MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

IMEP, PRESENT APPLICATIONS AND FUTURE DEVELOPMENTS

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- P. Rodriguez-Fernandez, J. Hughes and the C-Mod Team
- L. Frassinetti, S. Saarelma and the JET Team

EUROfusion

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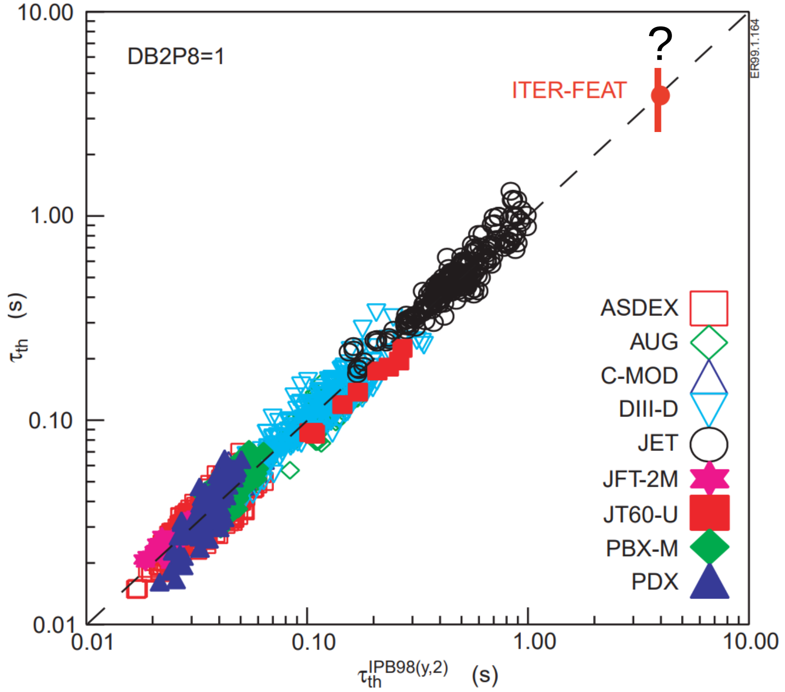
NO RELIABLE THEORY-BASED WAY TO PREDICT CONFINEMENT



[*ITER Physics Basis Editors 1999 Nucl. Fusion*]

$$\tau_{th}^{\mathrm{IPB98(y,2)}} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \epsilon^{0.58} \kappa^{0.78}$$

- Scaling laws (statistical regressions):
  - Simple, based on main engineering parameters
  - Robust to capture dominant dependencies
  - Do not capture other important dependencies
  - Limited extrapolation capabilities

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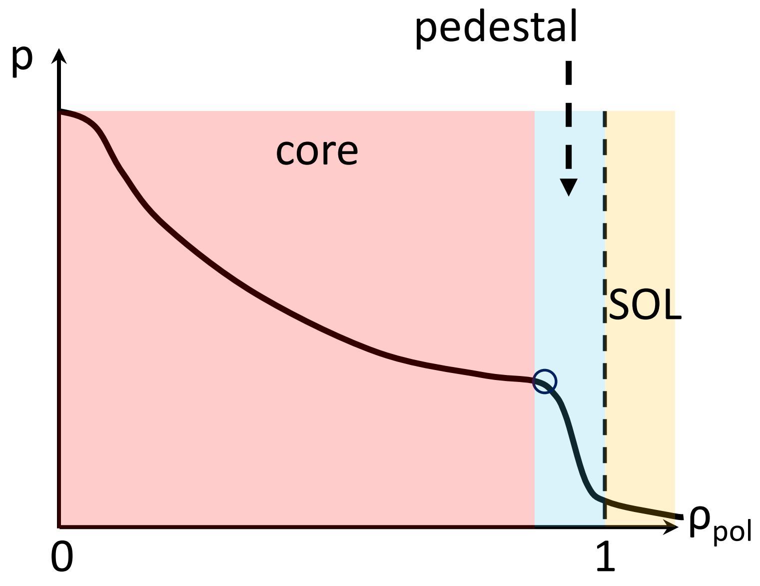
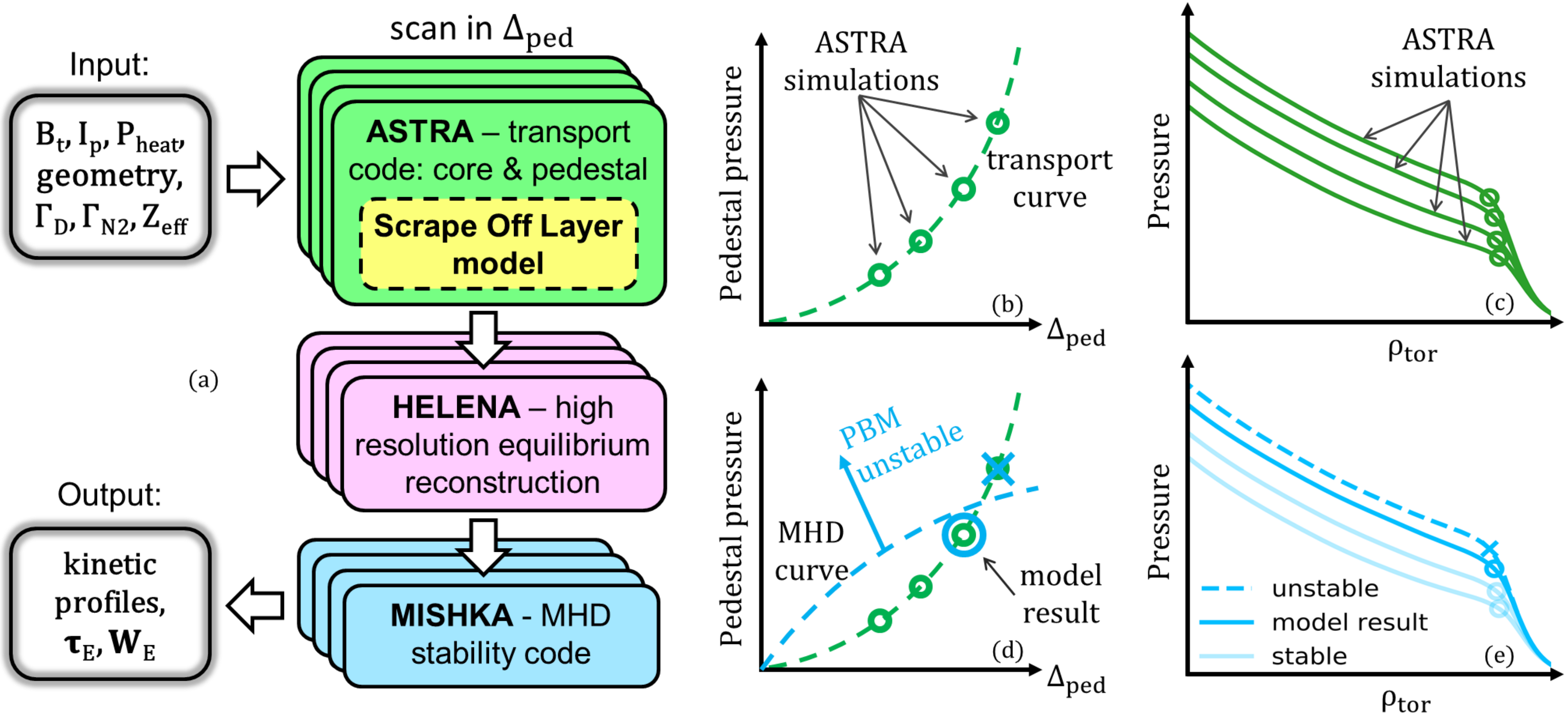


- Scaling laws (statistical regressions):
    - ○ Simple, based on main engineering parameters
    - ○ Robust to capture dominant dependencies
    - ○ Do not capture other important dependencies
    - ○ Limited extrapolation capabilities
- Simulations:
    - ○ Predict kinetic profiles (T_e, T_i, n_e, n_i)
    - ○ Theory-based description of core transport
    - ○ Pedestal top often set from measurements or to match global confinement scaling
    - ○ Transport models from core to plasma boundary can include empirical elements
    - ○ Limited coupling between core, pedestal and SOL effects

IMEP: INTEGRATED MODEL BASED ON ENGINEERING PARAMETERS



Input:

