Integrated modeling of tokamak plasma confinement

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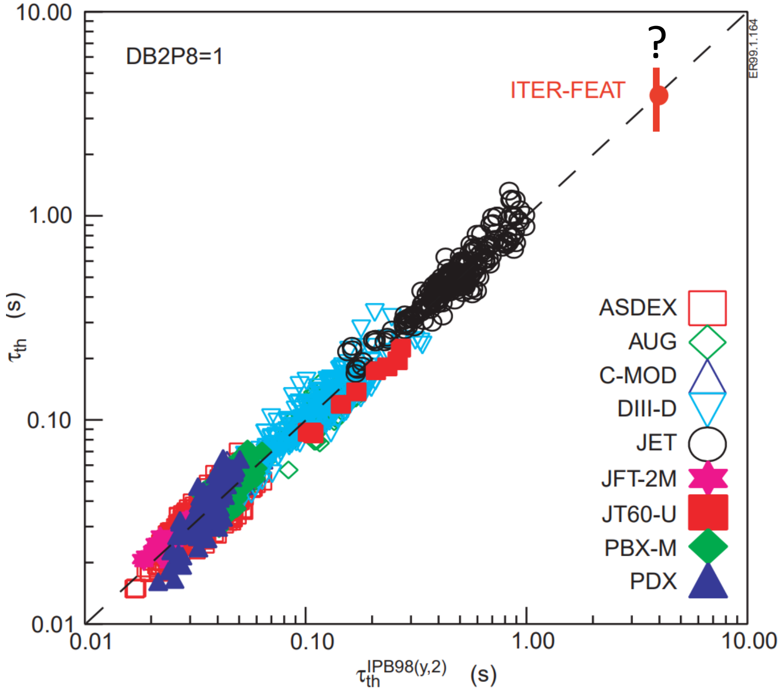
No reliable theory-based way to predict confinement

How can we predict H-mode energy confinement?



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

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

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

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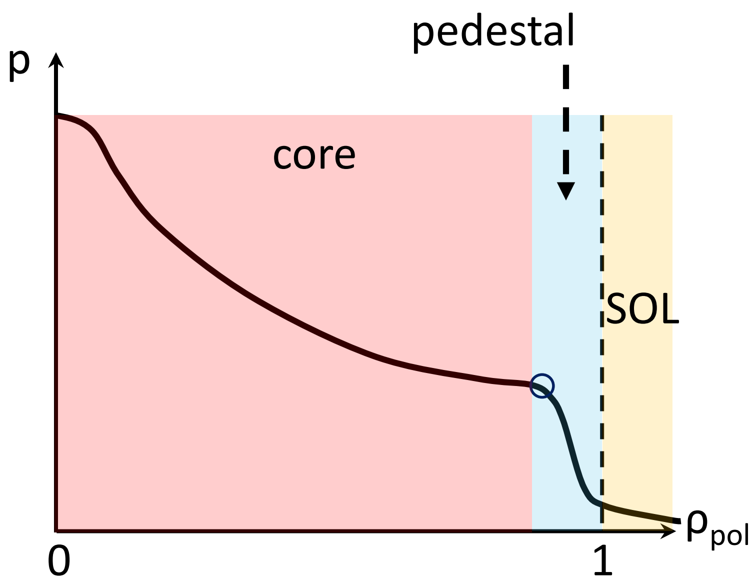

- Scaling laws (statistical regressions):
  - Simple, based on main engineering parameters
  - Robust to capture dominant dependencies
  - Do not capture other important dependencies
  - Limited extrapolation capabilities
- Simulations:
  - Predict kinetic profiles (T_e, T_i, n_e, n_i)
  - Theory-based 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

The goal of this project

Integrated model

Scrape Off Layer model

Transport code – ASTRA

MHD stability code - MISHKA

INTEGRATED MODEL: combination of different models to **simulate the confined plasma**

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OUR PROJECT: develop an integrated model to simulate the plasma using only global parameters as input, and **no information from measurements of kinetic profiles**

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OUR GOAL: take into account all the important dependencies affecting global plasma confinement

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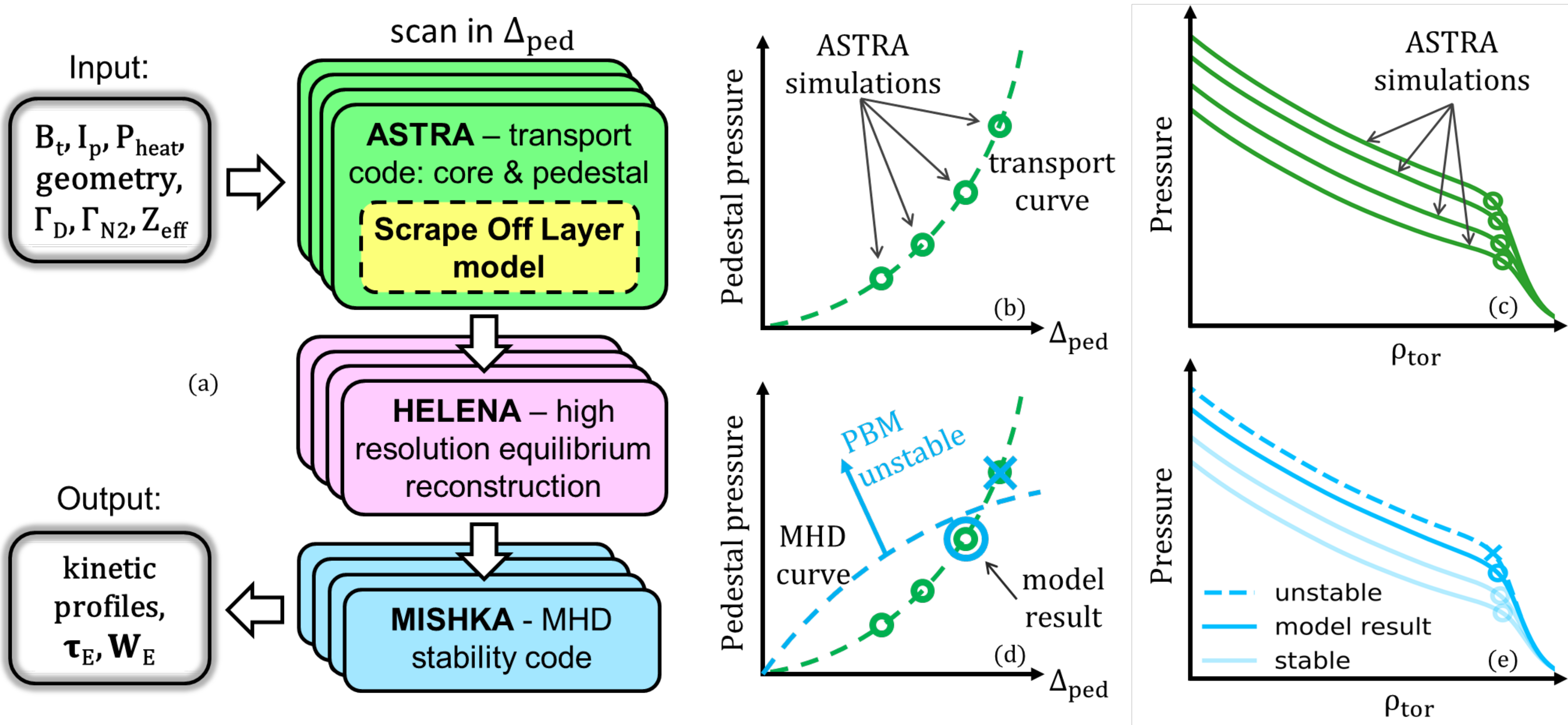
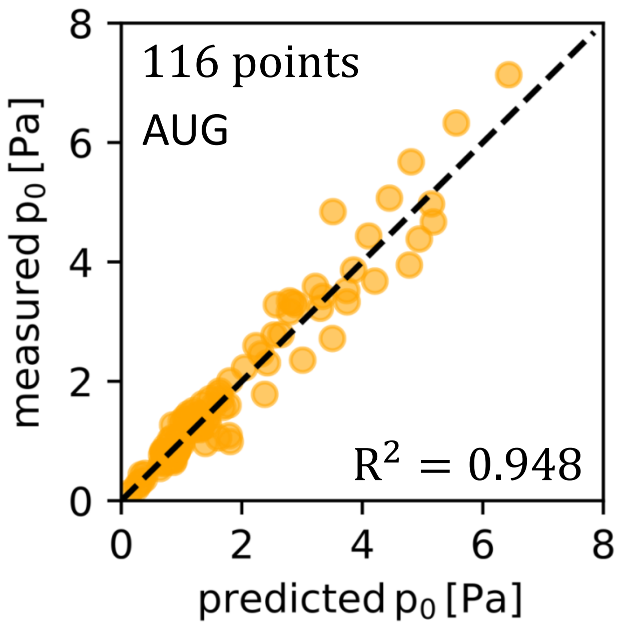
Can this approach reproduce present experiments with **higher accuracy** than an empirical scaling law?

Modelling workflow



Scrape Off Layer model

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



From the 2-point model:

$$\mathbf{T_{e,sep}} = \left(\frac{7P_{sep}\pi q_{cyl}R}{3k_0k_z}\right)^{2/7}$$

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

$$\mathbf{n_{e,sep}} = 0.35\left(\frac{P_{sep}B}{3\pi < \lambda_{q,HD} >< B_p >}\right)^{3/14} \cdot R^{-0.5}(\gamma \sin\alpha)^{-\frac{1}{2}}\left(\frac{2k_0k_z}{7\pi q_{cyl}}\right)^{\frac{2}{7}}\frac{2}{e}\left(\frac{m_D}{2}\right)^{0.5} \cdot (1.5\cdot 10^{23}\mathrm{Pa}/(\mathrm{at\,m^{-2}s^{-1}}))^{0.5}\mathbf{p_0}^{1/4}$$

Divertor neutral pressure → $\mathbf{p_0}$

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

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

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

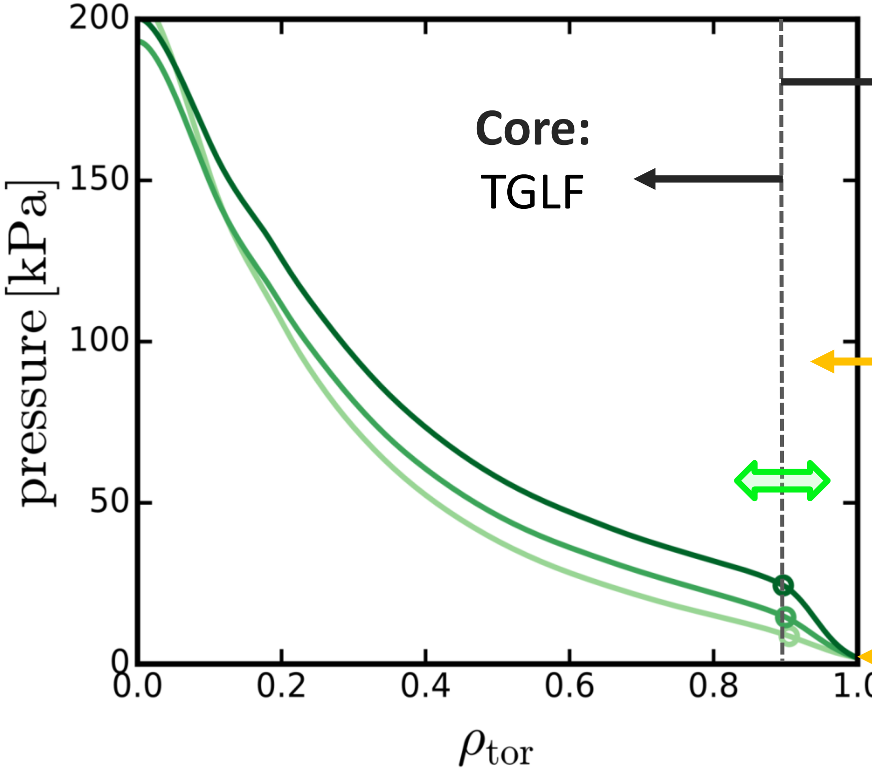
Confined plasma profiles prediction

Transport code - ASTRA
Evaluates the **kinetic profiles** from separatrix to magnetic axis, using global plasma parameters

Scan in pedestal width (Δ_{ped}):
many ASTRA simulations, one for each Δ_{ped}

Edge:
pedestal transport model (next slides)

Core:
turbulent transport model TGLF
[G.M. Staebler *PoP* 2007, *NF* 2017]



Edge:
pedestal
model

$\mathbf{\Gamma_{0,sep}}$

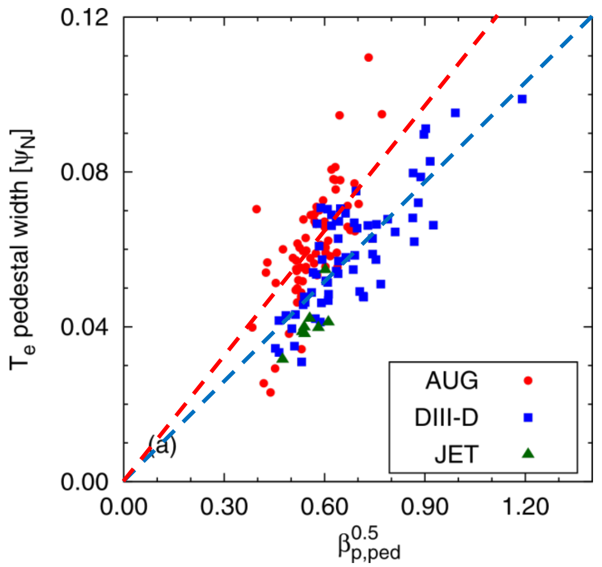
$\mathbf{\Delta_{ped}}$

$\mathbf{n_{e,sep}, T_{e,sep}}$
$\mathbf{(T_{i,sep} = 2T_{e,sep})}$

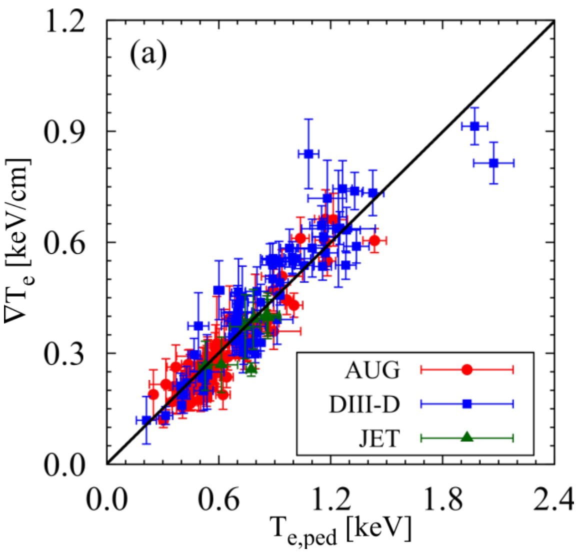
Core ⟲ **Pedestal**
Complete description of transport over the whole plasma radius, w/ b.c. from SOL model

