Effect of resistivity on the pedestal physics in JET-ILW

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Overview

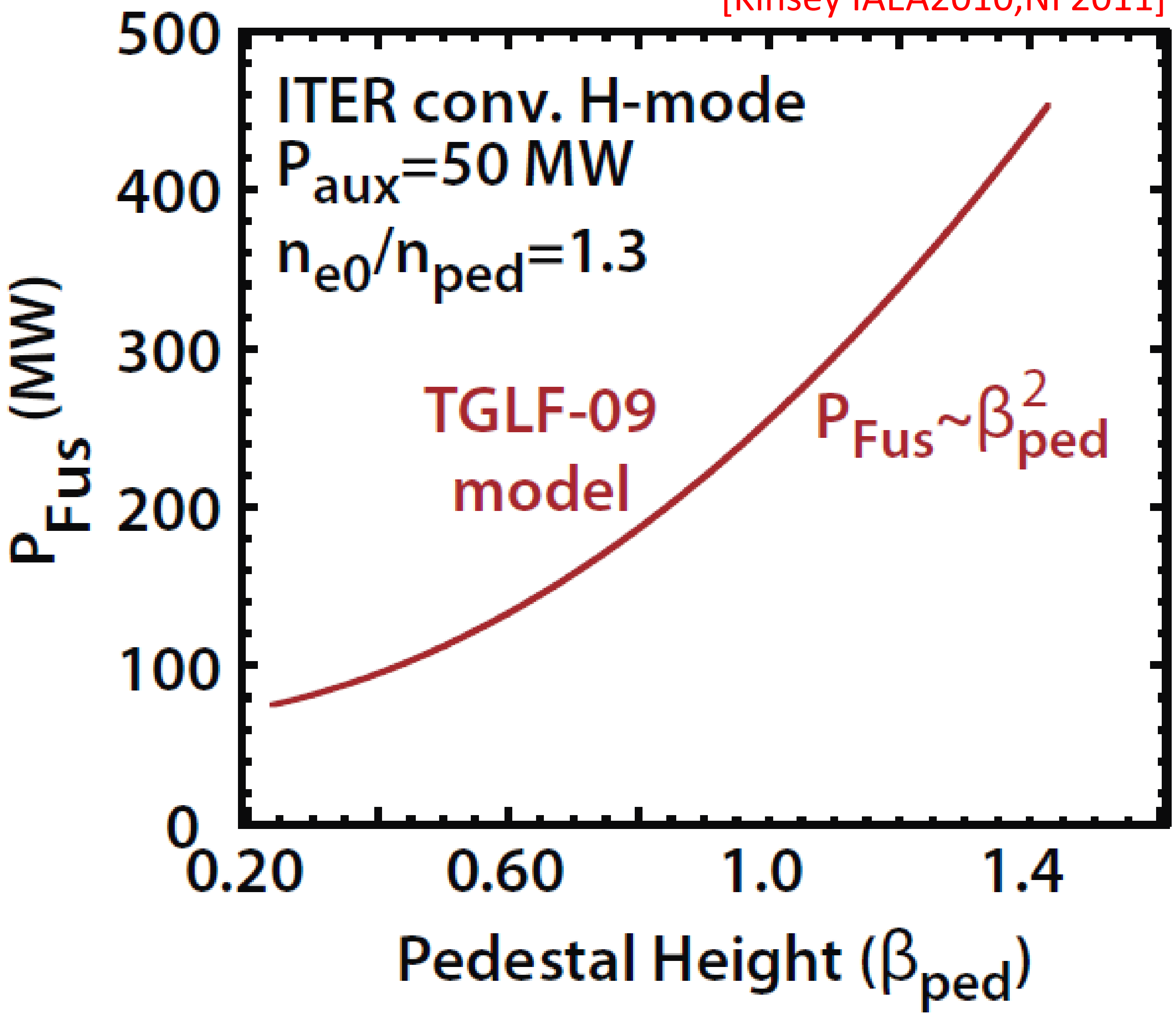
- Introduction and motivation
- Experimental results on the link between pedestal and resistivity
- Pedestal stability analysis with ideal MHD and with resistive MHD
- Some important applications of resistive MHD:
  - Explaining the effect of the isotope mass on the pressure gradient in JET- ILW ballooning limited plasmas
  - Pedestal predictions with resistive MHD (resistive Europed)
  - Application to several JET scenarios
- Relevance for other machines

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

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

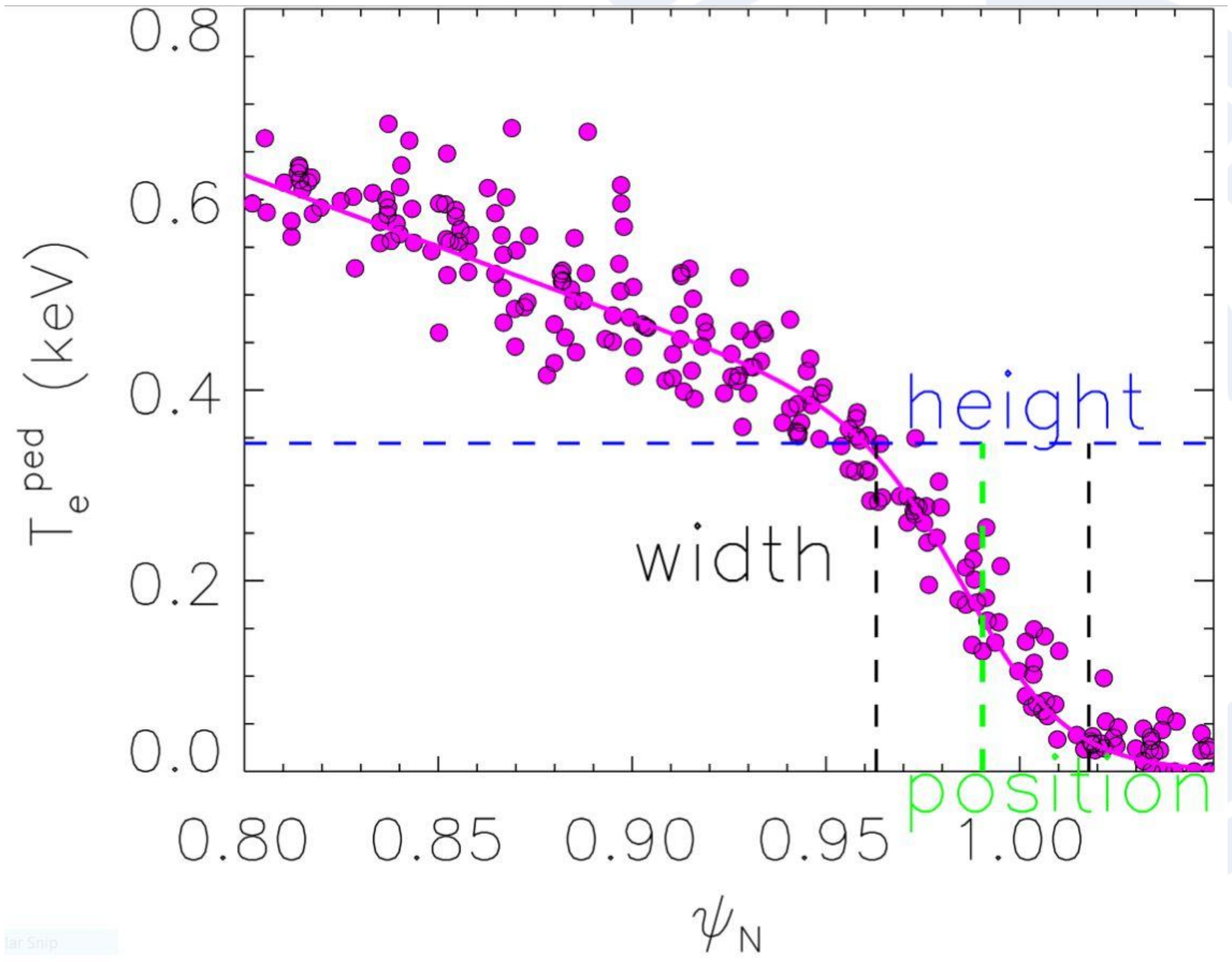
- Assessing and predicting the pedestal structure and the pedestal stability is essential

[Kinsey IAEA2010,NF2011]



Pedestal structure

- The pedestal structure can be characterized by:
  - height
  - width
  - gradient
  - position



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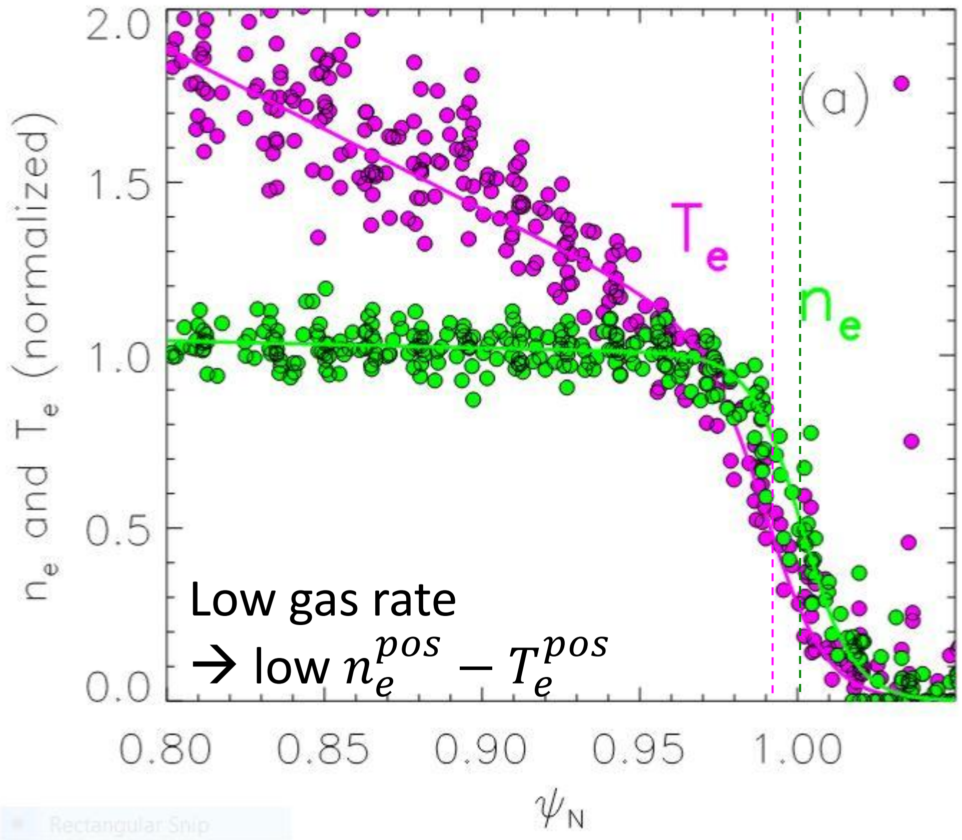

- Other important parameters are
  - The relative shift $(n_e^{pos} - T_e^{pos})$ → useful to describe the effect of the gas rate

[Stefanikova NF2017]

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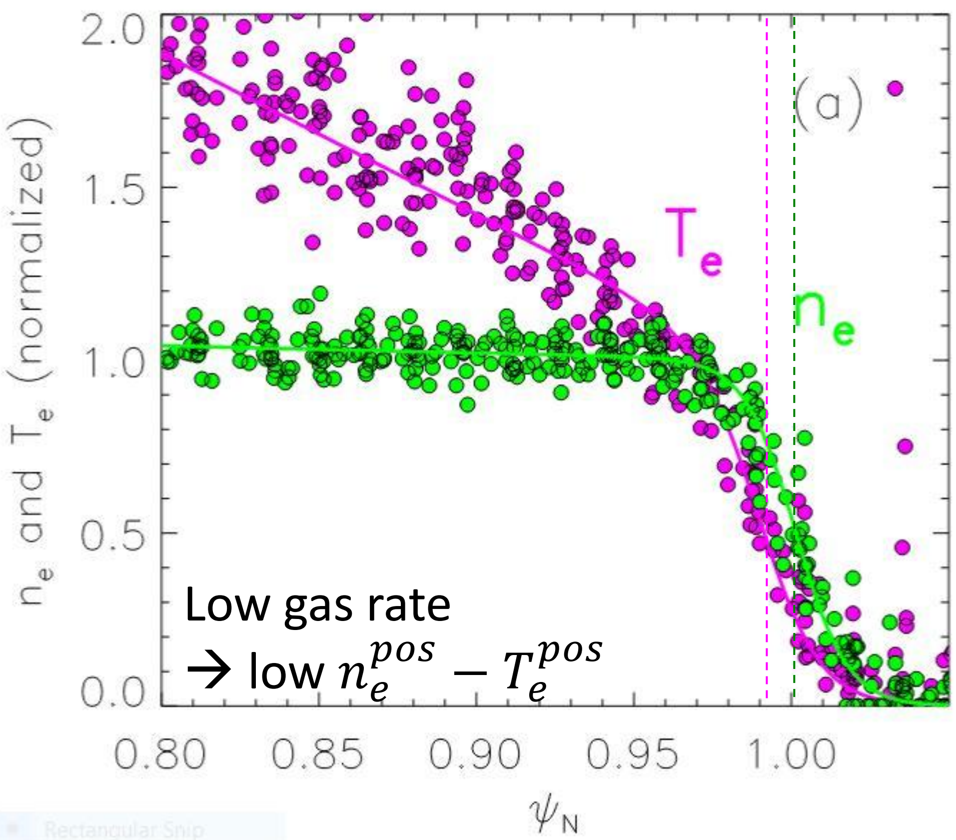

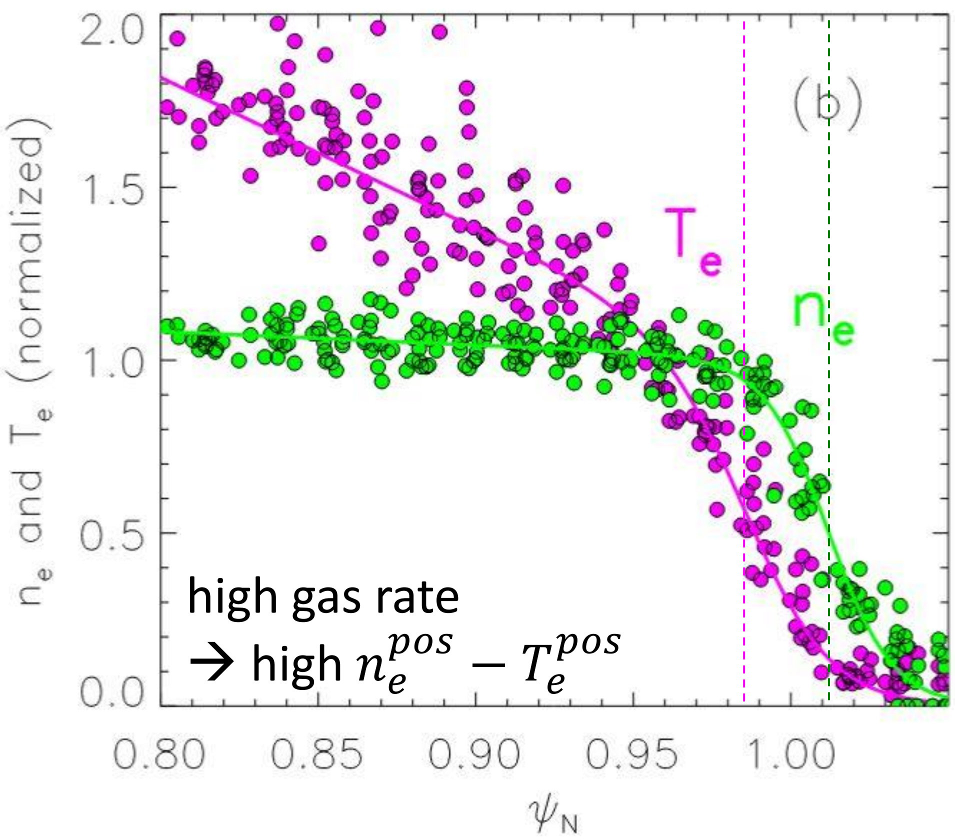

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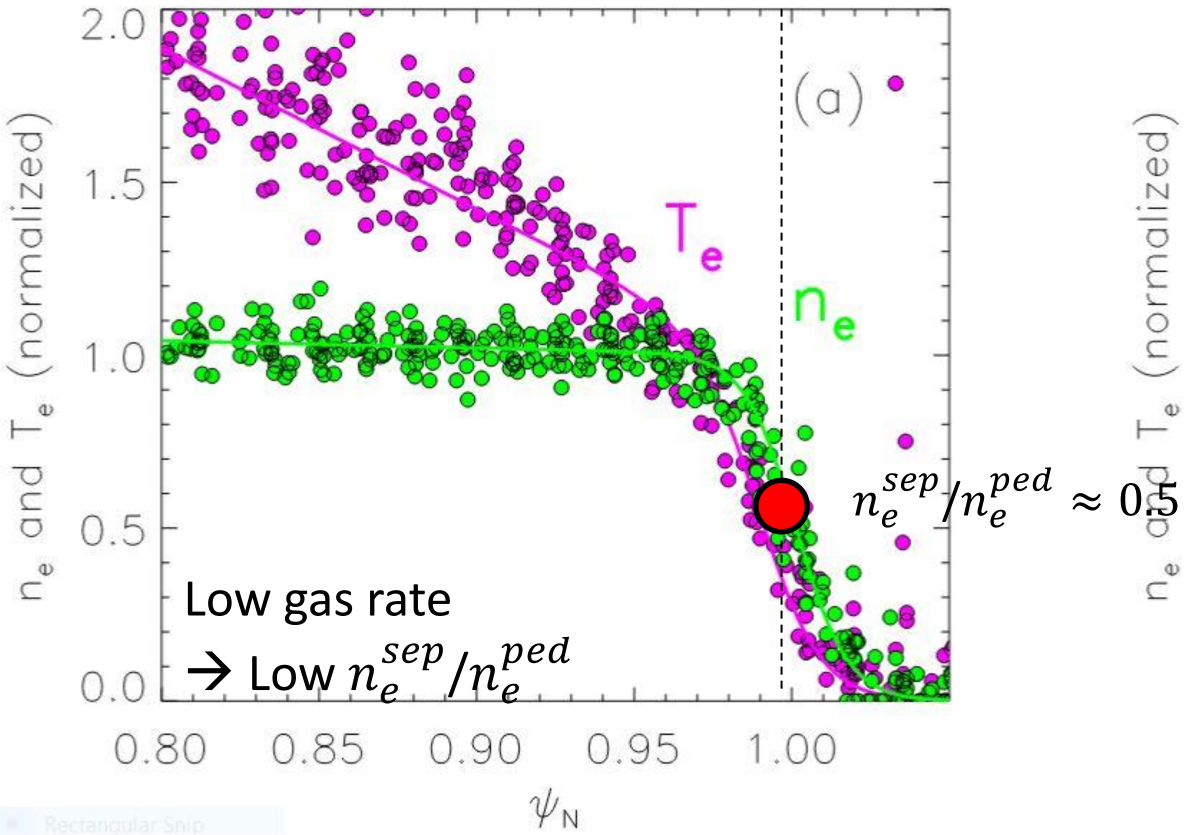
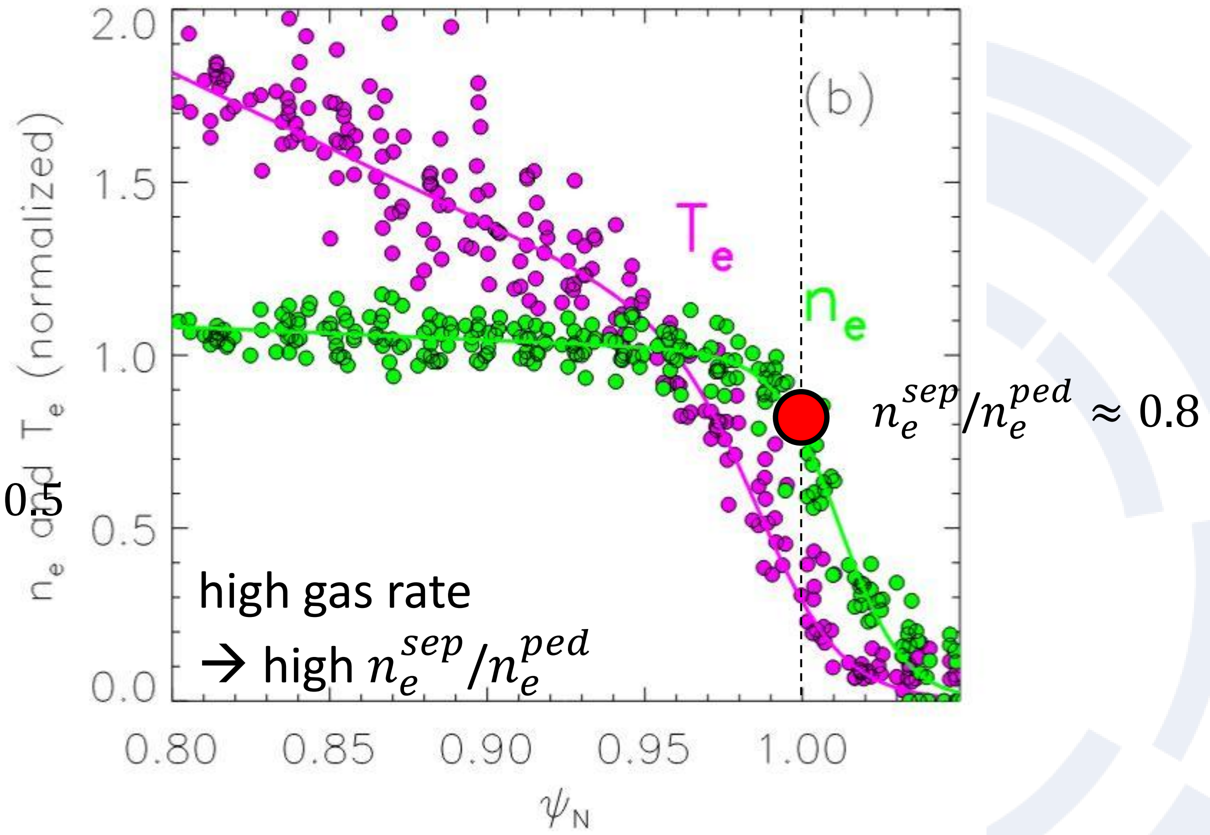


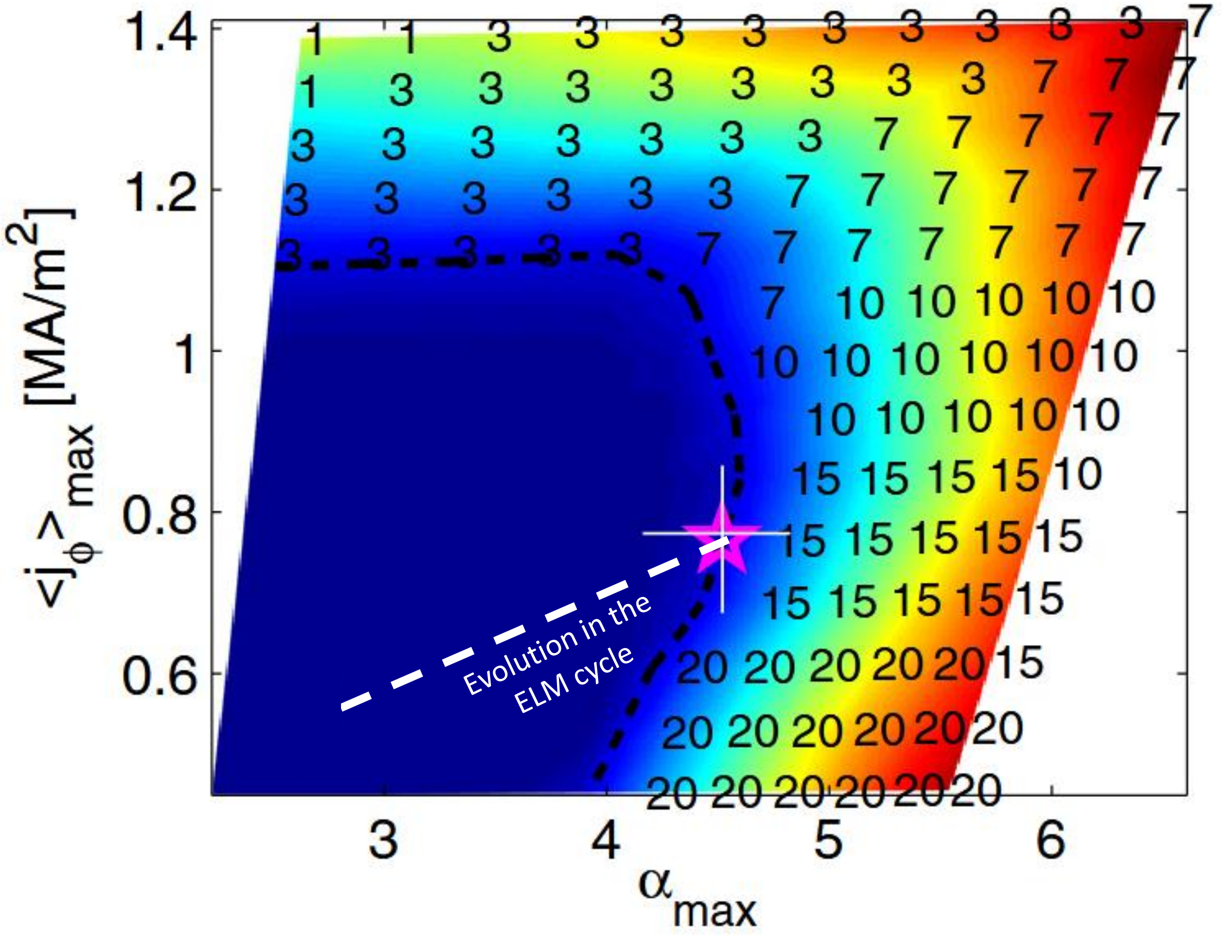


- Other important parameters are
  - The relative shift $(n_e^{pos} - T_e^{pos})$
  - The separatrix density n_e^{sep} and the ratio n_e^{sep}/n_e^{ped} → also useful to describe the effect of the gas rate

The standard picture in Type I ELMy H-modes and its issues

- In **type I ELMs**, the pedestal evolution is supposed limited by ideal MHD.