B_t, I_p, P_{heat}, geometry, Γ_D, Γ_{N2}, Z_{eff}

scan in Δ_{ped}

ASTRA – transport code: core & pedestal

Scrape Off Layer model

HELENA – high resolution equilibrium reconstruction

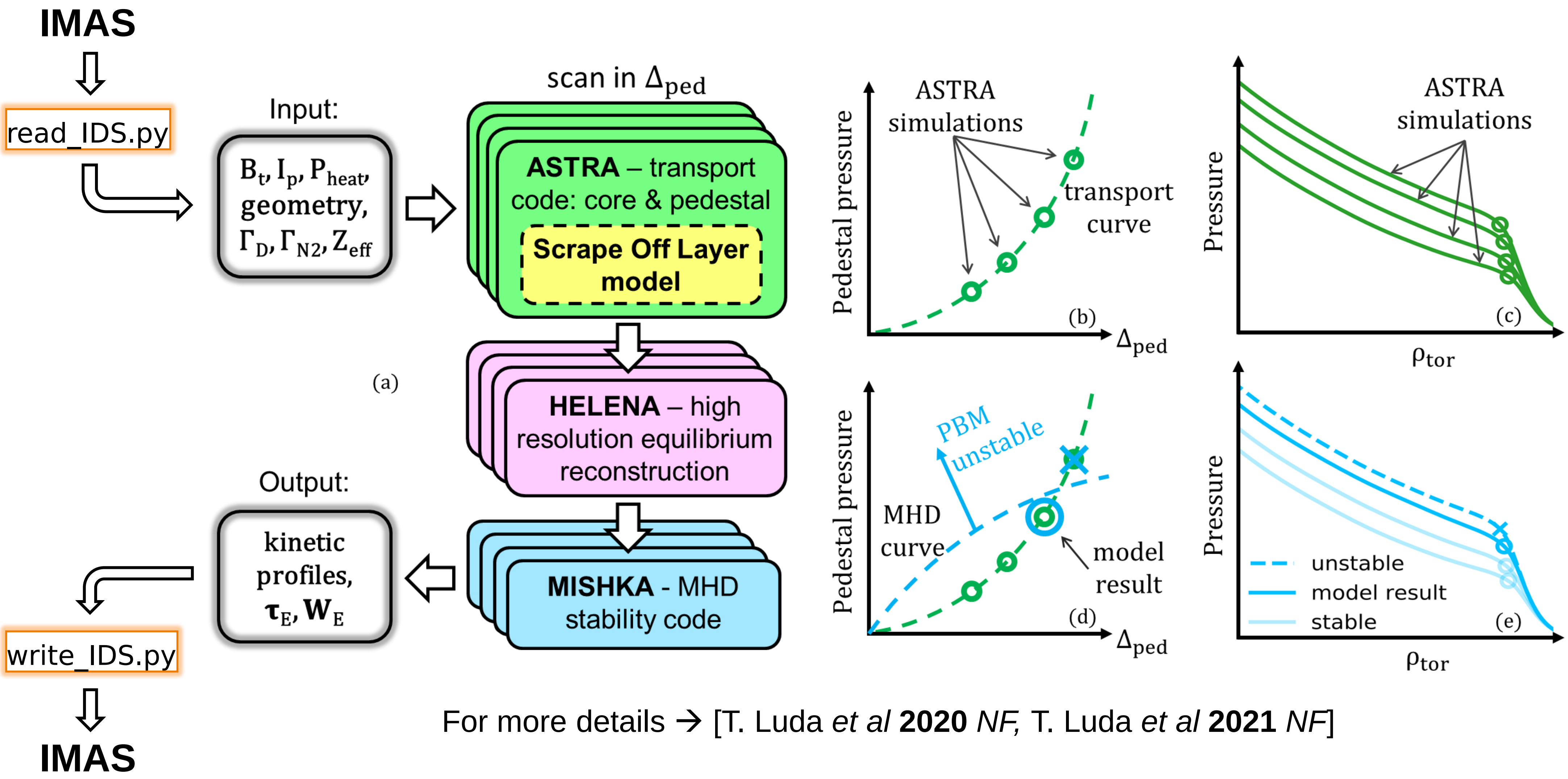
MISHKA - MHD stability code

Output:

kinetic profiles, τ_E, W_E

For more details → [T. Luda *et al* **2020** *NF,* T. Luda *et al* **2021** *NF*]

IMEP IS NOW INTERFACED TO IMAS AND AVAILABLE ON THE GATEWAY



IMAS

read_IDS.py

Input:

B_t, I_p, P_{heat}, geometry, $\Gamma_D, \Gamma_{N2}, Z_{eff}$

scan in Δ_{ped}

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IMAS

For more details → [T. Luda *et al* **2020** *NF,* T. Luda *et al* **2021** *NF*]

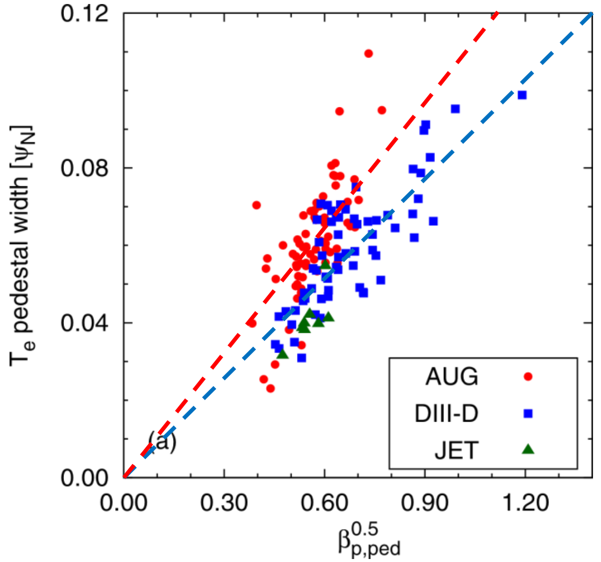
PEDESTAL TRANSPORT MODEL

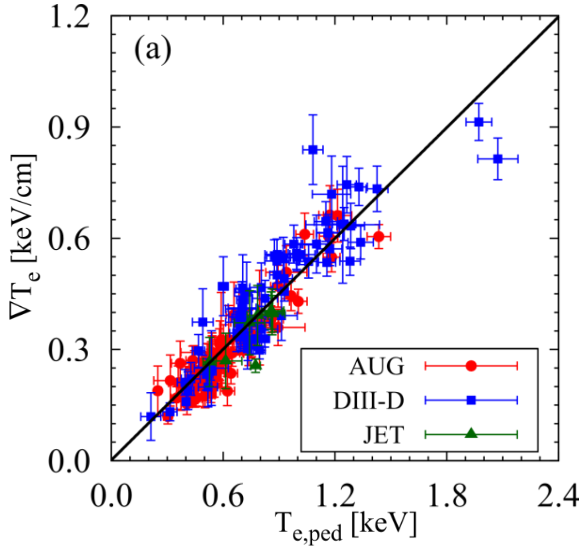
- The EPED pedestal model: [P. B. Snyder *et al* 2009 *PoP*]
  - ○ assumes: $\Delta\Psi_N \sim (0.076, 0.11)\beta_{p,ped}^{0.5}$
  - ○ requires $n_{e,top}$ as input
  - ○ assumes $T_{e,top} = T_{i,top}$

- AUG and DIII-D pedestals exhibit one common feature: $< \boldsymbol{\nabla T_e} > / \mathbf{T_{e,top}} \approx \mathbf{constant}$

  [P.A. Schneider *et al* 2013 *NF*]

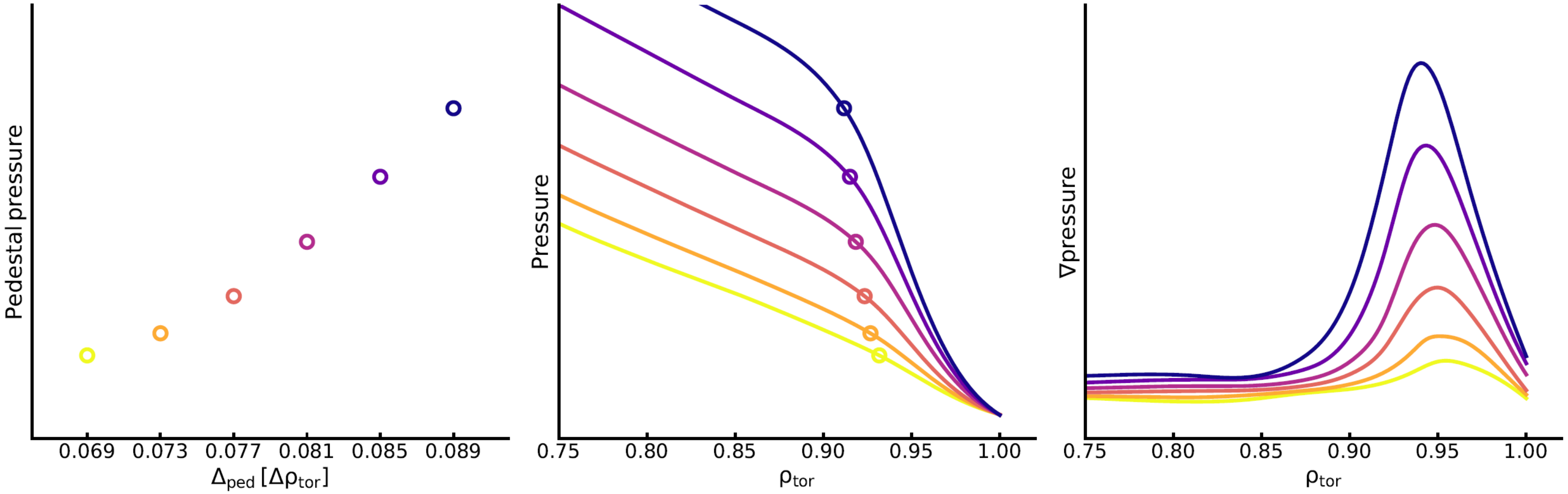
- We **implemented in our model** the condition $\frac{<\nabla T_e>}{T_{e,top}} = -0.5\ [1/\mathrm{cm}]$





PEDESTAL TRANSPORT MODEL → $p_{\mathrm{top}} \propto \Delta_{\mathrm{PED}}$

- For every Δ_{ped} of the scan, ASTRA changes $\boldsymbol{\chi}_{\mathbf{e,ped}}$ until $\frac{\mathbf{<\nabla T_e>}}{\mathrm{T_{e,top}}} = -0.5$ is satisfied
- The obtained $\chi_{\mathrm{e,ped}}$ is used to evaluate $\chi_{\mathrm{i,ped}}$: $\boldsymbol{\chi}_{\mathbf{i,ped}} = \boldsymbol{\chi}_{\mathbf{e,ped}} + \boldsymbol{\chi}_{\mathbf{i,NEO}}$
- Modelling of the electron density: $\mathbf{D_{n,ped}} = \mathbf{c}_{\mathbf{D}/\boldsymbol{\chi}}\boldsymbol{\chi}_{\mathbf{e,ped}} + \mathbf{D_{n,NEO}}$
- $\mathrm{c}_{\mathrm{D}/\chi} = 0.06$ and $\mathrm{C_{n,ped}} = -0.05$ [m/s] obtained with an **optimization** procedure trying to match different experimental pedestal density profiles