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 $T_{e,top} = T_{i,top}$



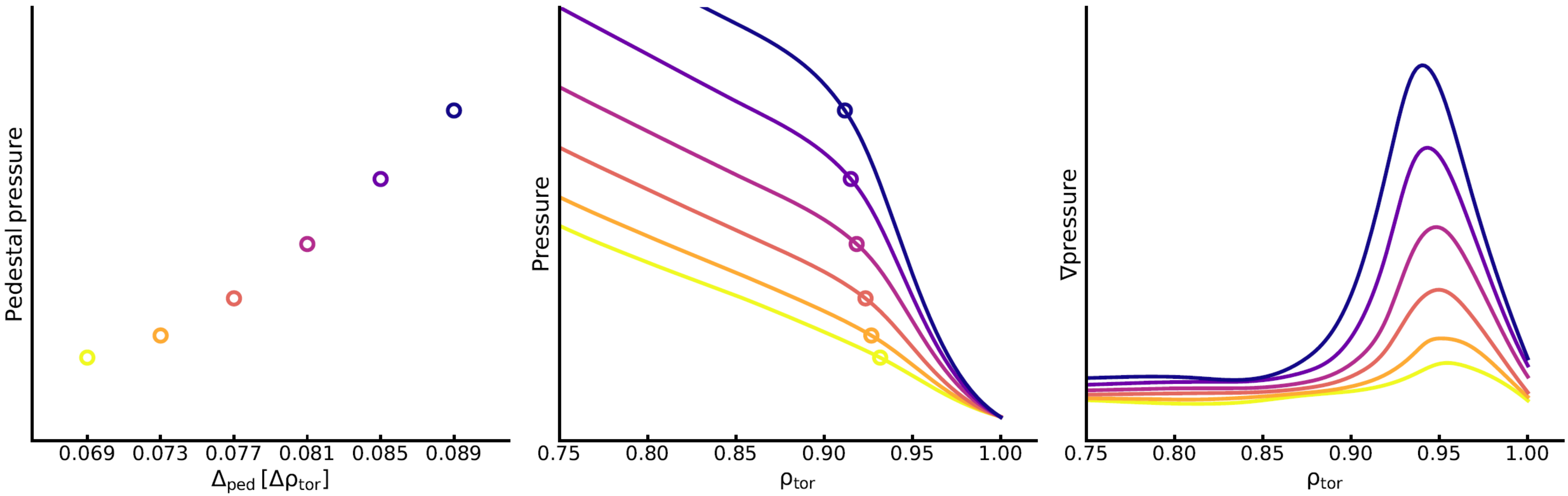
- AUG, DIII-D, and JET pedestals exhibit one common feature: $< \nabla \mathbf{T_e} > / \mathbf{T_{e,top}} \approx \textbf{constant}$
  [P.A. Schneider *et al* 2013 *NF*]



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

Pedestal transport model → $p_{top} \propto \Delta_{ped}$

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

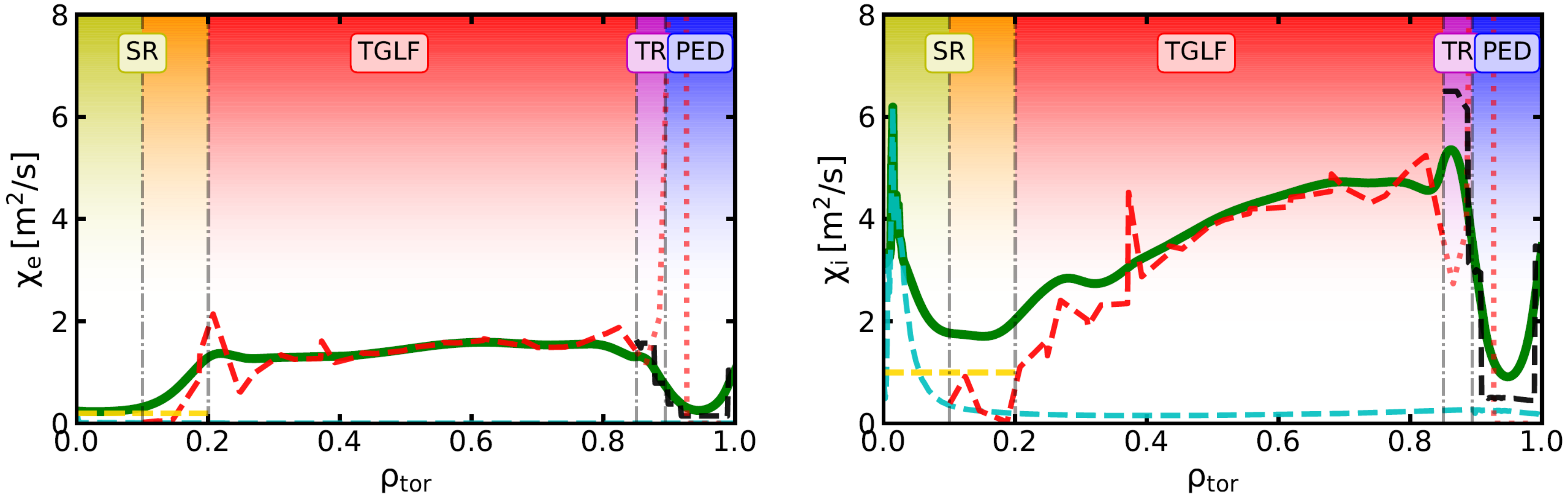


Connection of the different regions

Example of the heat diffusivities for electrons and ions for a given Δ_{ped}:

- - - Before smoothing

—— After smoothing



TGLF, **NCLASS**, **sawtooth transport**,

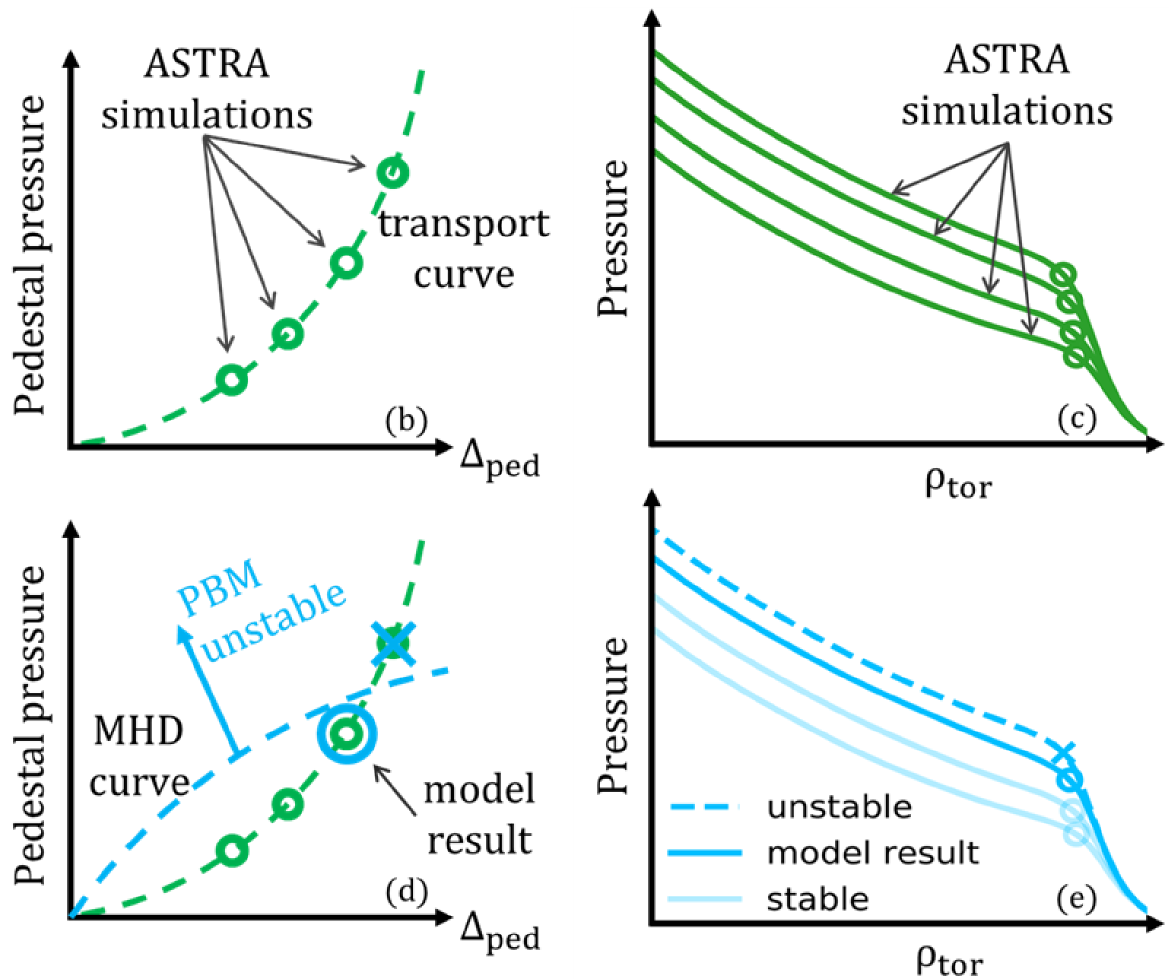
diffusivities in the **pedestal** and **transition** regions

$$\chi_{tr} = c_1 + c_2 \chi_{ped}$$

Pedestal MHD stability calculation

MHD stability code - MISHKA
Evaluates the critical
pedestal pressure

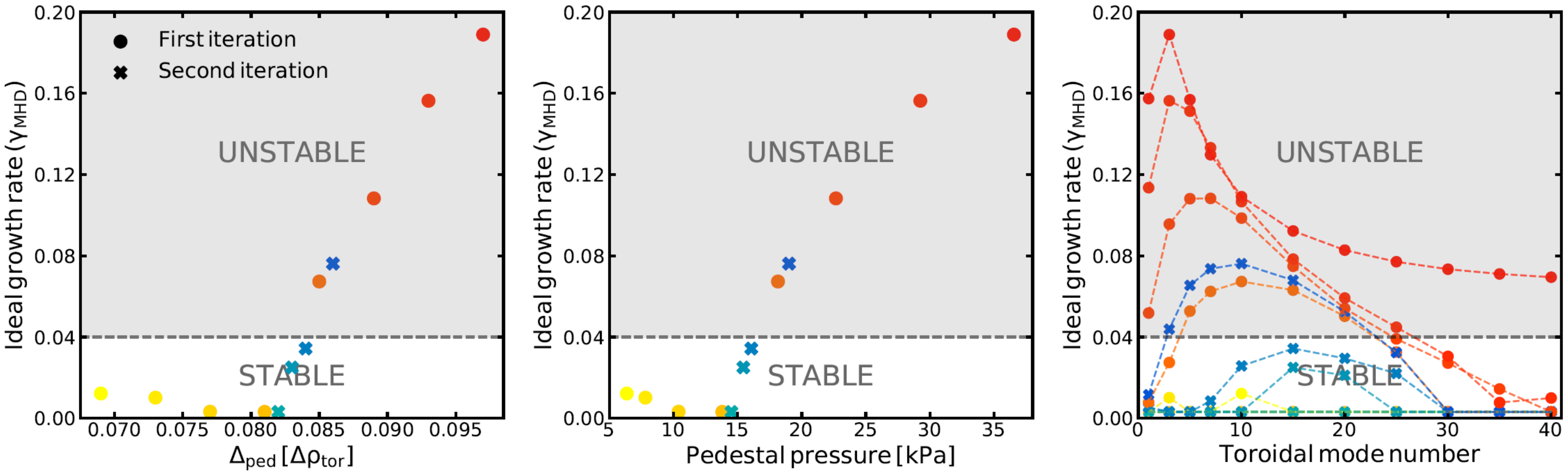
The MISHKA MHD stability code is run on every ASTRA simulation result to find the pedestal width corresponding to the **highest pedestal pressure** that is peeling-ballooning modes (PBM) stable



Pedestal width solver

- ○ **First iteration:** rough scan to identify transition from stable → unstable
- × **Second iteration:** finer scan to find highest stable pedestal pressure

MHD modes calculated by MISHKA



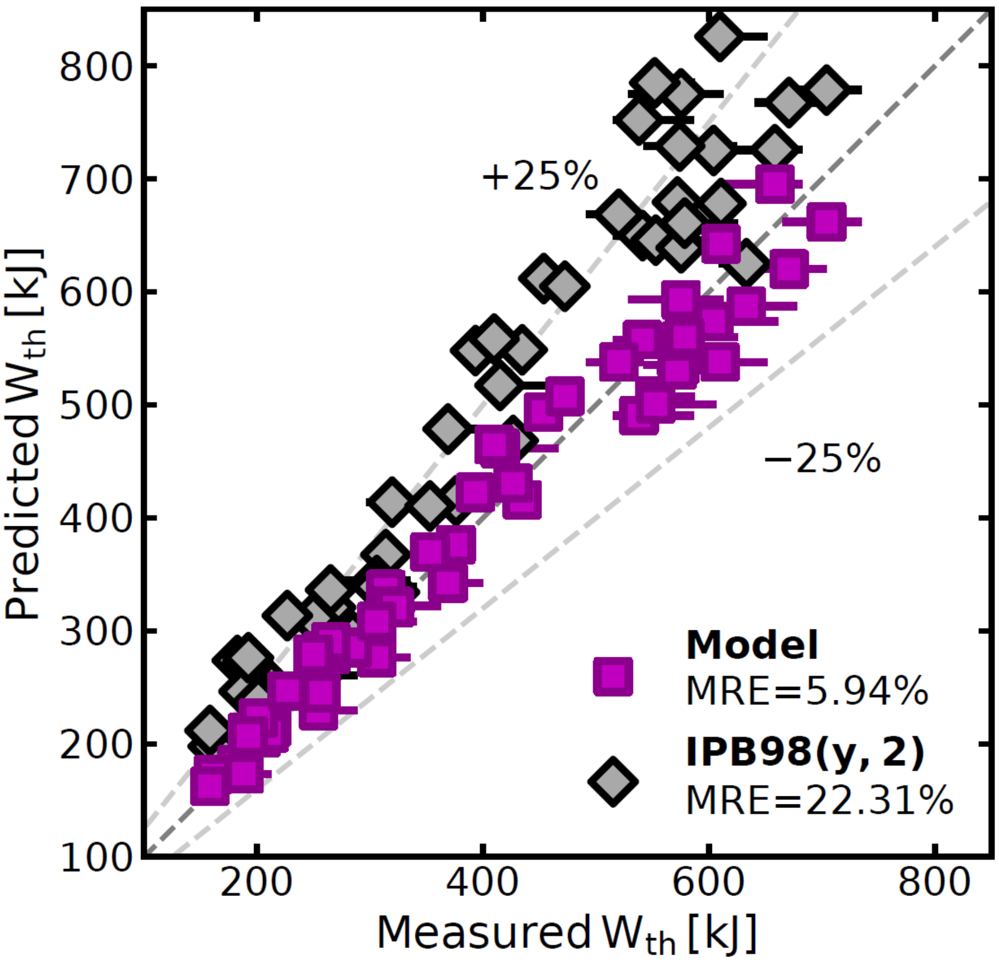
Fully automated procedure to run the workflow on a large number of cases, without requiring human intervention

Model 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:

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

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



… and than recent more accurate scaling laws

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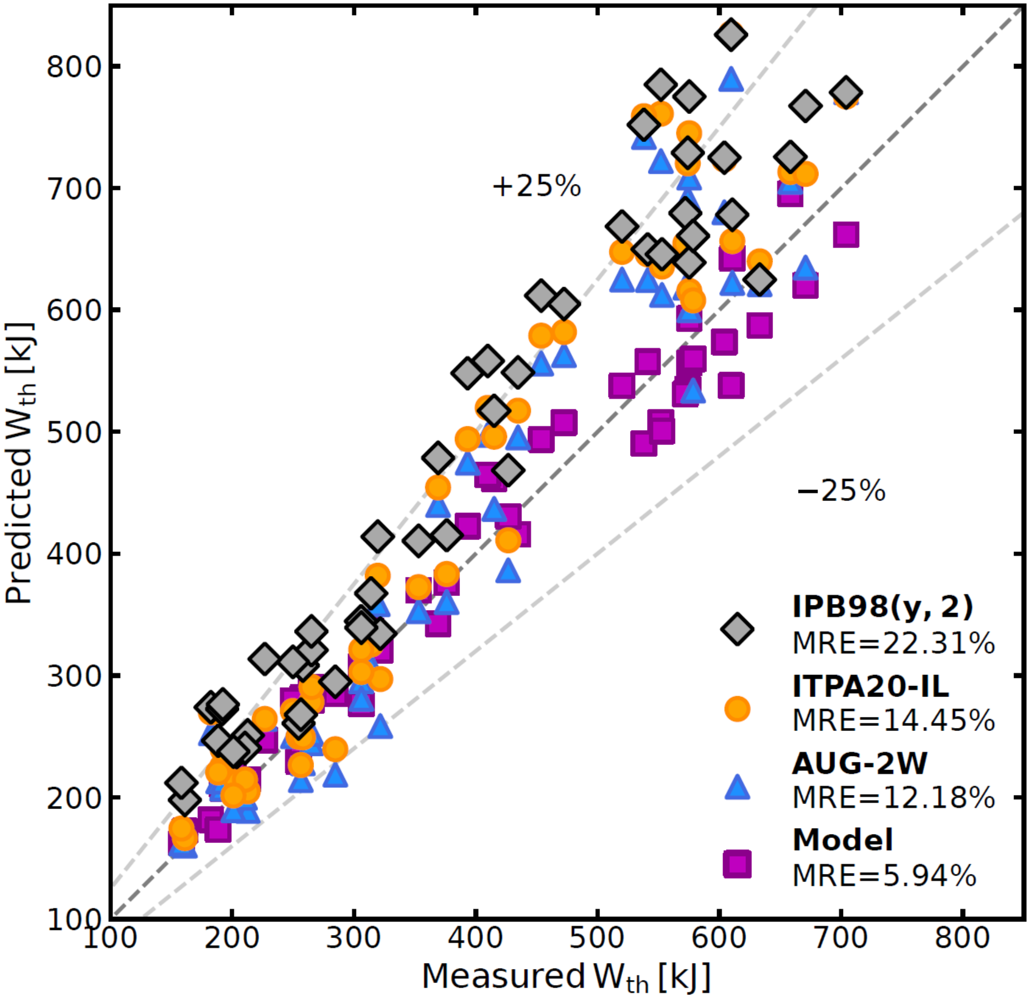
The model is even more accurate than a regression on **ASDEX Upgrade data only** (AUG-2W)