JET-C



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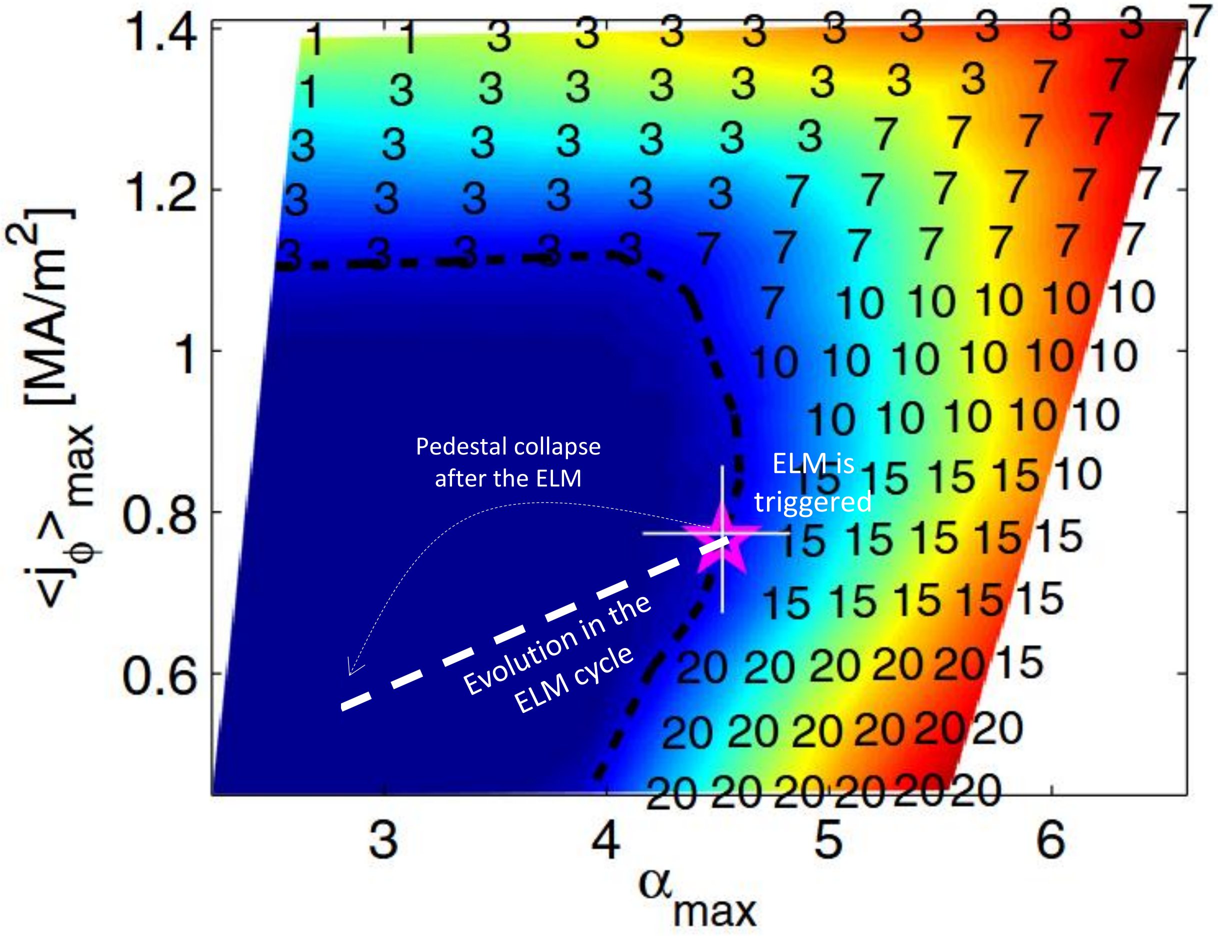

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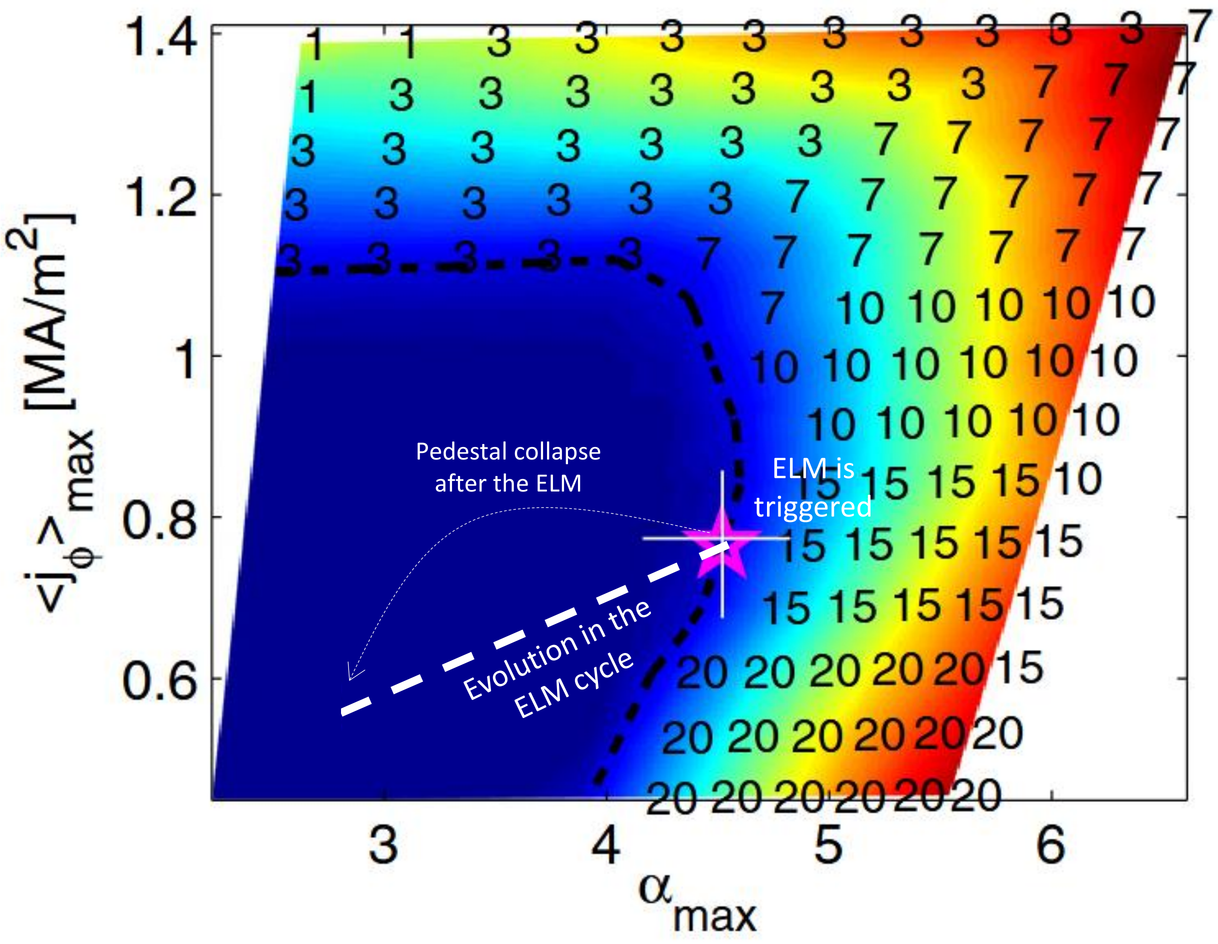

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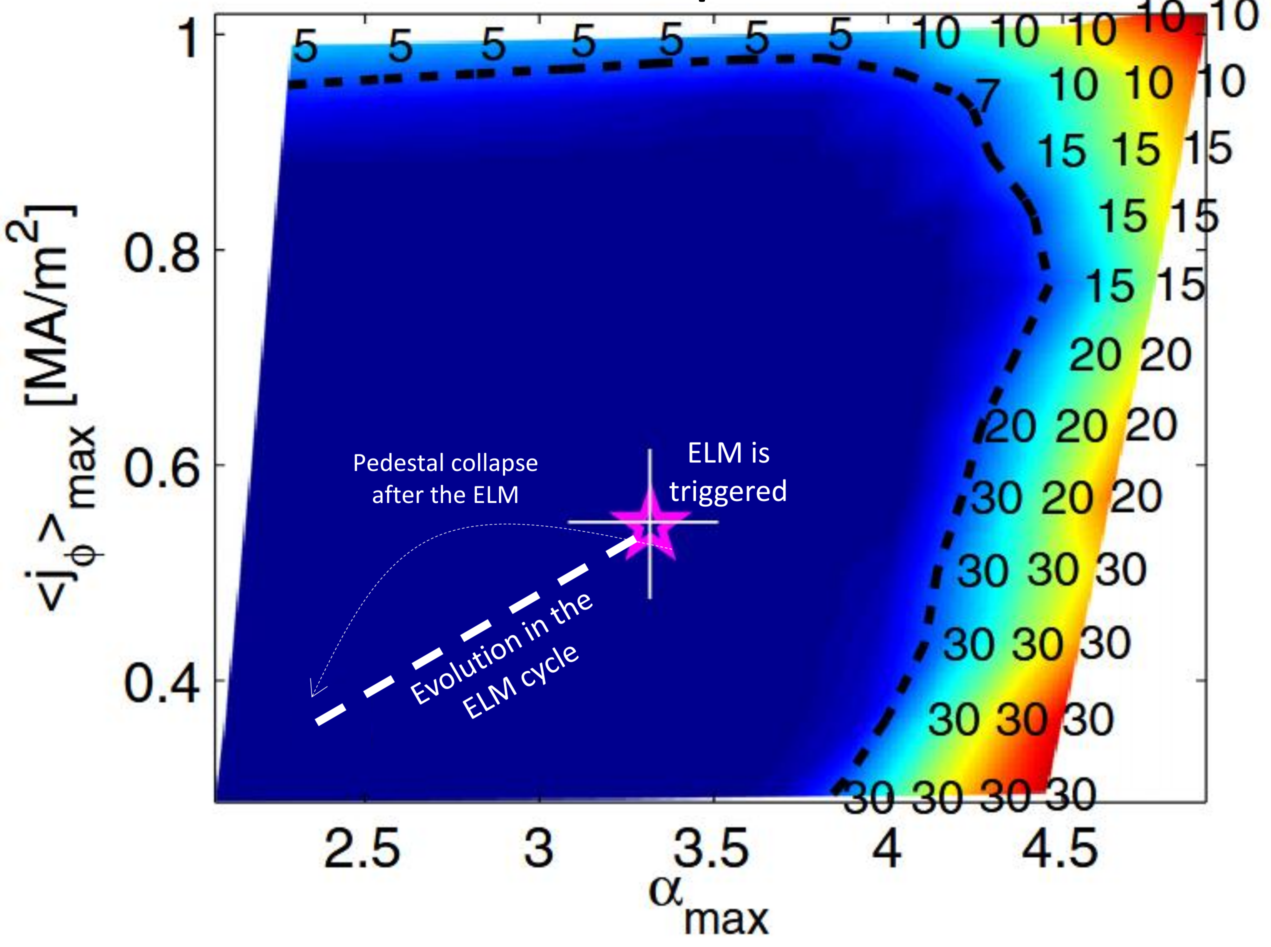
- This description is valid in many machines (DIII-D, JET-C, AUG, C-mode, NSTX…)
- However, some JET-ILW plasmas have challenged this interpretation

An example from JET-ILW



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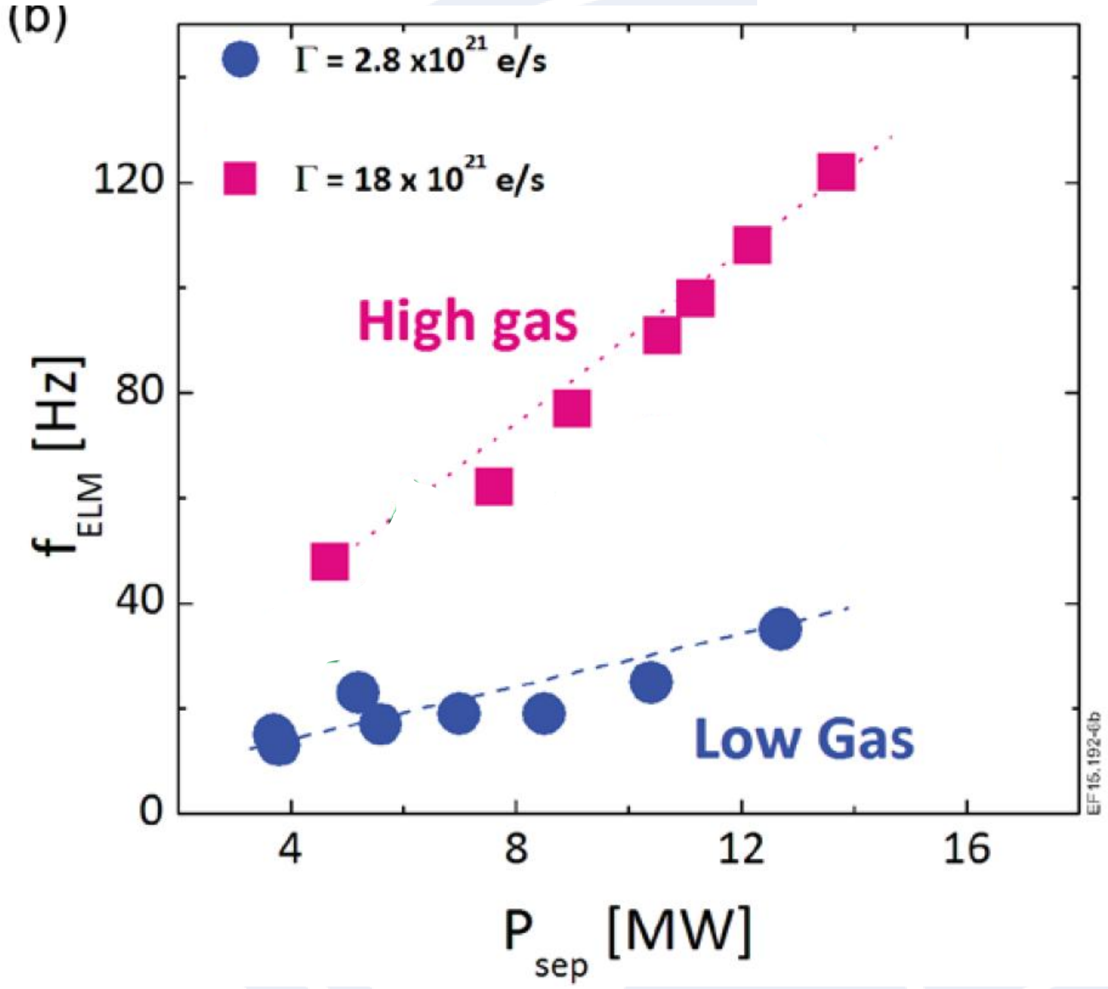

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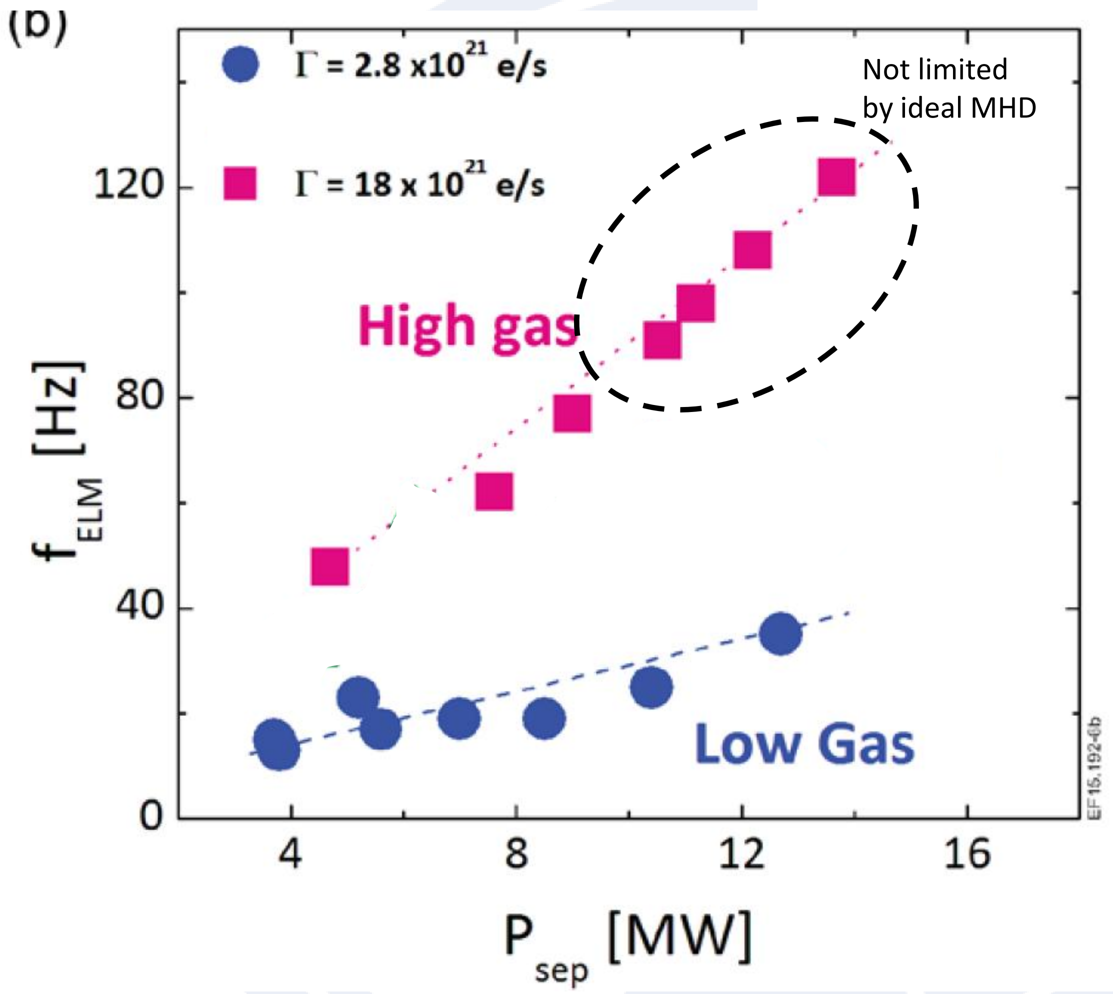

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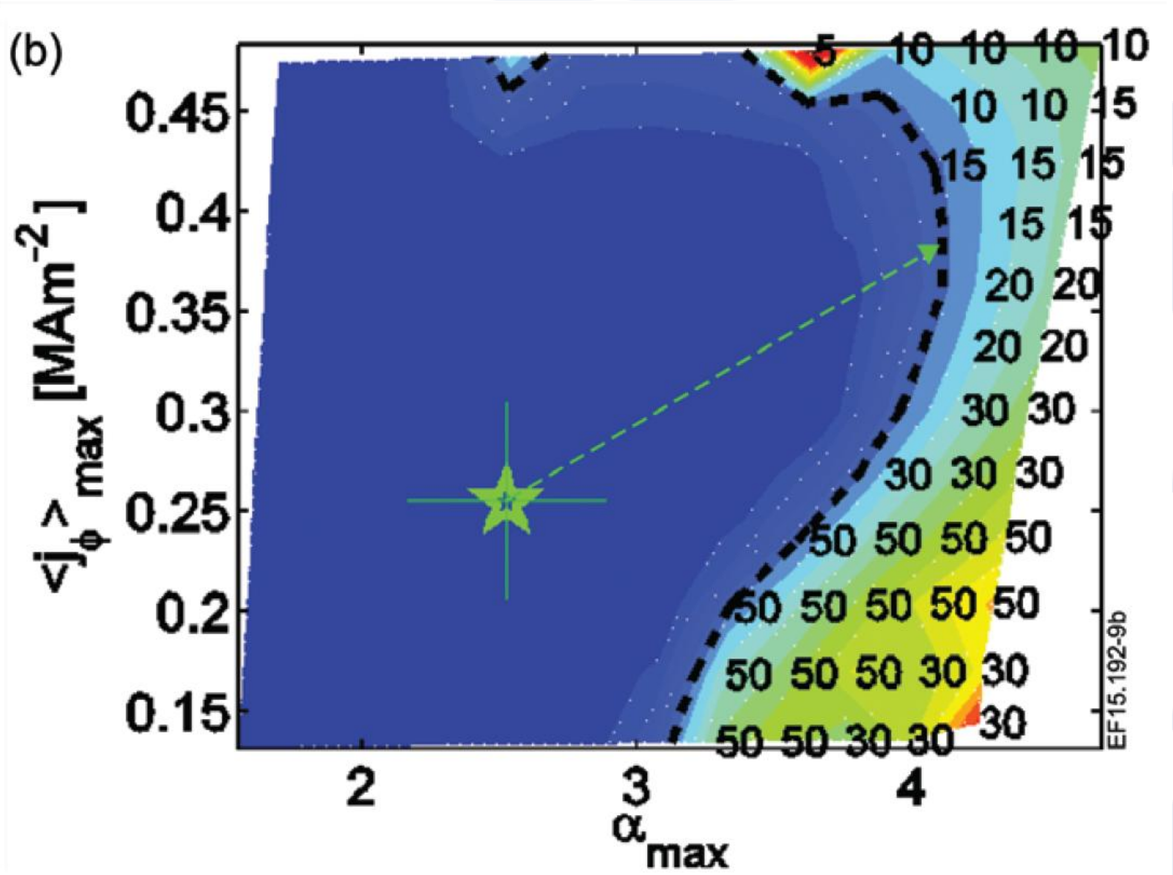

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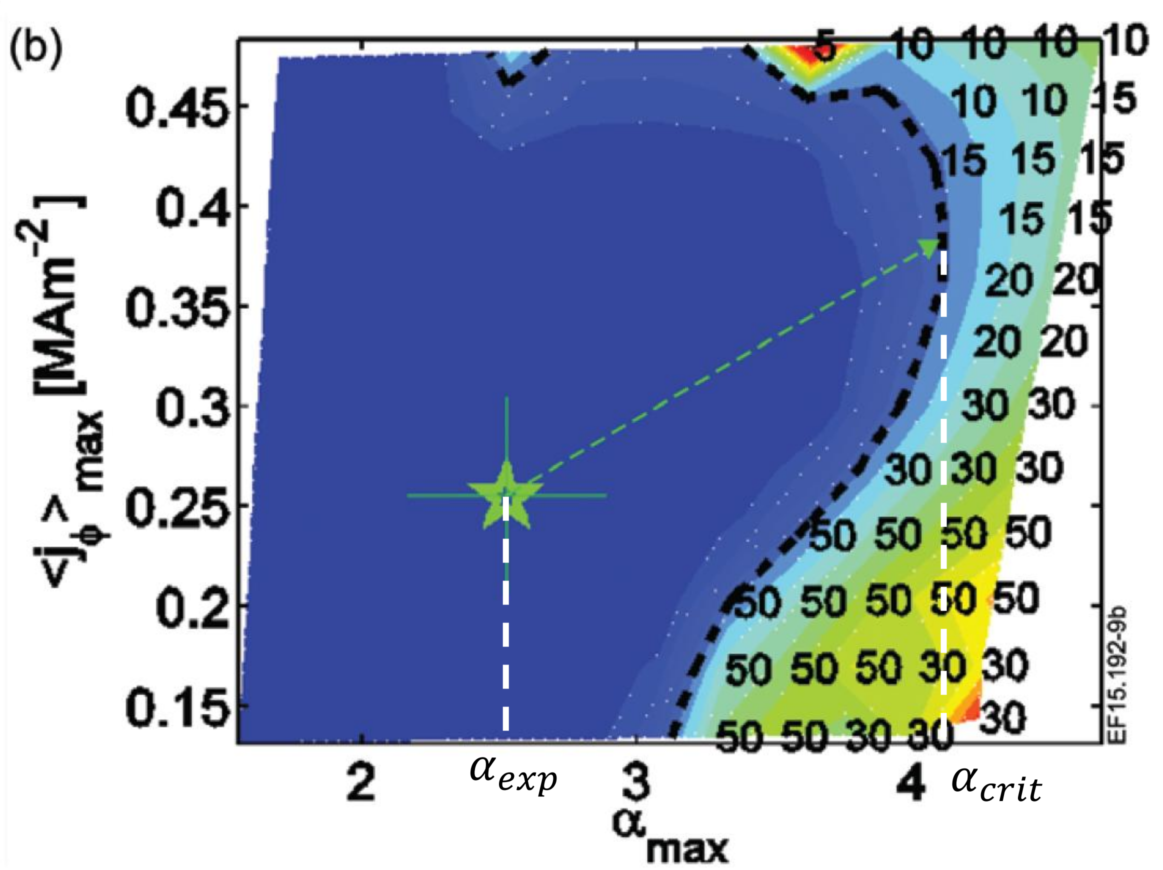
Plasma parameters linked to the disagreement

