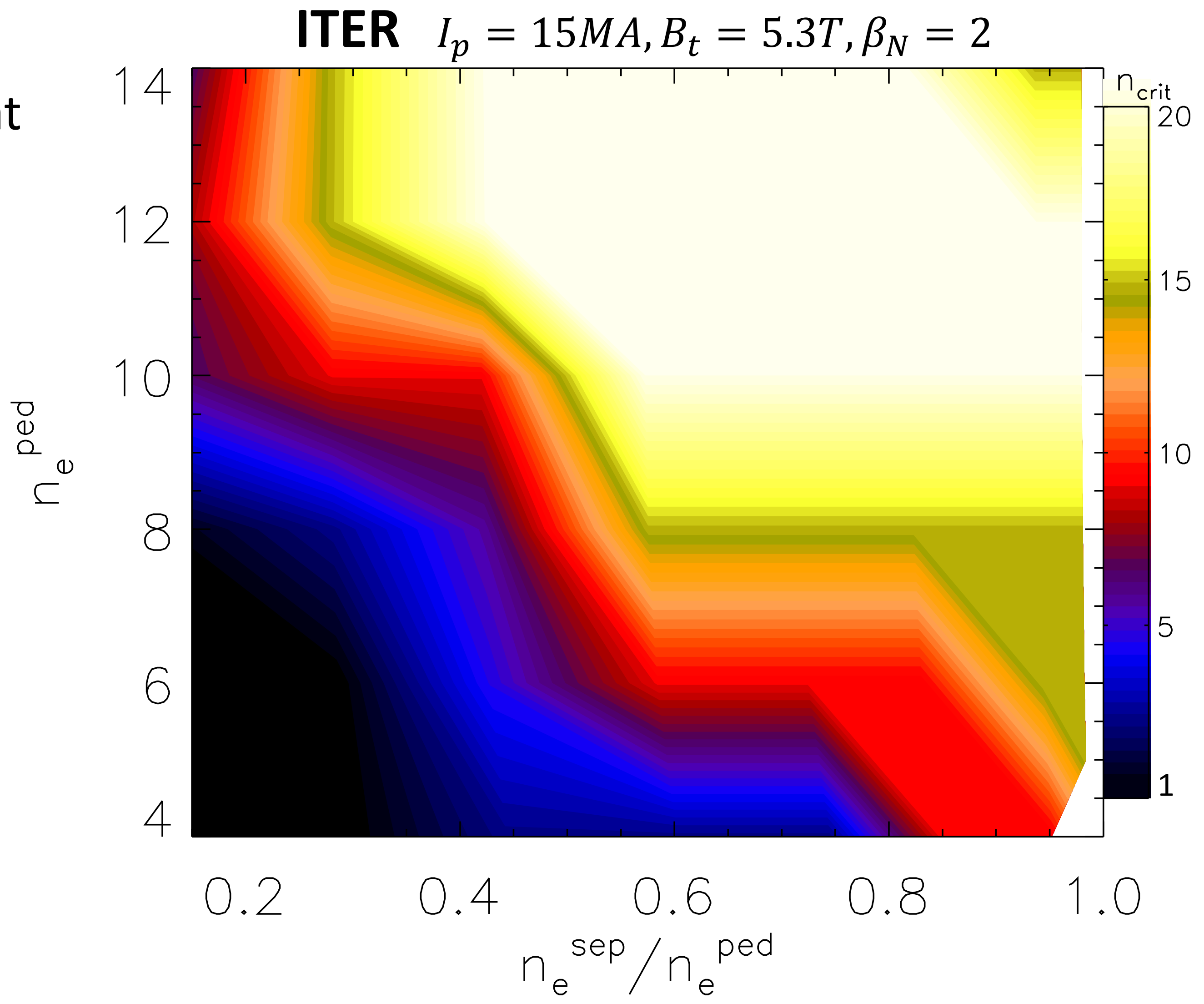

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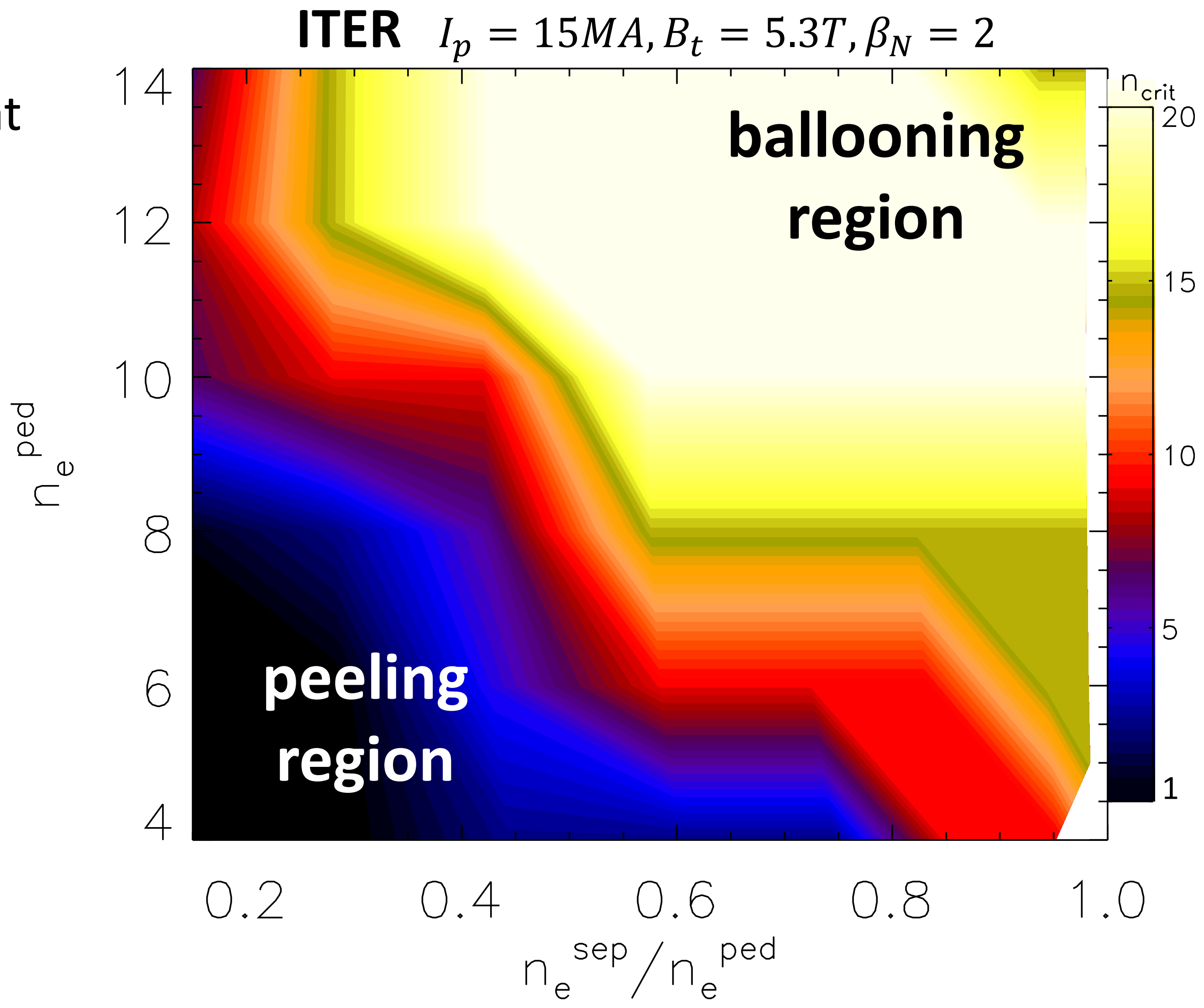

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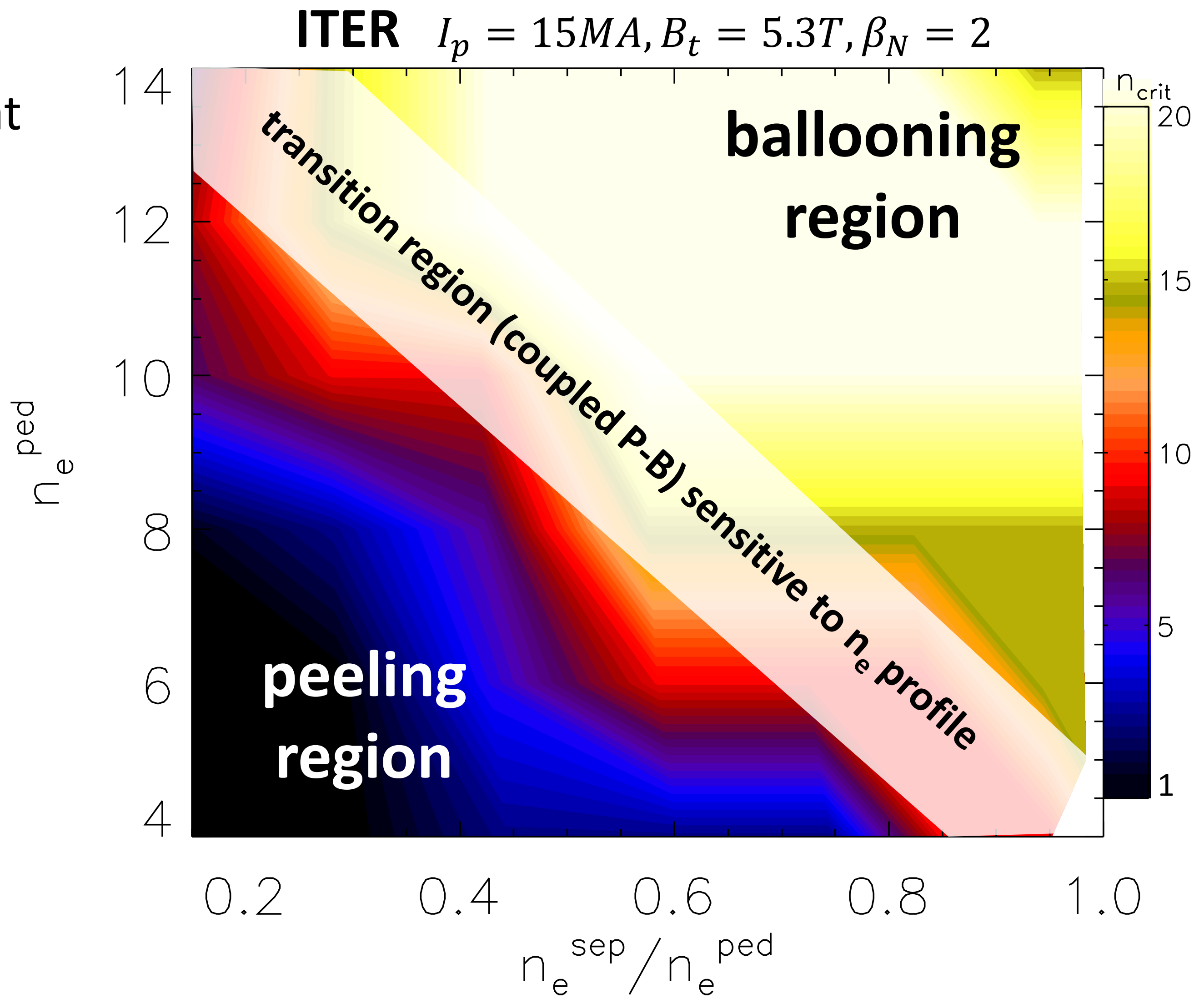