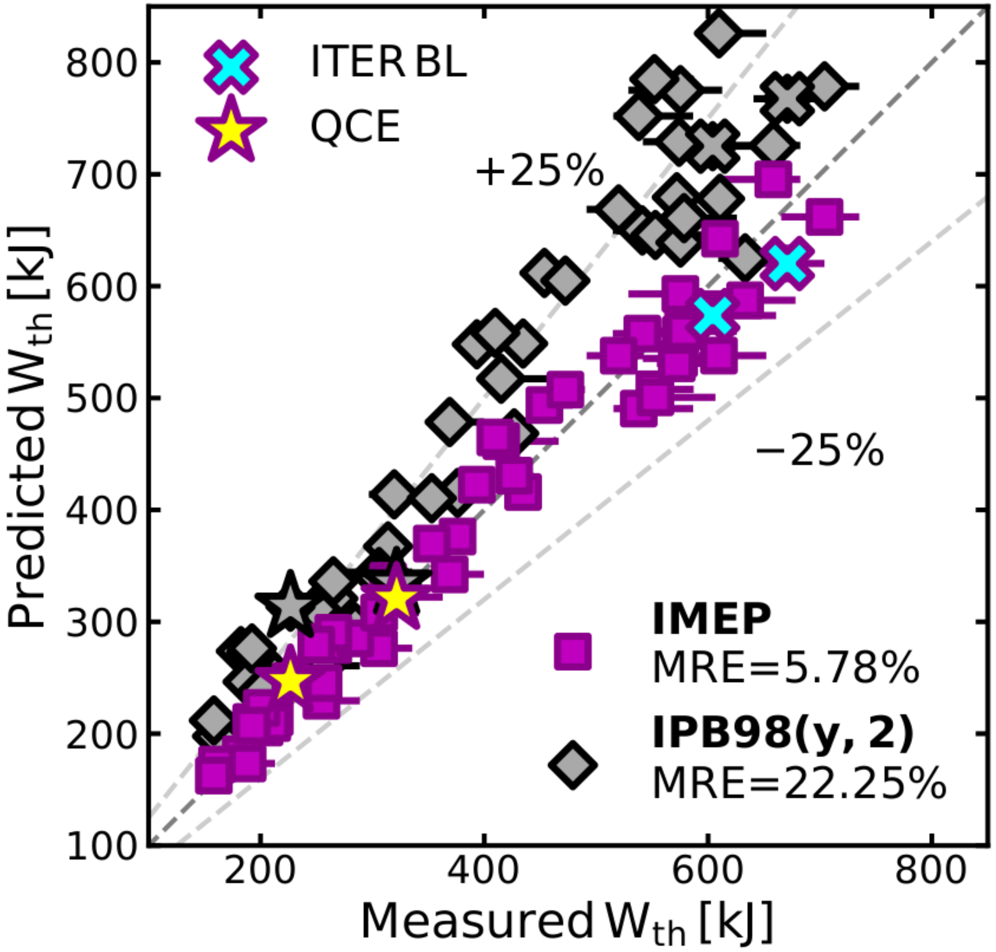


IMEP MORE ACCURATE THAN IPB98(Y,2) ON AUG

This modeling workflow is tested by simulating **50** H-mode stationary phases from ASDEX Upgrade discharges covering wide variations in:

$\mathbf{B_t}$ = 1.5 - 2.8 [T] $\mathbf{I_p}$ = 0.6 – 1.2 [MA]
$\mathbf{P_{net}}$ = 2 – 14 [MW] $\mathbf{q_{95}}$ = 3 - 8
$\mathbf{\Gamma_D}$ = 0 – 8 x 10^{22} [e/s]
δ = 0.19 – 0.42
$\mathbf{V_{NBI}}$ = 42 - 92 [kV]

IMEP:
- ✓ is **more accurate** with respect to the IPB98(y,2) scaling law
- ✓ can accurately **capture the effect** of the different operational parameters



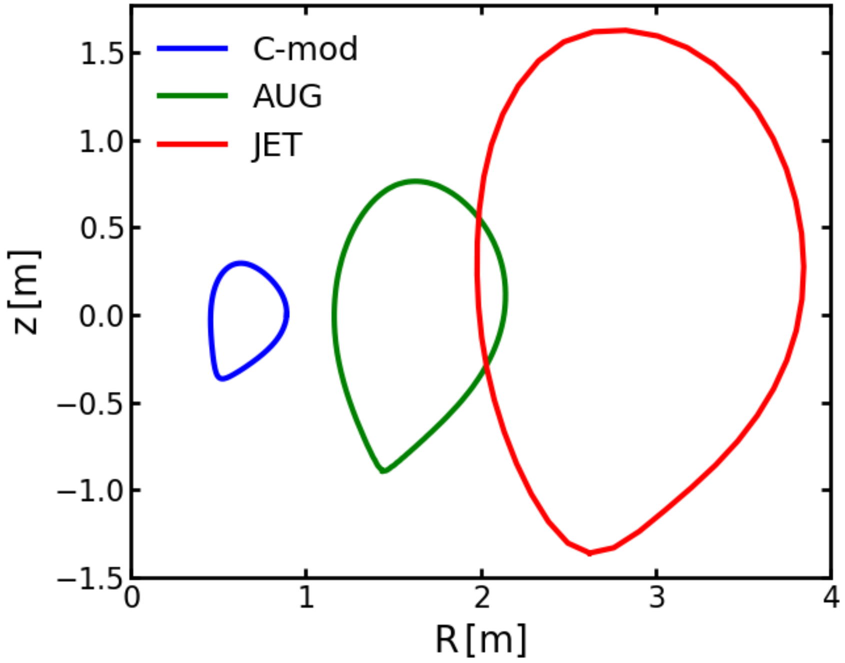
FIRST TEST ON C-MOD AND JET-ILW* ELMY H-MODE

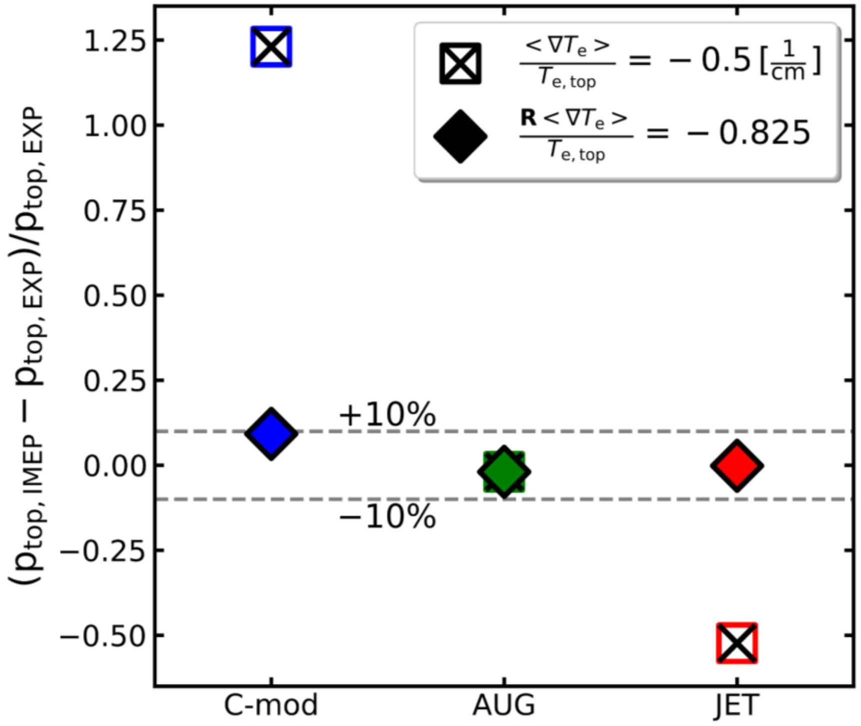
	P_{heat} [MW]	I_p [MA]	B_t [T]	q_{95}	$\overline{n_e}\ [\frac{10^{19}}{m^3}]$
C-Mod	2.0	0.9	5.5	4.3	16.5
AUG	12.0	1.0	2.5	4.0	7.0
JET	14.5	2.0	2.3	3.6	2.0

*JET-ILW case close to peeling-ballooning boundary

$$\frac{<\nabla T_e>}{T_{e,top}} = \text{constant}$$ → **large error!**

$$\frac{R<\nabla T_e>}{R_{AUG} T_{e,top}} = \text{constant}$$ → **very accurate!**





APPLICATION ON JET-ILW: DATABASE COMPOSITION

Validation of IMEP extended to **55** ELMy H-mode stationary phases from JET-ILW discharges featuring:

- **power scans** at low, medium and high **gas rate**. Low and high **triangularity,** at **1.4MA/1.7T** [Maggi *NF* 2015]
  (B. Chapman worked on GK pedestal analysis on plasmas from this database)

- 1 plasma at **3MA/2.8T**, low triangularity (used by D. Hatch for GK analysis [Hatch *NF* 2019])

- **gas scan** at low, medium, and high $\boldsymbol{\beta_N}$. Low **triangularity,** at **2MA/2.3T**
  (large part of L. Frassinetti database used in IAEA paper [Frassinetti *NF* 2021])

IMEP simulations setup:

- No SOL model → density b.c. **from experimental values**: $n_{e,sep}$, $n_{e,top}$; we **assume**: $T_{e,sep} = T_{i,sep} = 100\mathrm{eV}$
- **Power deposition** from PENCIL/PION
- Core **turbulent transport** by QuaLiKiz → faster than TGLF sat2
- **Pedestal transport** simulated by imposing a constant $\mathbf{R < \nabla T_e > / T_{e,top}}$ **= -0.825**