- Disagreement experimental results vs MHD stability boundary quantified as:

$$\alpha_{crit}/\alpha_{exp}$$



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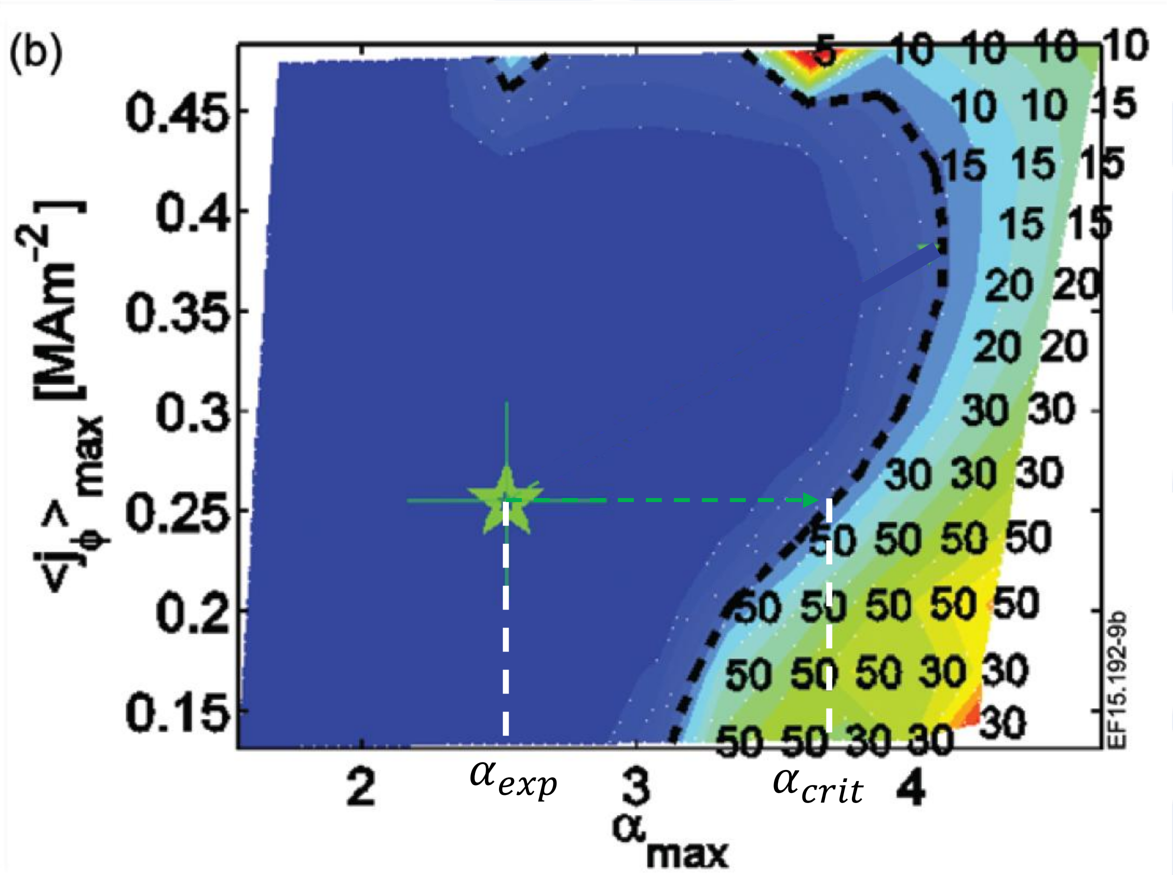

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  - $n_e^{pos} - T_e^{pos}$ (relative shift)
  - n_e^{sep}/n_e^{ped}
  - $\eta_{spitzer}^{foot}$ (resistivity at the pedestal foot)

[Frassinetti NF2021]

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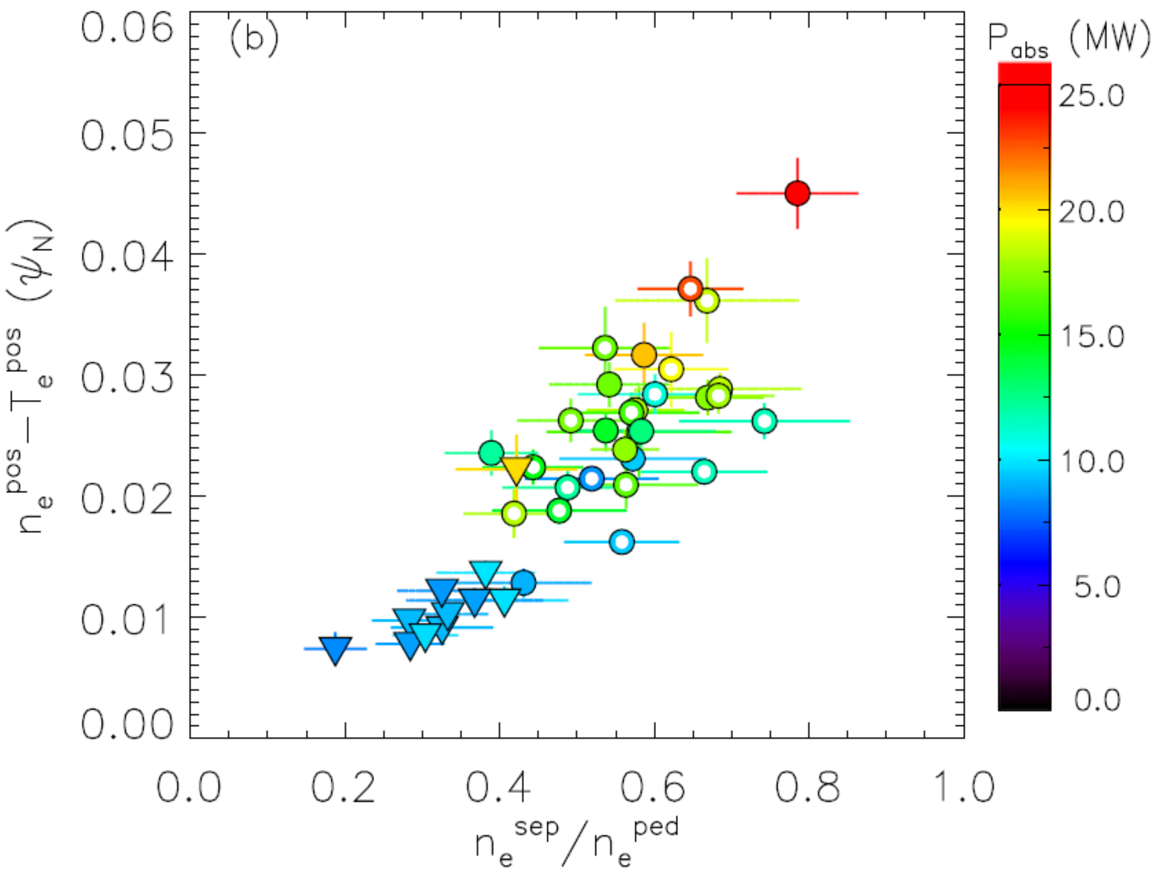

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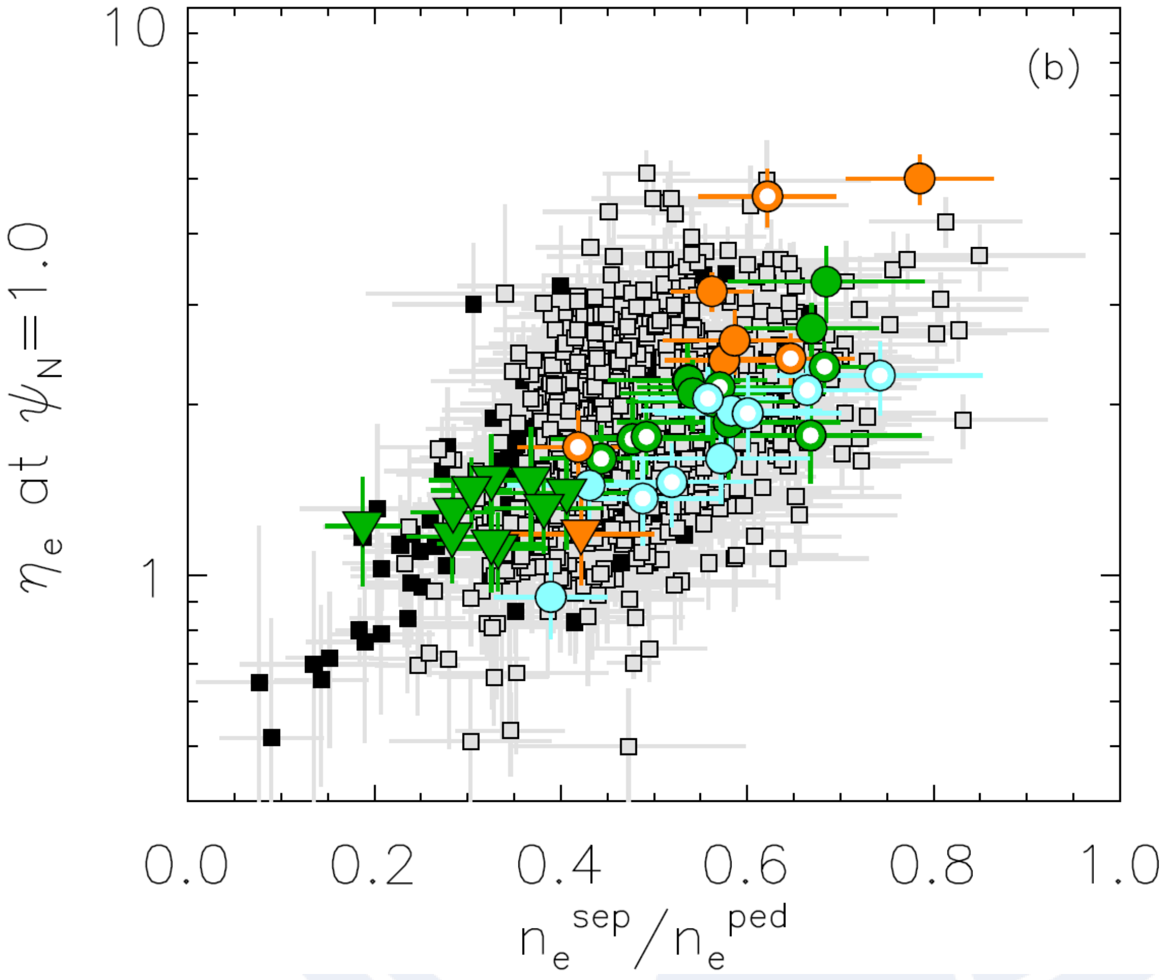

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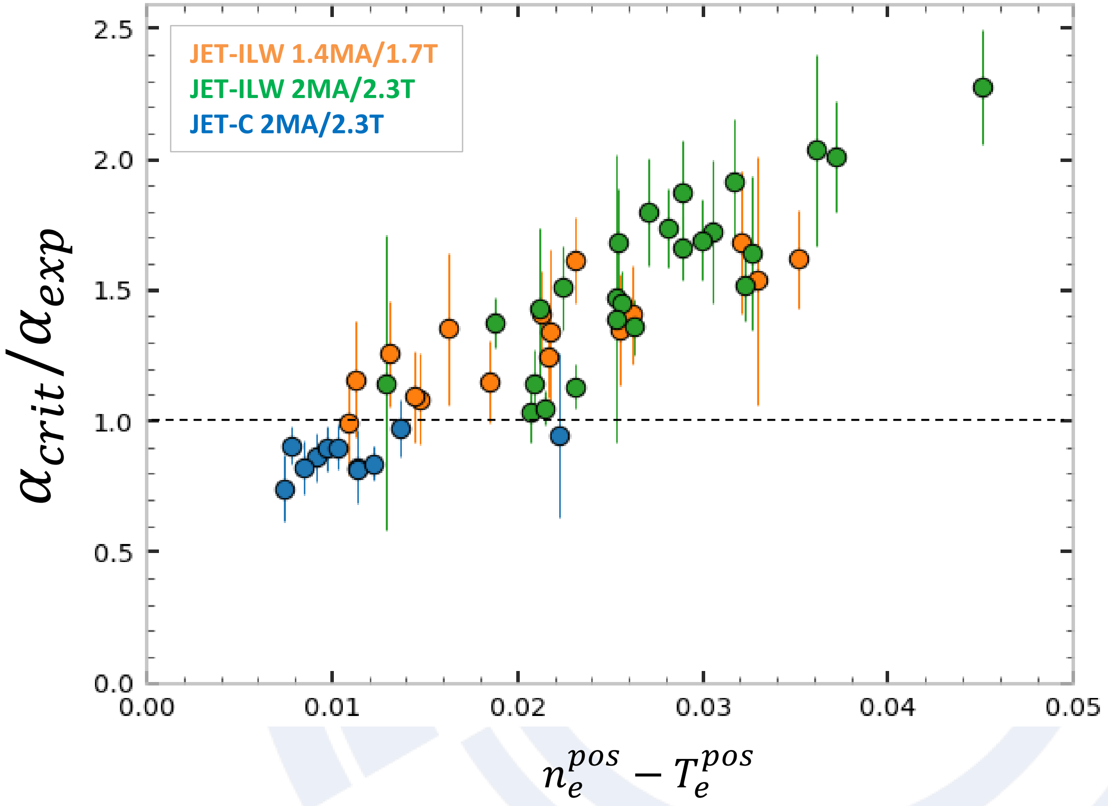

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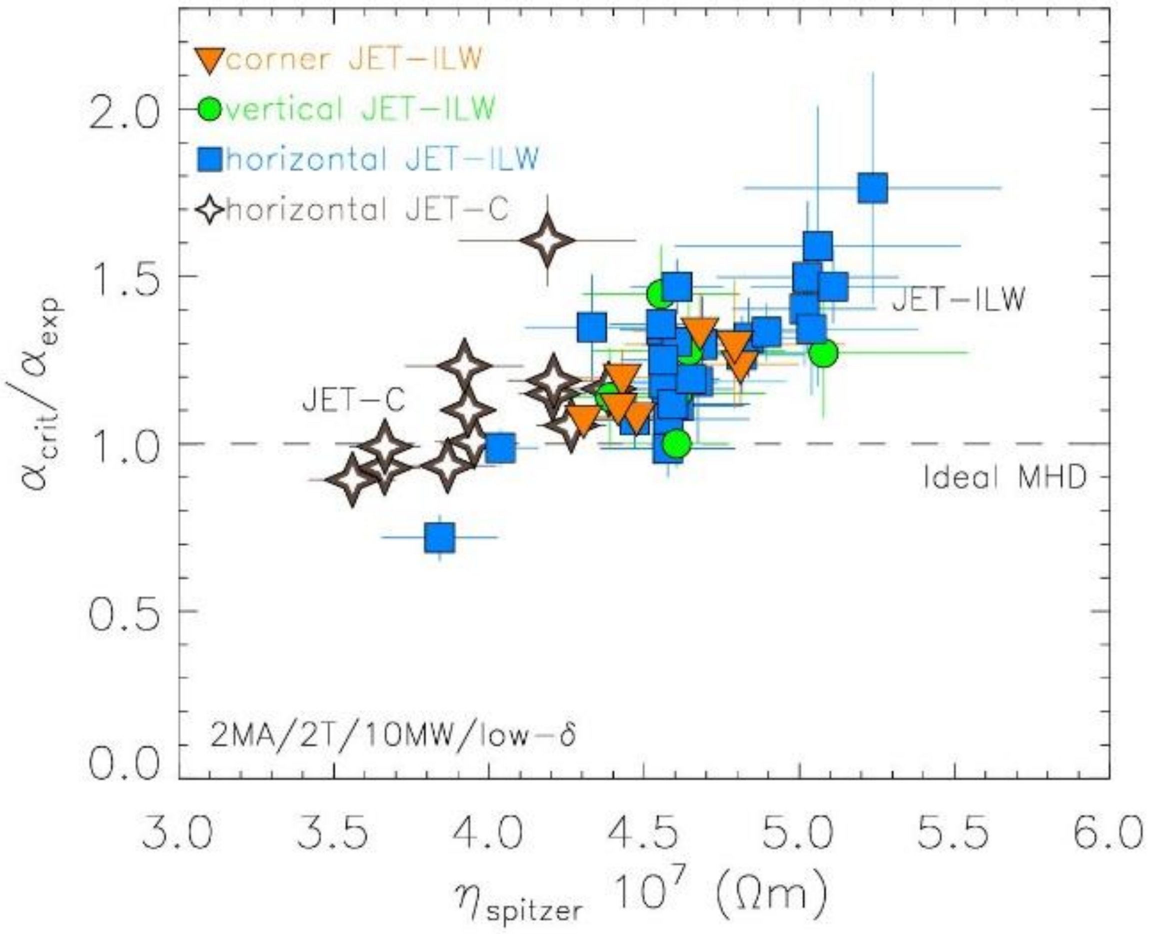

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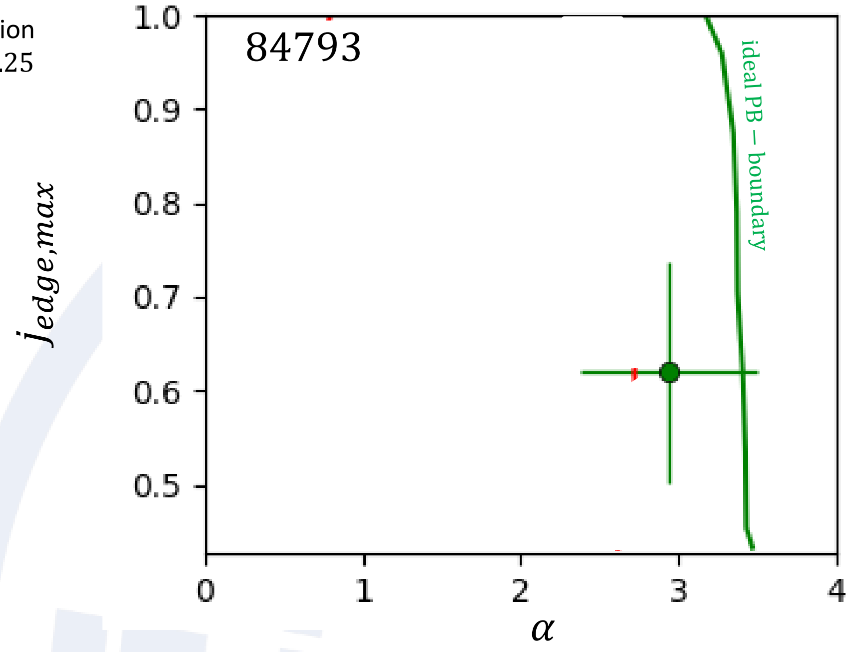
    - $\eta_{sp} = 0$ near the stability boundary

Diamagnetic criterion used $\gamma/\omega^*_{max} = 0.25$



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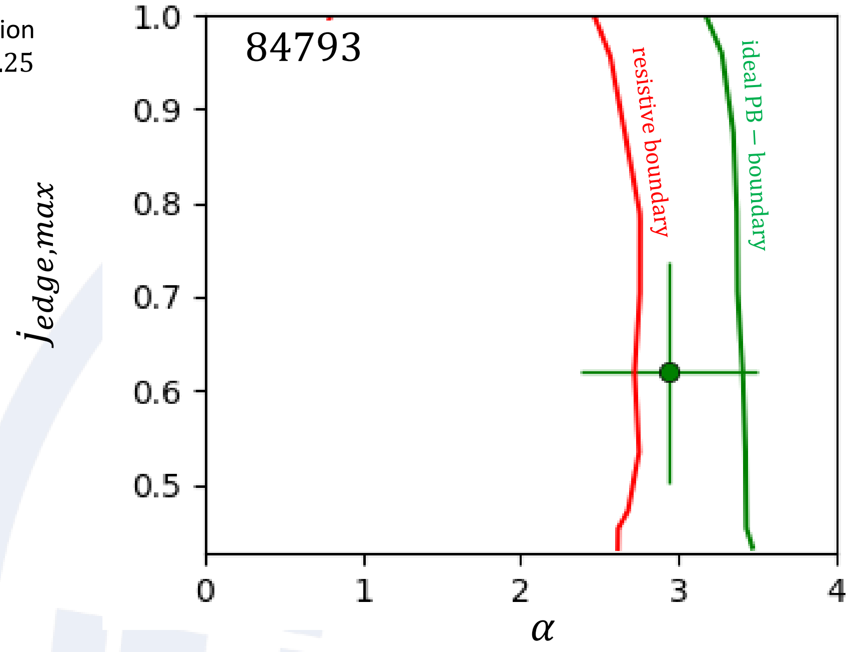

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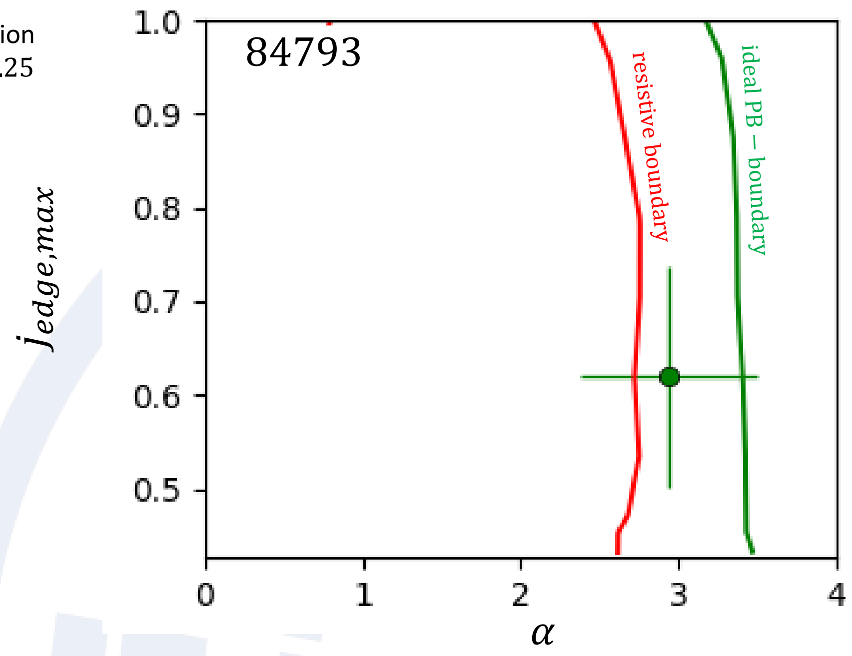

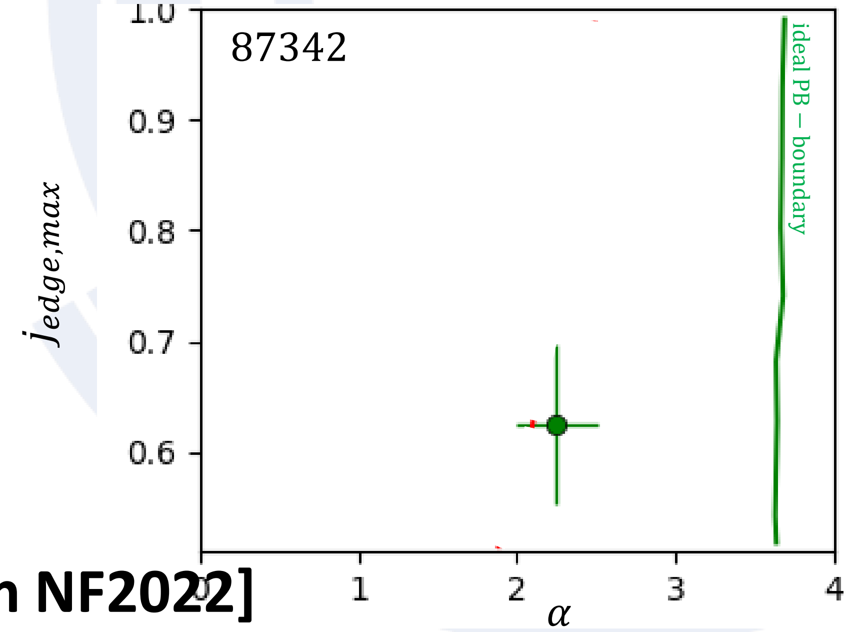

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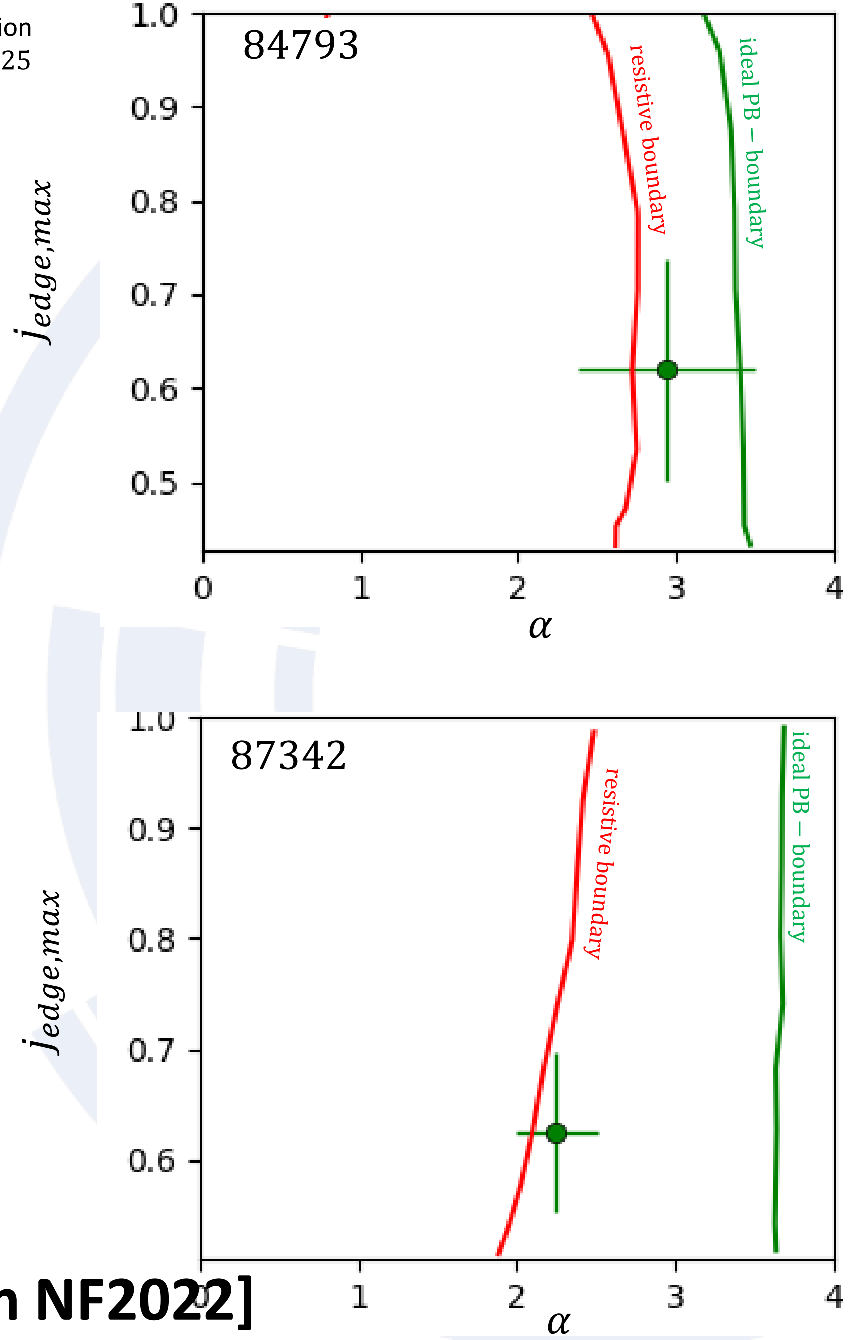
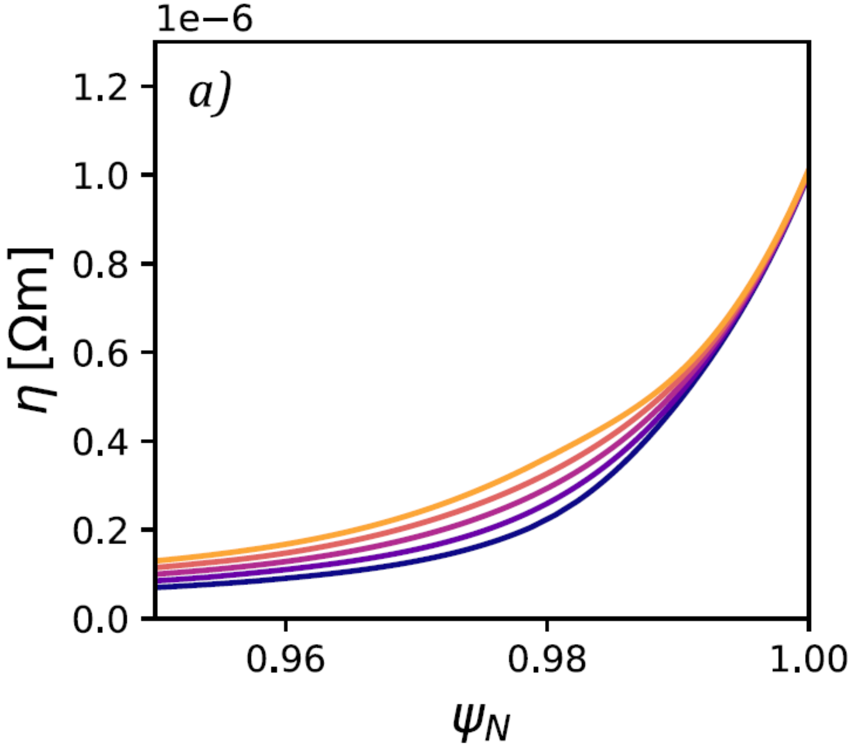