  → sharp transition region

  → result strongly dependent on the details of the density profiles consistent with [Maget NF2013]



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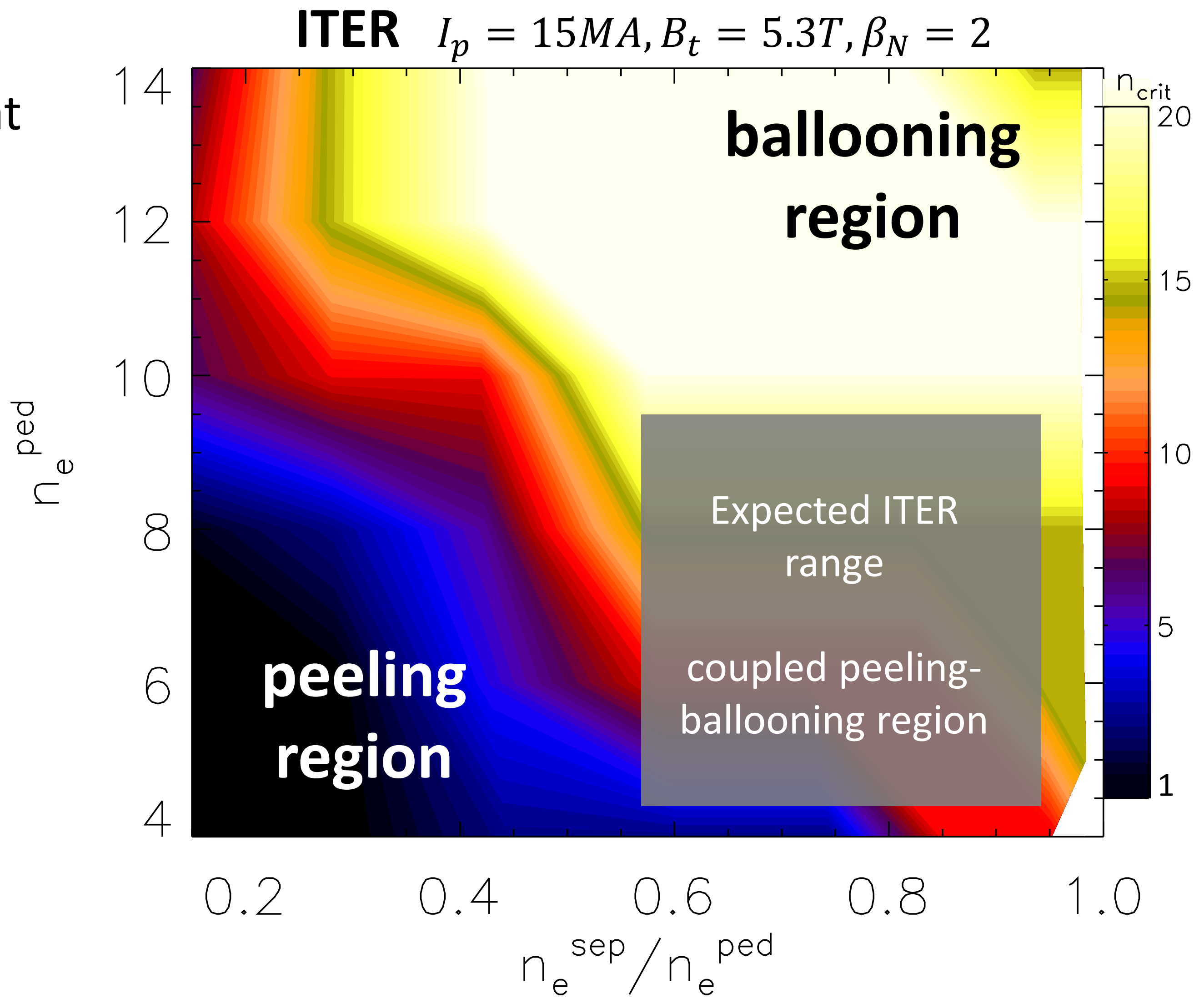