Core and pedestal confinement

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

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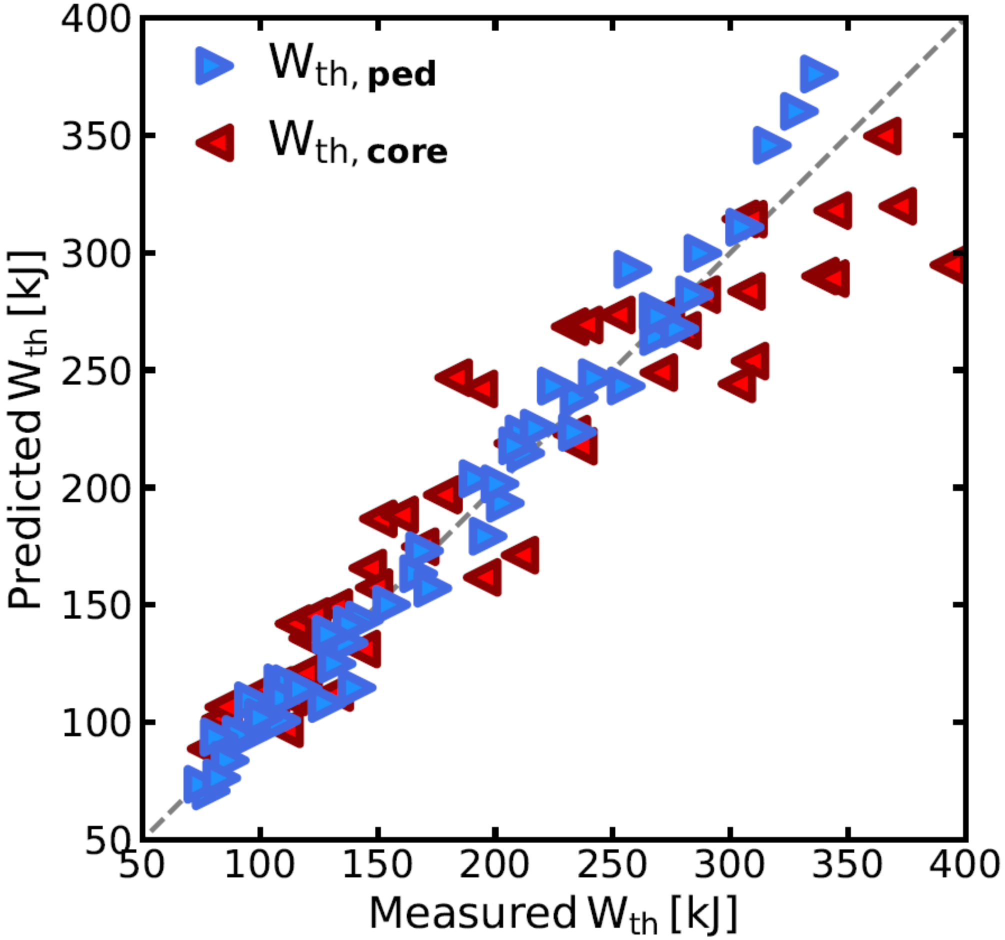
$\mathbf{\Gamma_D}$ = 0 – 8 x 10^{22} [e/s]
$\boldsymbol{\delta}$ = 0.19 – 0.42
$\mathbf{V_{NBI}}$ = 42 - 92 [kV]

This approach can accurately predict the **pedestal energy**, and can describe the effect of the different parameters on pedestal confinement for this database

The **core energy** can be overpredicted by TGLF due to low stiffness, or underpredicted due to too low stabilization mechanisms (fast ions, β effects)



Density prediction

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

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$\mathbf{P_{net}}$ = 2 – 14 [MW] $\mathbf{q_{95}}$ = 3 - 8

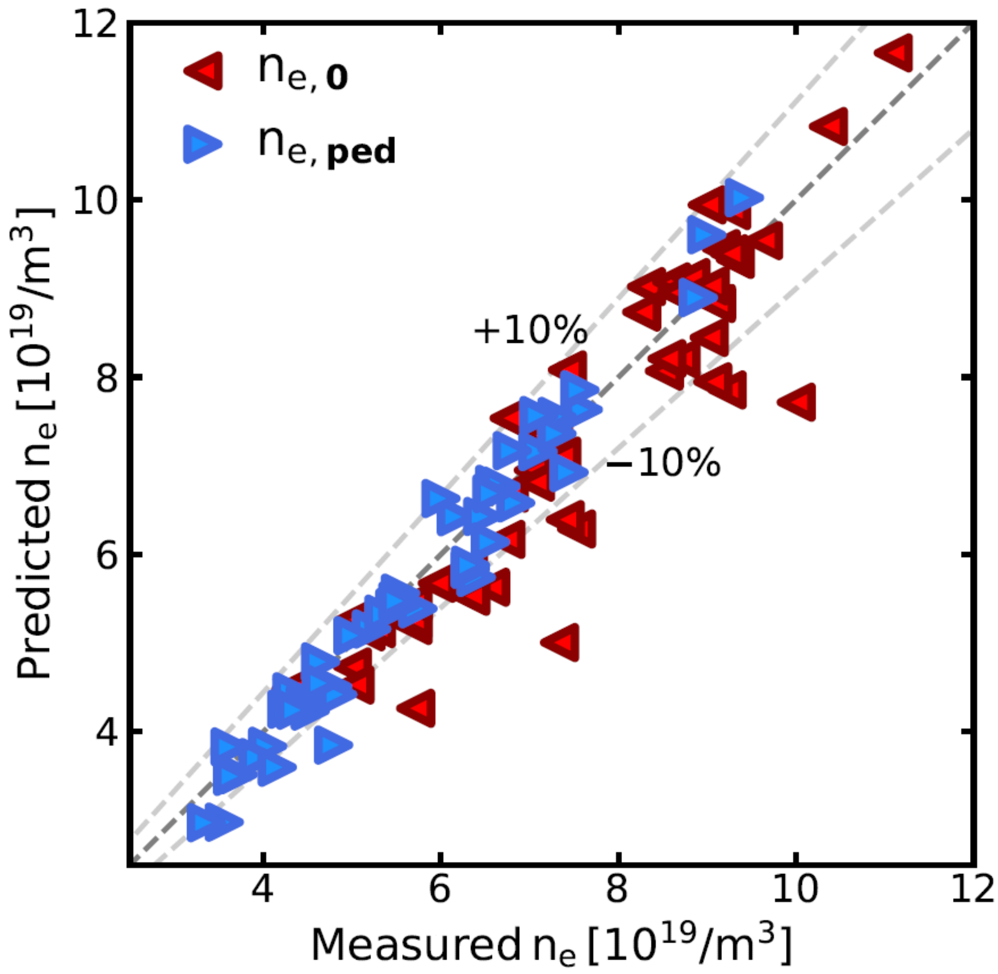
$\mathbf{\Gamma_D}$ = 0 – 8 x 10^{22} [e/s]

$\boldsymbol{\delta}$ = 0.19 – 0.42

$\mathbf{V_{NBI}}$ = 42 - 92 [kV]

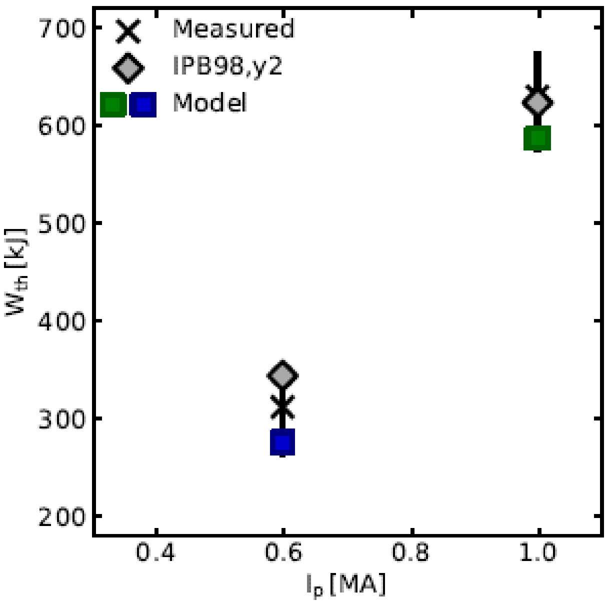
The model can accurately predict the **pedestal top density**, a great advantage over the EPED model where this must be given as input

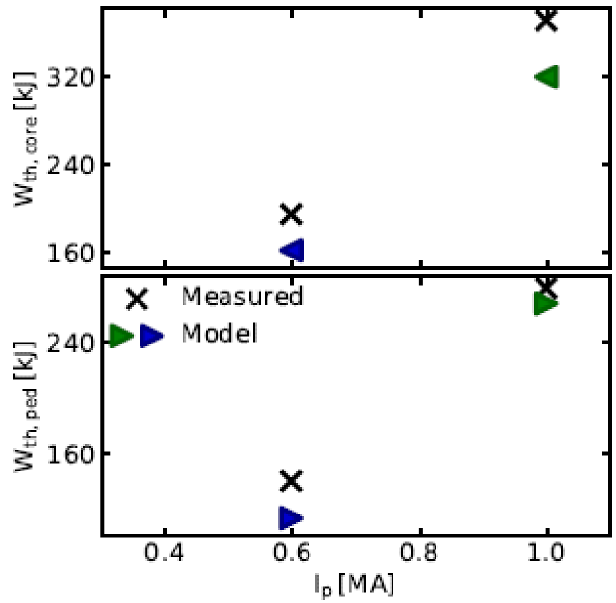
The **core density** prediction is also accurate, it might be underpredicted due to too low stabilization mechanisms (fast ions, β effects)

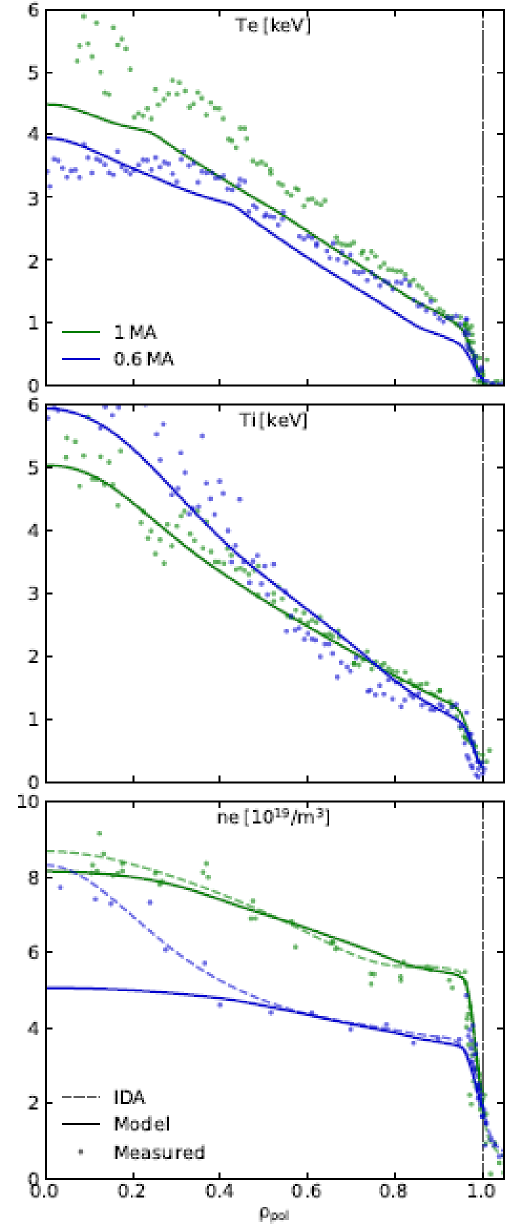


Current scan at fixed fueling rate Γ_D

	B_t [T]	I_p [A]	P_{NBI} [MW]	P_{ECRH} [MW]	q_{95}	$\bar{n}_e$ $[10^{19}/m^3]$	Γ_D $[10^{22}e/s]$	Z_{eff}
■ (blue)	2.5	0.6	10	1.77	7.1	4.8	0.46	1.80
■ (green)	2.5	1	10	2.00	4.0	6.3	0.46	1.45