[Nyström NF2022]

Resistivity at the pedestal foot has the major effect



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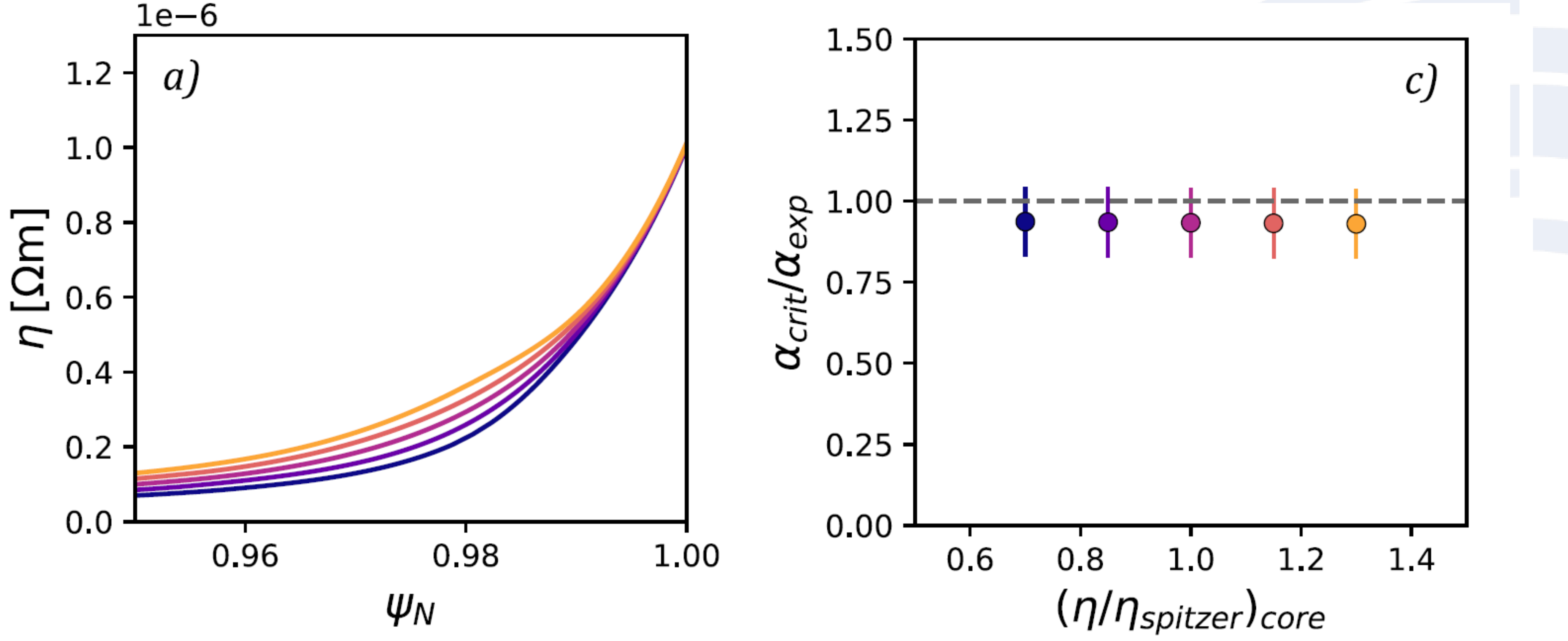

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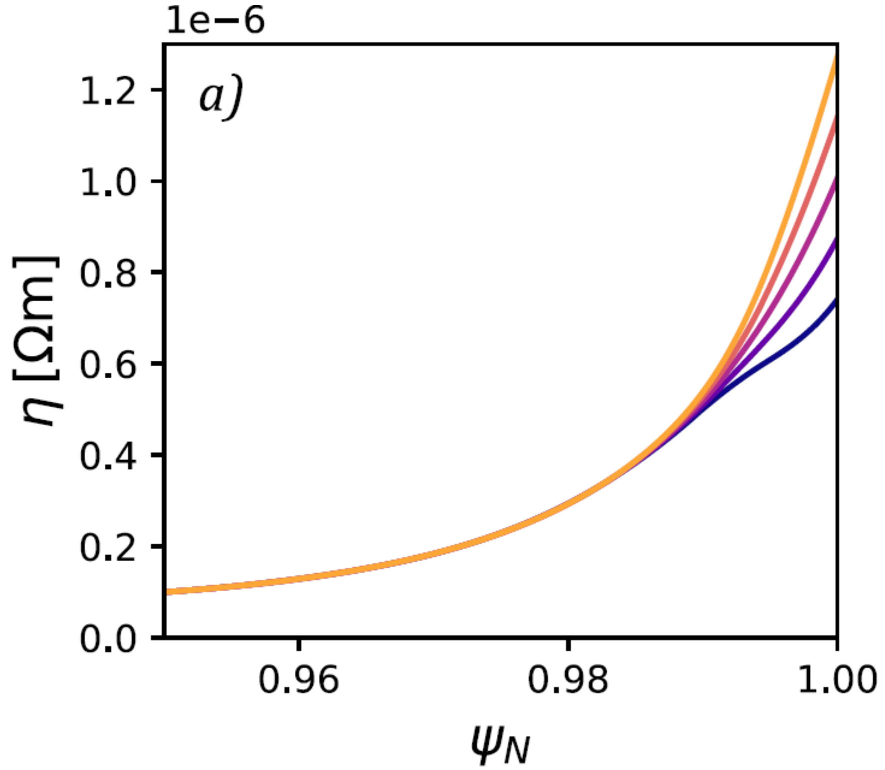

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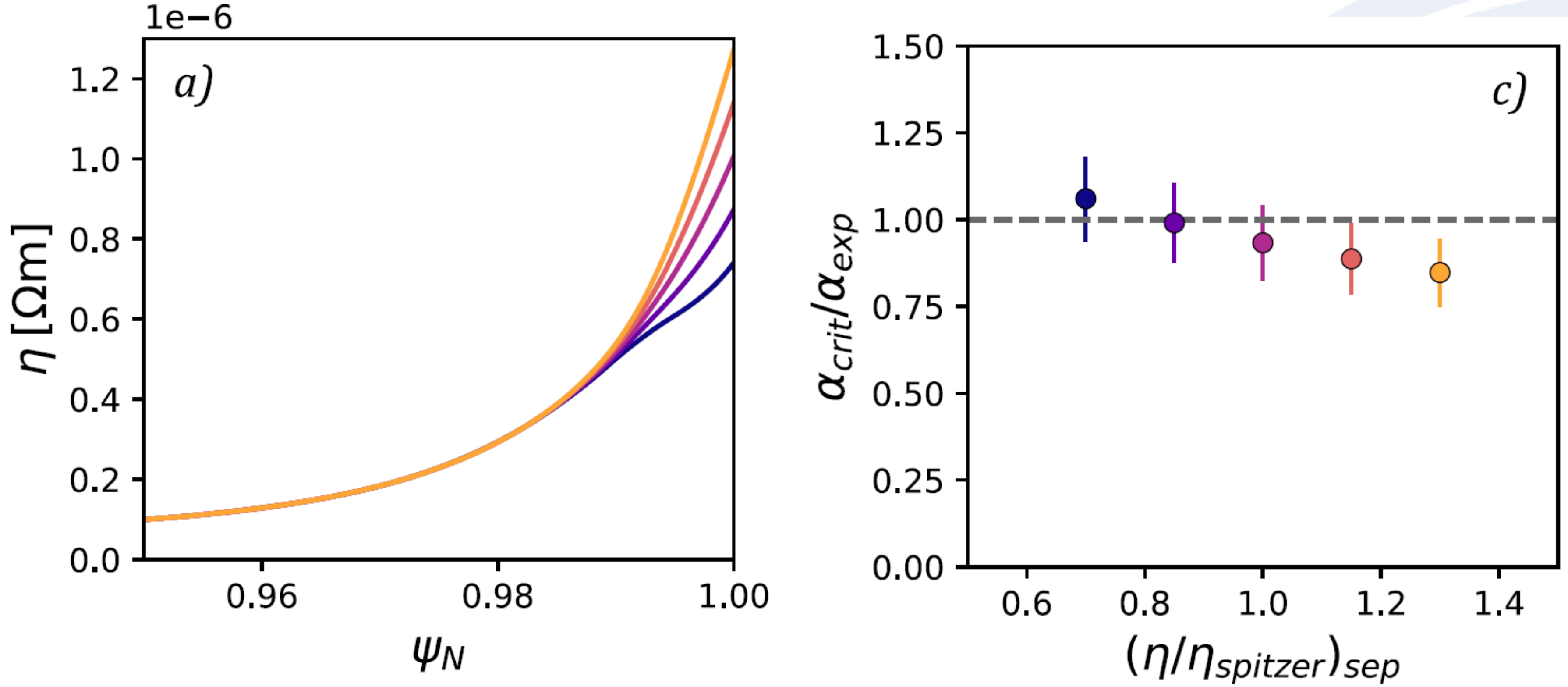

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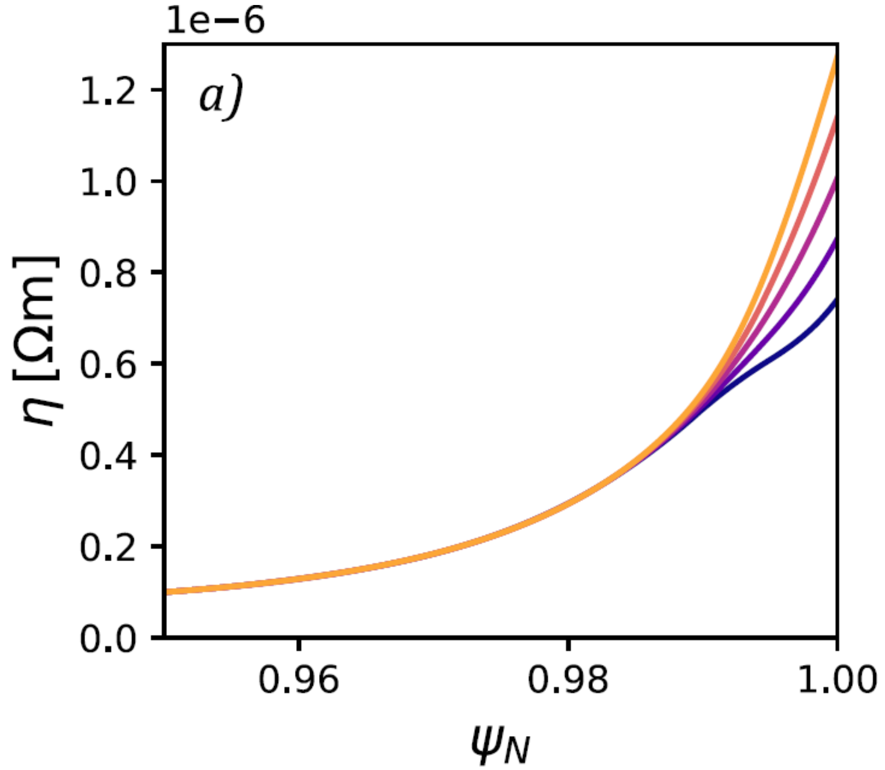

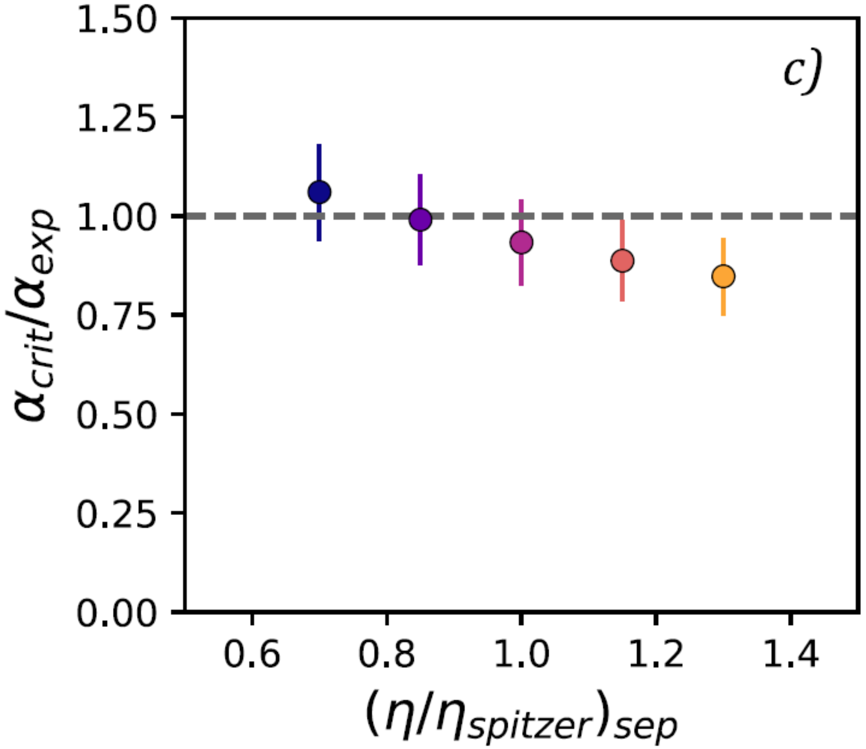

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- We have artificially varied the resistivity:
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- Important result:

  resistive effects might be important also in high T_e^{ped} plasmas

Application to a large dataset

JET-ILW 1.4MA/1.7T
JET-ILW 2MA/2.3T
JET-C 2MA/2.3T

- Resistive MHD has been applied to 3 datasets:
  - JET-ILW, 1.4MA/1.7T power and gas scans
  - JET-ILW, 2.0MA/2.3T power and gas scans
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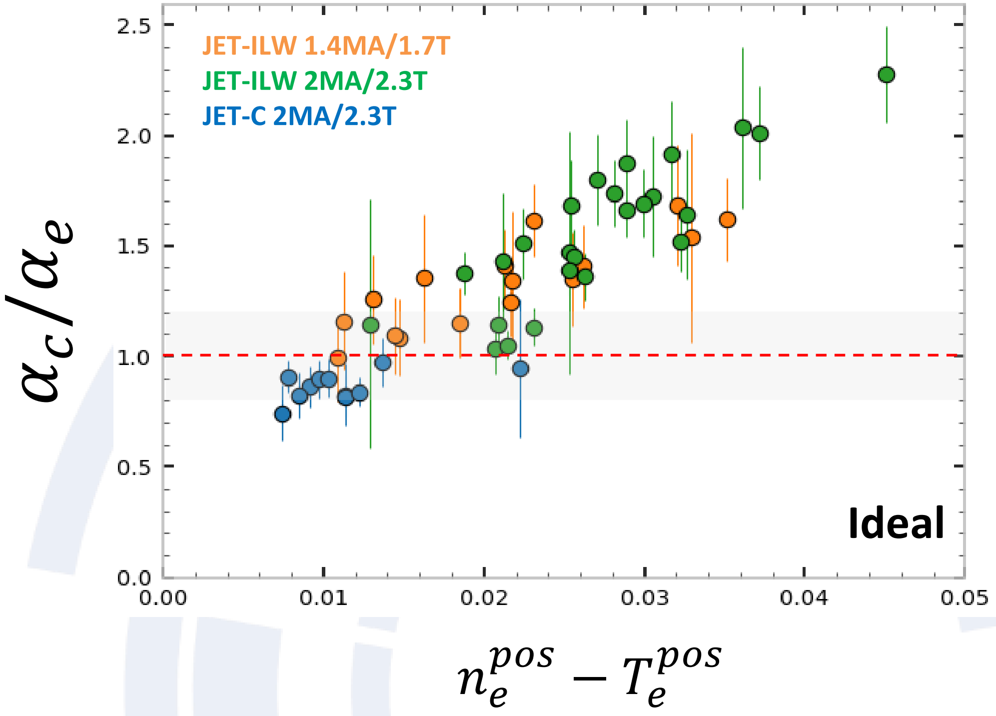
  - The disagreement increases systematically with increasing $n_e^{pos} - T_e^{pos}$



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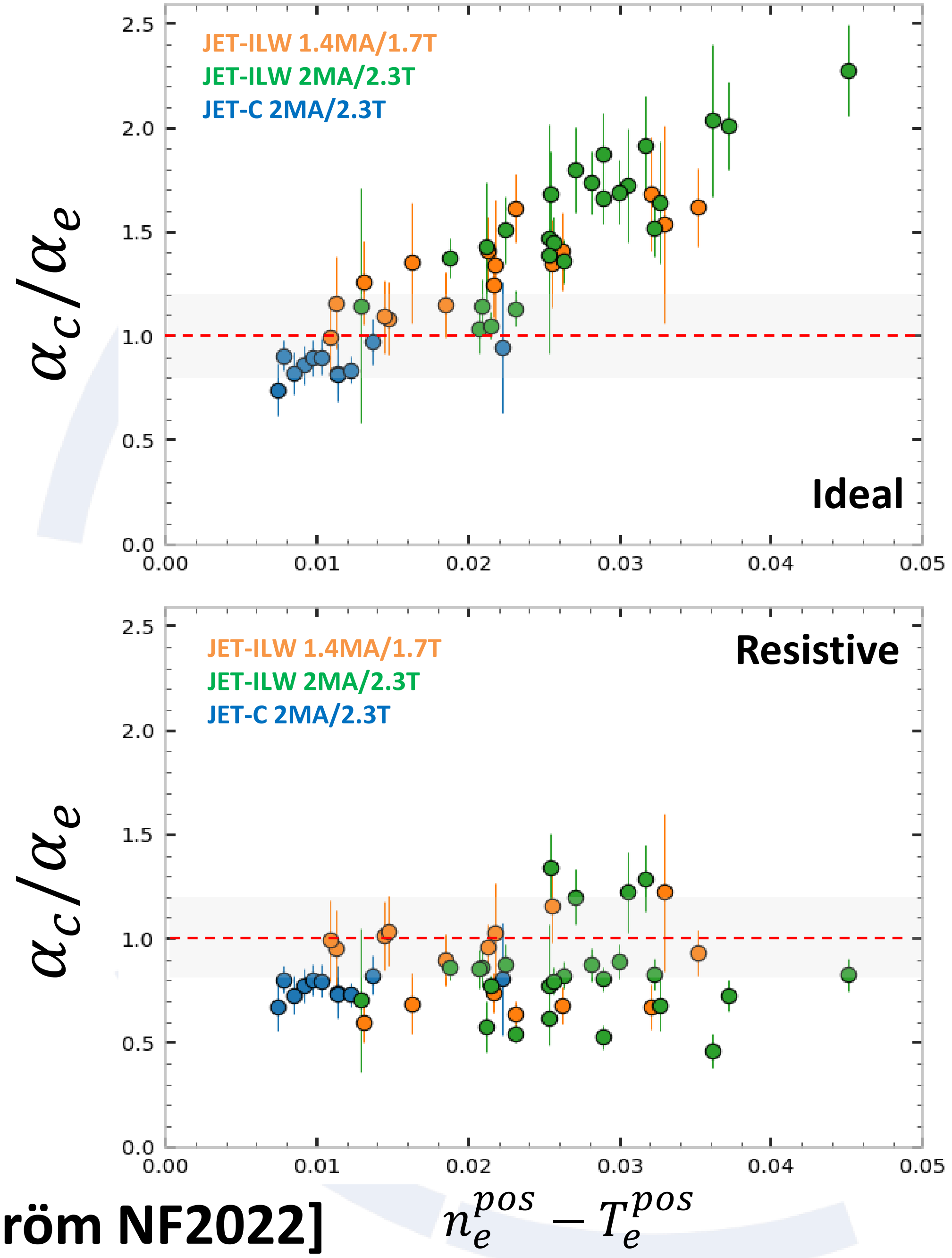
- Resistive MHD (CASTOR with $\eta = \eta_{sp}$):
  - Trend with $n_e^{pos} - T_e^{pos}$ removed
  - Major improvement achieved, but not perfect agreement



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Some key results on pedestal physics obtained during DTE2

Dataset at 2MA/2.3T, constant gas rate and constant β_N

- Effect of the isotope mass on medium/high collisionality ballooning limited pedestal studied during JET-ILW DTE2 campaign

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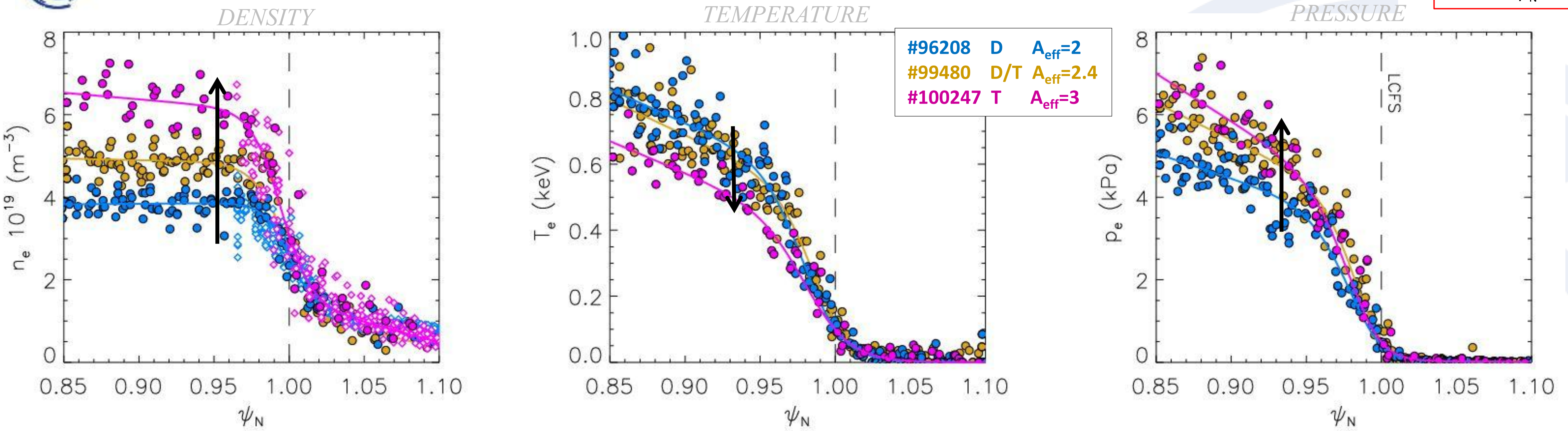

- Effect of the isotope mass on medium/high collisionality ballooning limited pedestal studied during JET-ILW DTE2 campaign
- Increasing the isotope mass from D to T leads to:
  - signifcant increase in n_e^{ped}
  - no major effect on T_e^{ped}
  - increase in p_e^{ped}

[Frassinetti NF2023, Schneider NF2023]