APPLICATION ON C-MOD: DATABASE COMPOSITION

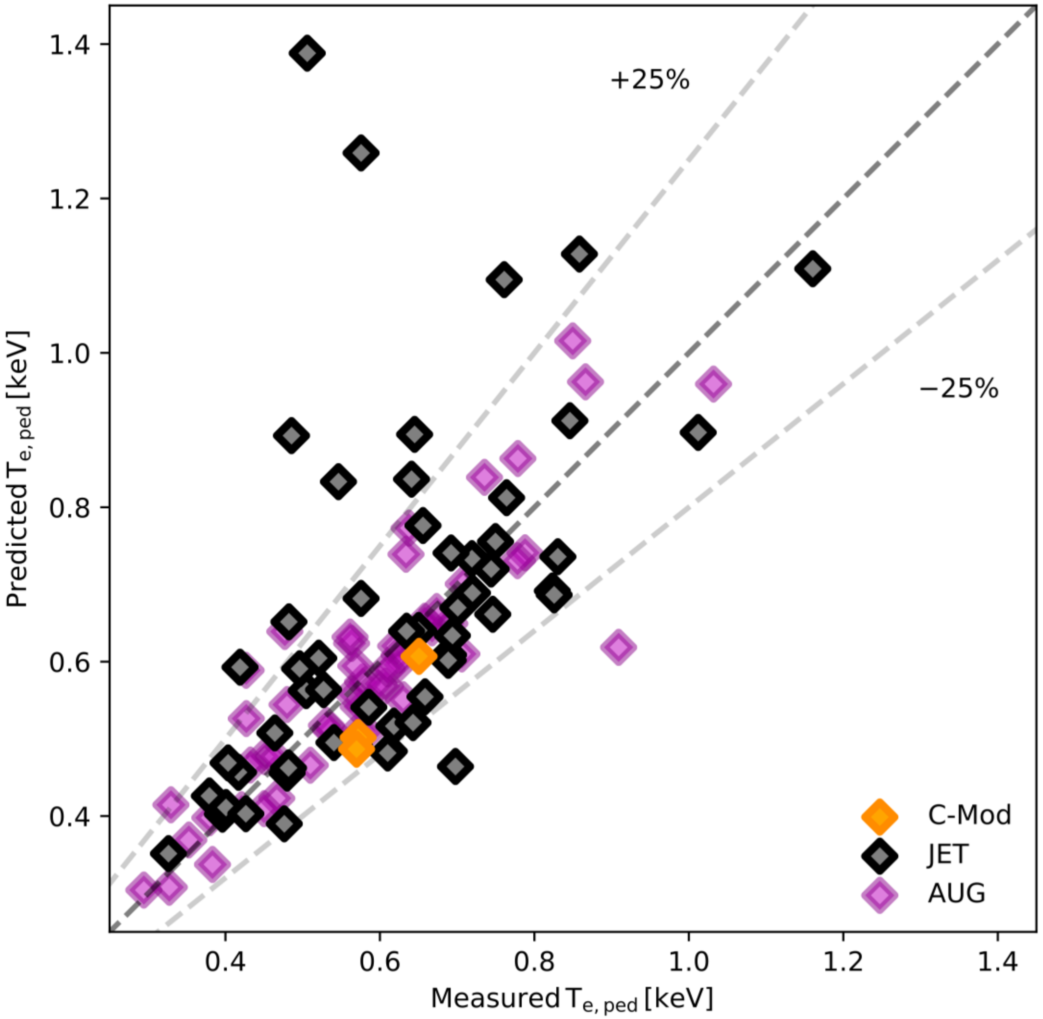
Validation of IMEP extended to **3** ELMy H-mode stationary phases from C-Mod discharges featuring:

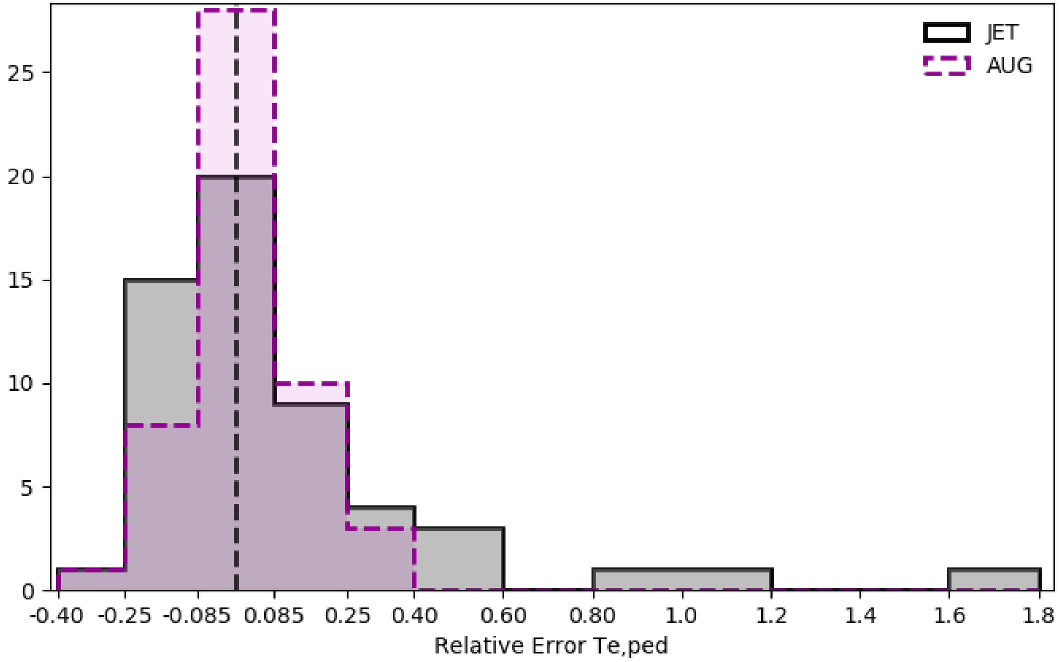
- similar shots with scans in **density** (fueling) and **heating power** (2-3 MW of ICRH power) [Diallo *NF* 2015]

IMEP simulations setup:

- No SOL model → b.c. **from experimental values**: $T_{e,sep} = T_{i,sep}, \; n_{e,sep}, \; n_{e,top}$
- **Power deposition** from TRANSP
- Core **turbulent transport** by QuaLiKiz → faster than TGLF sat2
- **Pedestal transport** simulated by imposing a constant $\mathbf{R < \nabla T_e > / T_{e,top}}$ **= -0.825**

PEDESTAL TOP TEMPERATURE PREDICTION: C-MOD, AUG, JET



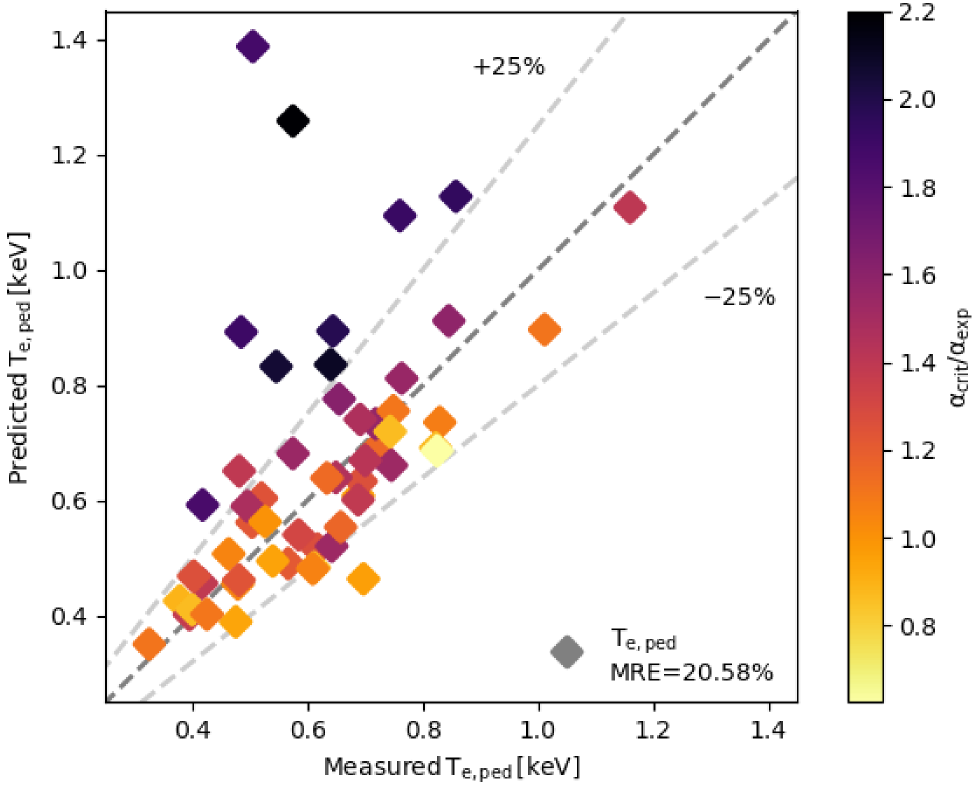


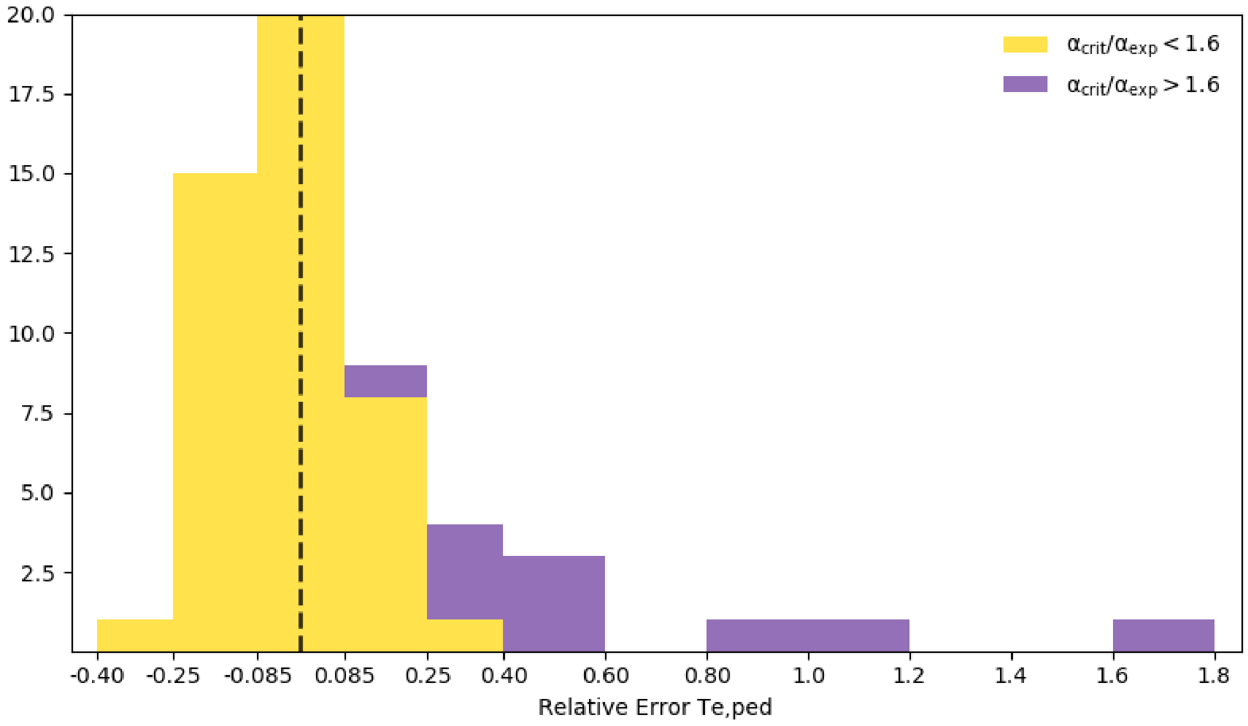
Similar accuracy in Te,ped prediction for AUG and JET-ILW, except for a few cases…