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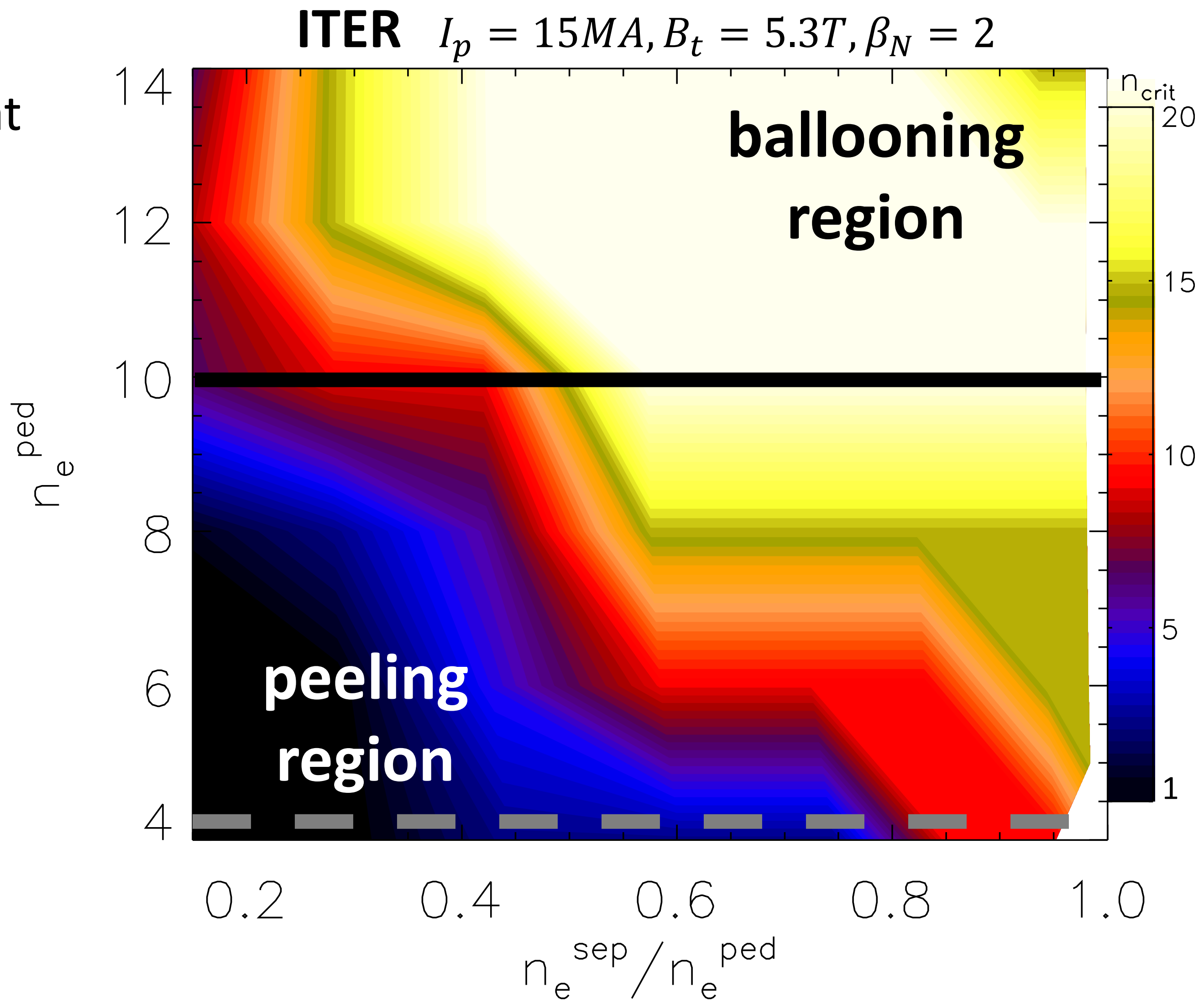

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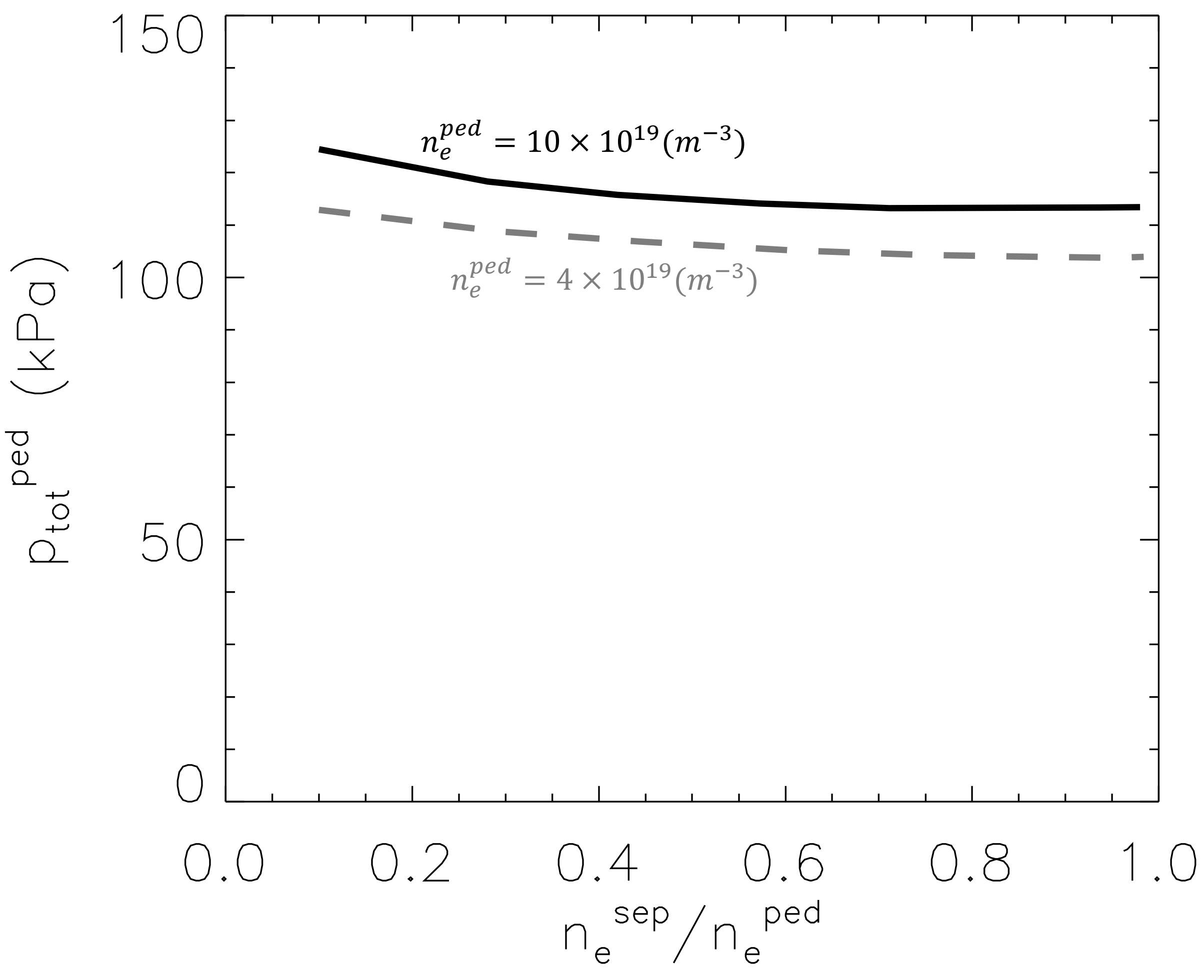