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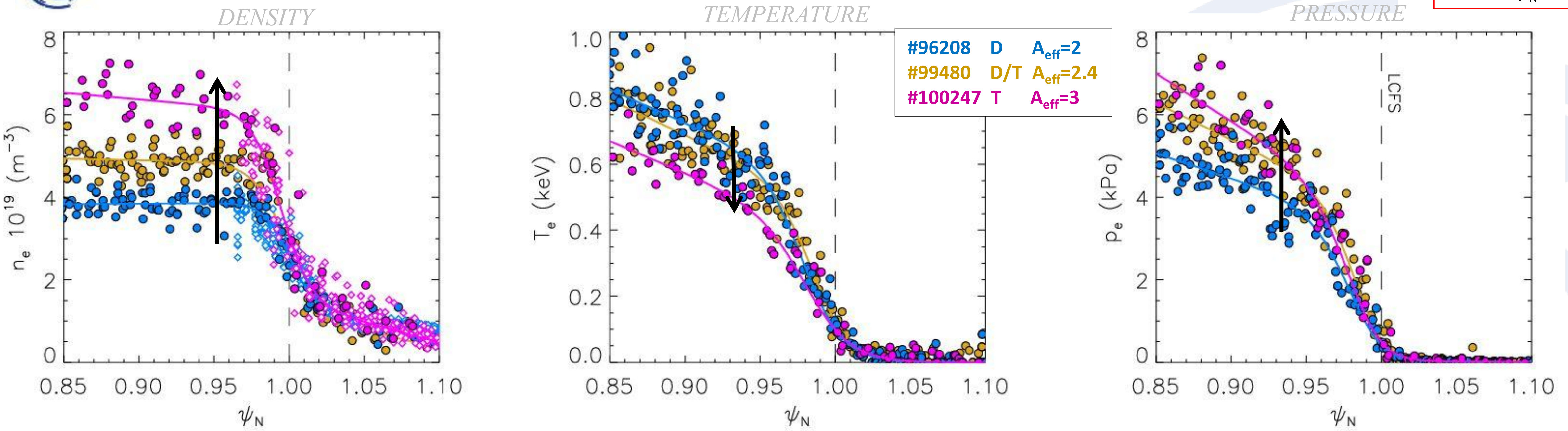

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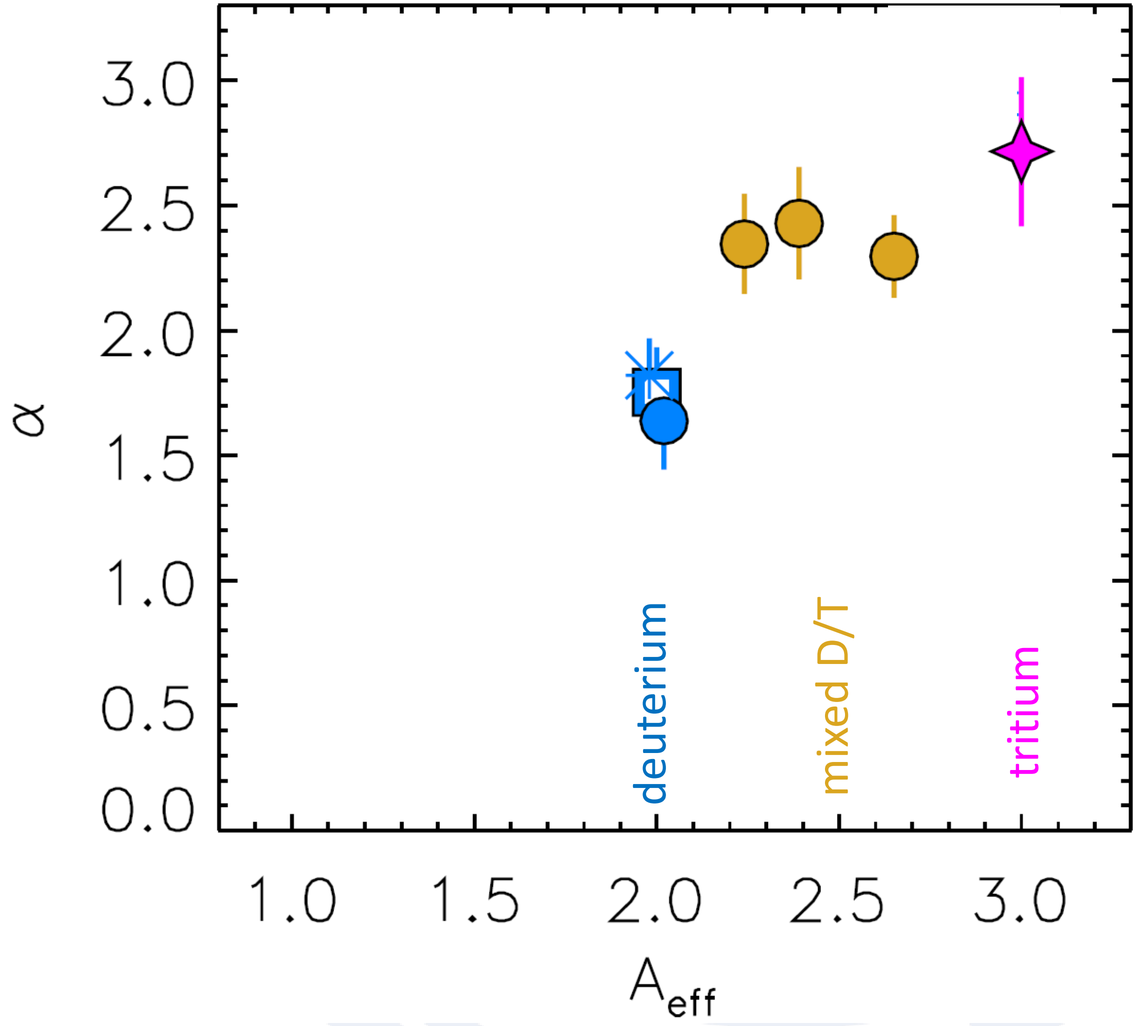
Due to variation in the gradients, not in the pedestal width

[Frassinetti NF2023, Schneider NF2023]

Some key results on pedestal physics obtained during DTE2

- Normalized pressure gradient increases with increasing isotope mass



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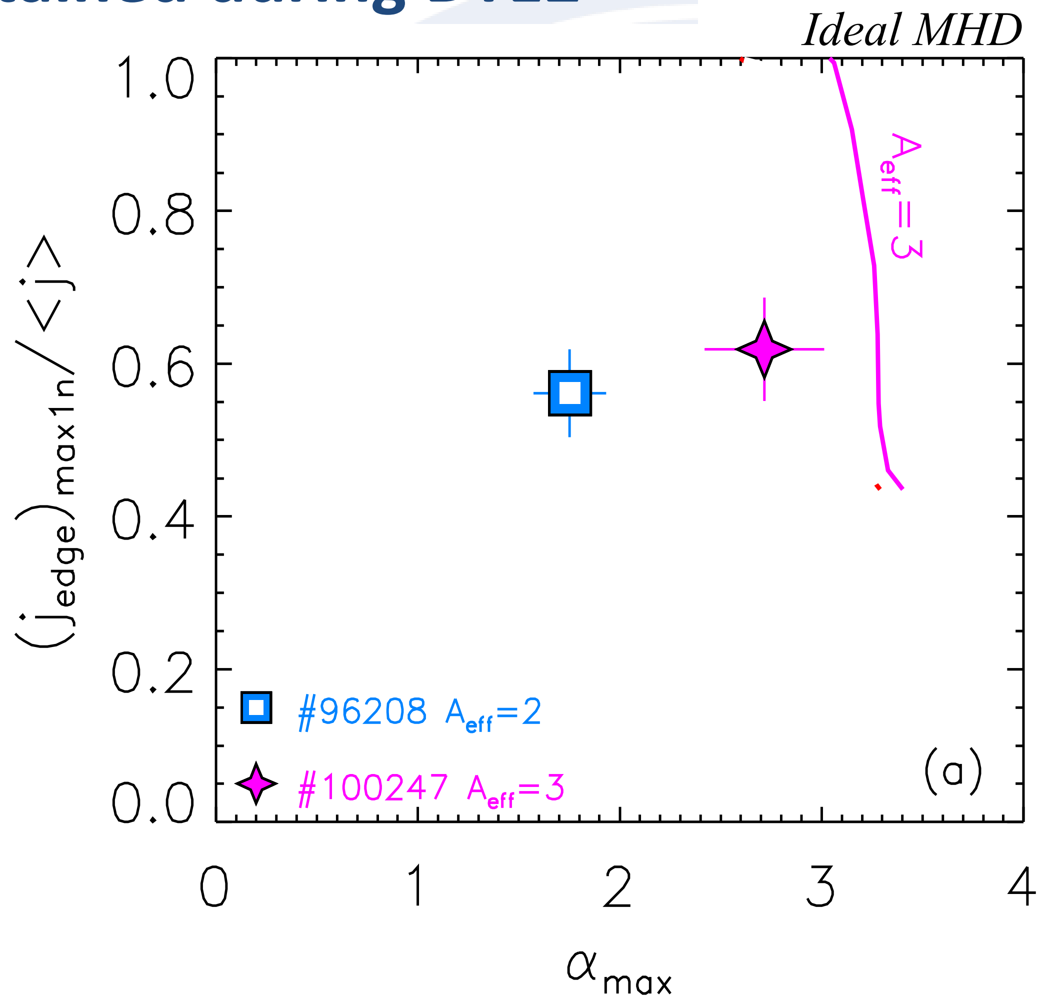

[Frassinetti NF2023]

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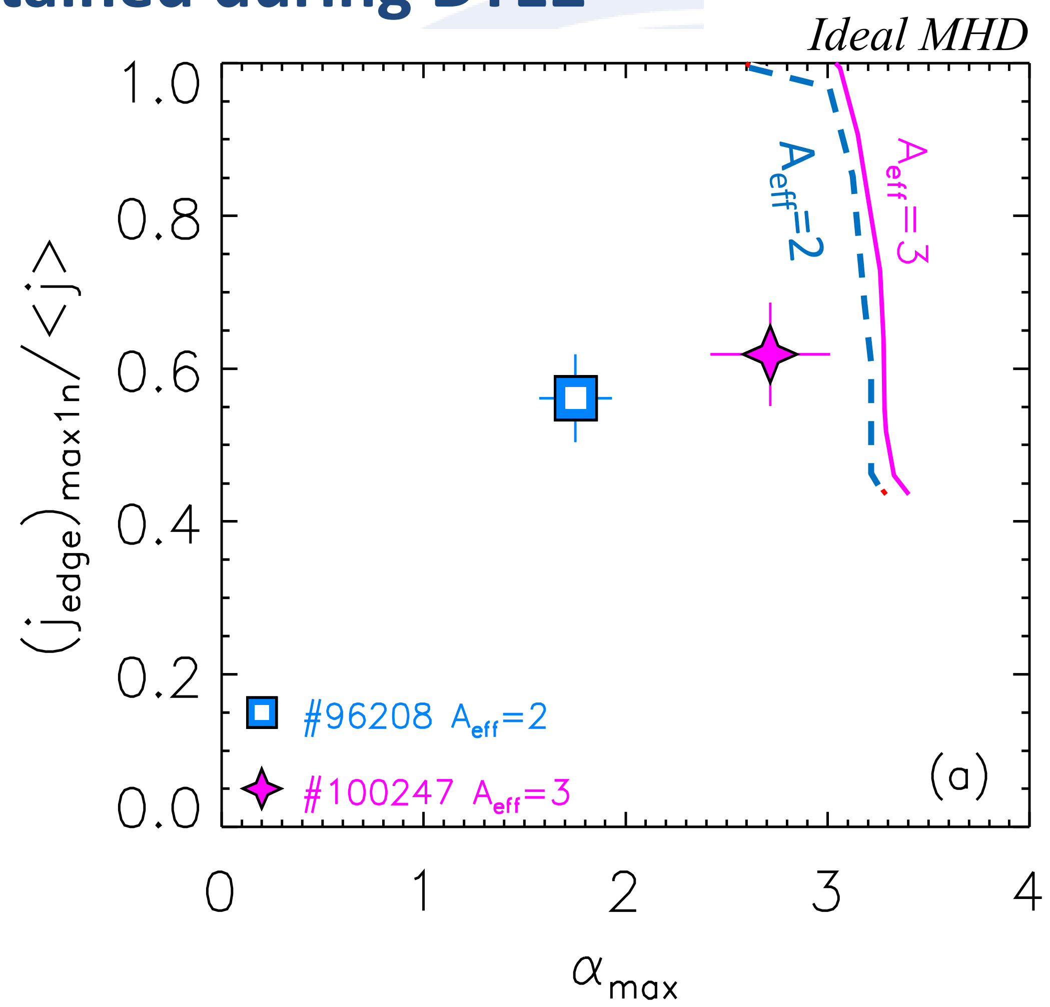

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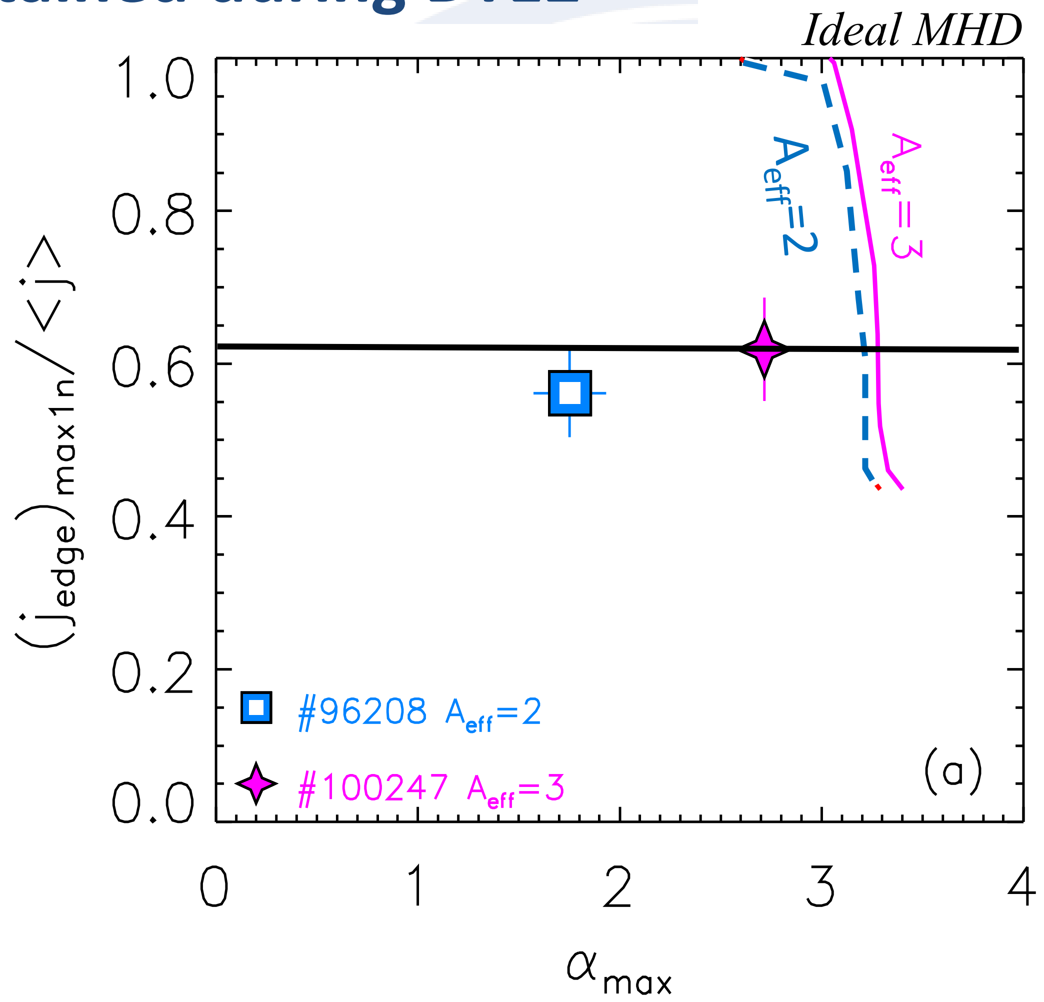

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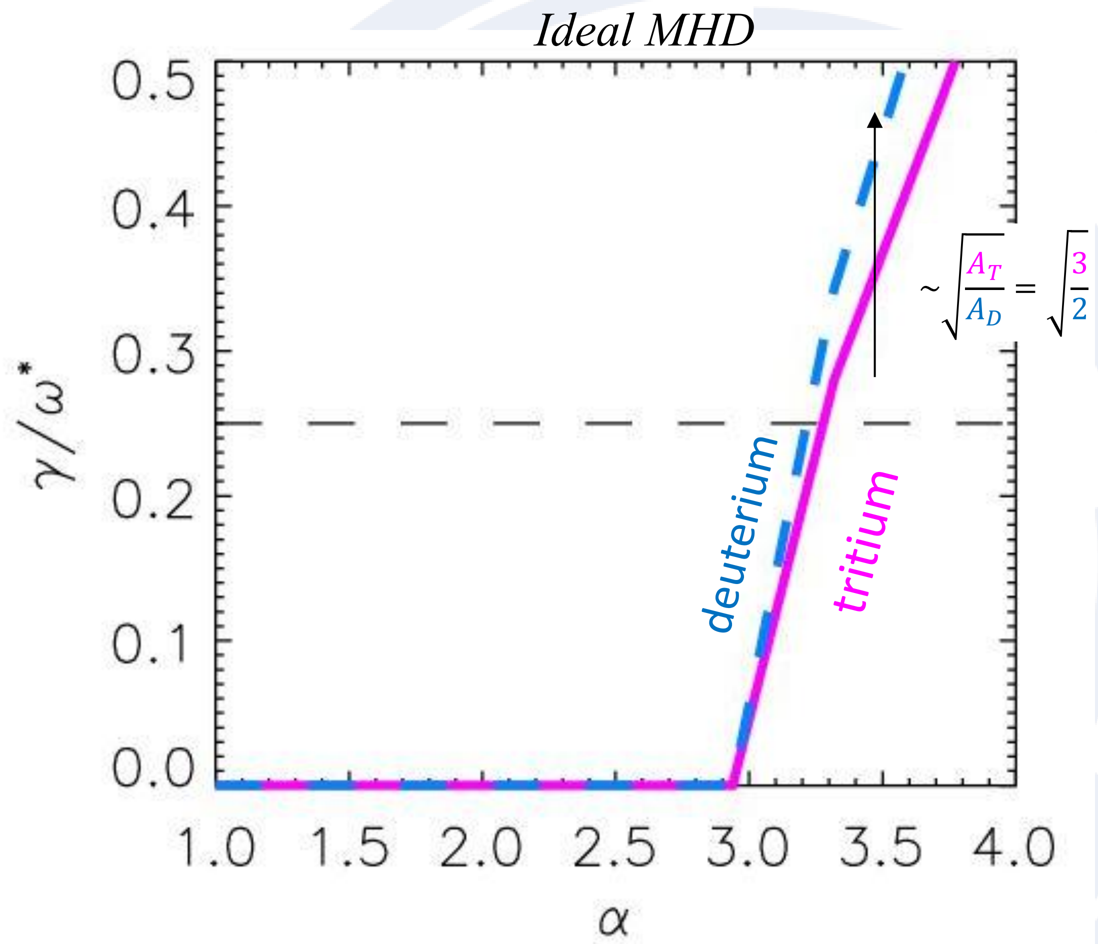

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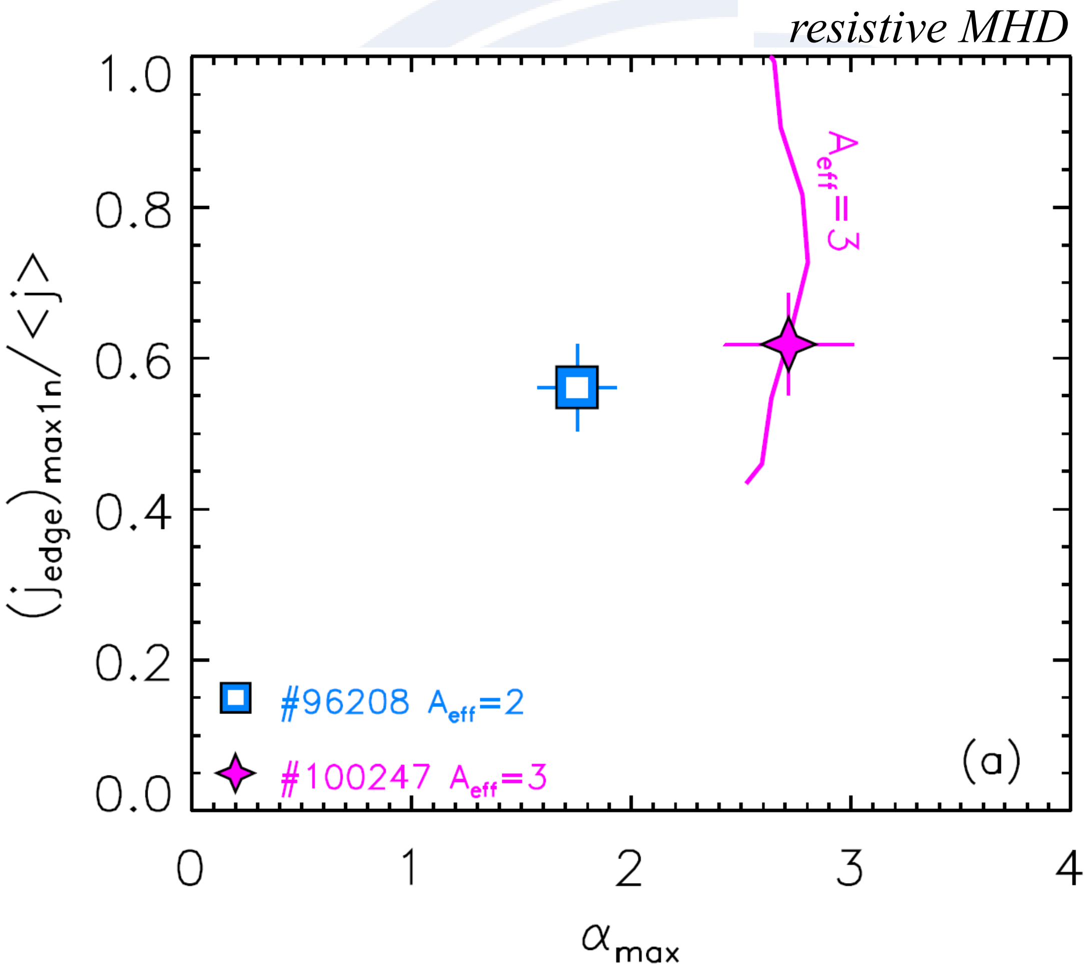

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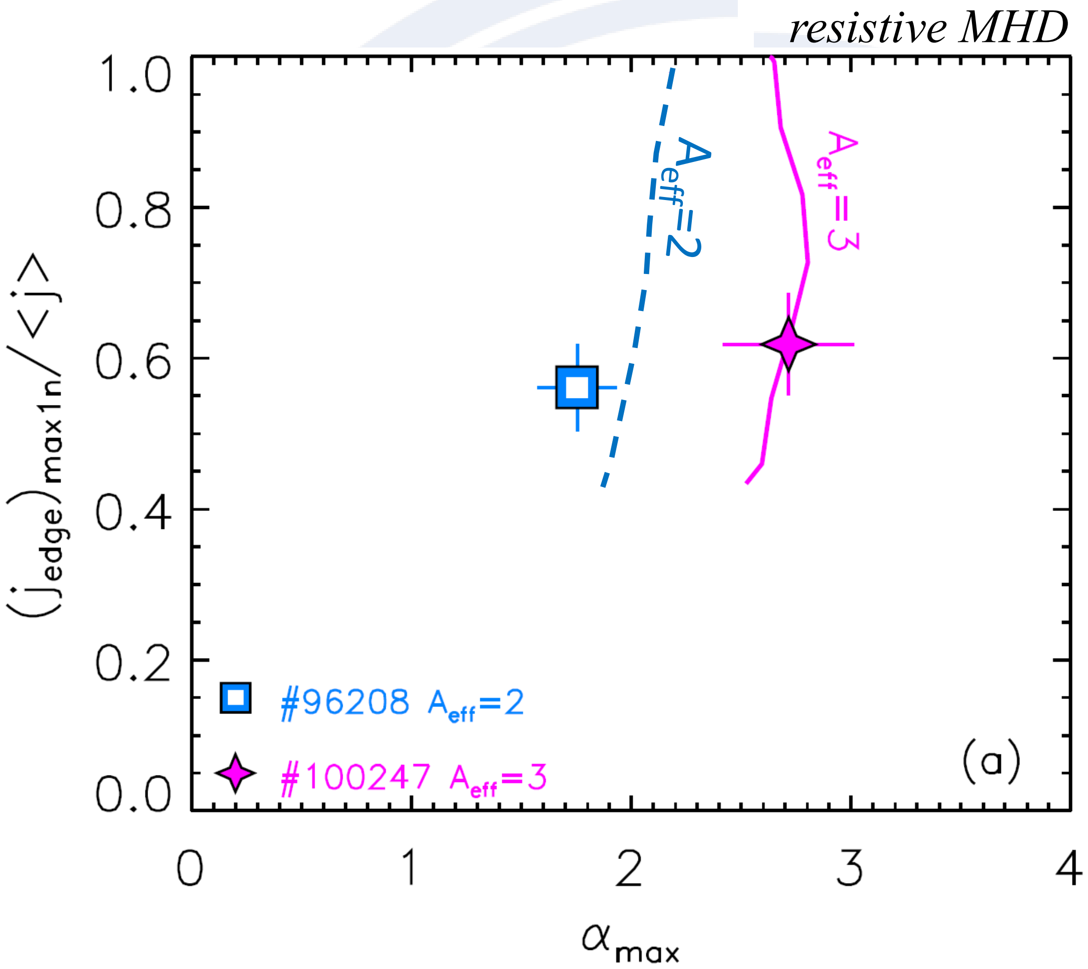