PEDESTAL TOP TEMPERATURE PREDICTION: JET-ILW

$\alpha_{\mathrm{crit}}/\alpha_{\mathrm{exp}}$ values from stability analysis as in L. Frassinetti IAEA paper [Frassinetti *NF* 2021]

$$\alpha = -2 \times \frac{Rq^2}{B^2}\frac{\mathrm{d}p}{\mathrm{d}r}$$

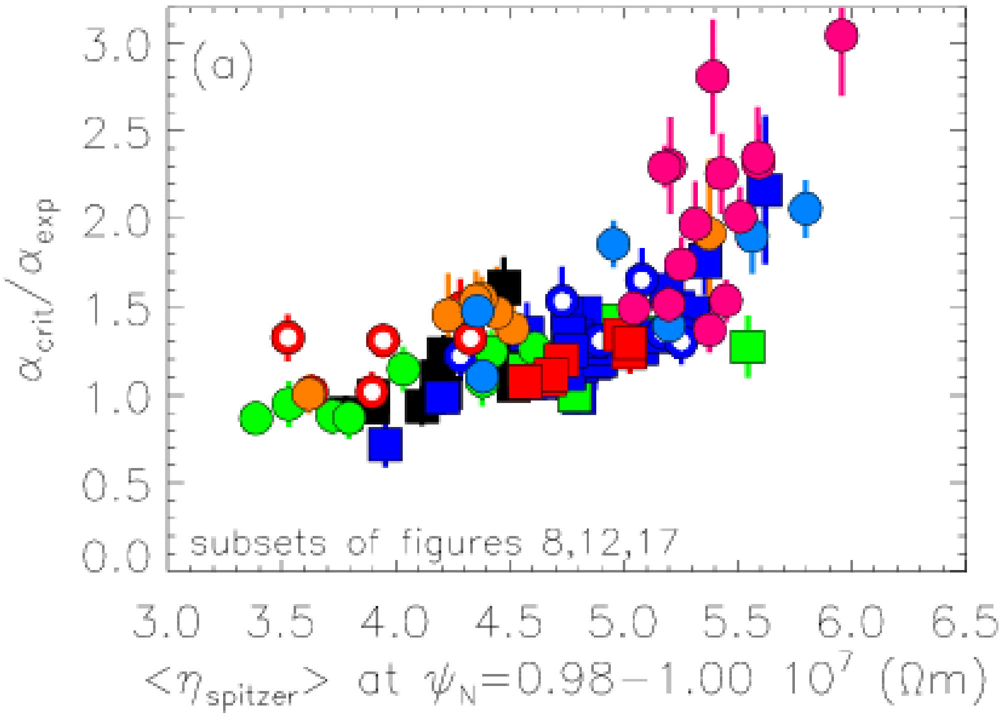


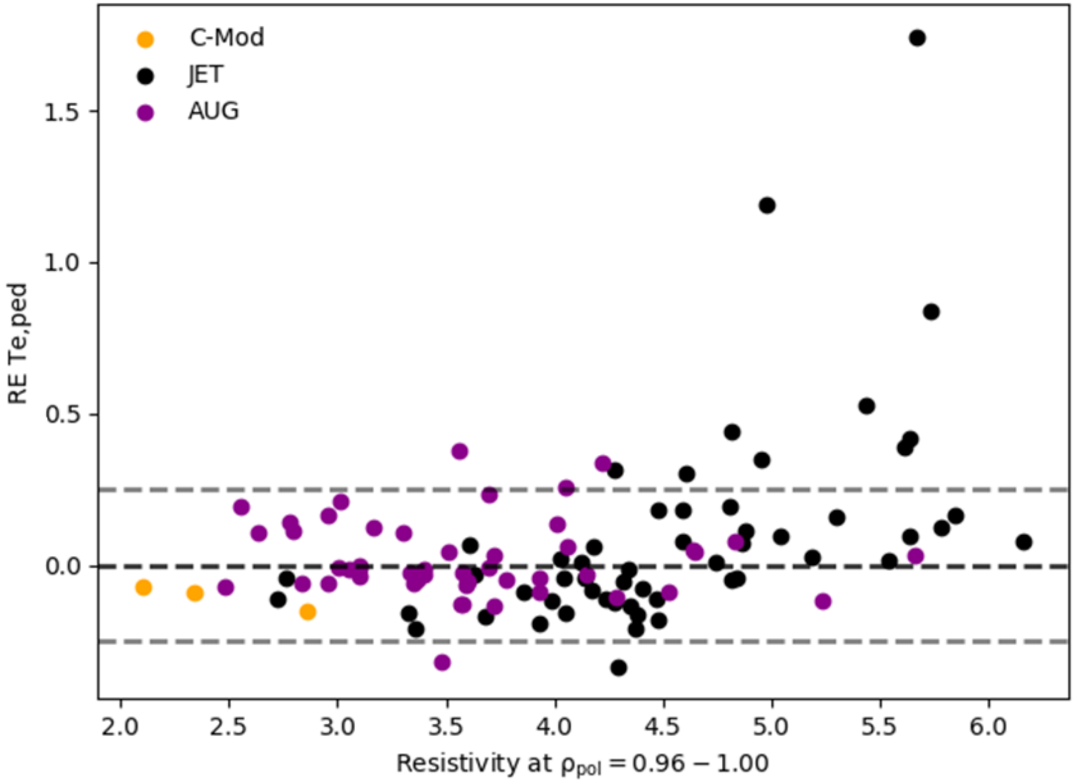


Highly overpredicted cases correspond to $\frac{\alpha_{\mathrm{crit}}}{\alpha_{\mathrm{exp}}} > 1.6$

PEDESTAL PREDICTION AND RESISTIVITY

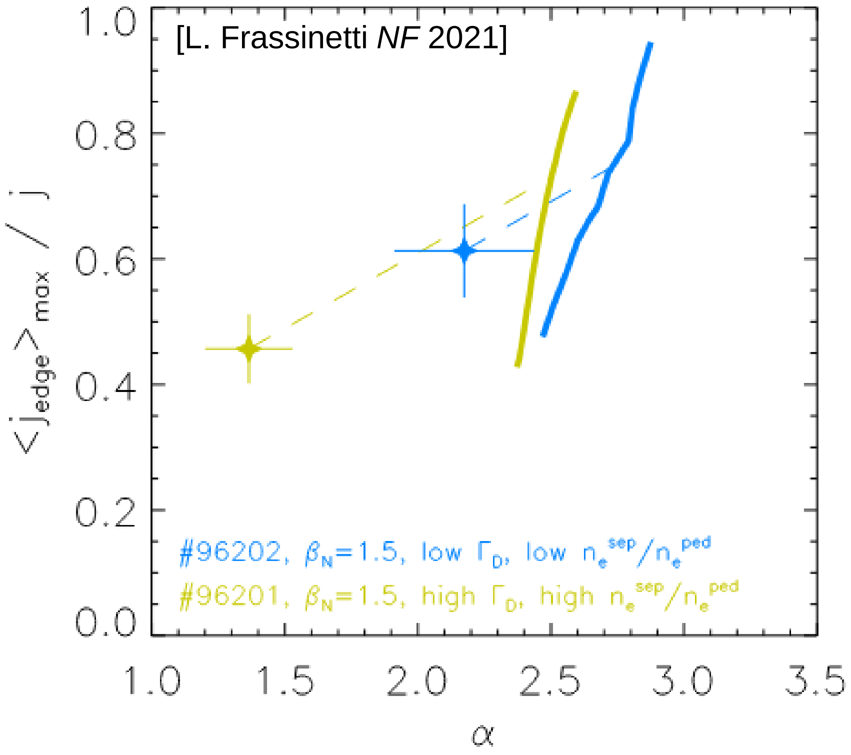
[L. Frassinetti *NF* 2021]