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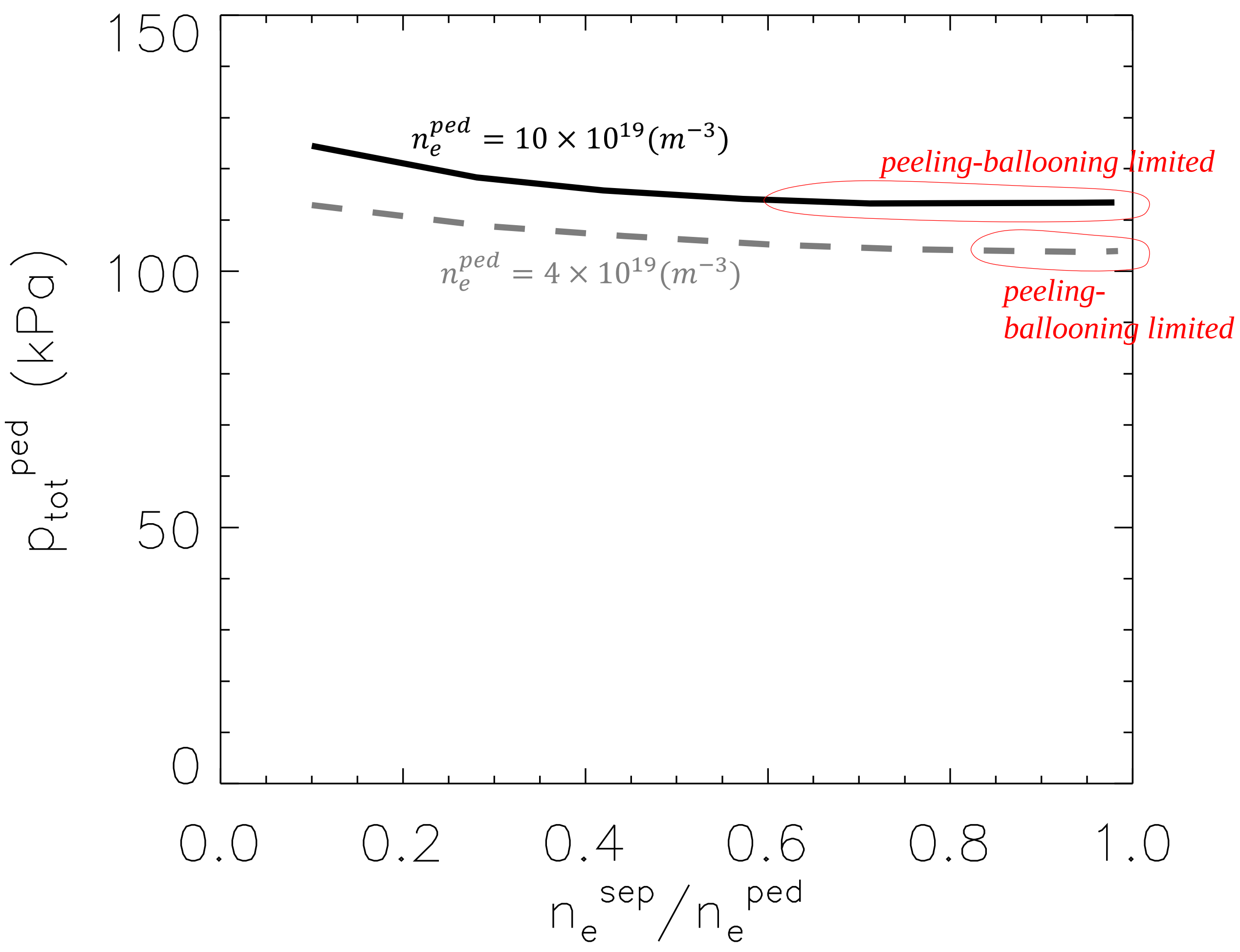

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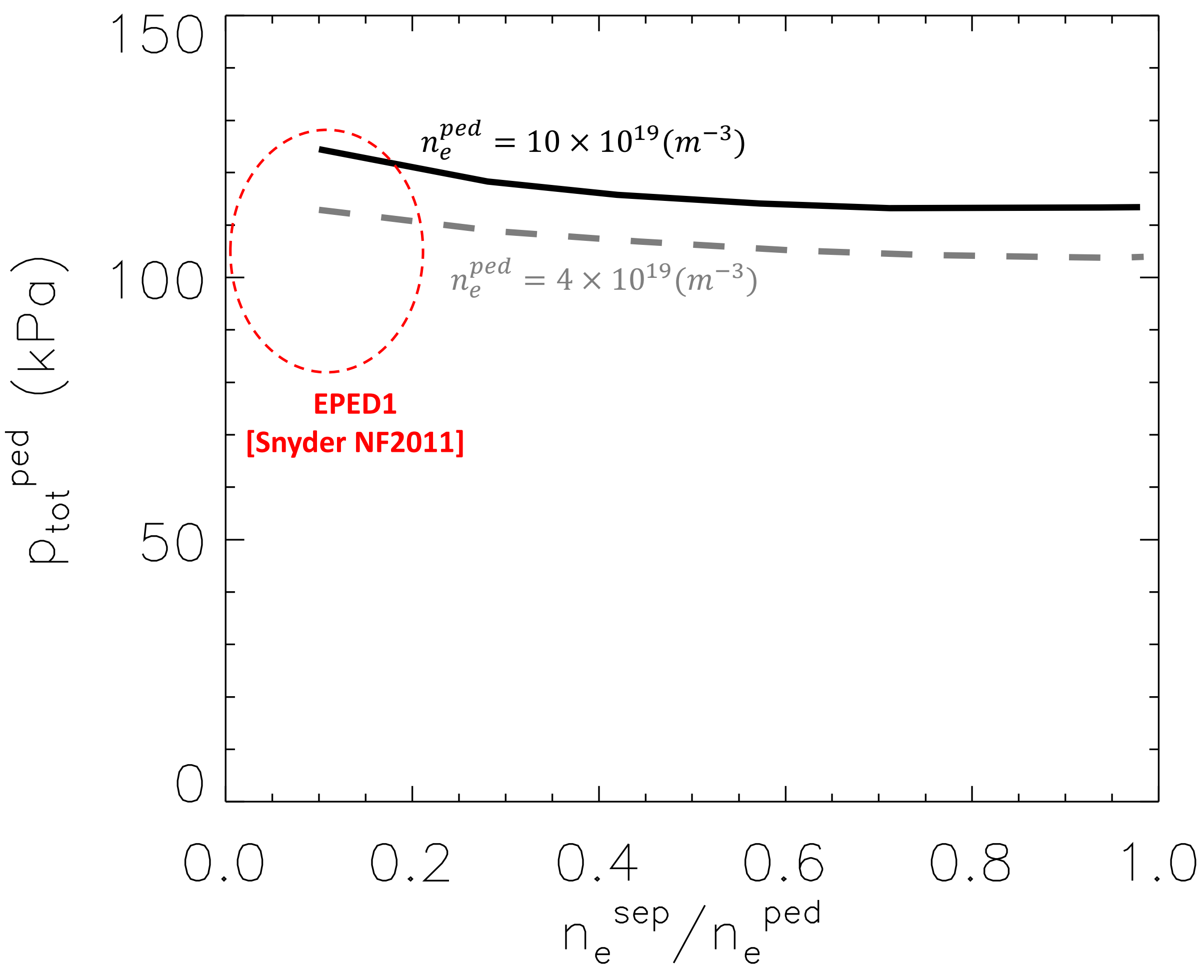

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Positive