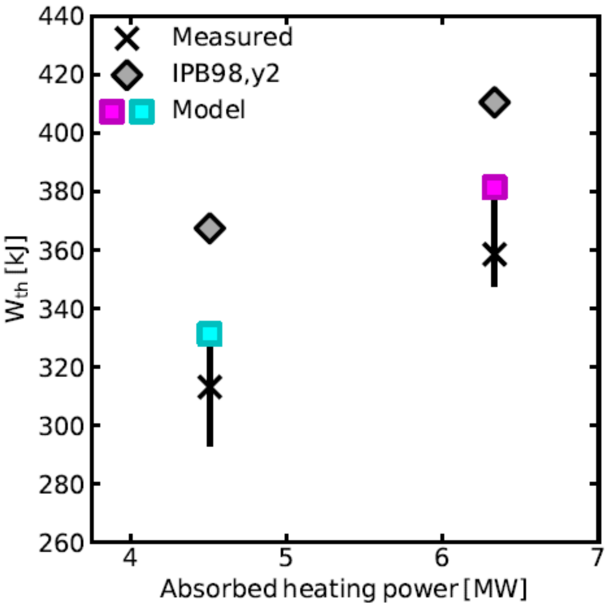


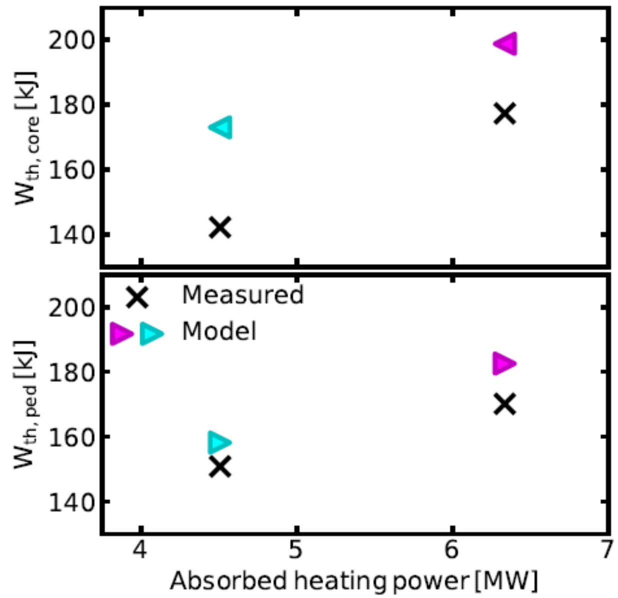


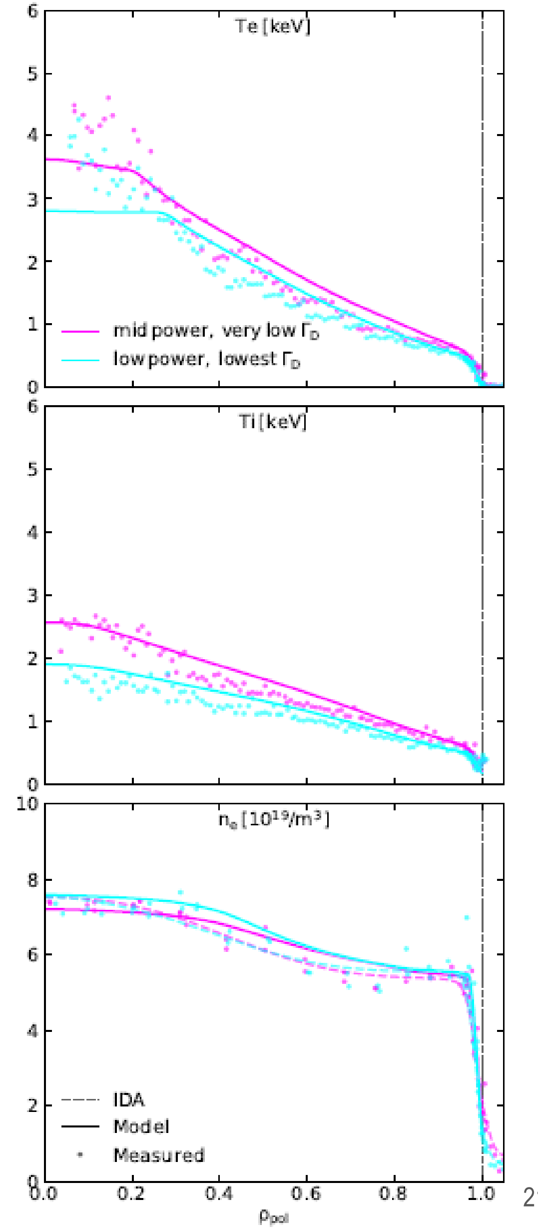
Like the IPB98(y,2) the model well captures the change in confinement caused by a current scan, with a similar accuracy for these cases

Heating power scan at fixed $\bar{n}_e$

	shot	time [s]	B_t [T]	I_p [A]	P_{NBI} [MW]	P_{ECRH} [MW]	q_{95}	$\bar{n}_e$ [$10^{19}/m^3$]	Z_{eff}
magenta	33616	5.2	2.5	0.8	5	1.16	5.2	6.1	1.12
cyan	33616	7.2	2.5	0.8	2.5	1.63	5.2	6.1	1.12



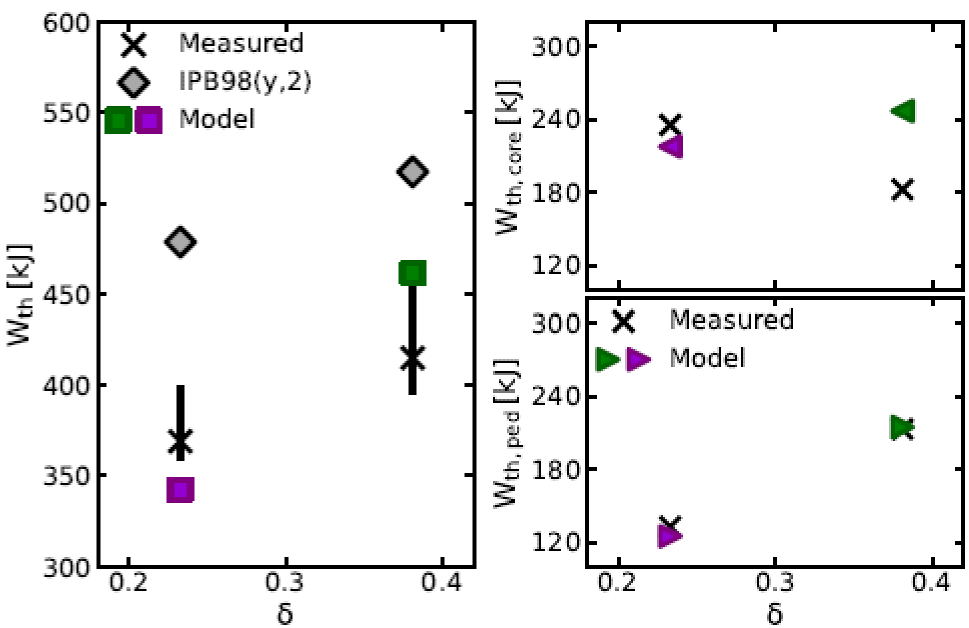


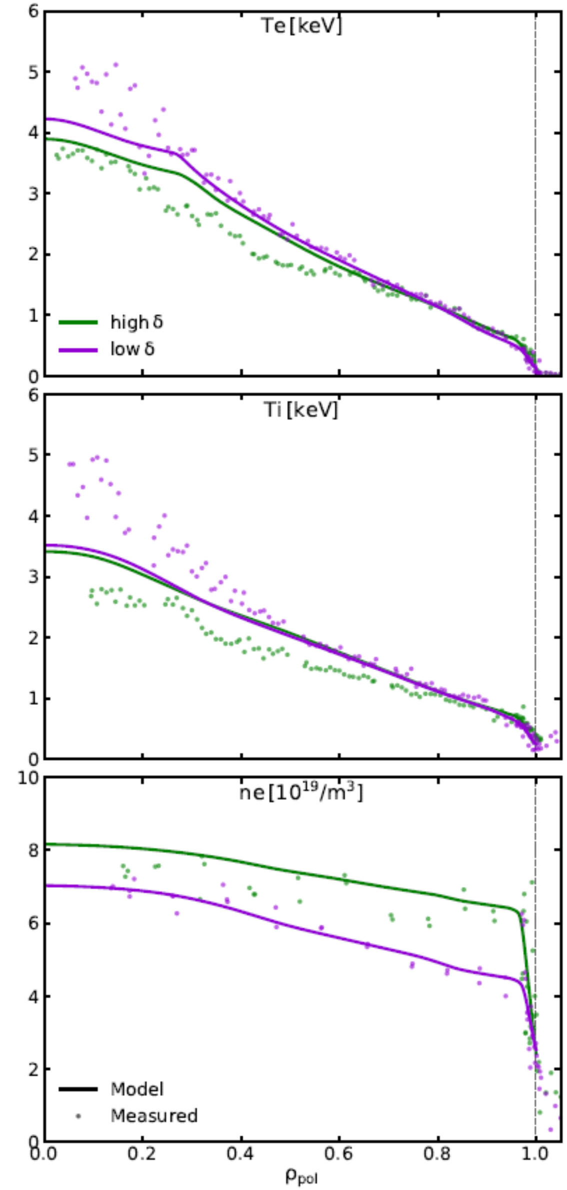


Like the IPB98(y,2) the model well captures the change in confinement caused by a heating power scan, but is more accurate

δ scan at fixed fueling rate Γ_D

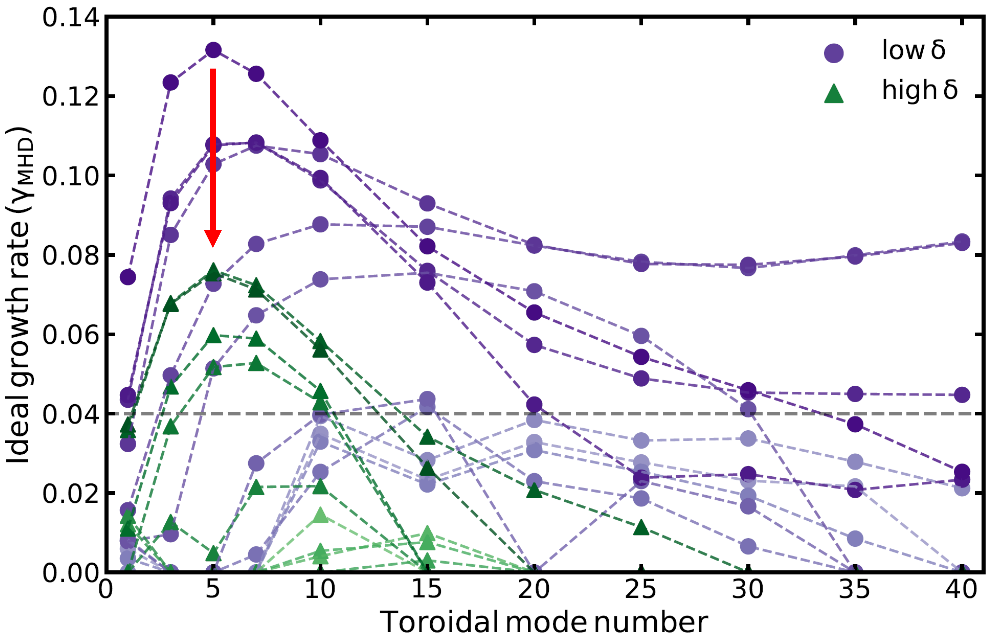
– Like the IPB98(y,2) the model **well captures** the change in confinement caused by a triangularity scan, but is more accurate.
– The change in global confinement is slightly overestimated due to underestimated core transport for the **high triangularity case**

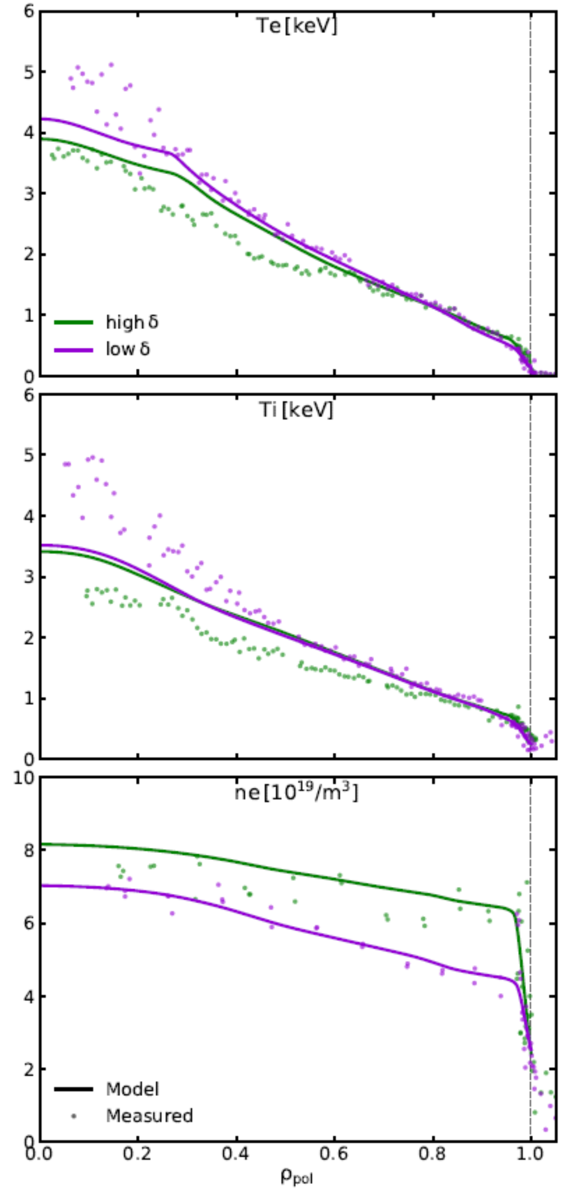




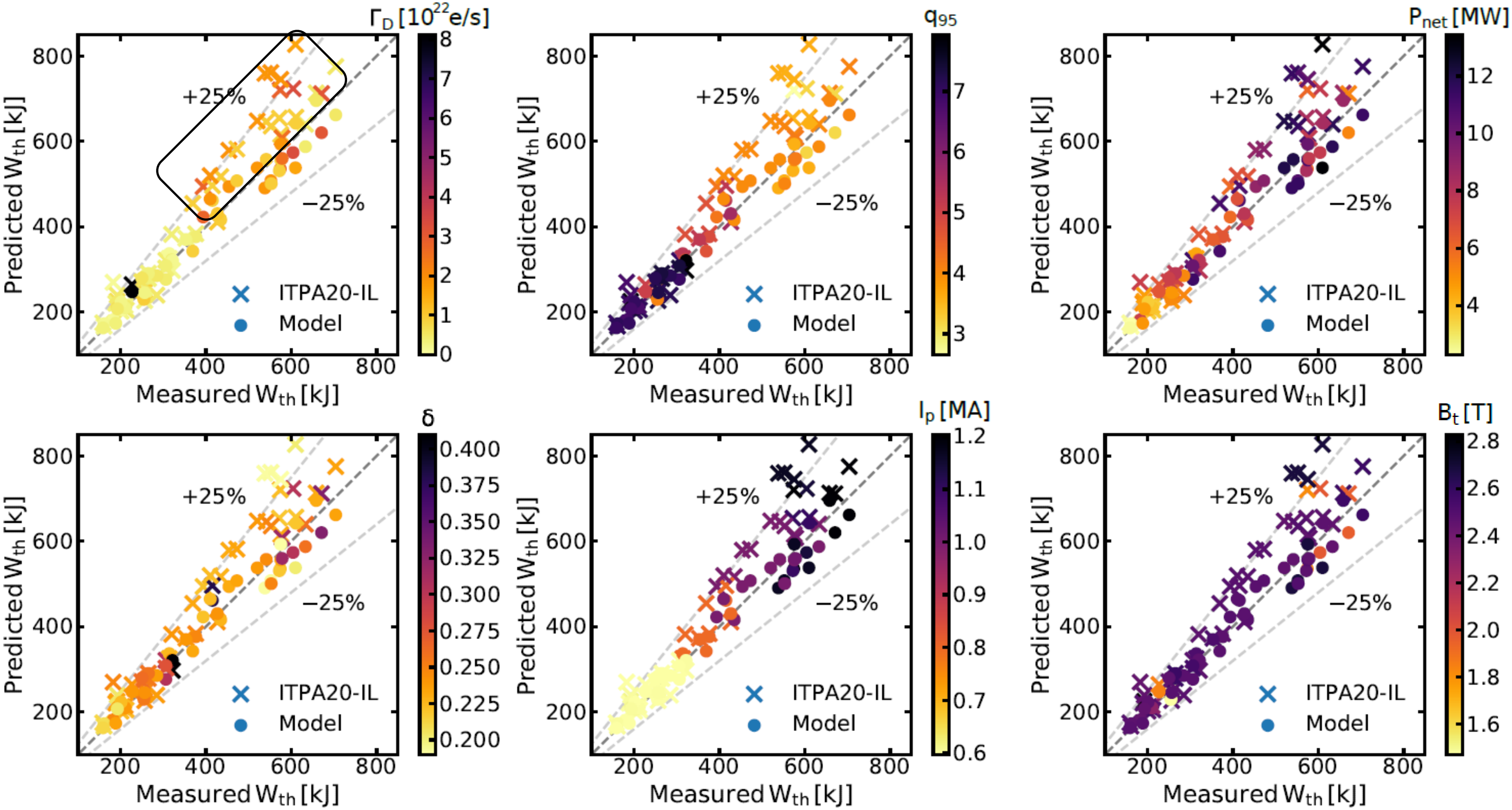
δ scan at fixed fueling rate Γ_D

- For the same value of pedestal width and pressure the growth rates calculated by MISHKA are lower at **high triangularity**
- The pedestal is allowed to reach a higher pressure at higher δ