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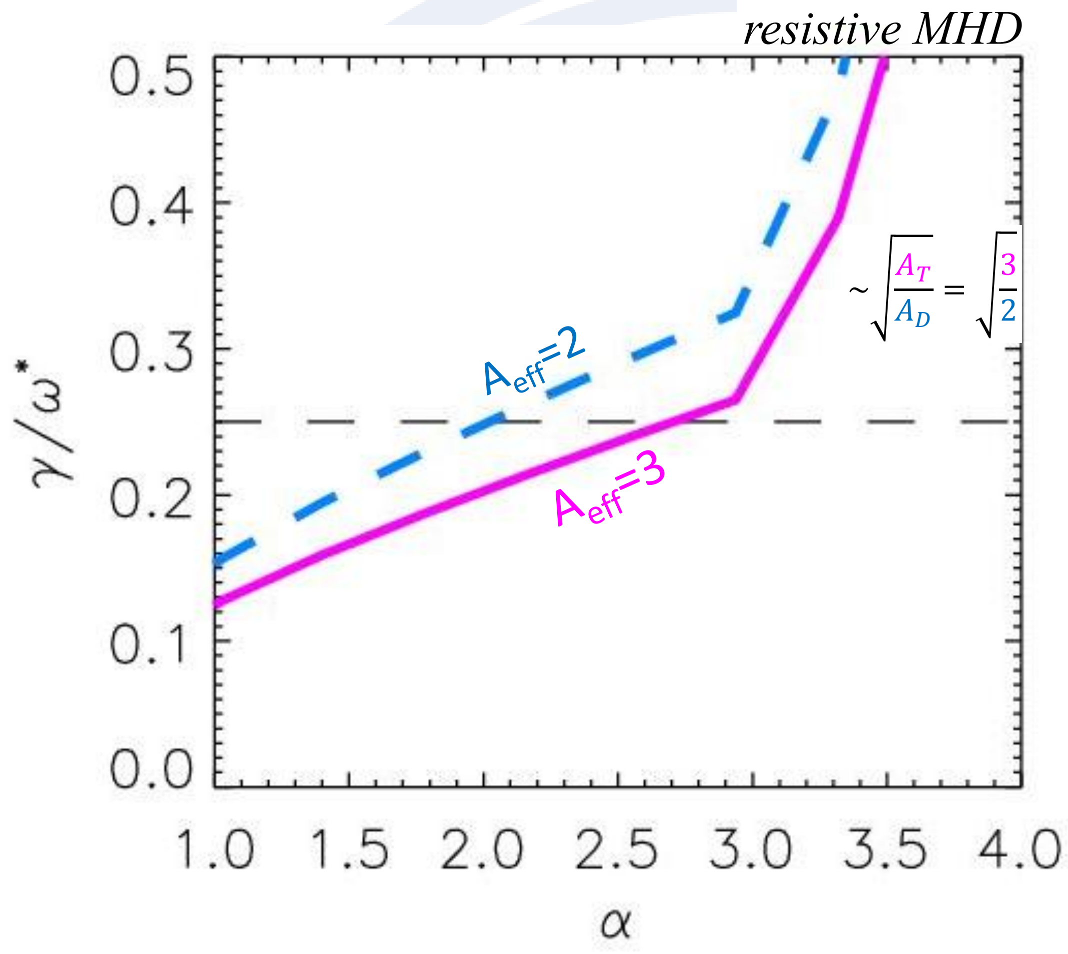

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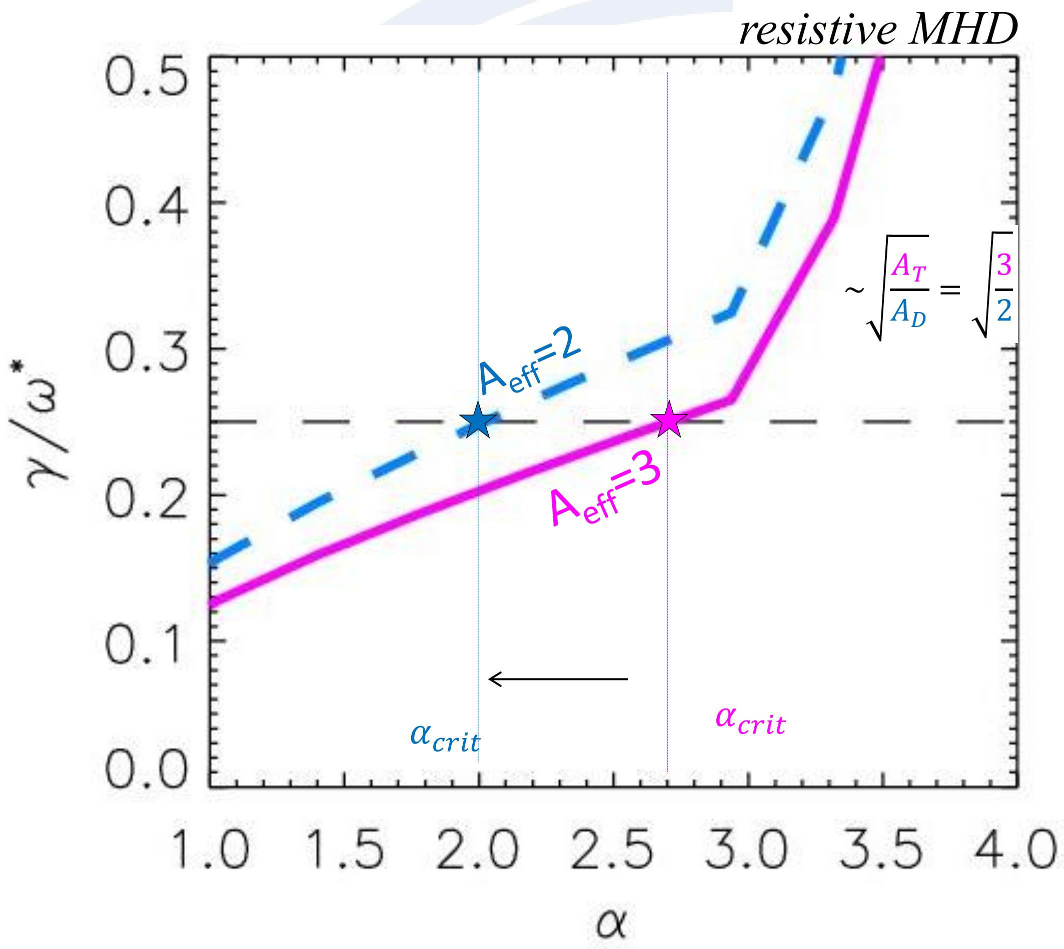

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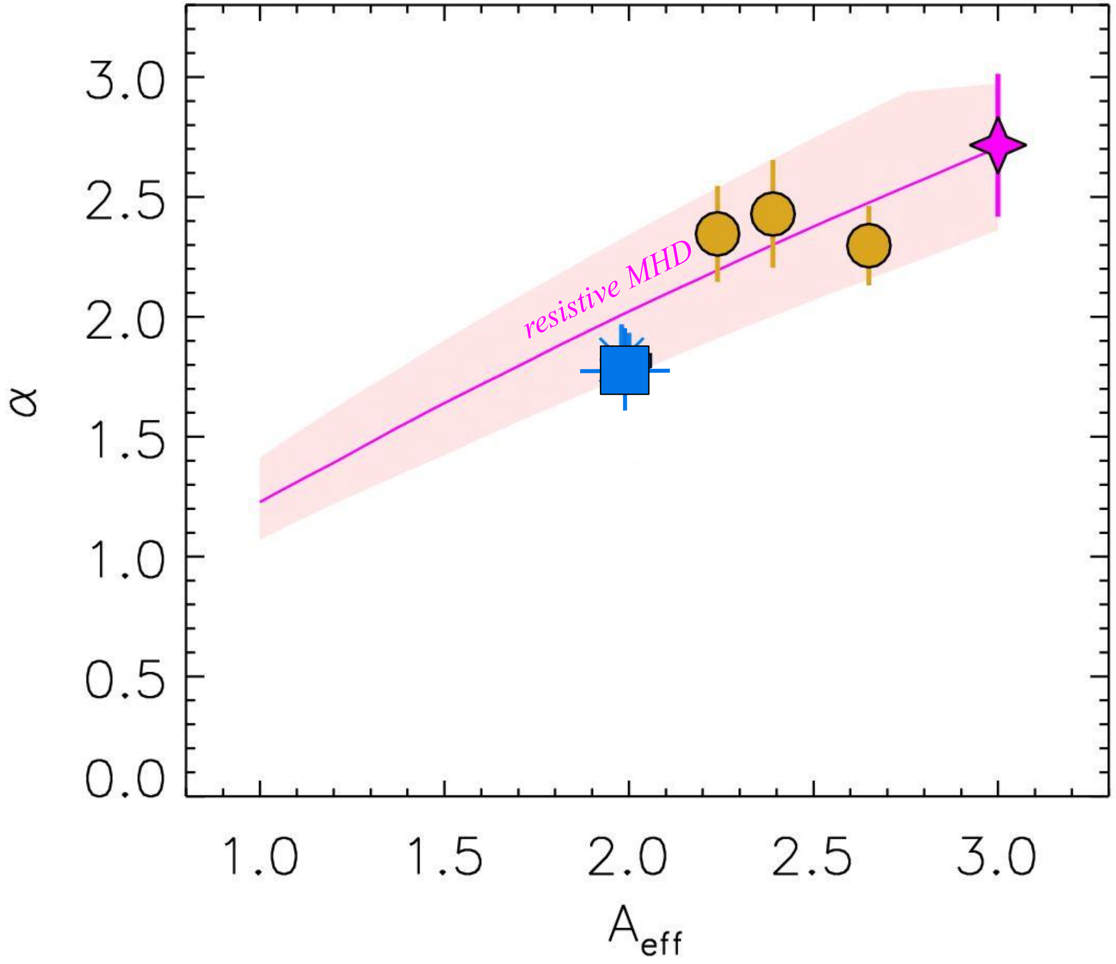
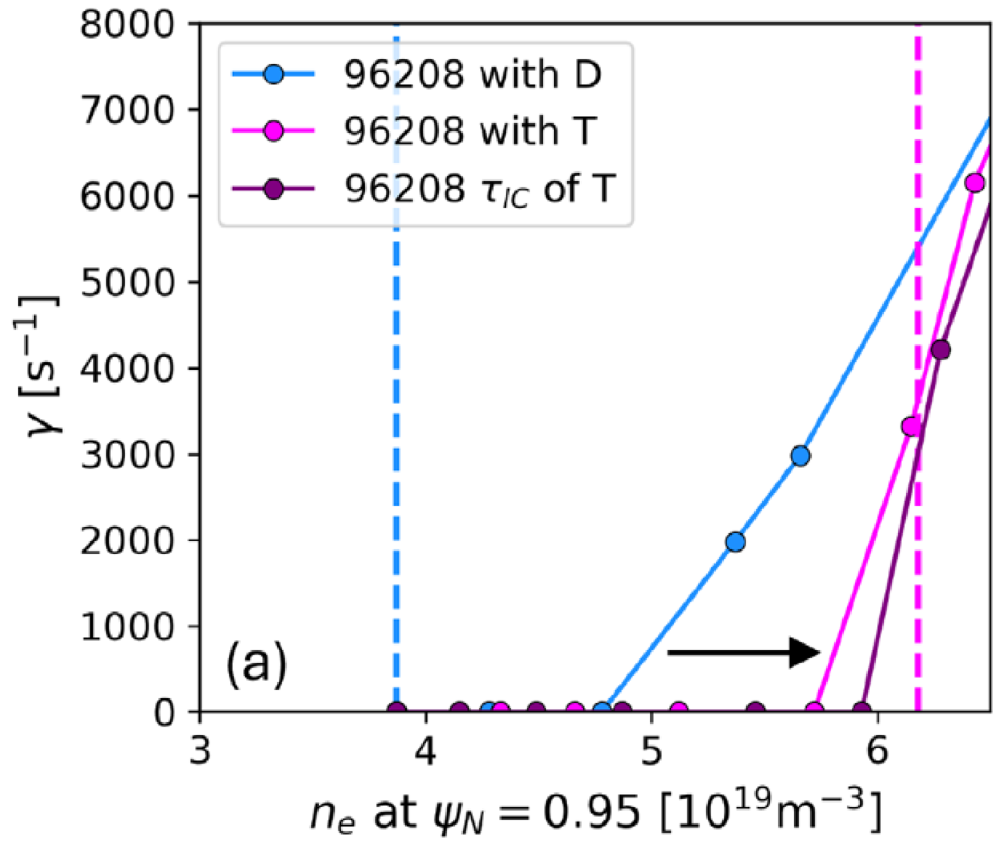


[Frassinetti NF2023]

Main conclusions related to the isotope mass effect confirmed with JOREK

- Linear visco-resistive MHD stability done with JOREK to confirm and extend the previous results obtained with CASTOR
- JOREK applied to a subset of the shots from the previous slide
- Key messages:
  - Resistivity is essential (with low resistivity JOREK does not find any pedestal instability)
  - The effect of the isotope mass on the pedestal stability is due, at least in part, to the diamagnetic stabilization



[Nyström PoP2026]

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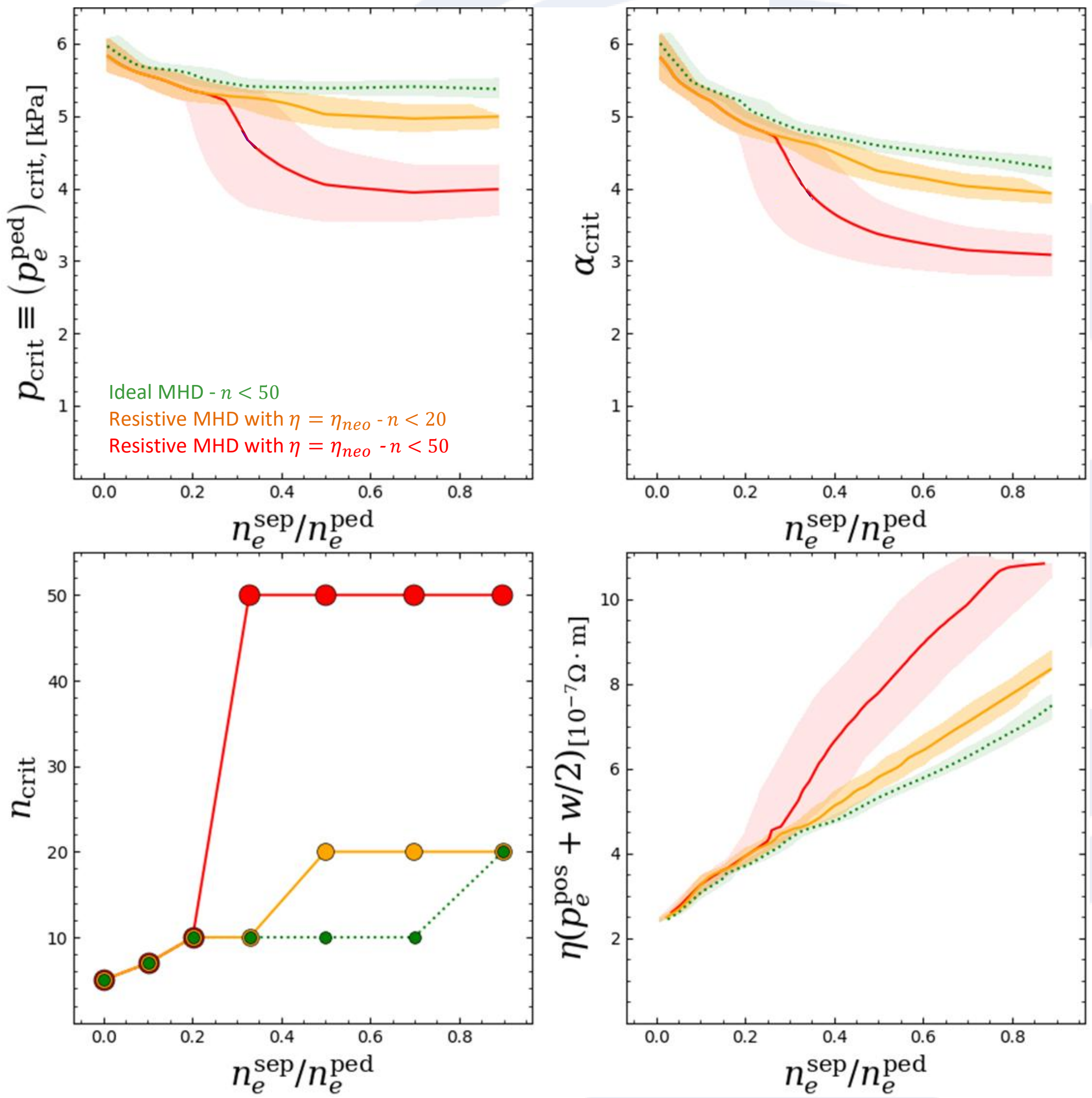
Example: effect of n_e^{sep}/n_e^{ped} with ideal and resistive MHD

[Lafay NF2026]

- Threshold fine tuned to a reference case
  - 1.4MA/1.7T/15MW low gas rate
  - Neoclassical resistivity self-consistently calculate with the Redl formula



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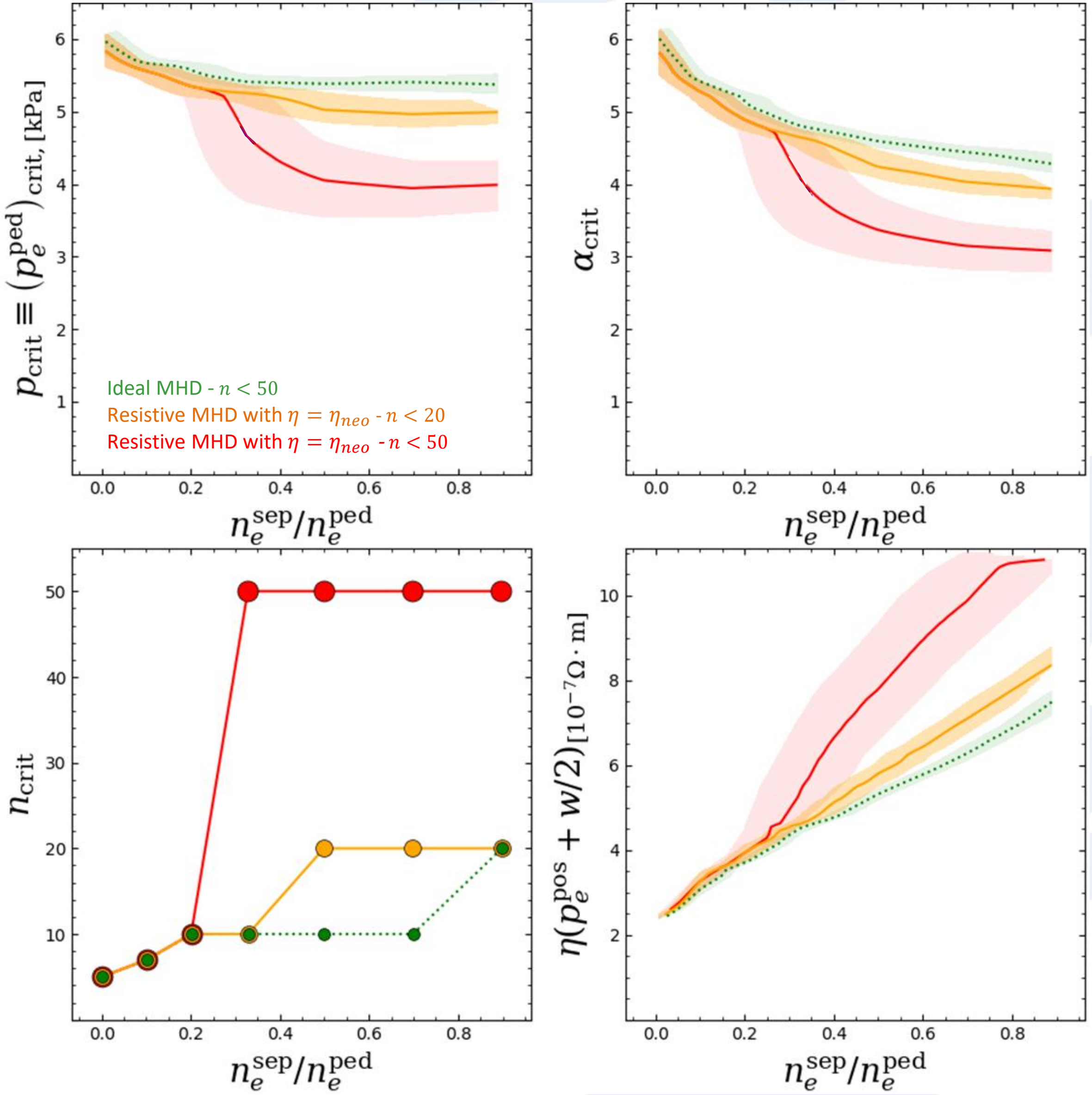

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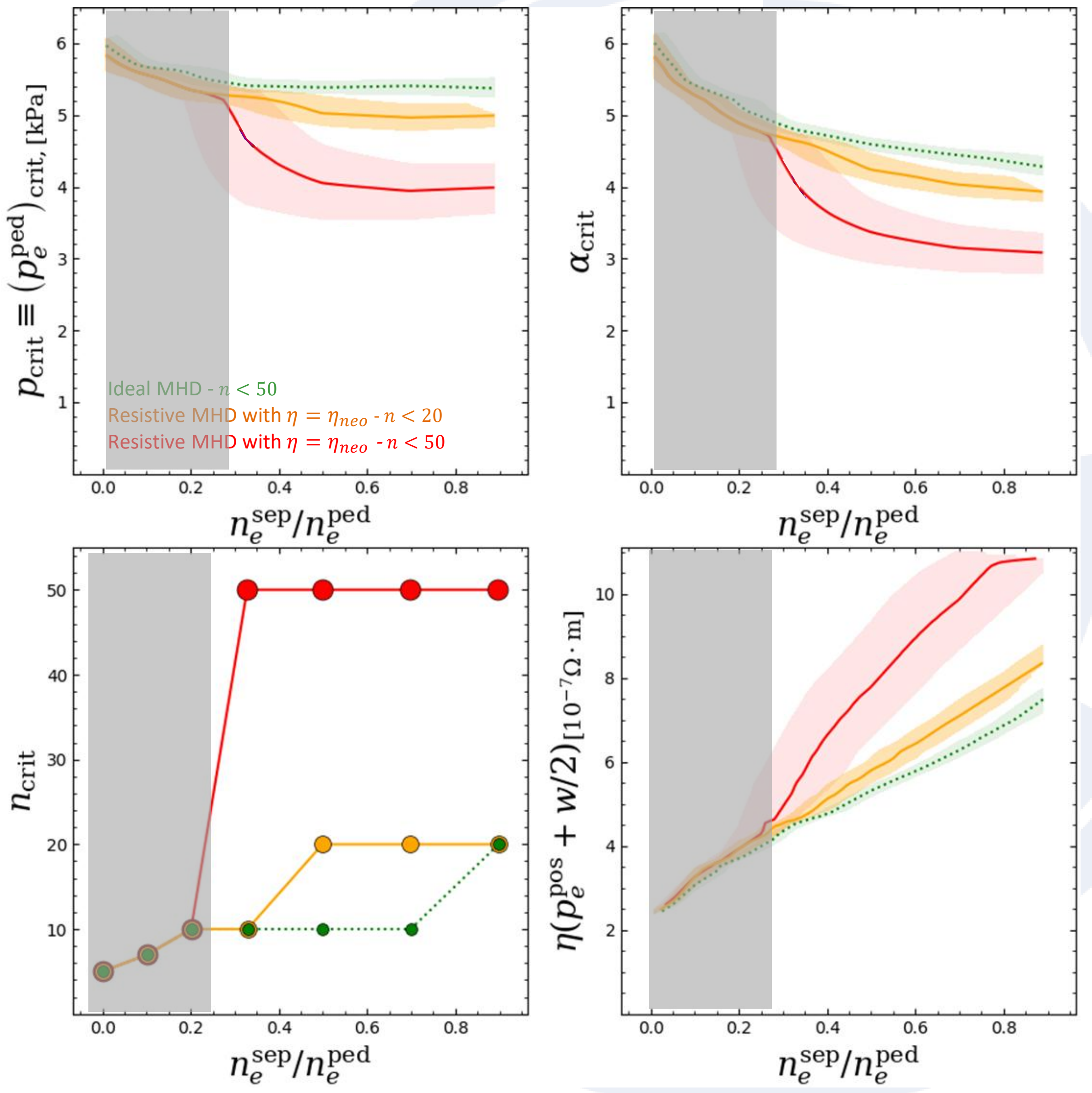

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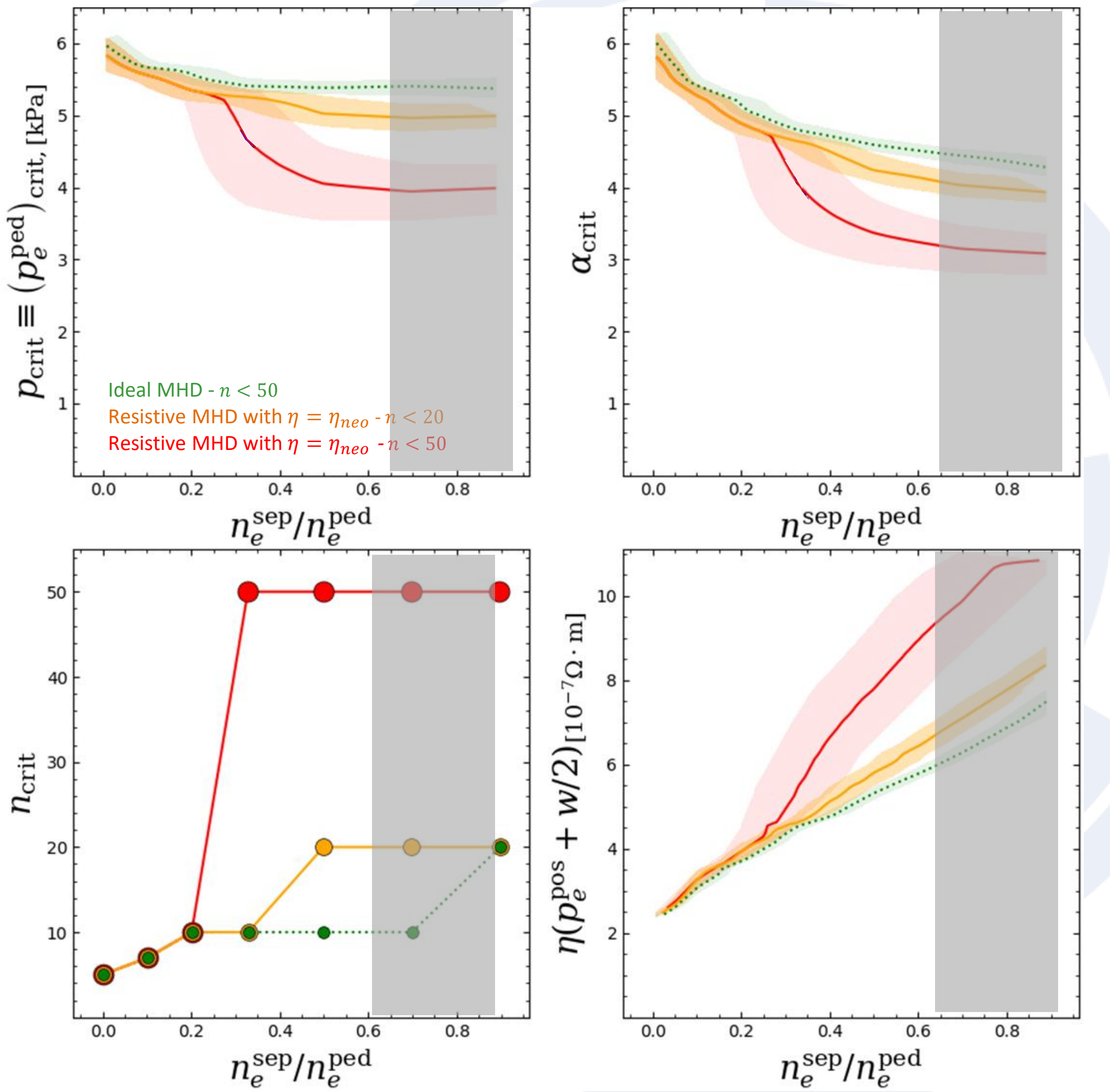
  - high n_e^{sep}/n_e^{ped} → T_e^{ped} is low → η is high → resistive effects are not negligible → resistive MHD predicts a lower pressure