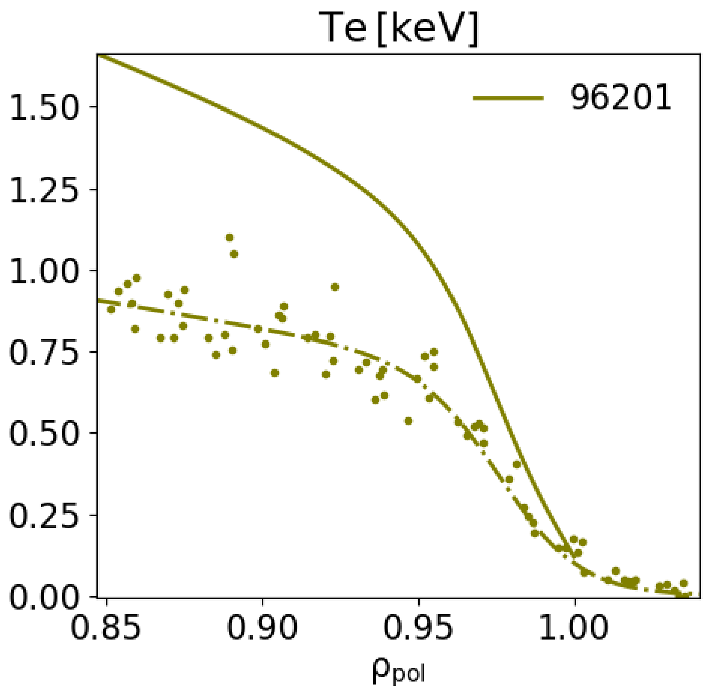




- JET-ILW tends to have higher resistivity than AUG near the separatrix
- Strongly overpredicted cases correspond to high resistivity
- For more details about effect of resistivity [Nyström, submitted to *NF*]

JET – 96201 HIGH FUELING CASE Γ_D=5.0X10^22 - 18 MW

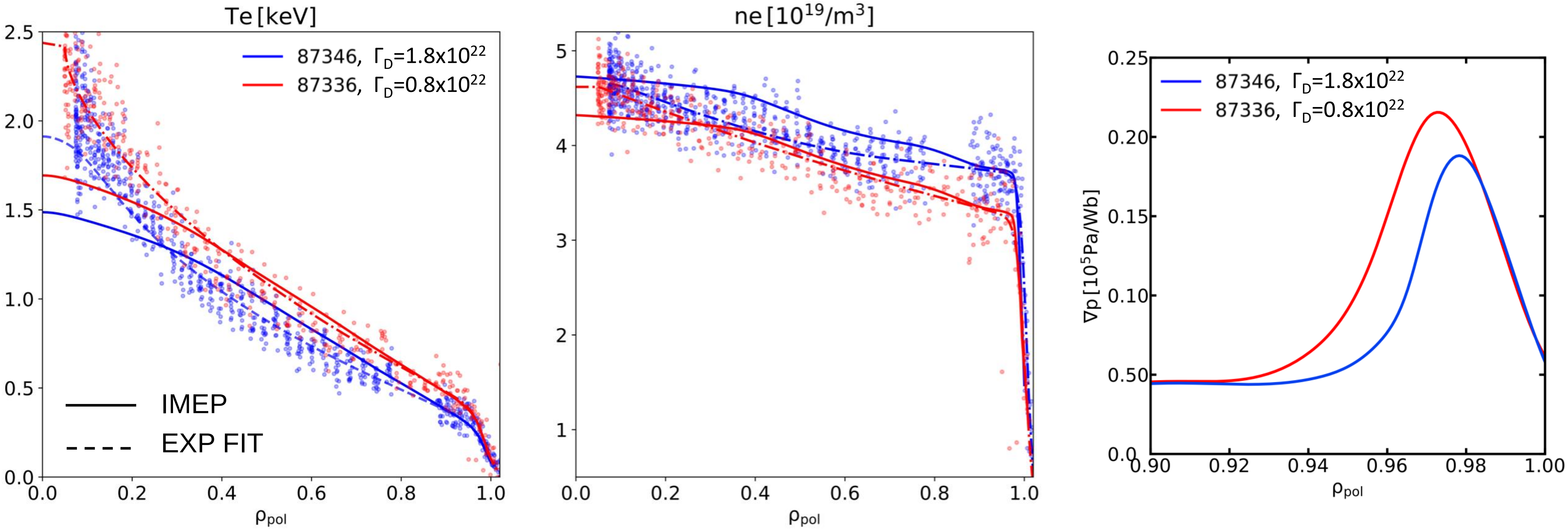

[L. Frassinetti *NF* 2021]



High fueling case strongly **overpredicted** also by IMEP (MISHKA)

What about using a MHD code which includes **resistive effects**?
[Nyström, submitted to *NF*]

JET FUELING SCAN AT 1.4MA/1.7T – NBI 4.7 MW

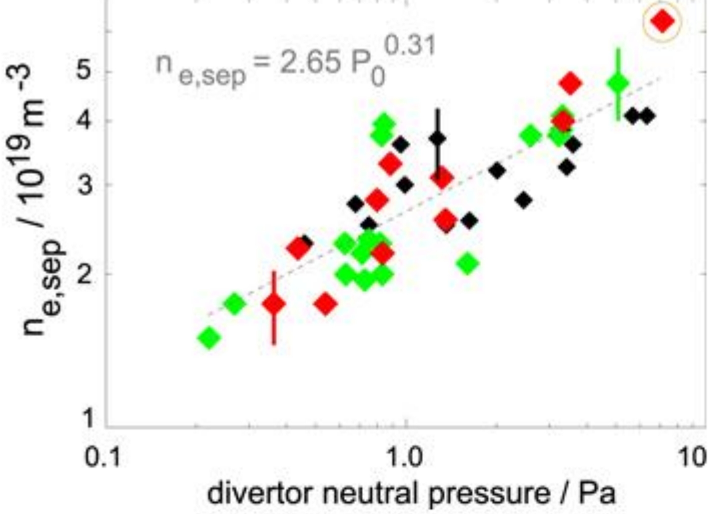


- Higher fueling rate causes the density profile to **shift outwards** (closer to the separatrix)
- Peak of pressure gradient shifts outwards, **destabilizing ballooning modes**
- **Decrease of pedestal pressure** with higher fueling rate, consistent with stability analysis from [Maggi *NF* 2015]

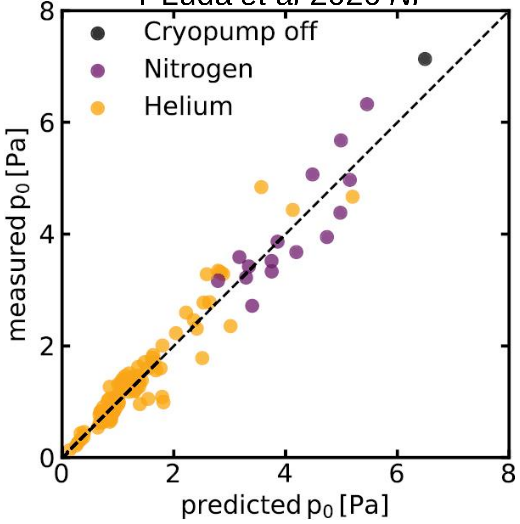
RELATION BETWEEN SEPARATRIX DENSITY AND FUELING RATE

On **AUG** ne,sep has been found to strongly depend on p_0 and p_0 to strongly depend on Γ_D → $\mathbf{n_{e,sep} = c\ \Gamma_D^{0.16}}$

A Kallenbach *et al* 2018 *PPCF*



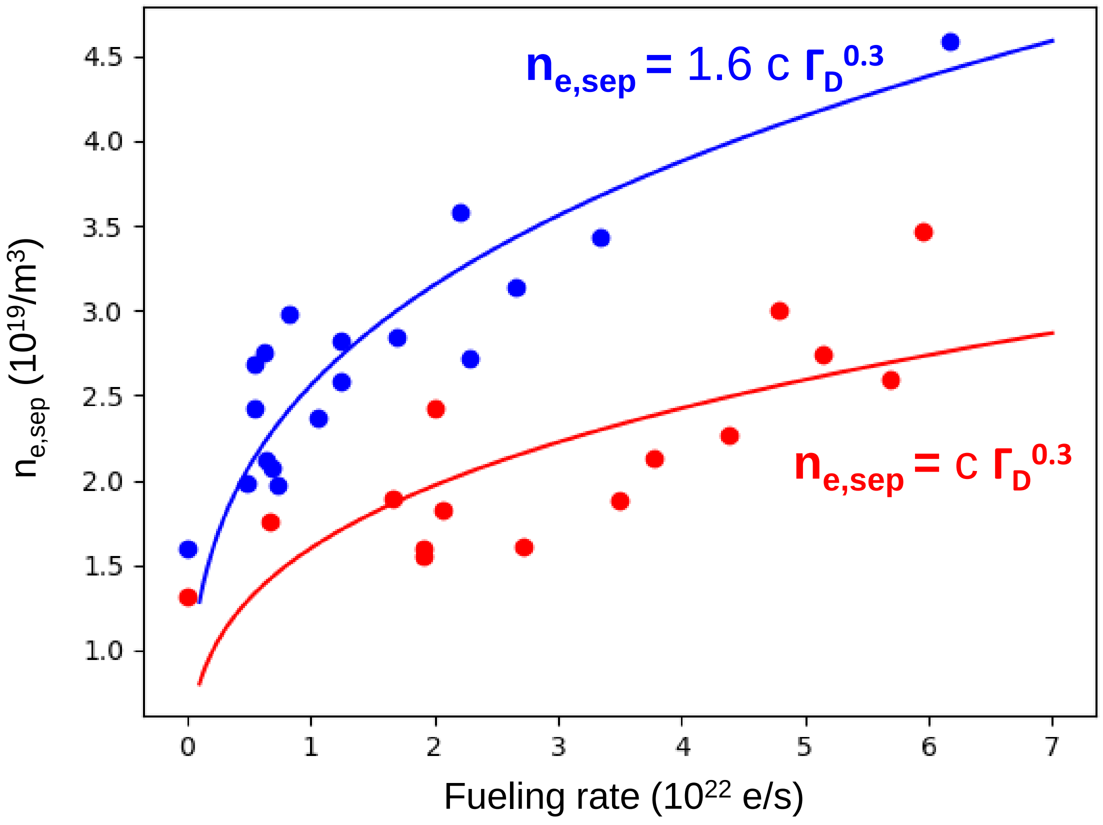
T Luda *et al* 2020 *NF*



$$p_0 = 0.174\ \Gamma_D^{0.63}\ \Gamma_{N2}^{-0.057}\ P_{NBI}^{0.33}\ v_{pump}^{-0.67}$$

What about JET-ILW?