result for ITER

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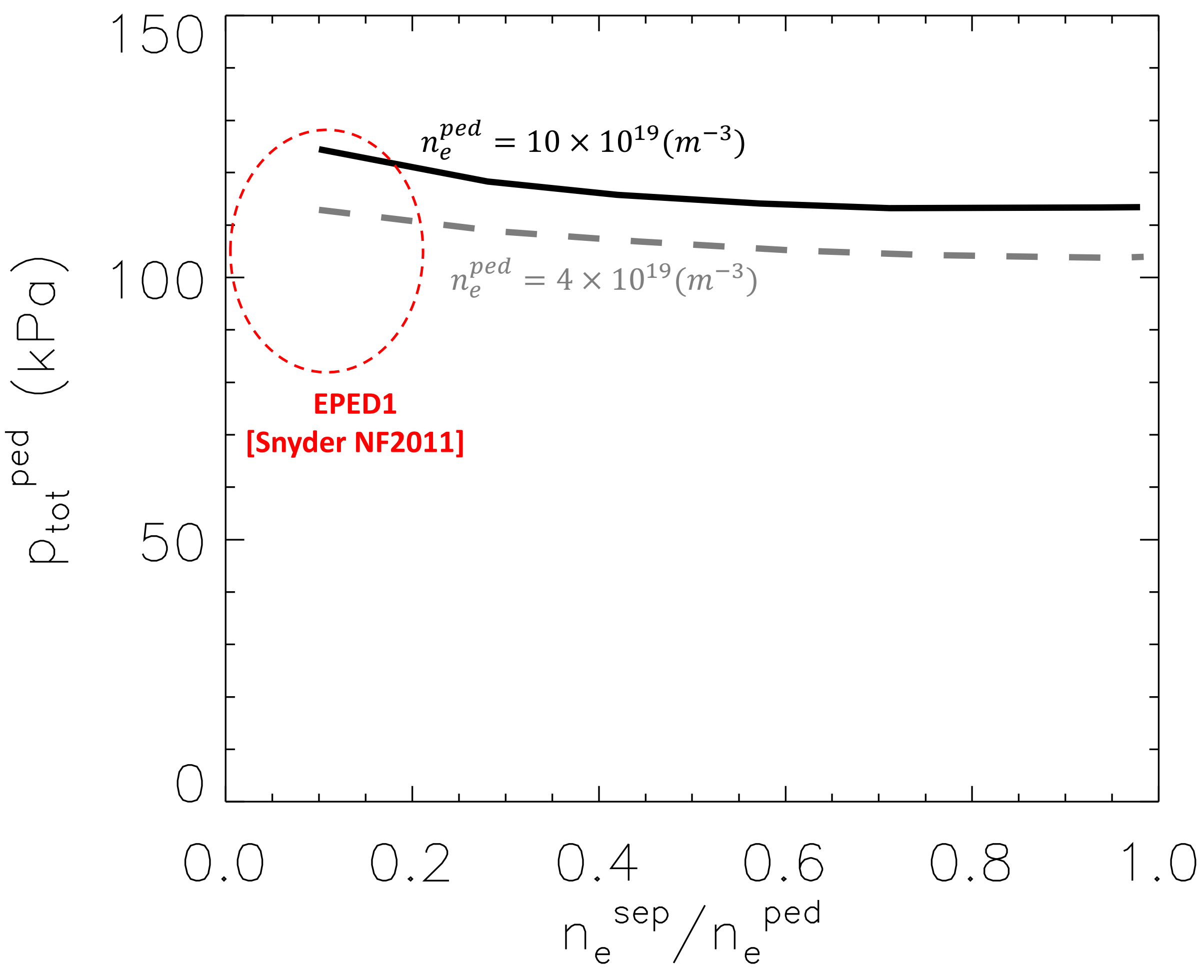

CONCLUSIONS

- Low ν_{ee}^{*ped}/peeling limited pedestals reached in JET-ILW, MAST-U, TCV
- No major qualitative difference observed between metal wall and carbon wall machines
- Some promising results in view of ITER:
  - p^{ped} does not degrade with increasing n_e^{sep}/n_e^{ped}
  - p^{ped} increases with increasing isotope mass
- Reasonable Europed predictions in the ITER range of ν_{ee}^{*ped}, ρ_i^{*ped}, n_e^{sep}/n_e^{ped}
- ITER pedestal predictions:
  - Q=10 scenario will have coupled peeling-ballooning instabilities
  - However, no pedestal degradation expected

- The work increases the relevance for ITER of small/no ELMs regimes [Giroud IAEA2025, Dunne IAEA2025] which have been achieved in ballooning limited pedestals.