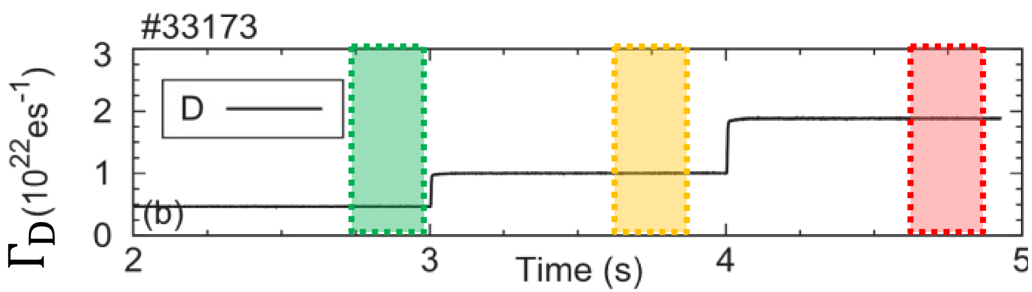


Scaling laws are less accurate at high fueling on AUG

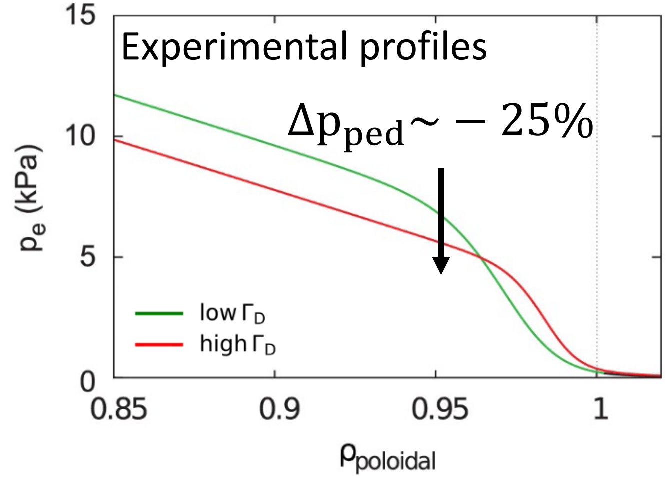


Negative impact of fueling rate on plasma confinement

We focus on an **experimental scan in fueling rate Γ_D**, which shows the typical confinement degradation with gas puff



[M G Dunne et al 2017 Plasma Phys. Control. Fusion]



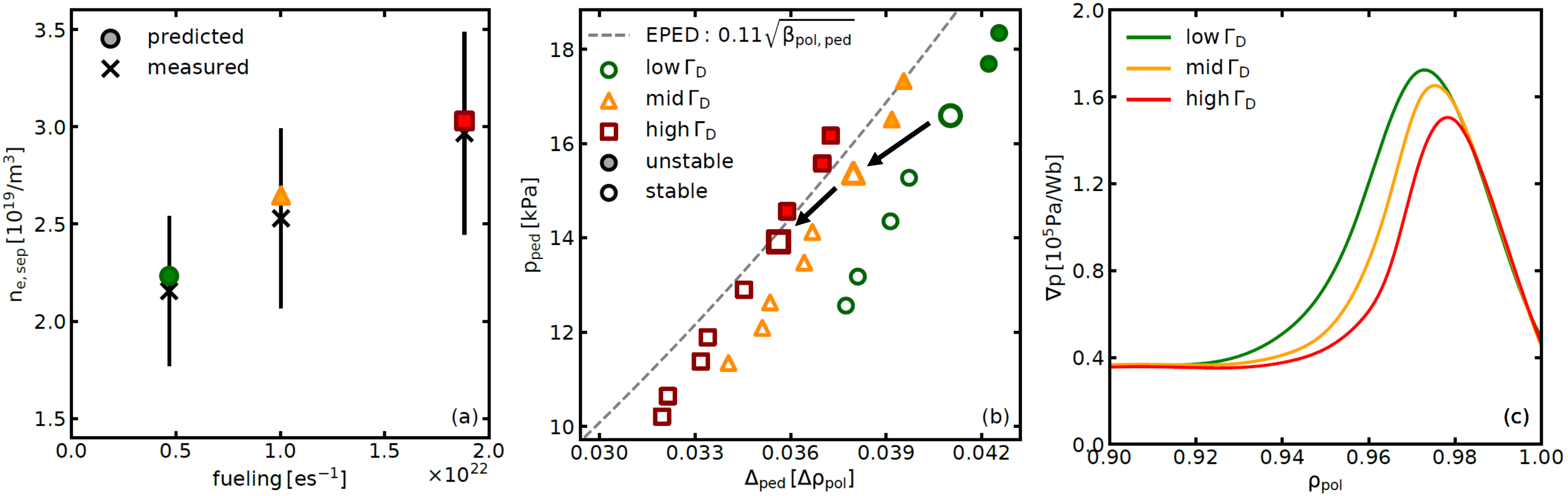
1. The increase in fuelling causes an **increase in $n_{e,sep}$**, and shifts the density profile outwards

2. This shift is also evident in the gradients of the pressure profile, and this has a strong impact on the ballooning stability → the **pedestal pressure decreases**

3. Corresponding to the increase in fueling, the pedestal pressure has decreased by ~**25%**

Negative impact of fueling reproduced by integrated modeling

Simulations results

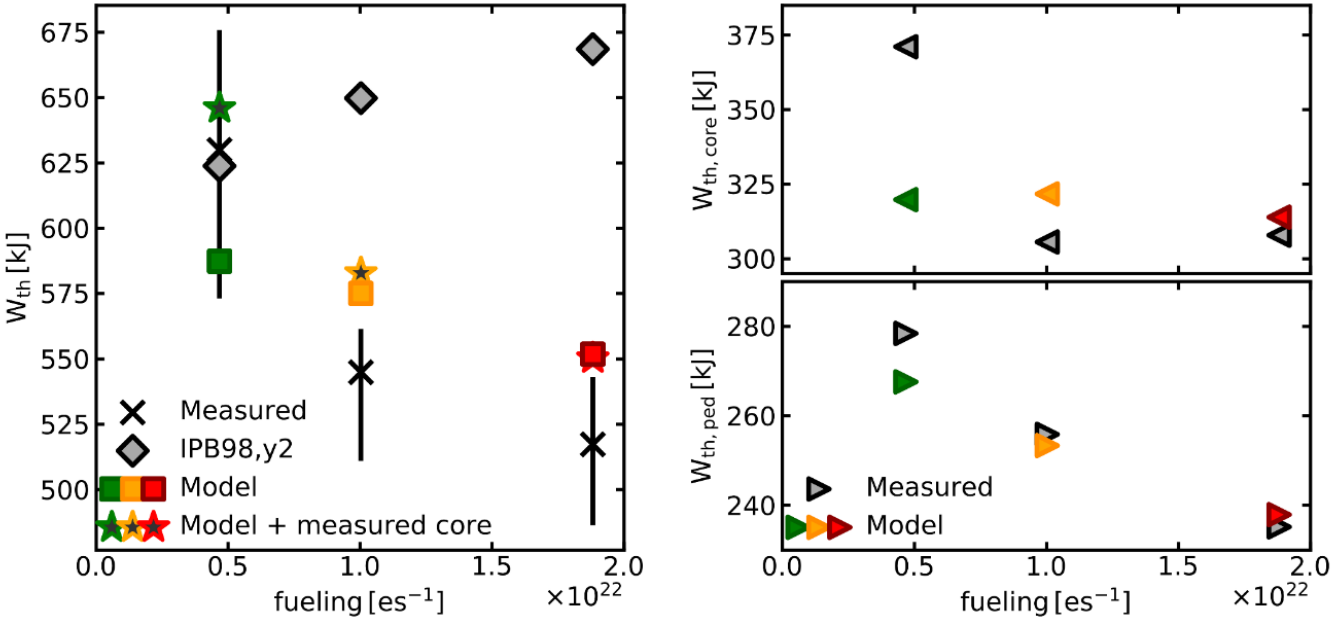


1. The SOL model describes correctly the $n_{e,sep}$ increase with fueling

2. The predicted p_{ped} decreases with increasing fueling

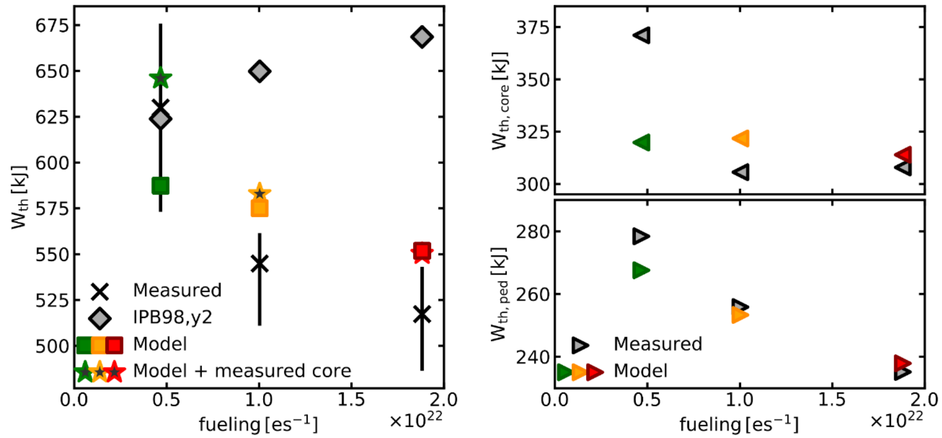
3. This is because of the shift in the peak of the pressure gradients

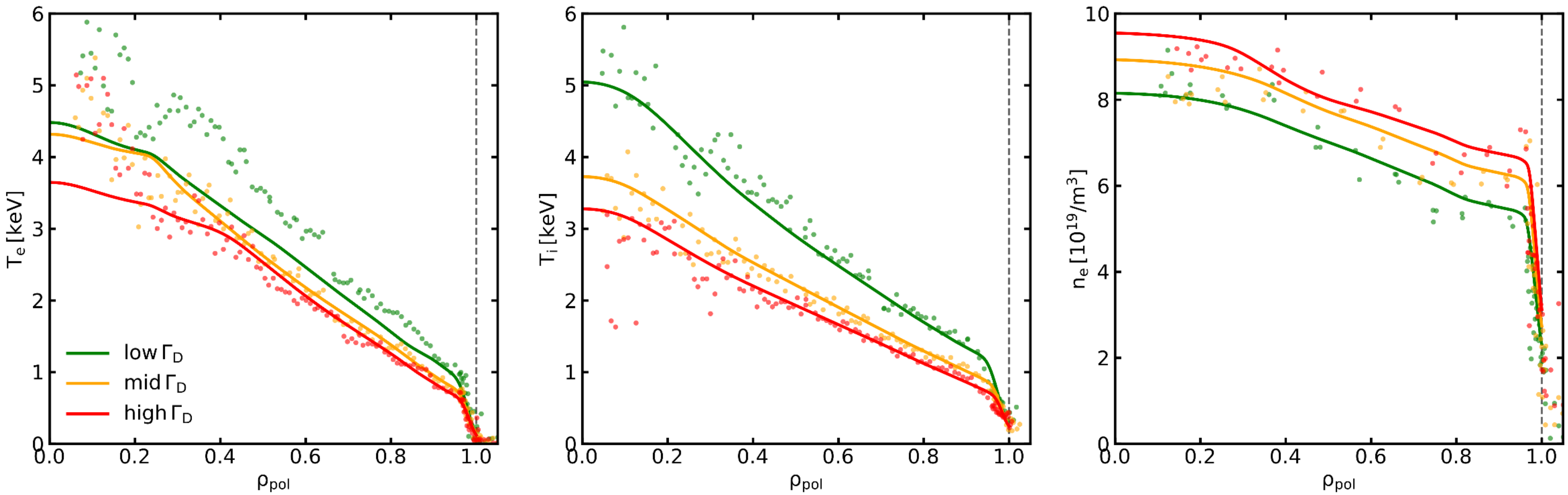
Beyond the possibilities of empirical scaling laws



4. The change in pedestal energy is well reproduced by the model
5. At lowest fueling the core energy is underpredicted by TGLF
6. Using experimental core profiles we get a very good agreement on W_{th}
7. The IPB98(y,2) scaling law instead predicts an increase in W_{th} due to the positive dependence on the density $\tau_{E,th(IPB98)} \propto n^{0.41}$

Capturing the impact of fueling rate on the kinetic profiles





The integrated model also allows us to understand the physics of interdependencies connecting the different plasma regions: **SOL** ⇄ **pedestal** ⇄ **core**

Reproducing other subtle effects: V_{NBI} scan

NBI voltage scan: 2 similar discharges with

P_{NBI} = 5 [MW], **V_{NBI} = 42 [kV],** **V_{NBI} = 92 [kV],** $S_{n,\ V=42[kV]} \approx 2x S_{n,\ V=92[kV]}$

8 NBI sources **3 NBI sources**

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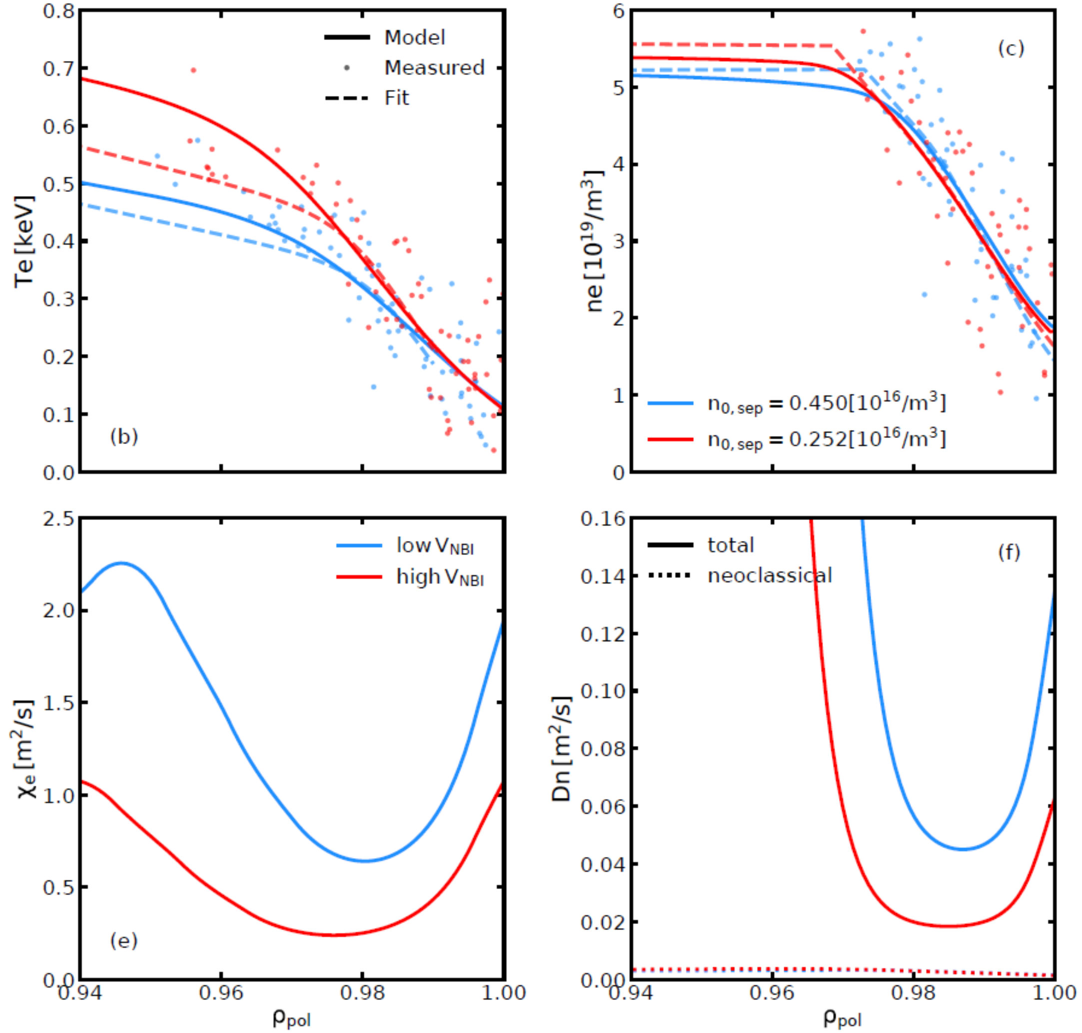