Focusing on subset of the JET-ILW database (2MA/2.3T) it looks like the scaling applies when considering different divertor configurations: **horizontal** and **corner**



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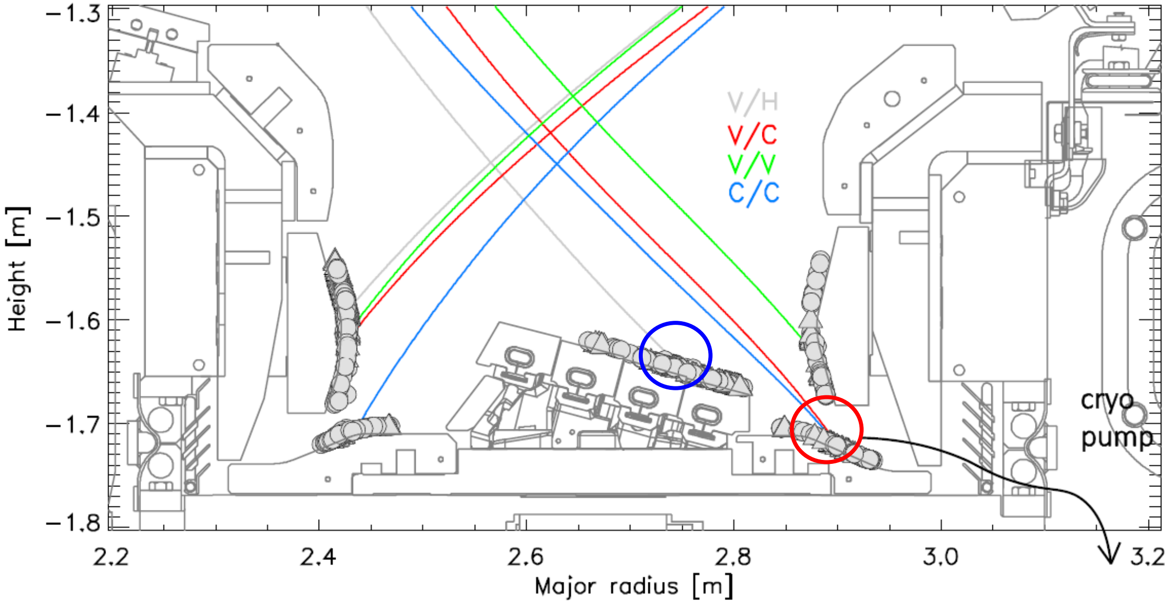
[L. Frassinetti *NF* 2021]



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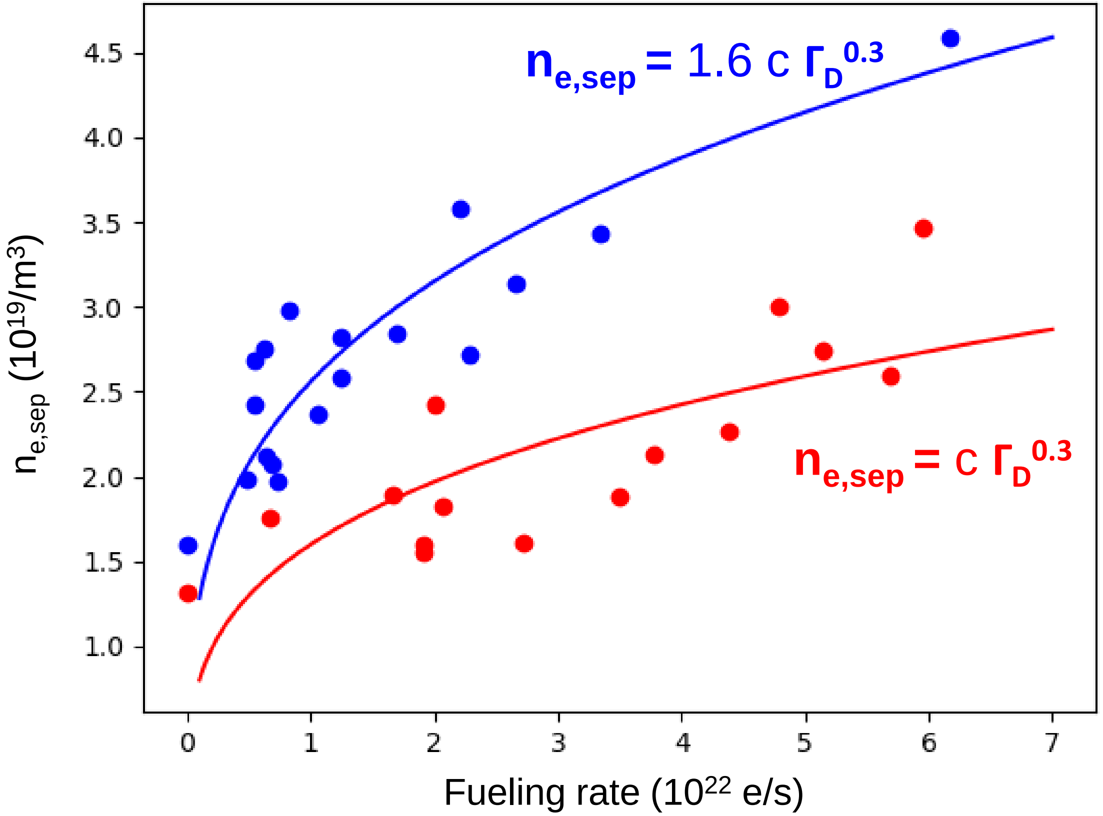


IMEP: FUTURE DEVELOPMENTS

Test and validate other reduced models for pedestal transport [D. R. Hatch *Phys. Plasmas* 2022]

What other physics can be included in IMEP?

- **impurity seeding → PhD project** (Daniel Fajardo): update coupling of STRAHL in ASTRA + description of **impurities** in IMEP → self-consistent prediction of $\mathbf{Z_{eff}}$ and $\mathbf{P_{rad}}$
- **detachment → its onset** can be described with threshold **heat flux** and **impurity concentration ?**

  from *Kallenbach PPCF 2017*

  $$P_{\mathrm{sep}}/R|_{\mathrm{det.point}} = \frac{1}{1.3} p_0 (1 + f_z c_z) \cdot (\lambda_{\mathrm{int}}/0.005\ \mathrm{m}) \cdot (R/1.65\ \mathrm{m})^{r_z}$$

  or by the **0D model** developed by *Siccinio PPCF 2016, Siccinio NF 2018* ***?***

Test additional scenarios:

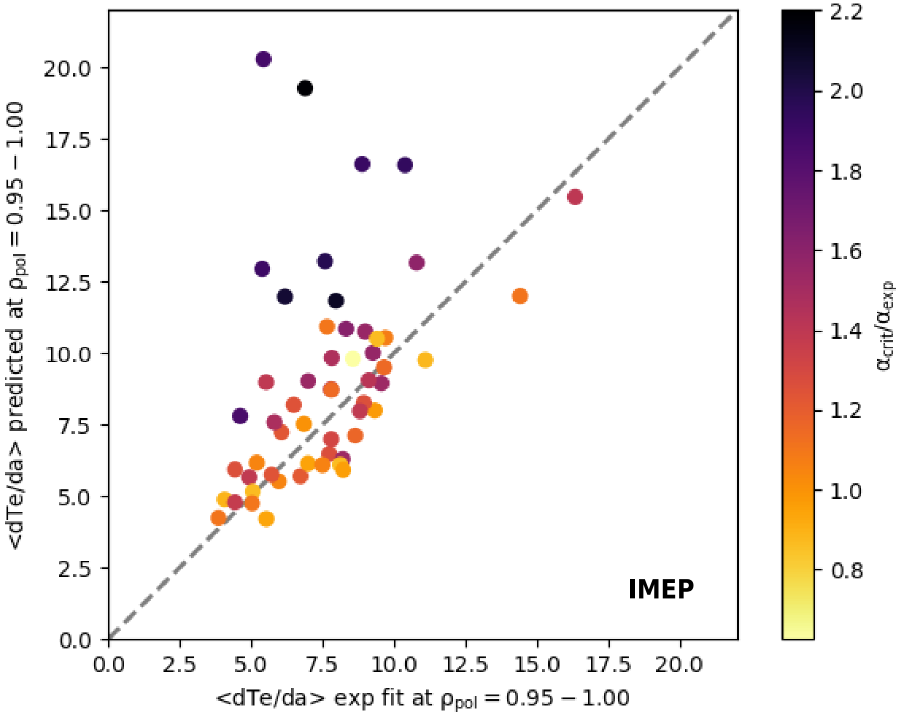
- **pellet** fueled plasmas → can IMEP reproduce the effect of pellets on pedestal and global confinement?
- **QCE** and **EDA** H-mode → can IMEP reproduce the experimental pedestal pressure? Resistive MHD important?