Application to an experimental gas scan

- Predictions tested on a gas scan:
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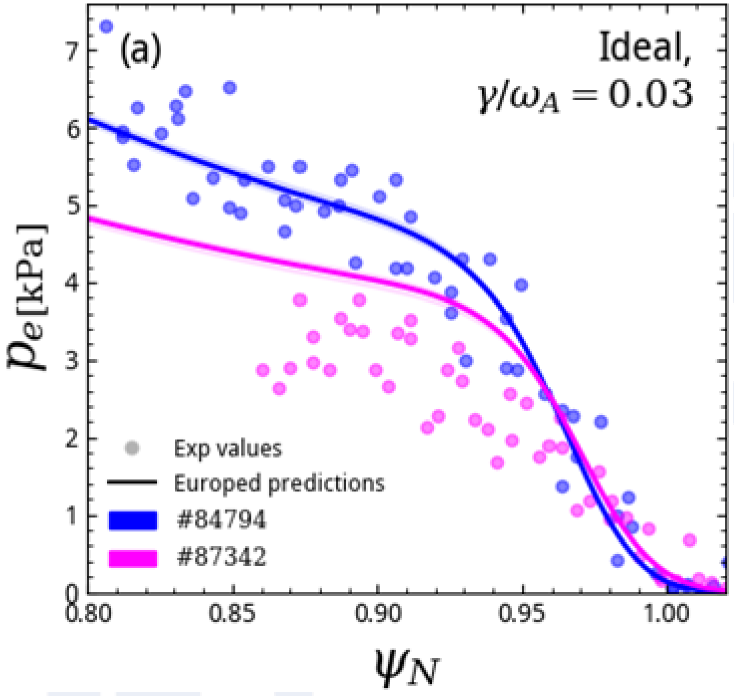

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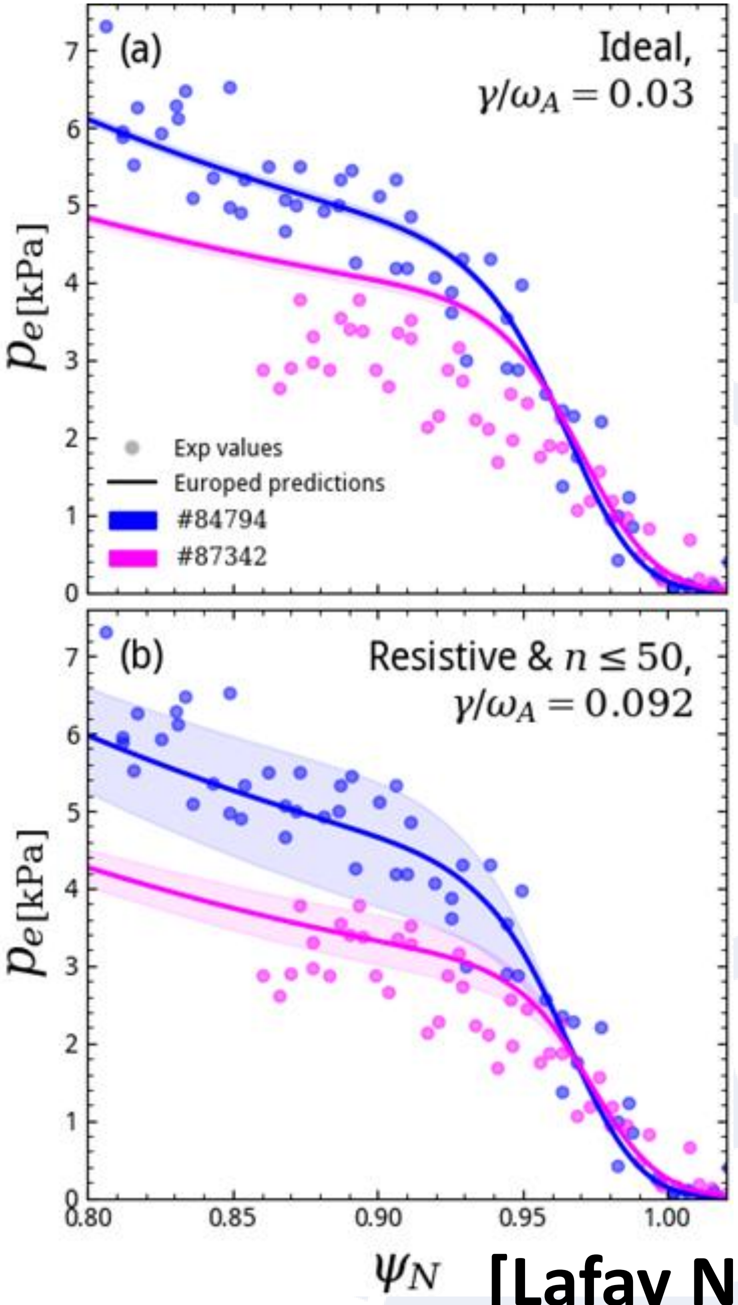
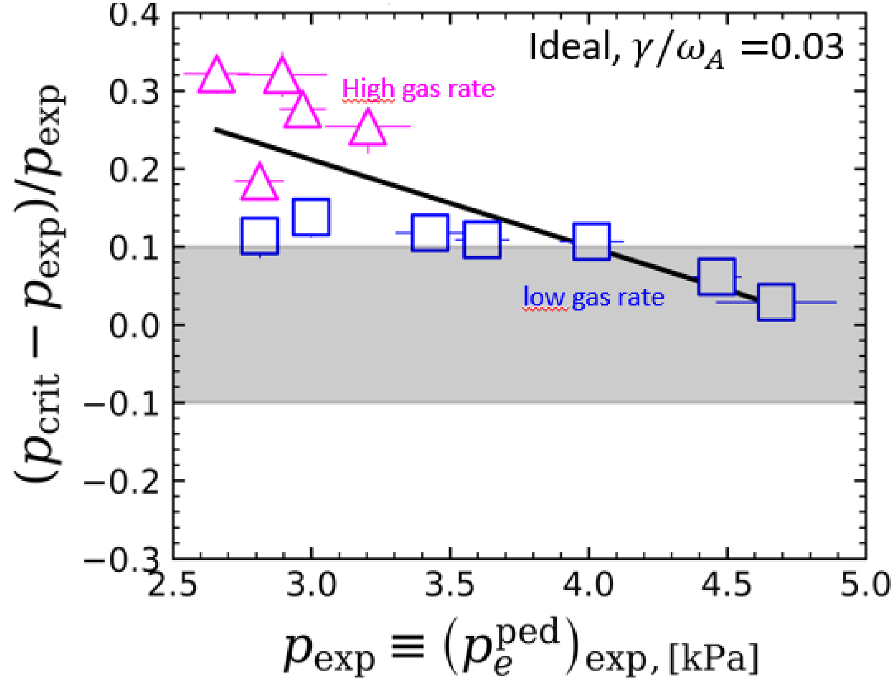
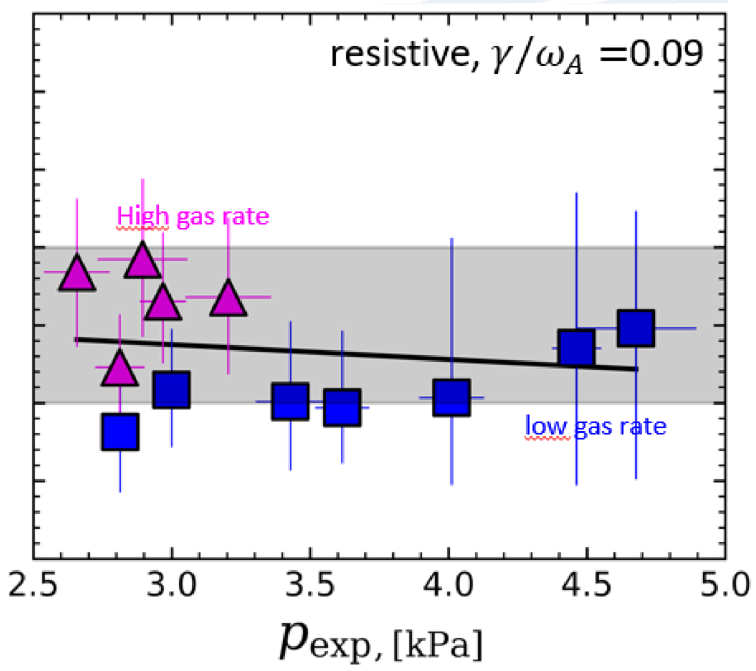


[Lafay NF2026]

Extension to a larger dataset





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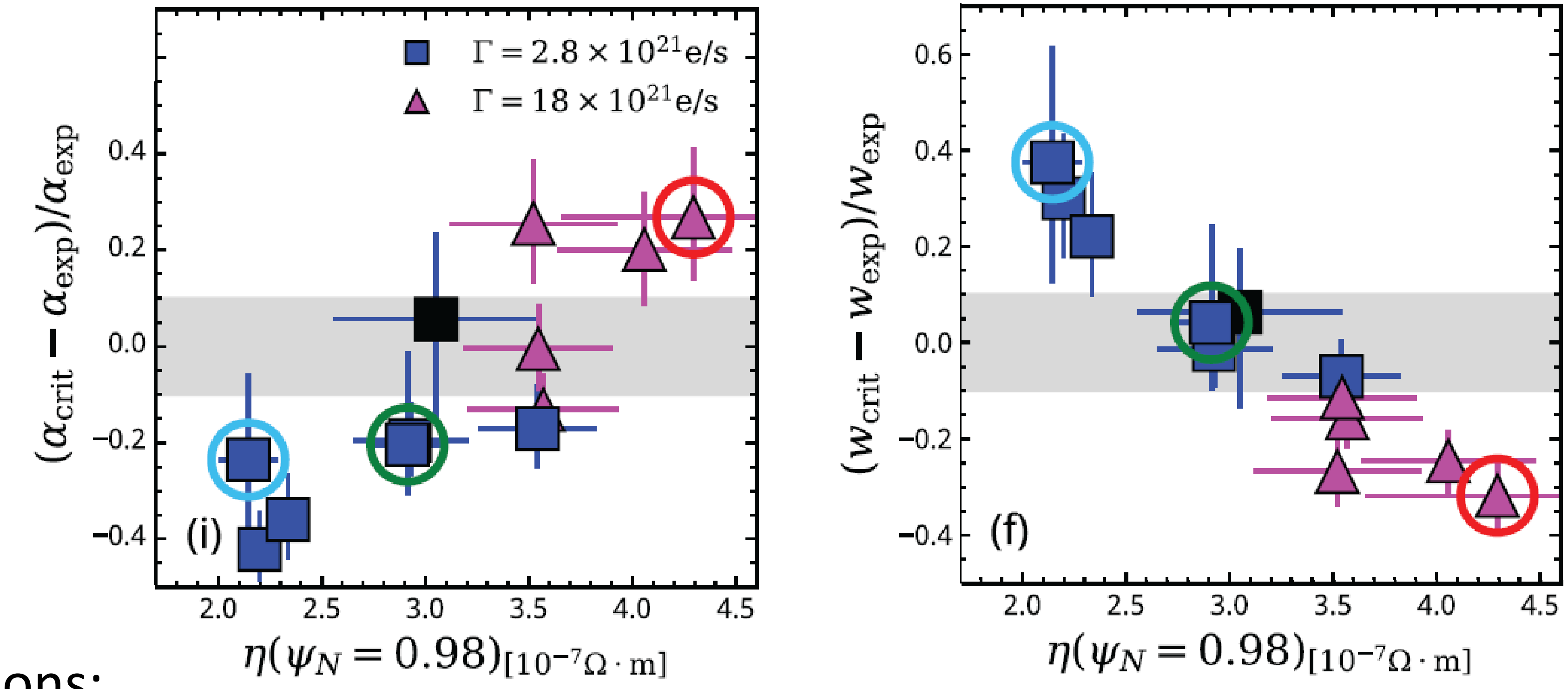

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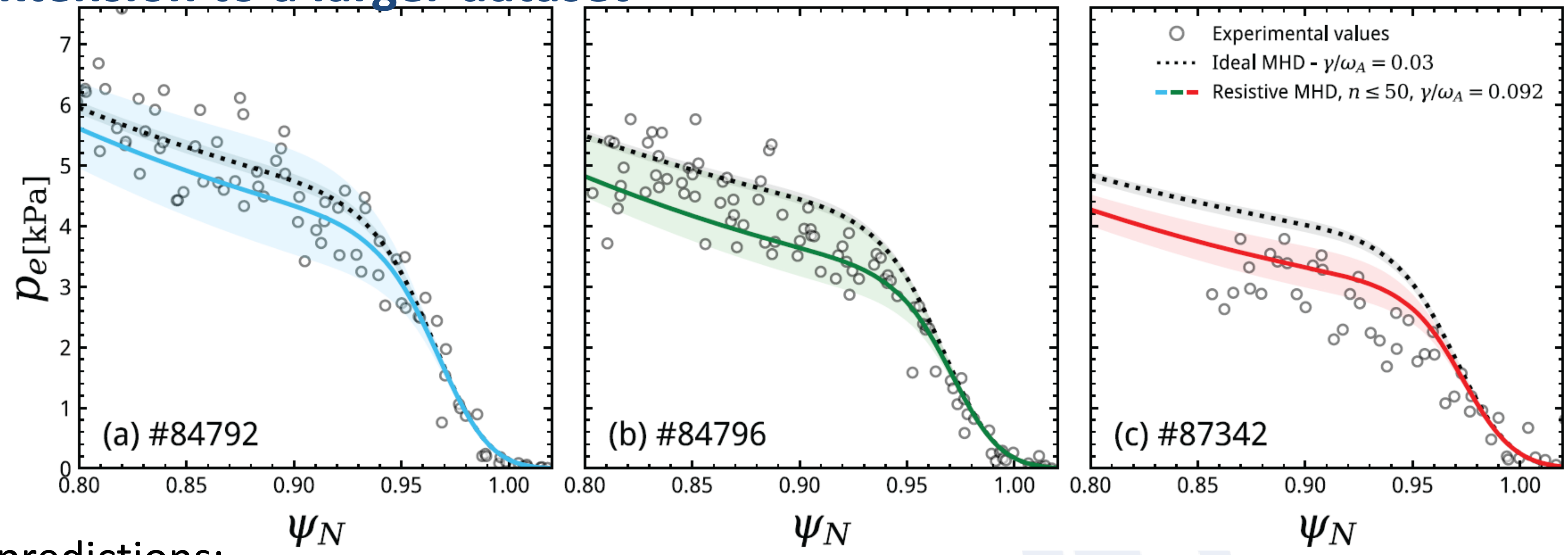

- p^{ped} predictions:
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- gradient and width predictions are NOT perfect
- However: within the experimental scatter of the data point the agreement is significantly better with resistive MHD

[Lafay NF2026]

Good predictions also for JET-C

- JET-C has ofs often higher Teped than JET-ILW
  - are resistive MHD predictions still valid in JET-C?

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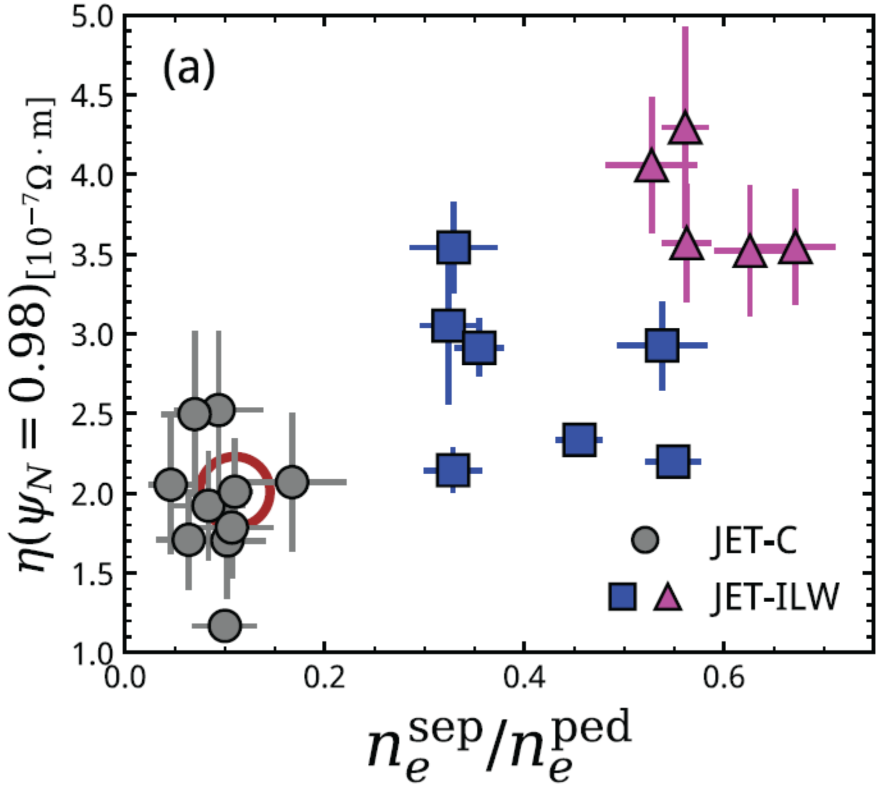

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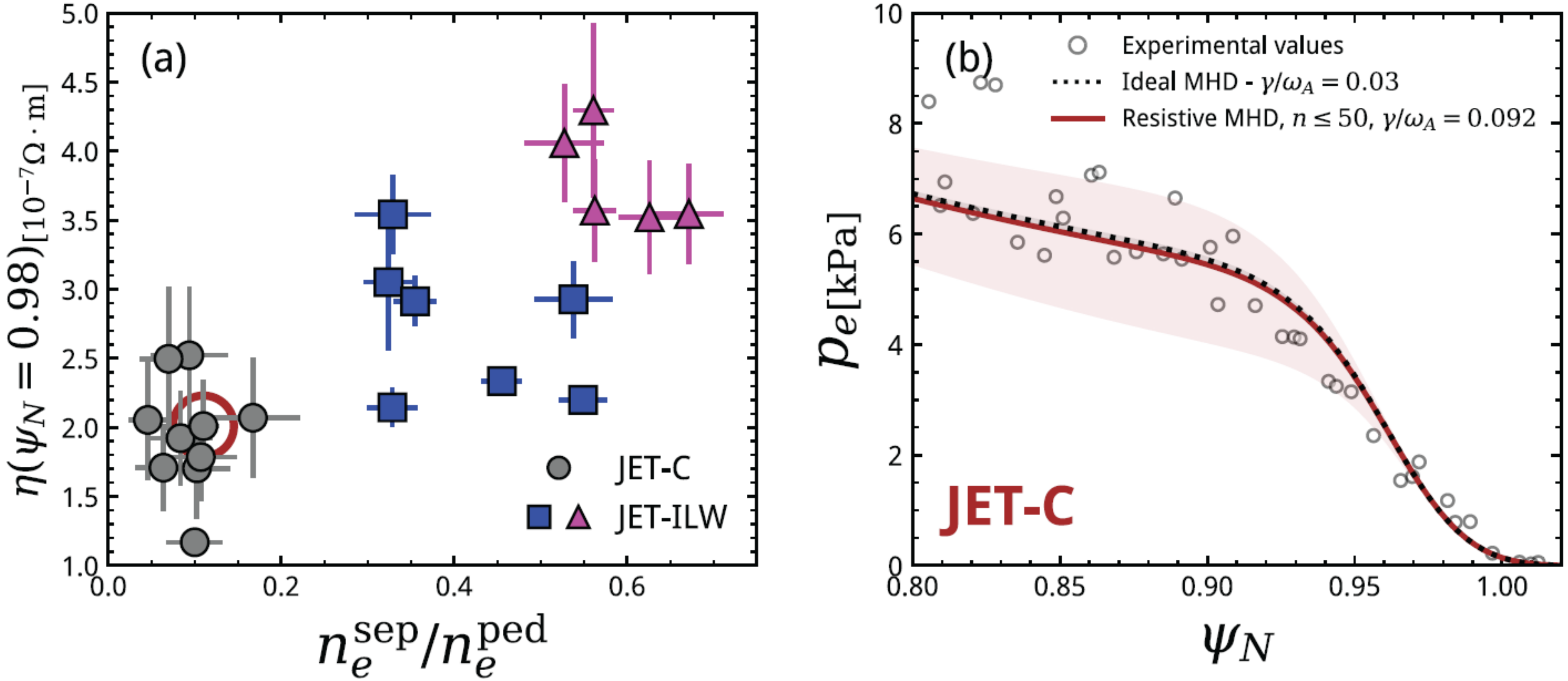

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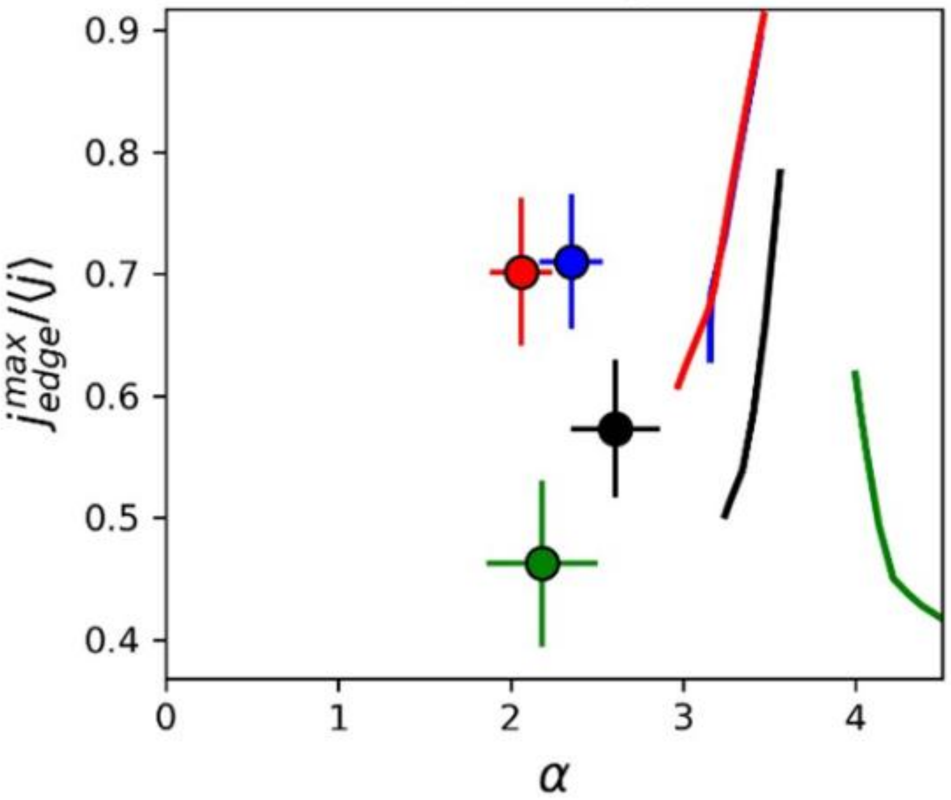
ITER-baseline Neon seeded scenario

Ideal MHD



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[Nyström NF2026]
[Giroud submitted to NF]

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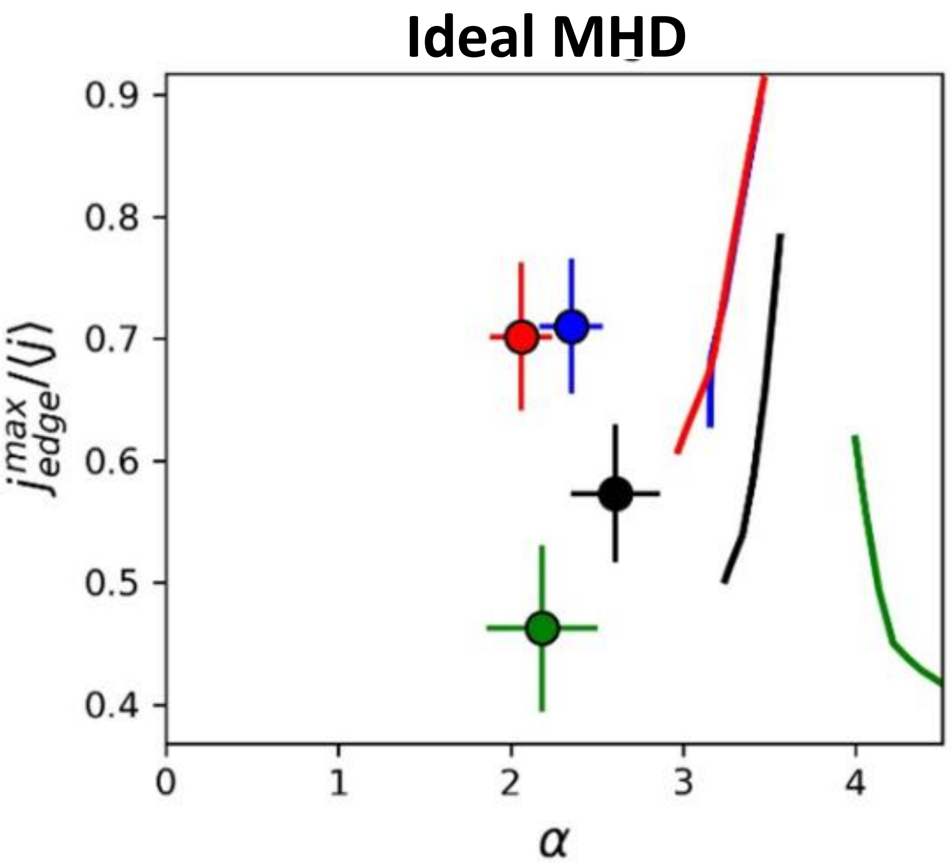