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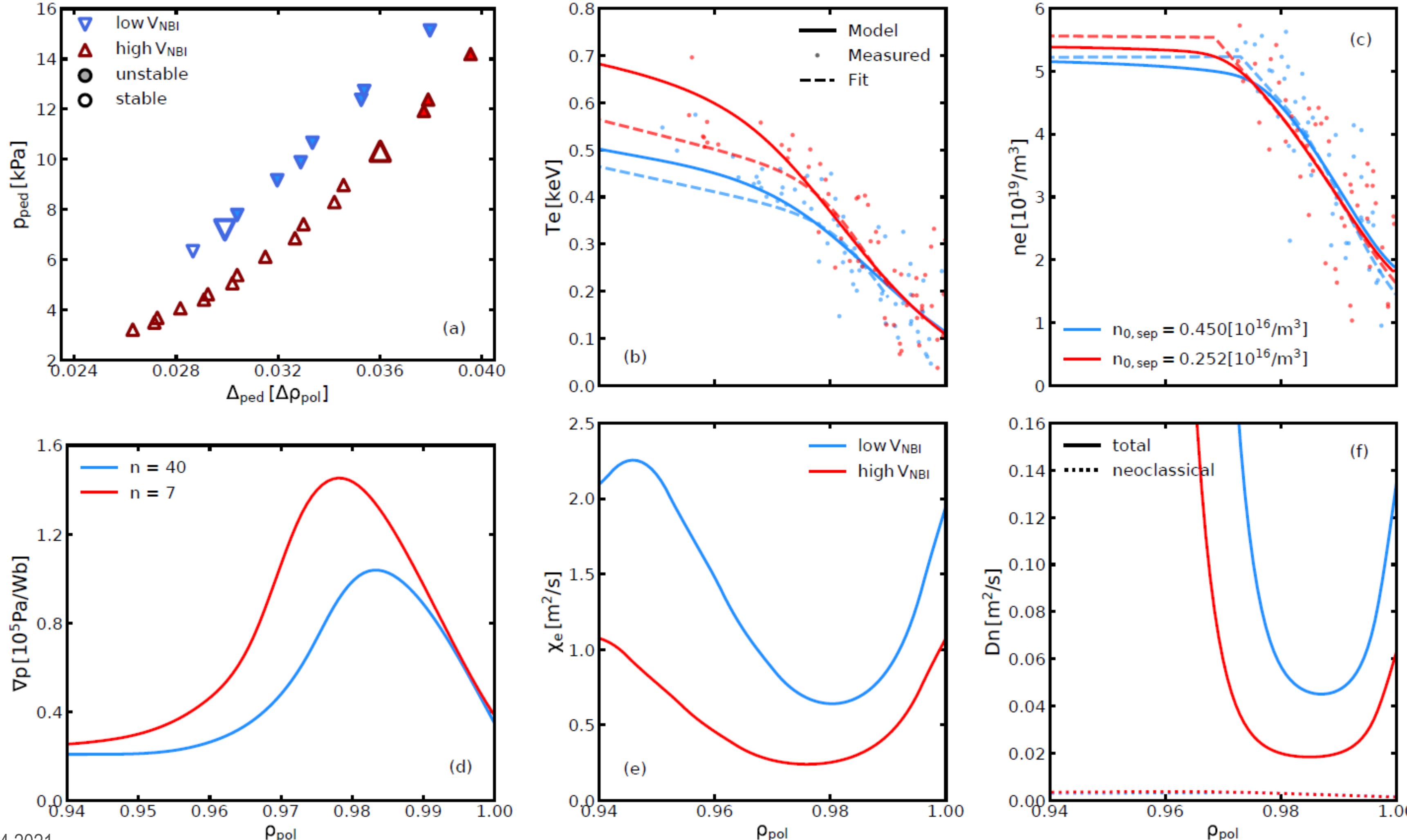

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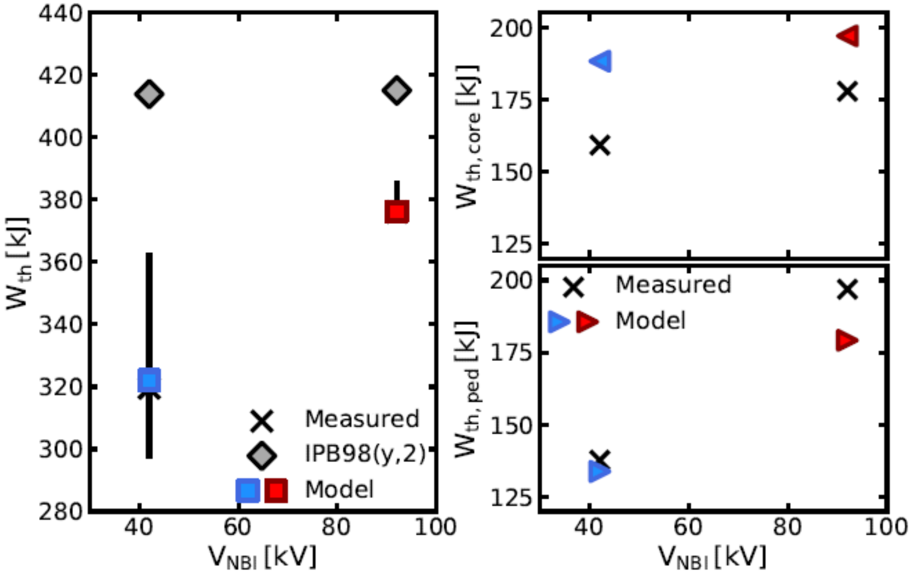


The model **well captures** the change in confinement caused by the NBI voltage scan

IPB98(y,2) predicts **no change** in confinement with V_{NBI}

This case demonstrates again of how important it is to take into account core, pedestal, and SOL effects self-consistently: **SOL** ⇄ **pedestal** ⇄ **core**

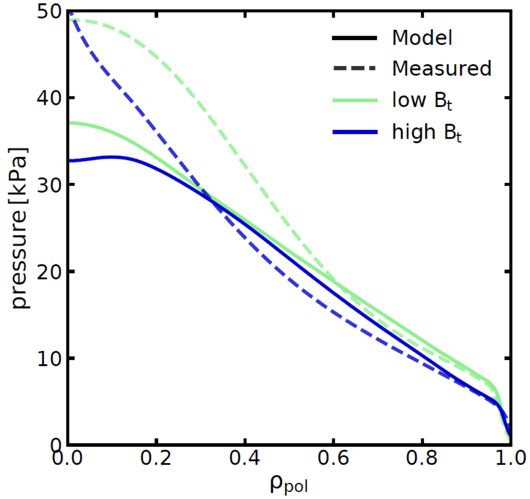
Change in core particle **transport** and **sources** with different V_{NBI} ⇨ Change in SOL **neutrals** via recycling ⇨ Change in **pedestal** MHD stability and global **confinement**

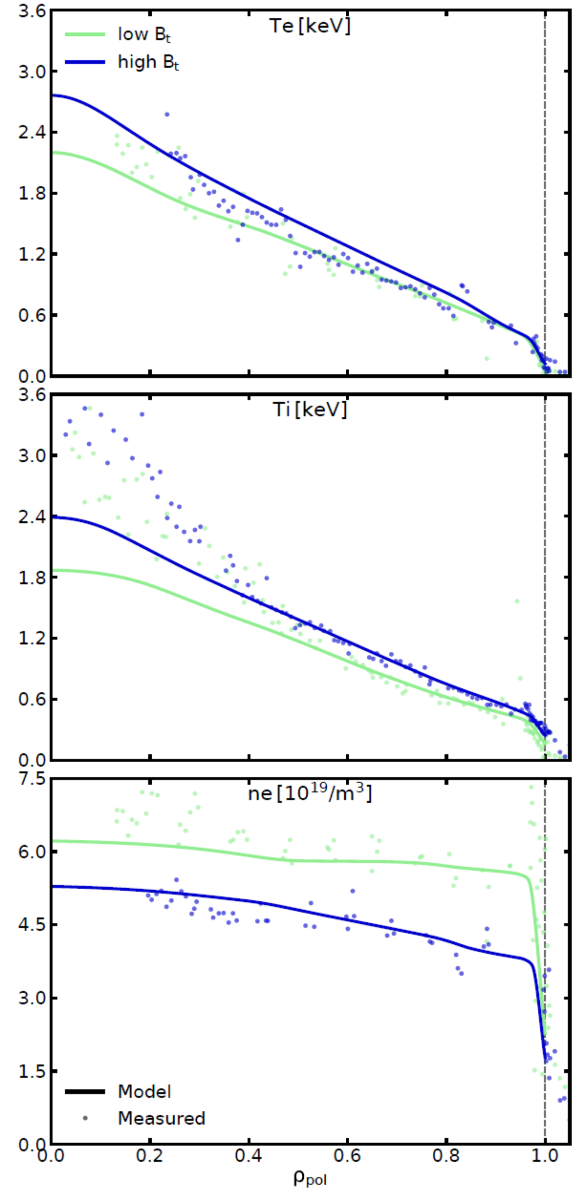
B_t scan

B_t = 1.5 T → B_t = 2.8 T

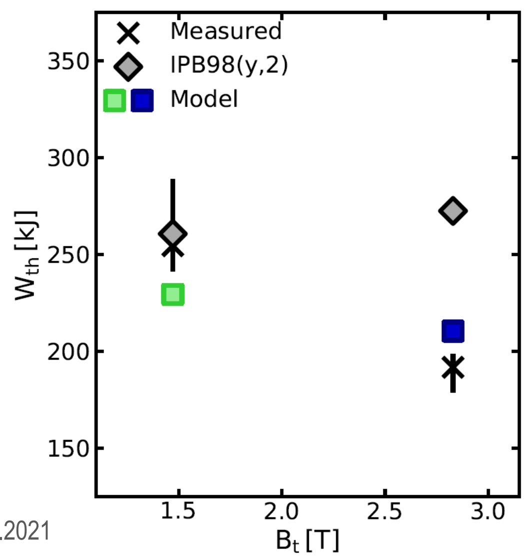
The model **correctly captures** the effect of B_t on the pedestal pressure.

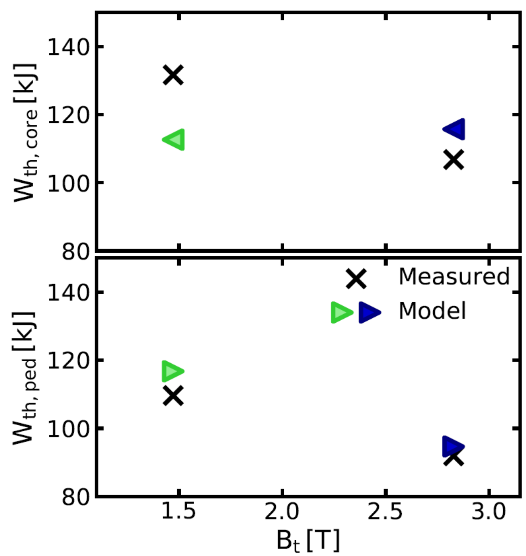
TGLF underestimates the reduction of transport caused by the **increase of β_e** ($\beta_{e,\,1.5\,[T]} \approx 5 \times \beta_{e,\,2.8\,[T]}$)





As a result the model does not predict a change in confinement as strong as observed in the experiments





B_t scan

B_t = 1.5 T → B_t = 2.8 T

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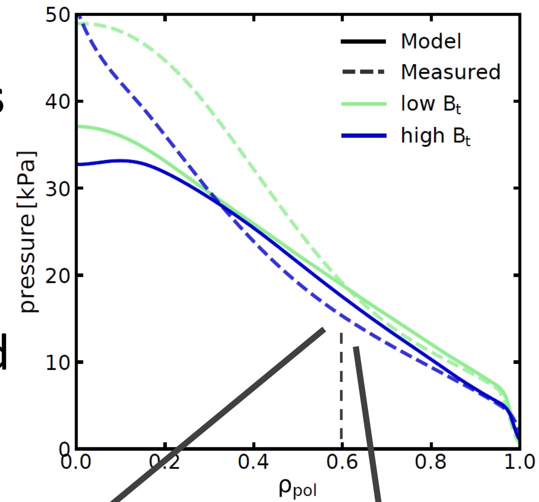
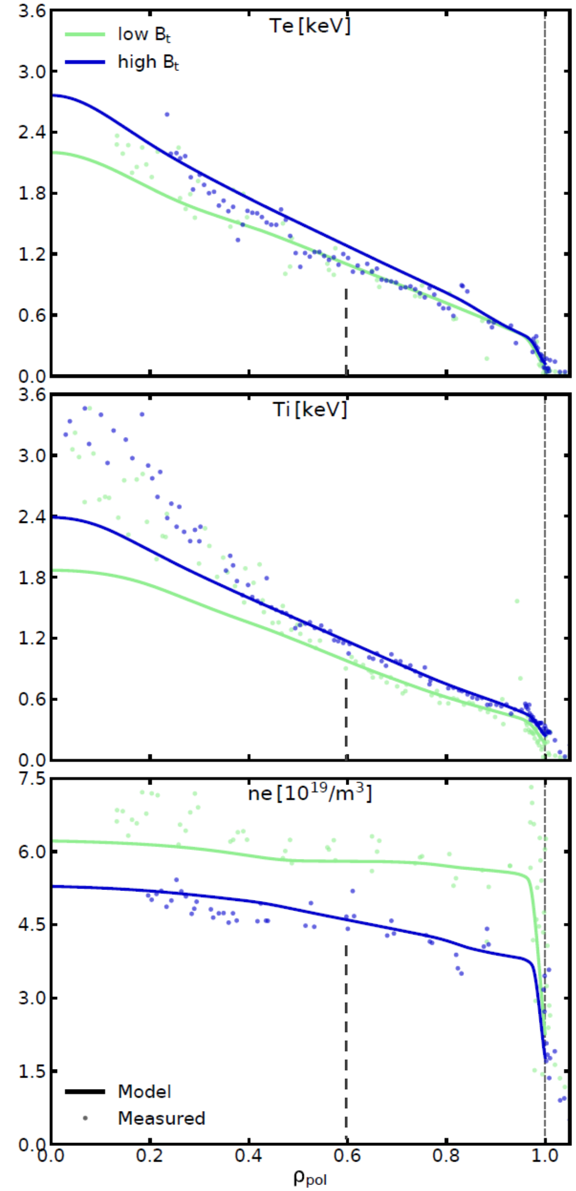
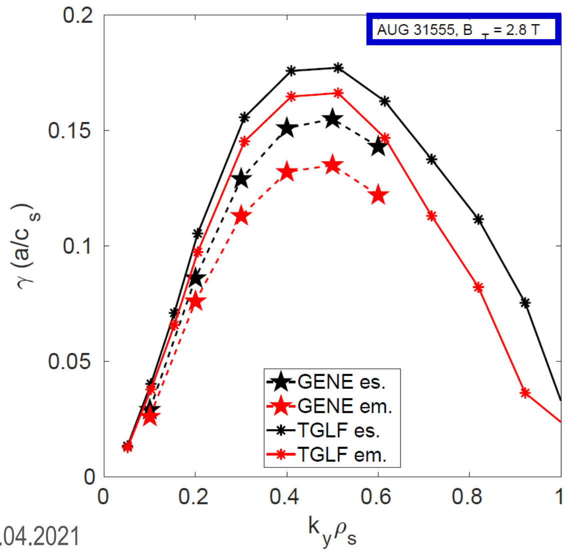
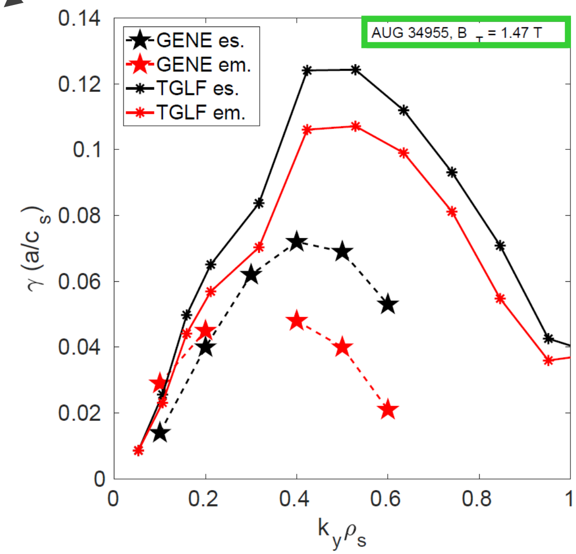