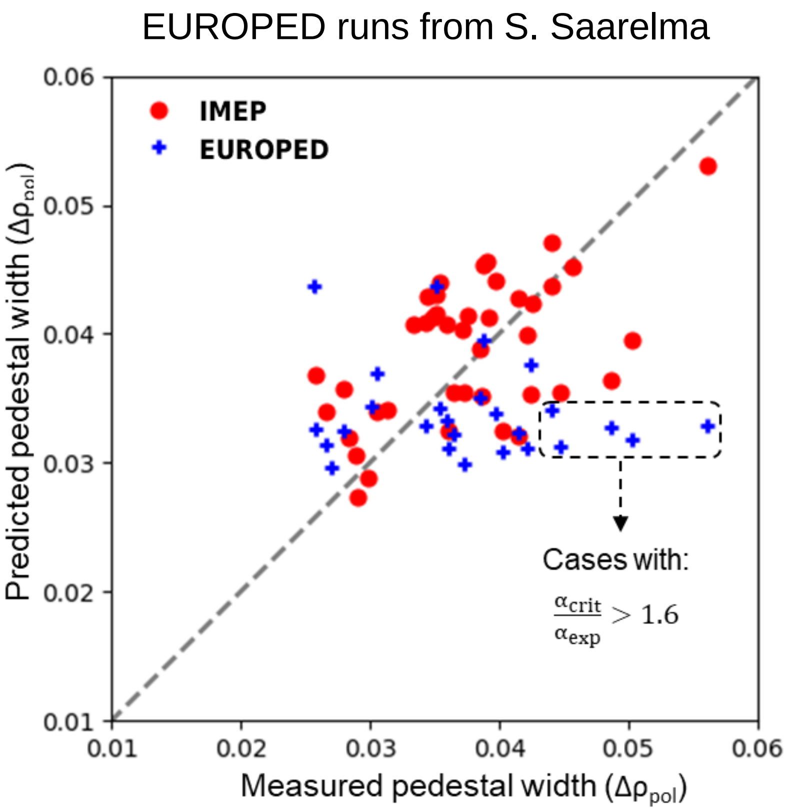
CONCLUSIONS

- IMEP accurately predicts **entire radial profiles** of AUG H-mode plasmas, from magnetic axis to separatrix, only using engineering parameters as inputs
- Dimensionless parameter $\frac{R<\nabla T_e>}{T_{e,top}}$ = const. is promising candidate in AUG, C-Mod, and JET-ILW (PB limited pedestals) to accurately **predict the pedestal pressure in different devices – M5.1/D5.1**
- The **coupling to a resistive MHD stability code** could allow a more accurate pedestal prediction for cases far from ideal peeling-ballooning boundary
- The **empirical elements of the SOL model** need to be generalized in order to be applied also to different machines. In particular, the scaling for the divertor neutral pressure p_0 is AUG specific
- New elements can be included in IMEP to **describe additional physics**, in particular for the SOL and pedestal (e.g. detachment, impurity seeding)
- In the long term IMEP could contribute to **develop and optimize** ITER, DEMO, and SPARC scenarios to reach the best fusion performance

BACKUP

PEDESTAL TEMPERATURE GRADIENT AND WIDTH PREDICTIONS

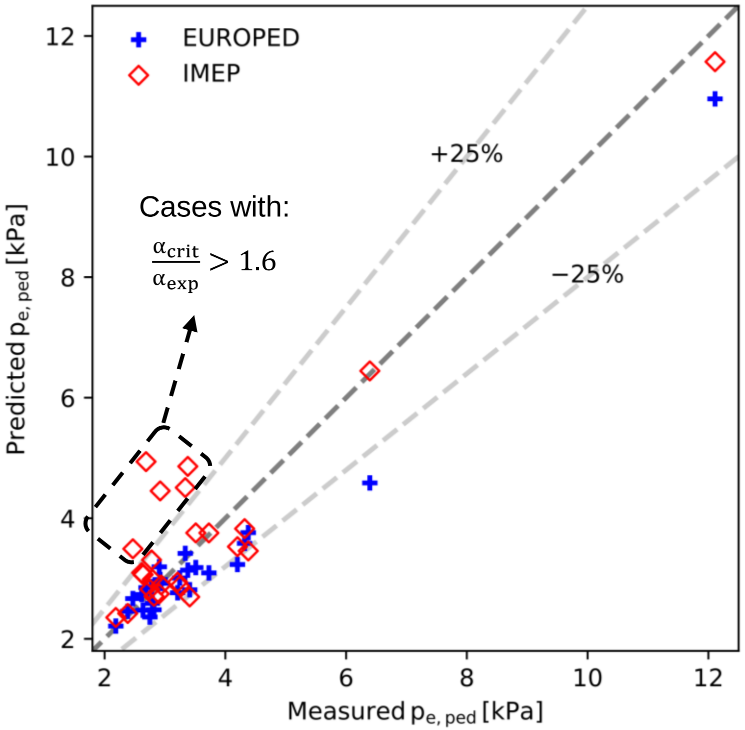


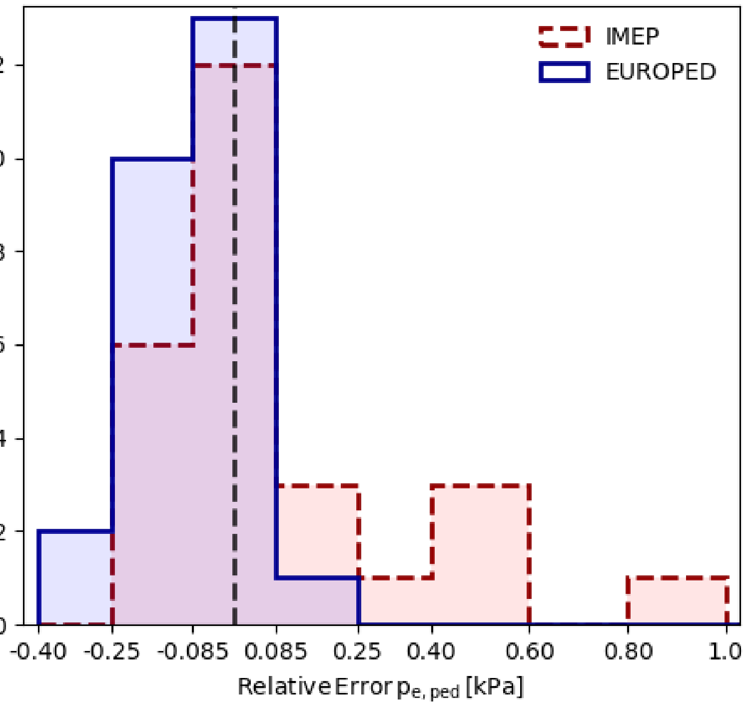


- IMEP **more accurate** than EUROPED for pedestal width prediction
- IMEP takes exp. value of $\mathbf{n_{e,sep}}$, EUROPED assumes $\mathbf{n_{e,sep} = n_{e,top}/4}$
- IMEP pedestal transport constraint ($R < \nabla T_e > / T_{e,top}$ = const.) links pedestal width to top temperature but not to top density, while EUROPED links pedestal width to top pressure (via $\Delta\Psi_N \propto \beta_{p,ped}^{0.5}$)
- These elements provide a more **realistic description of the density profile** and allow IMEP to capture the effect of the fueling rate on the pedestal stability

PEDESTAL PRESSURE PREDICTIONS

EUROPED runs from S. Saarelma

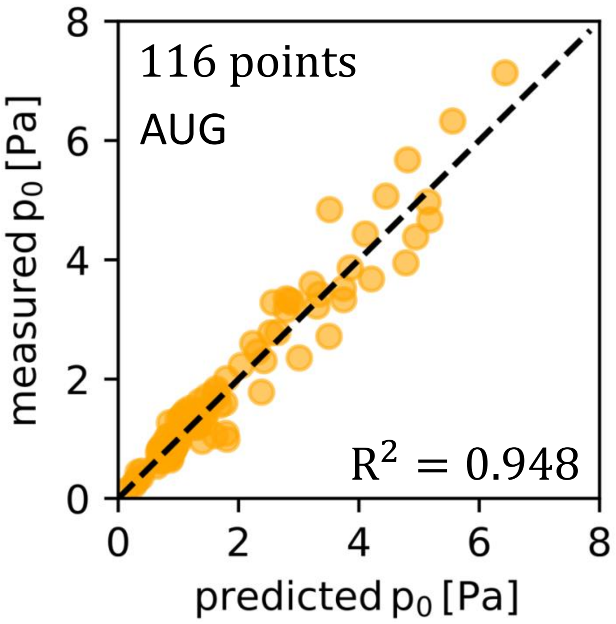




- Differently from IMEP, EUROPED does not overpredict the pedestal pressure at high $\alpha_{crit}/\alpha_{exp}$, but underestimates width
- This might be because of the different **values of $\mathbf{n_{e,sep}}$** used by the 2 models
- The cases with $\frac{\alpha_{crit}}{\alpha_{exp}} > 1.6$ feature a high fueling rate, where the experimental value of $n_{e,sep}/n_{e,top}$ becomes large and the pedestal density gradient becomes small
- This means that IMEP needs a very large temperature gradient to reach a large enough pressure gradient to destabilize peeling-ballooning modes (α_{crit})
- EUROPED instead needs lower temperature gradients since $n_{e,sep}/n_{e,top}$ is given by $n_{e,sep} = n_{e,top}/4$

BACKUP

Scrape Off Layer model
Gives a relation between gas puffing, separatrix density, and incoming neutral particles



$$\mathbf{p_0} = 0.174 \mathbf{\Gamma}_D^{0.63} \mathbf{\Gamma}_{N2}^{-0.057} P_{NBI}^{0.33} v_{pump}^{-0.67}$$

From the 2-point model:

$$\mathbf{T_{e,sep}} = \left(\frac{7 P_{sep} \pi q_{cyl} R}{3 k_0 k_z}\right)^{2/7}$$

[A Kallenbach *et al* 2018 *Nuclear Materials and Energy*]

$$\mathbf{n_{e,sep}} = 0.35 \left(\frac{P_{sep} B}{3\pi < \lambda_{q,HD} >< B_p >}\right)^{3/14} \cdot$$

$$\cdot R^{-0.5} (\gamma \sin \alpha)^{-\frac{1}{2}} \left(\frac{2 k_0 k_z}{7 \pi q_{cyl}}\right)^{\frac{2}{7}} \frac{2}{e} \left(\frac{m_D}{2}\right)^{0.5} \cdot$$

$$\cdot \left(1.5 \cdot 10^{23} \mathrm{Pa}/(\mathrm{at\, m^{-2} s^{-1}})\right)^{0.5} \mathbf{p}_0^{\;1/4}$$

Divertor neutral pressure

$$\mathbf{\Gamma_{0,sep}} = \alpha \left(f_R \mathbf{\Gamma_{e,sep}} + c_{div,wall} \left(\Gamma_D - \Gamma_{pump}\right)\right)$$

α: ionization and CX procceses considering Franck-Condon neutrals ($T_0 = 5\mathrm{eV}$)