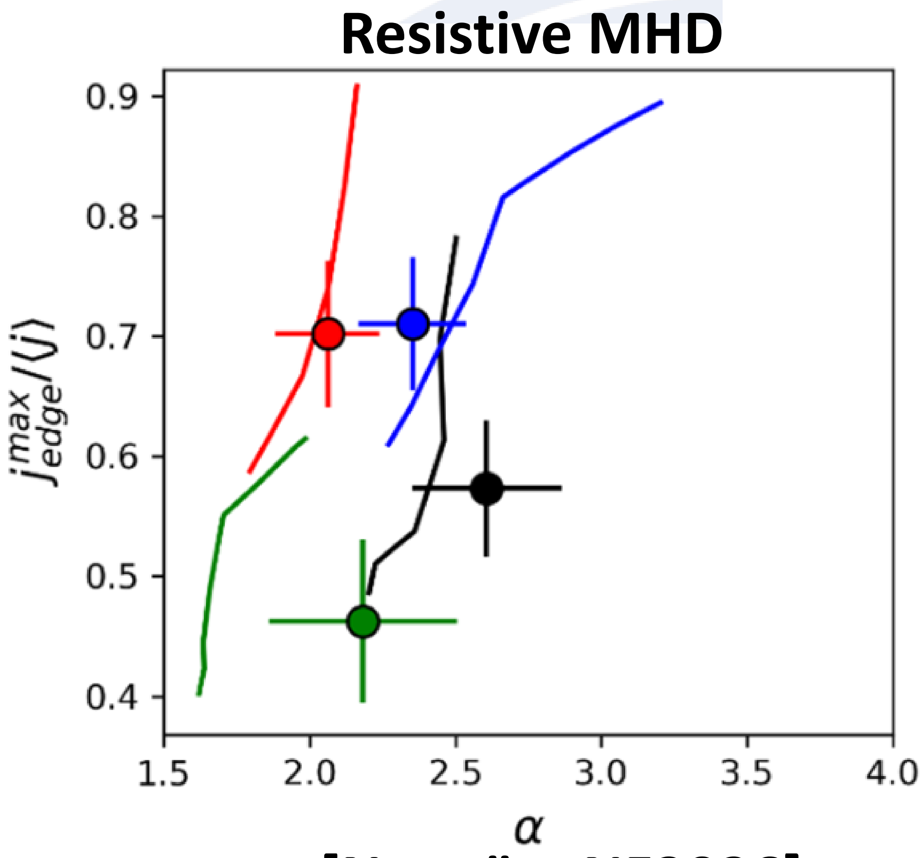

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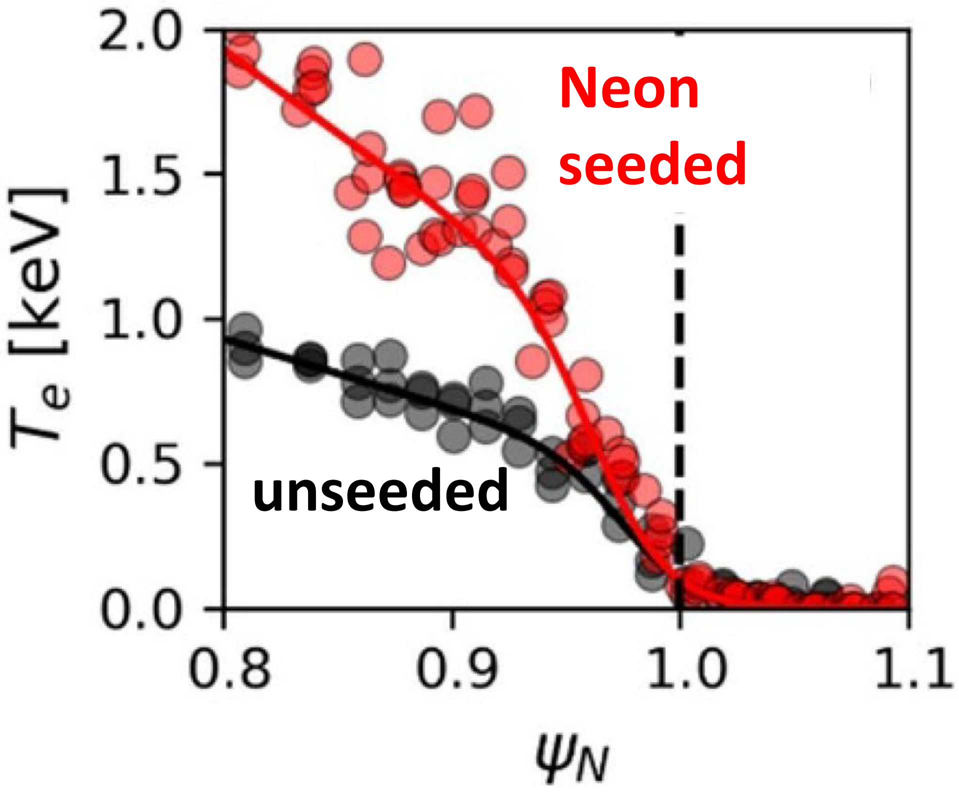

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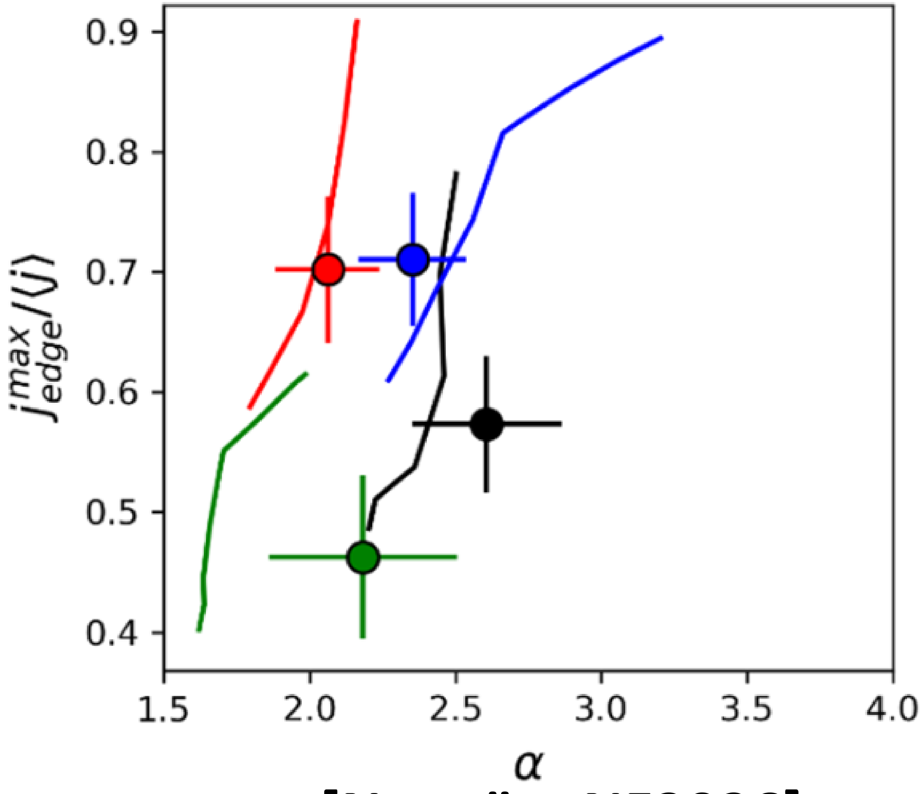

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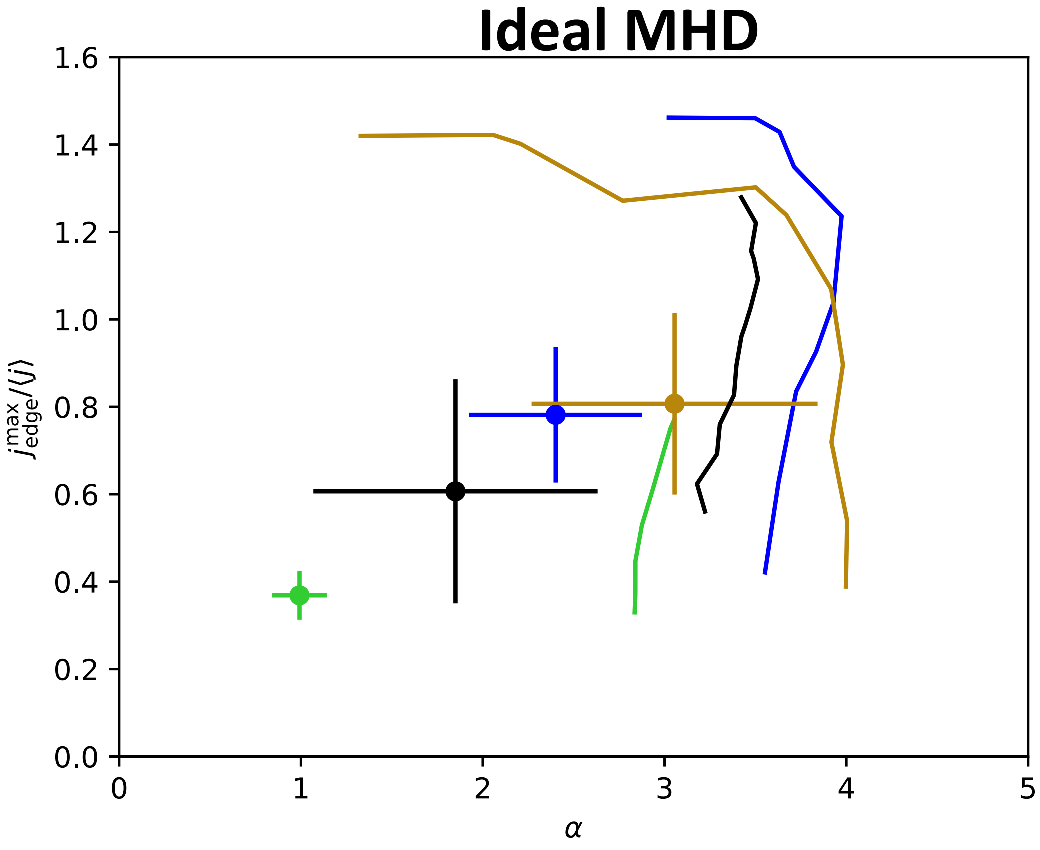
- Important: the Neon seeded pulses have very high T_e^{ped}. Resistivve effect are important because the pedestal is very wide (→wider region of the pedestal foot with low T_e)

JET-baseline scenario



[Lafay, work in progress]

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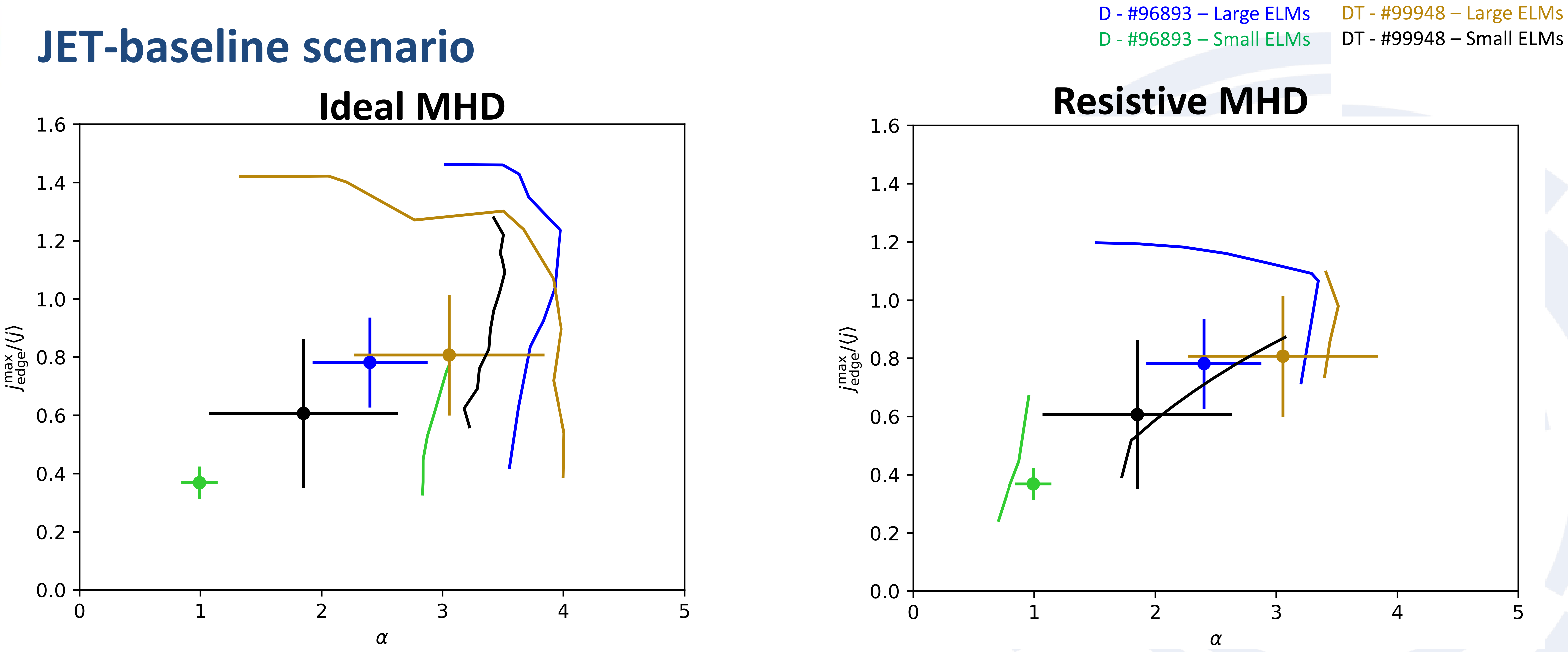

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Extension to TCV: work in progress

[Lafay EPS2026]

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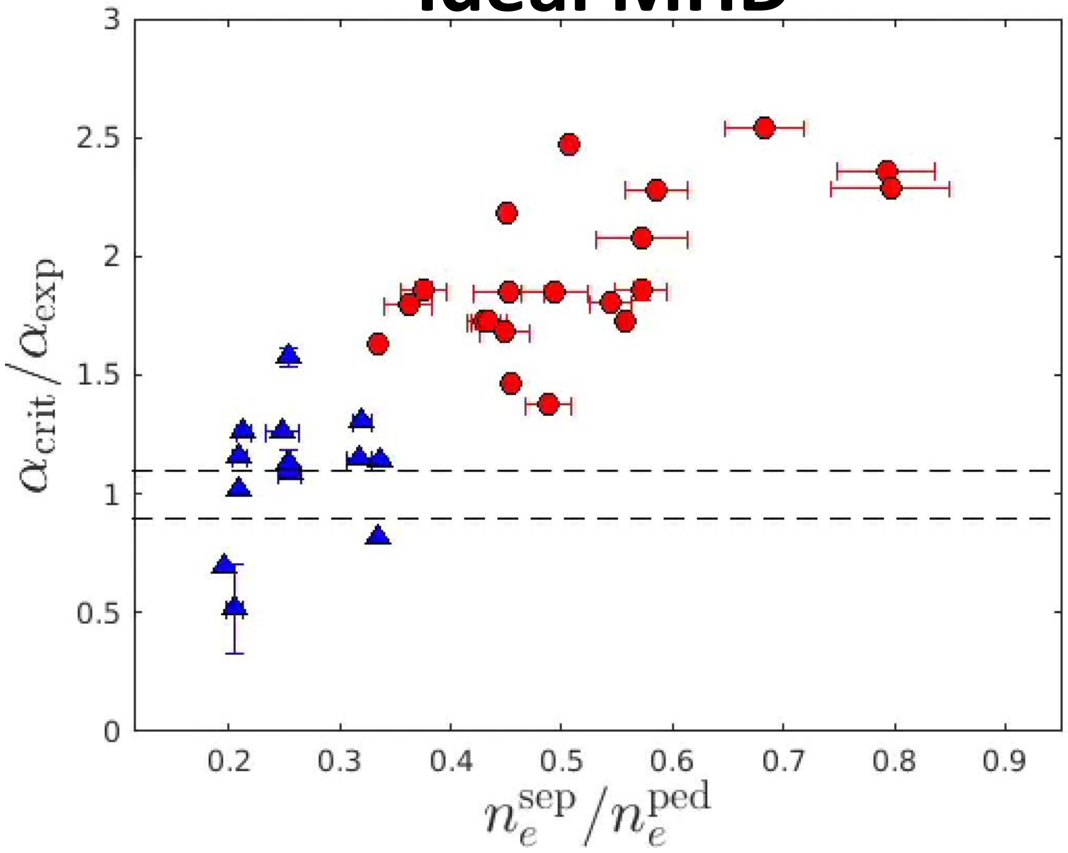

- TCV: preliminary results suggest it can be important also in TCV [Lafay EPS2026]
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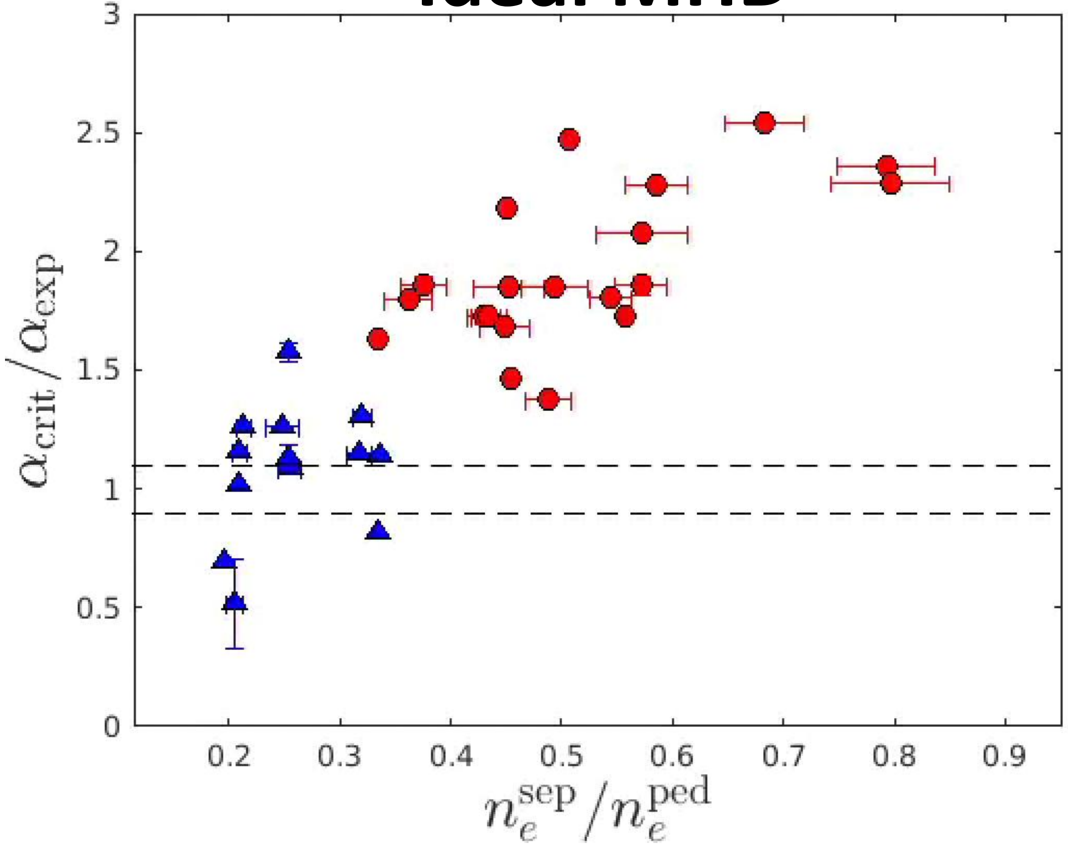

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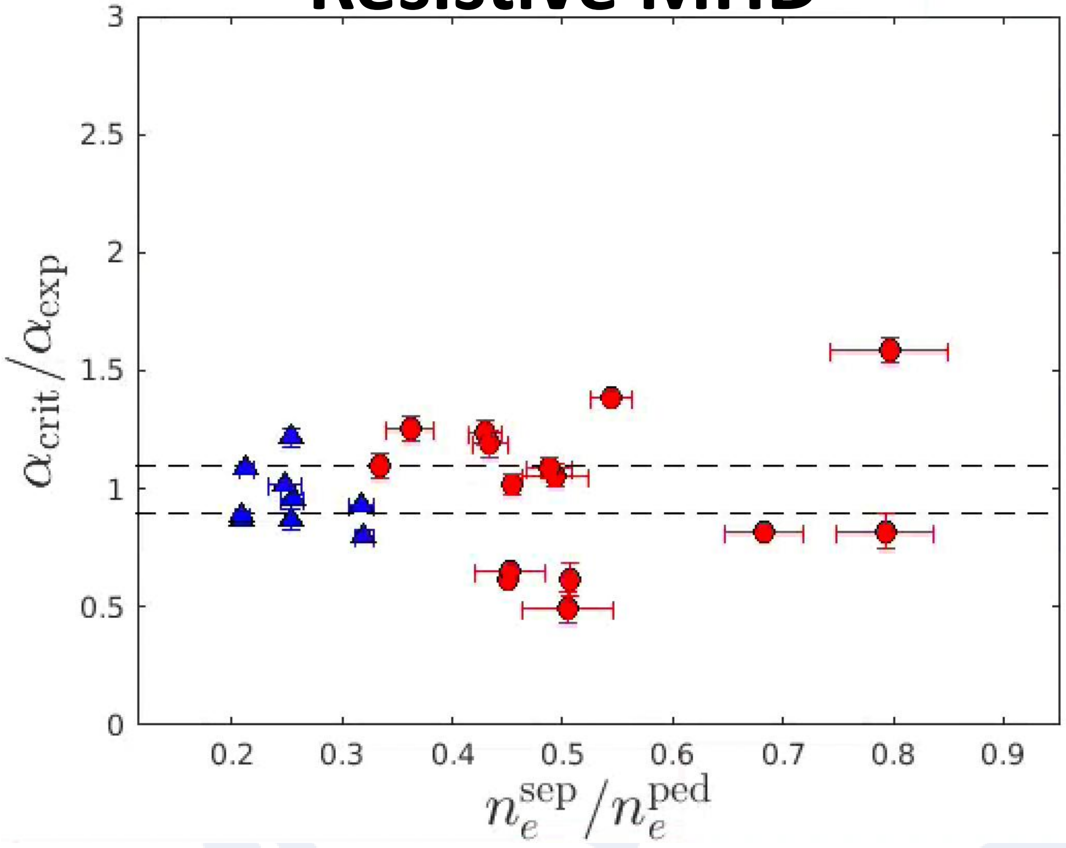

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  - is relevant not only at JET
- The key parameter is the resistivity at the pedestal foot

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  → possible impact also on high T_e^{ped} plasmas. To be tested if it is releveant in ITER
- It will be important to include resistive MHD for pedestal predictions in integrated core-pedestal modelling

  → next presentation:
  - plan to integrate Europed (ideal in 2026 and resistive in 2027) in ETS (O. Sundberg) (project supported by Swedish Research Council)
  - Link with TSVV-H: benchmark with HFPS

Drawbacks

- Drawback
  - Resistive MHD codes are much slower than ideal MHD
  - A 2D stability run can take 3 days vs 3h

- Corresponding actions
  - Collaboration with EnR project of A. Järvinen: ”pedestal MHD surrogate model status” (see A. Bruncrona talk)

Key papers on the importance of resistive MHD in the pedestal

- **L. Frassinetti et al**.,
  "Role of the separatrix density in the pedestal performance in deuterium low triangularity JET-ILW plasmas and comparison with JET-C"
  Nucl. Fusion 61 (2021) 126054
- **H. Nyström et al**.,
  "Effect of resistivity on the pedestal MHD stability in JET"
  Nucl. Fusion 62 (2022) 126045
- **L. Frassinetti et al.,**
  "Effect of the isotope mass on pedestal structure, transport and stability in D, D/T and T plasmas at similar βN and gas rate in JET-ILW type I ELMy H-modes"
  Nucl. Fusion 63 (2023) 112009
- **H. Nyström et al**.,
  "Isotope and non-ideal effects on pedestal stability in JET plasmas"
  Phys. Plasmas 33, 032509 (2026)
- **F. Stefanelli et al.,**
  "Non-ideal MHD analysis of pedestal scans of AUG and JET"
  Nucl. Fusion 65 (2025) 086025
- **A. Kleiner et al**.,
  "A study of resistive peeling–ballooning modes across spherical tokamaks"
  Plasma Phys. Control. Fusion 67 (2025) 085026
- **H. Nyström et al**.,
  "Effect of neon seeding on the pedestal structure and stability in the JET-ILW deuterium JET-ITER baseline scenario using both ideal and resistive MHD"
  Nucl. Fusion 66 (2026) 026039
- **A. Lafay et al.,**
  "Qualitative effects of resistivity in JET-ILW Europed pedestal predictions",
  Nucl. Fusion 66 (2026) 056030