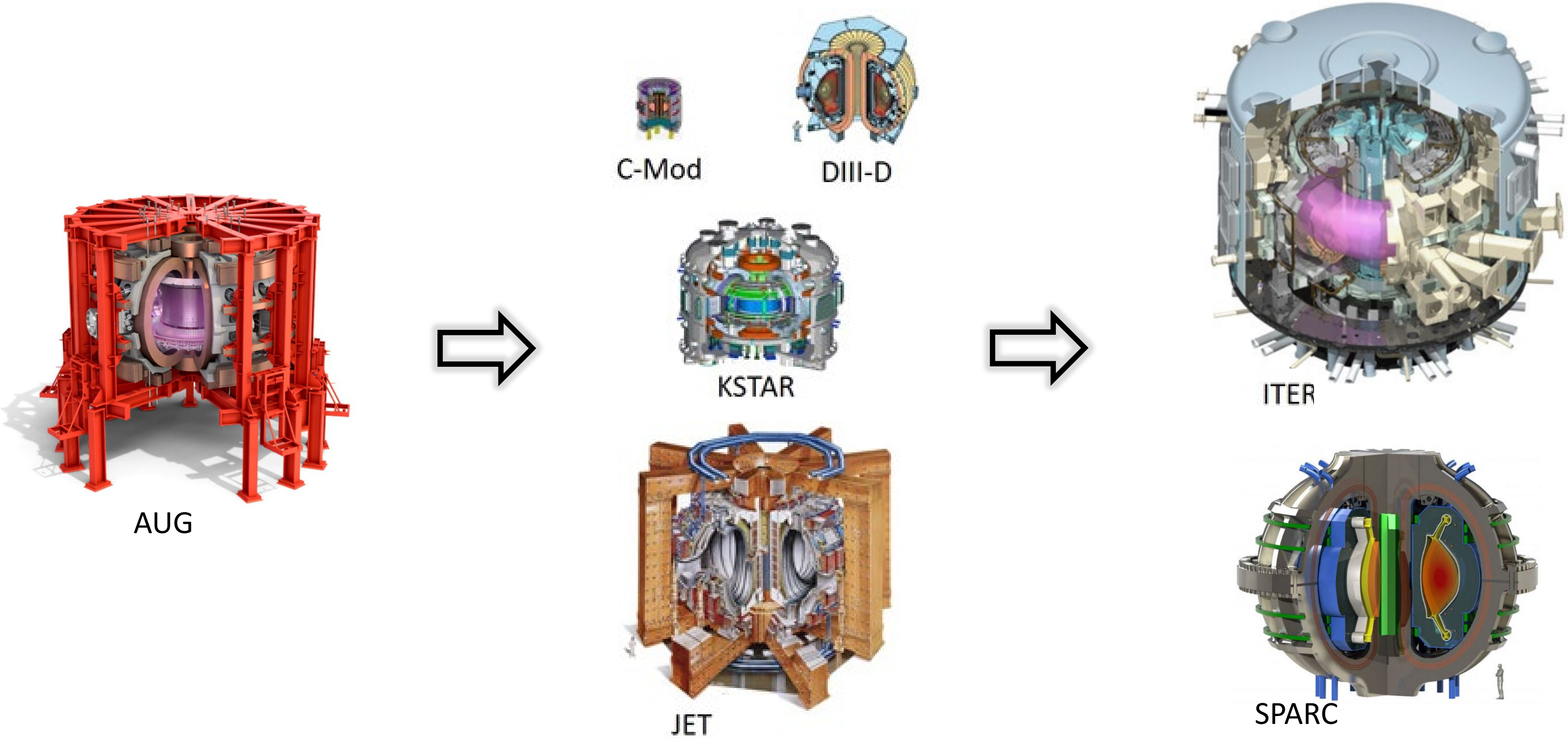






Application of the model to other devices

- The successful validation of the model on a database of AUG experiments is very promising for a more **physics based prediction** of plasma confinement
- It is important to extend the validation to **other devices** to test the validity of the assumptions and to gain confidence for the prediction of future devices



Application of the model to other devices

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- It is important to extend the validation to **other devices** to test the validity of the assumptions and to gain confidence for the prediction of future devices
- A **validation on C-mod and JET** would be very interesting due to the very different size and magnetic field from AUG. Pedestal model still valid?
- The **SOL model** contains elements that are AUG specific: scaling for $\mathbf{p_0}$, formulas for $\mathrm{n_{e,sep}}$, $\mathrm{n_{0,sep}}$
- A database of **10 H-mode stationary phases** with scans in fueling, and other main engineering parameters sufficient to calibrate SOL model?
- For **future devices** like SPARC or ITER data from SOLPS simulations can be used to obtain $\mathbf{p_0}$ scaling and coefficients in $\mathrm{n_{e,sep}}$, $\mathrm{n_{0,sep}}$ formulas

Summary 1/2

- **Established automated workflow** to predict entire radial domain of H-mode confined plasmas, only using global parameters as inputs

- Core-edge coupling allows us to include physics effects determining plasma confinement **beyond the possibilities of empirical scaling laws:** the model reproduces not only dependencies captured by scaling laws, but also hidden dependencies

- The **self-consistent treatment of the boundary conditions** is a key element of this approach, and is necessary to capture the **impact of fueling** on pedestal and global confinement

- The model can accurately **predict the pedestal top density**, which is a great improvement over the current situation where this must be given as input

Summary 2/2

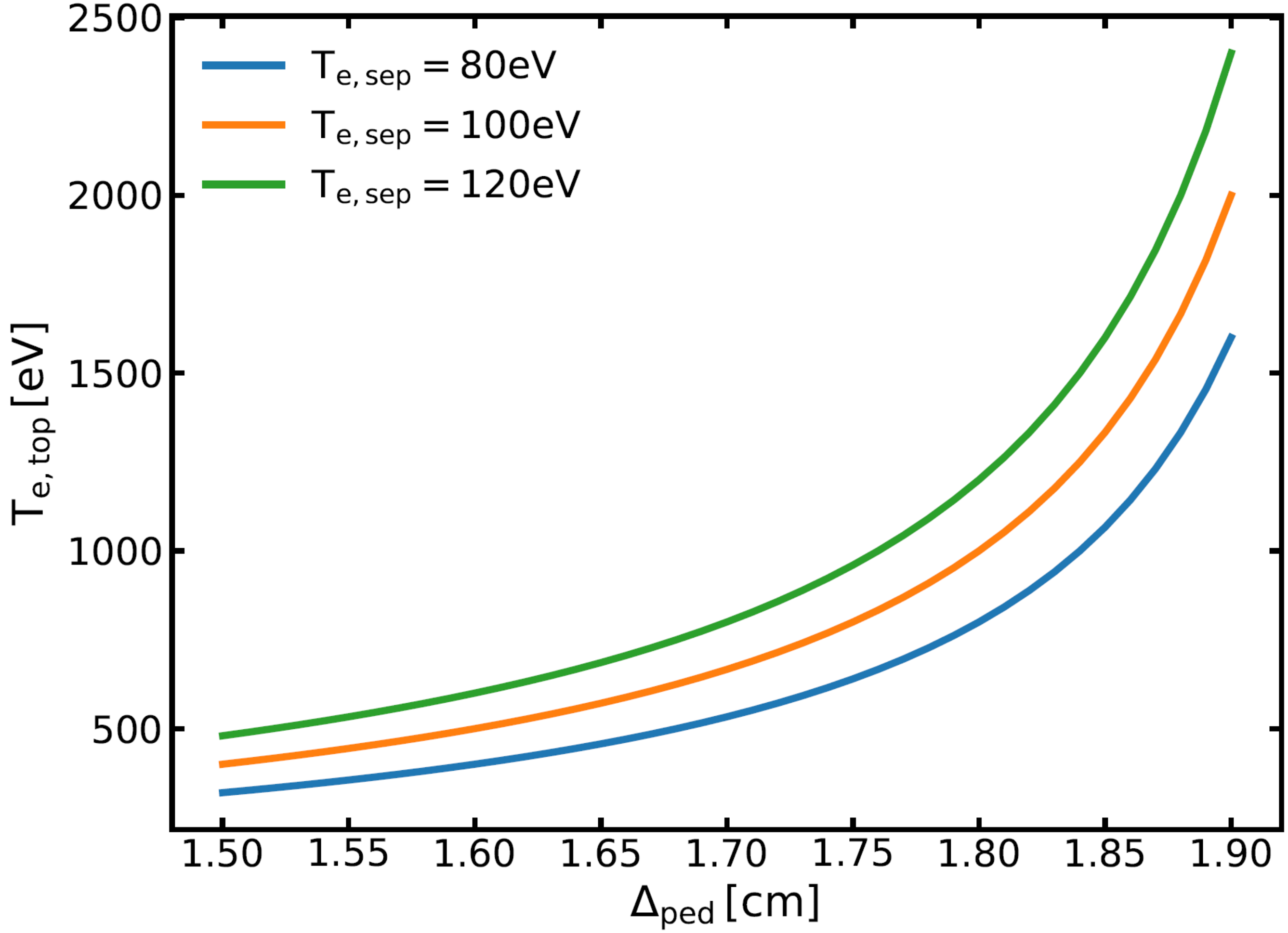
- The empirical elements of the model (pedestal and SOL) need to be generalized in order to be applied also to **different machines**. In particular, the scaling for the divertor neutral pressure $\mathbf{p_0}$ is AUG specific

- This work demonstrated that the integration of different models can provide important insights to **better understand the physics of interdependencies**, particularly between different plasma regions, which are not possible to explore otherwise

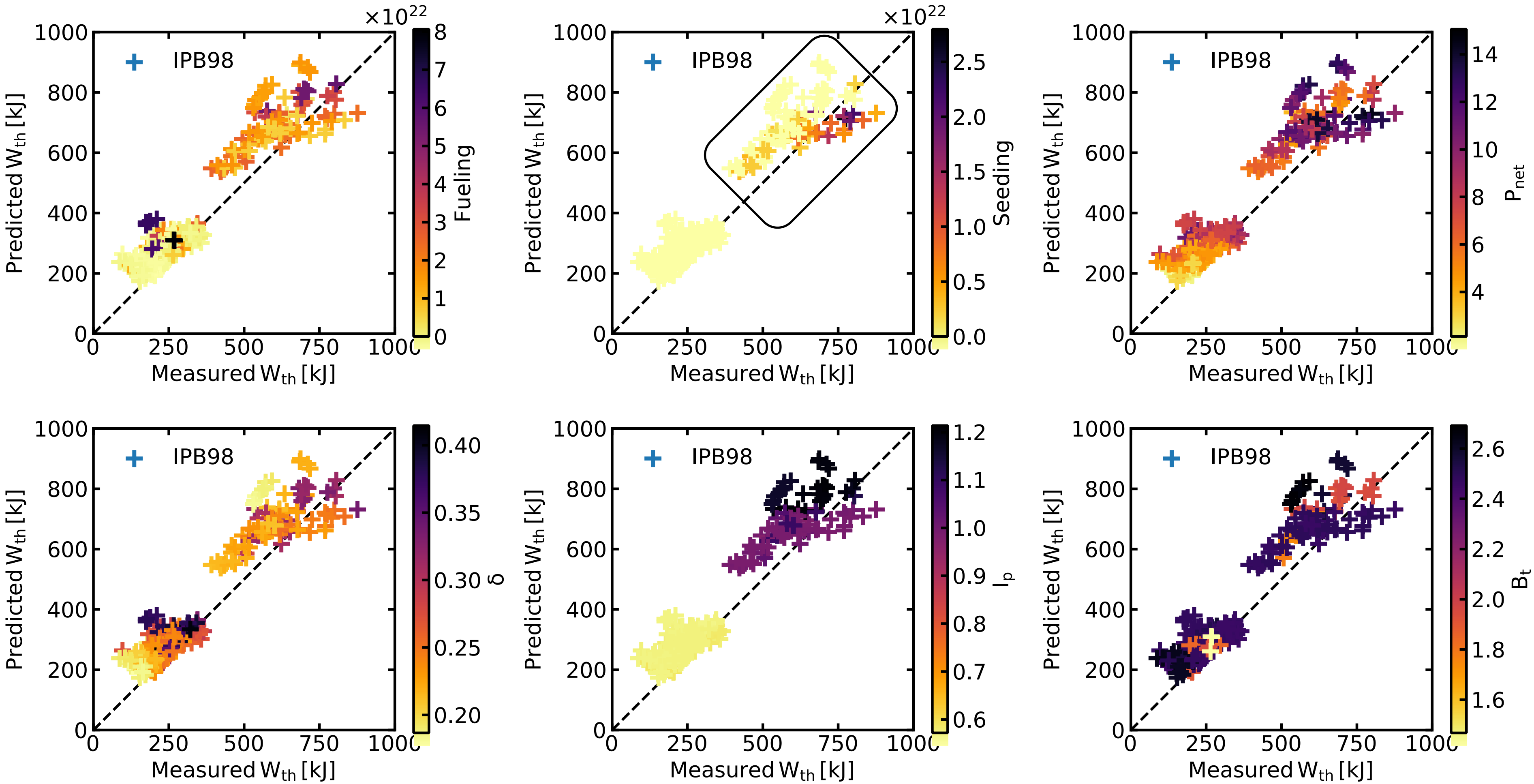
- In the long term the model could contribute to develop and optimize ITER / DEMO scenarios to **reach the best fusion performance**

Backup slides

$$T_{e,top} = \frac{T_{e,sep}}{(1 - 0.5\,\Delta_{ped})}$$

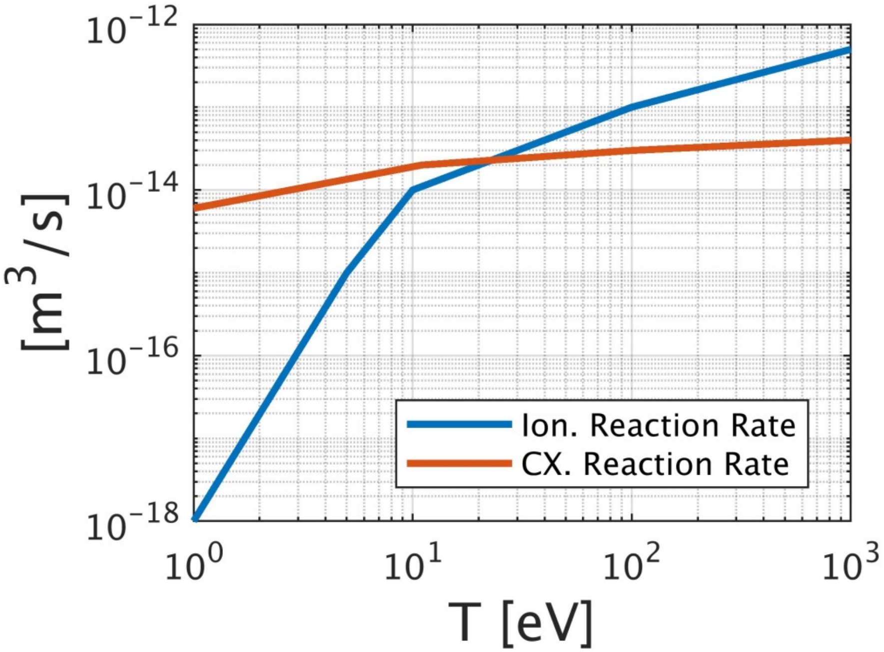


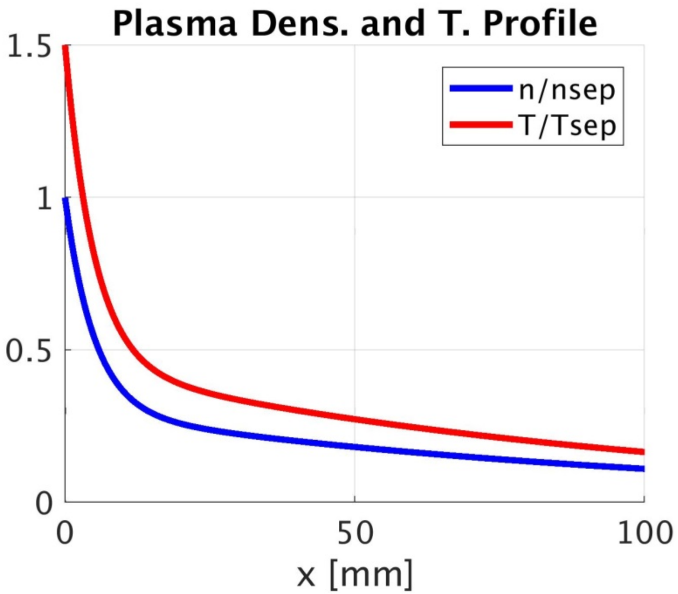
Backup slides



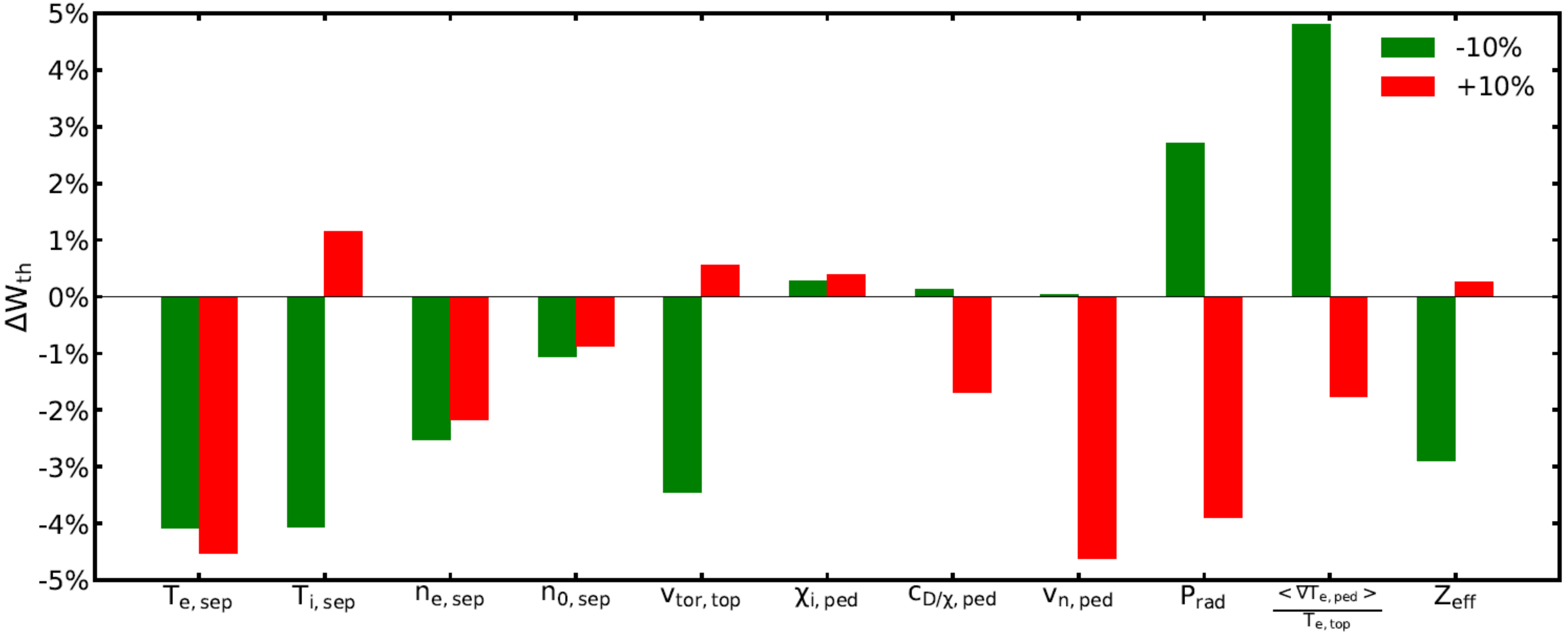
Backup slides

$$\frac{\mathbf{n_{0,sep}}}{\mathbf{n_{0,wall}}} = 87.6 - 18.9\mathbf{n_{e,sep}}[10^{19}/\mathrm{m}\hat{}3]^{0.016} - 67.2\mathbf{T_{e,sep}}[\mathrm{eV}]^{0.0027} - 1.28\mathbf{d_{wall,sep}}[\mathrm{m}]^{0.94}$$

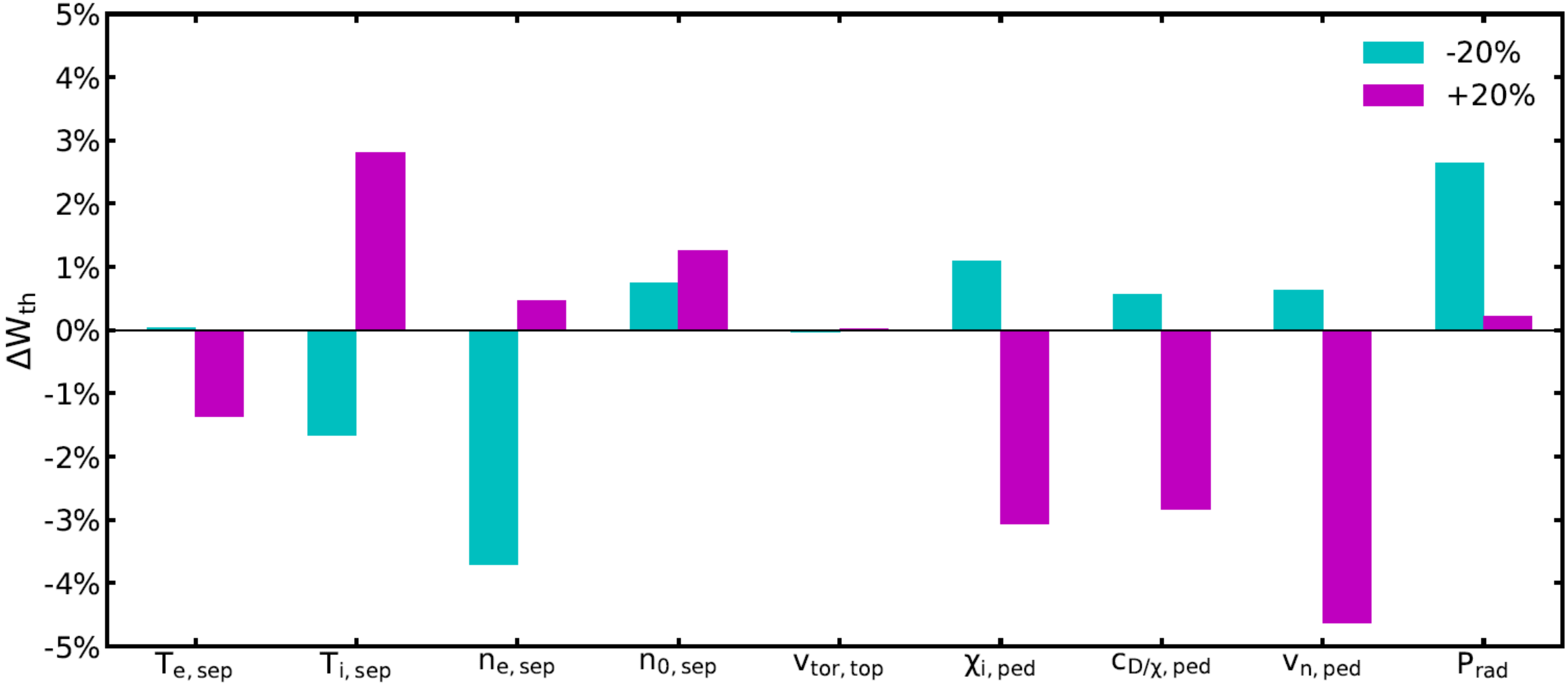




Backup slides



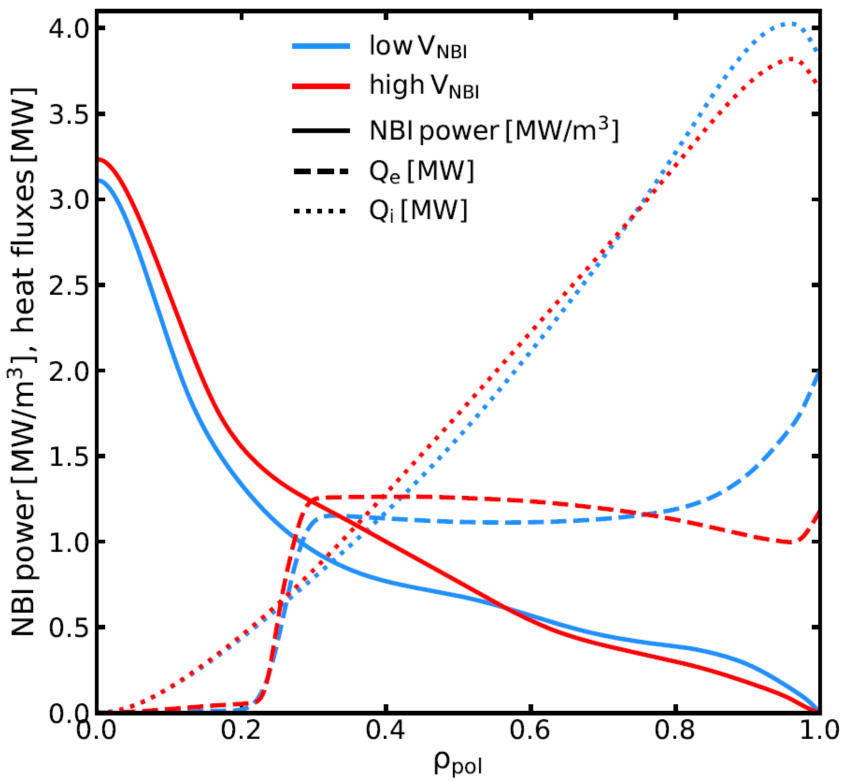
Backup slides

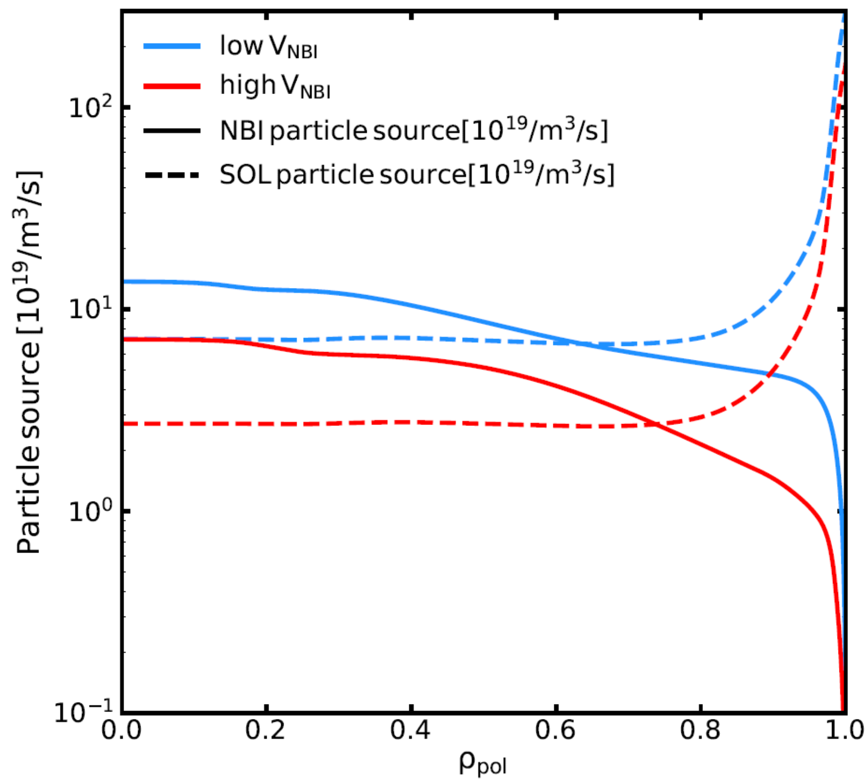


V_{NBI} scan

NBI voltage scan: 2 similar discharges with

P_{NBI} = 5 [MW], **V_{NBI} = 42 [kV]**, **V_{NBI} = 92 [kV]**, $S_{n,\ V=42[kV]} \approx 2xS_{n,\ V=92[kV]}$



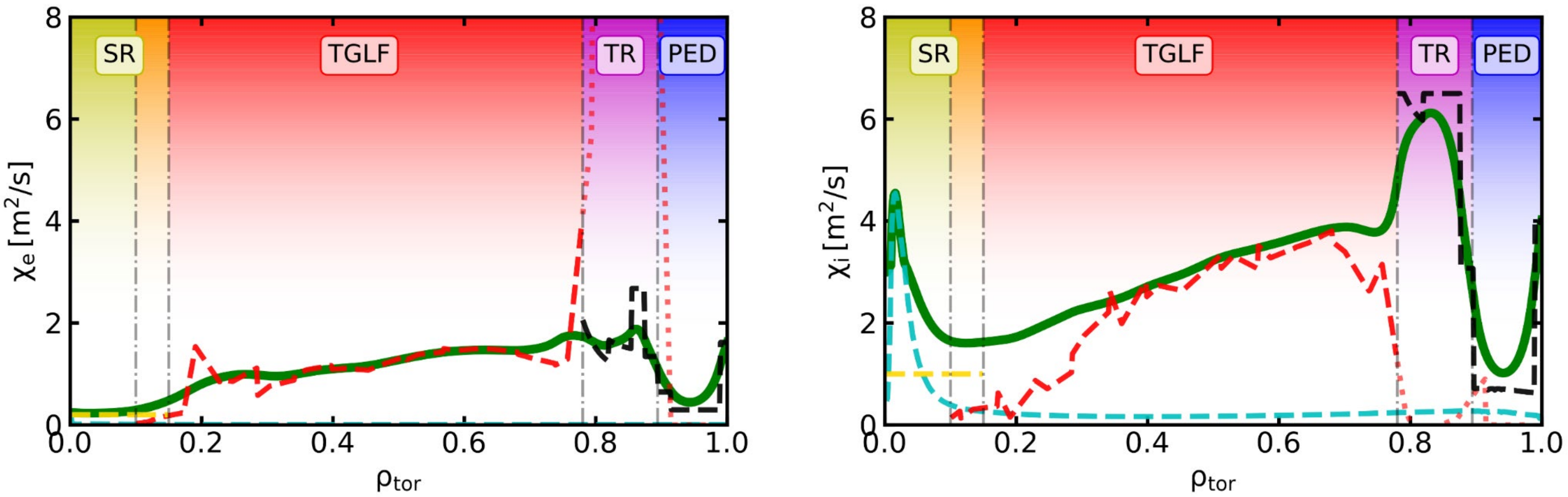


Smoothing and connection of different regions

Example of the heat diffusivities for electrons and ions:

- - - Before smoothing

—— After smoothing



TGLF, **NCLASS**, **sawtooth transport**,

diffusivities in the **pedestal** and **transition** regions

$$\chi_{tr} = c_1 + c_2 \chi_{ped}$$

Backup slides

	input:								output:
2 options	$\overline{\mathbf{n_e}}$	→	**ASTRA**	→	neutrals source	→	**SOL model**	→	$\mathbf{n_{e,sep}}$
for $\mathbf{n_e}$:	$\mathbf{D, N_2}$	→	**SOL model**	→	neutrals source	→	**ASTRA**	→	$\overline{\mathbf{n_e}}$