Max-Planck-Institut für Plasmaphysik

Integrated modeling of tokamak plasma confinement with IMEP

T. Luda, C. Angioni, M. G. Dunne, E. Fable, A. Kallenbach, N. Bonanomi, P. A. Schneider, M. Siccinio, G. Tardini, the ASDEX Upgrade Team, the EUROfusion MST1 Team, P. Rodriguez-Fernandez and the C-Mod Team, L. Frassinetti and the JET Team

Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES — MAX PLANCK GESELLSCHAFT — EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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**

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**

⇩

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

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**

⇩

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

⇩

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

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**

⇩

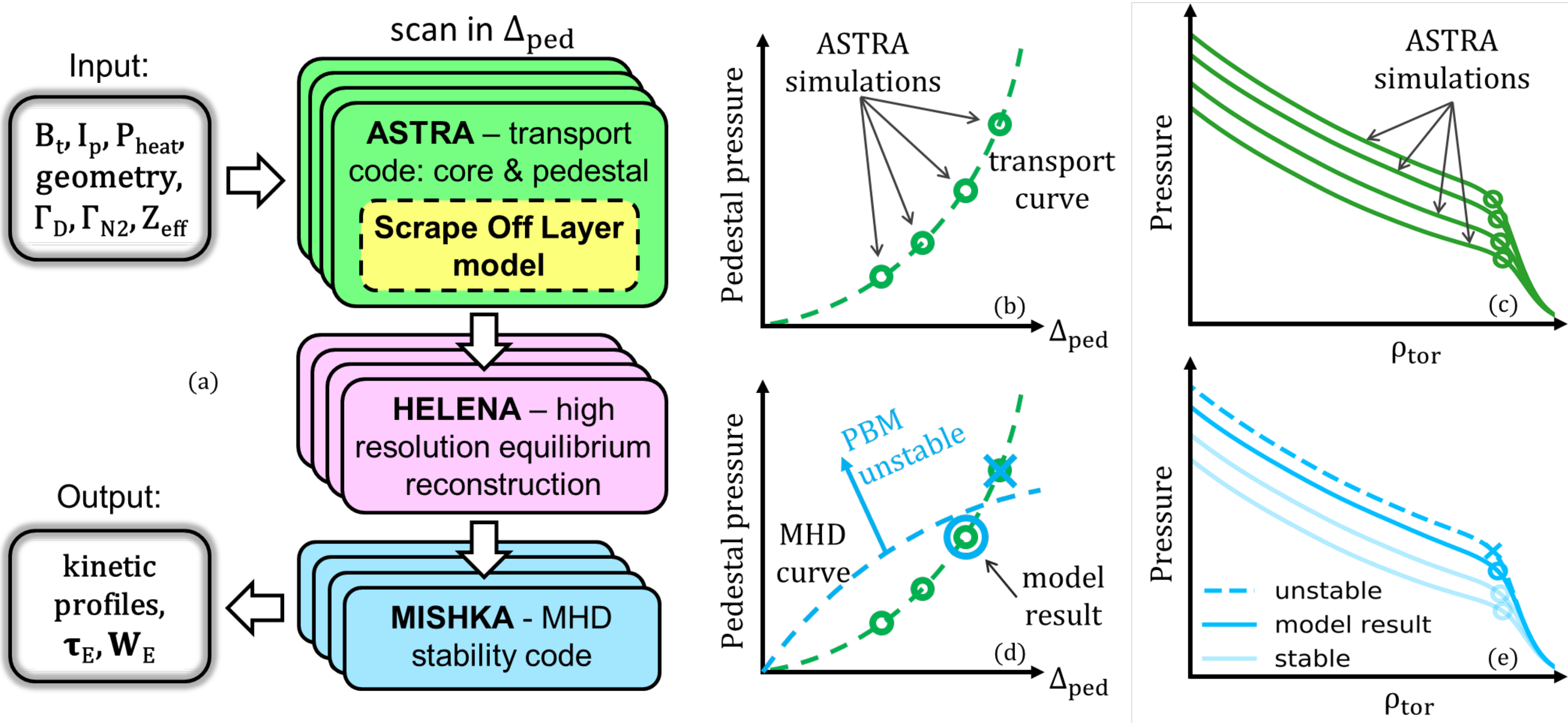
OUR PROJECT: develop an integrated model to simulate the plasma using only global parameters as input, and **no information from measurements of kinetic profiles**

⇩

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

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

IMEP: Integrated Model Based on Engineering Parameters



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

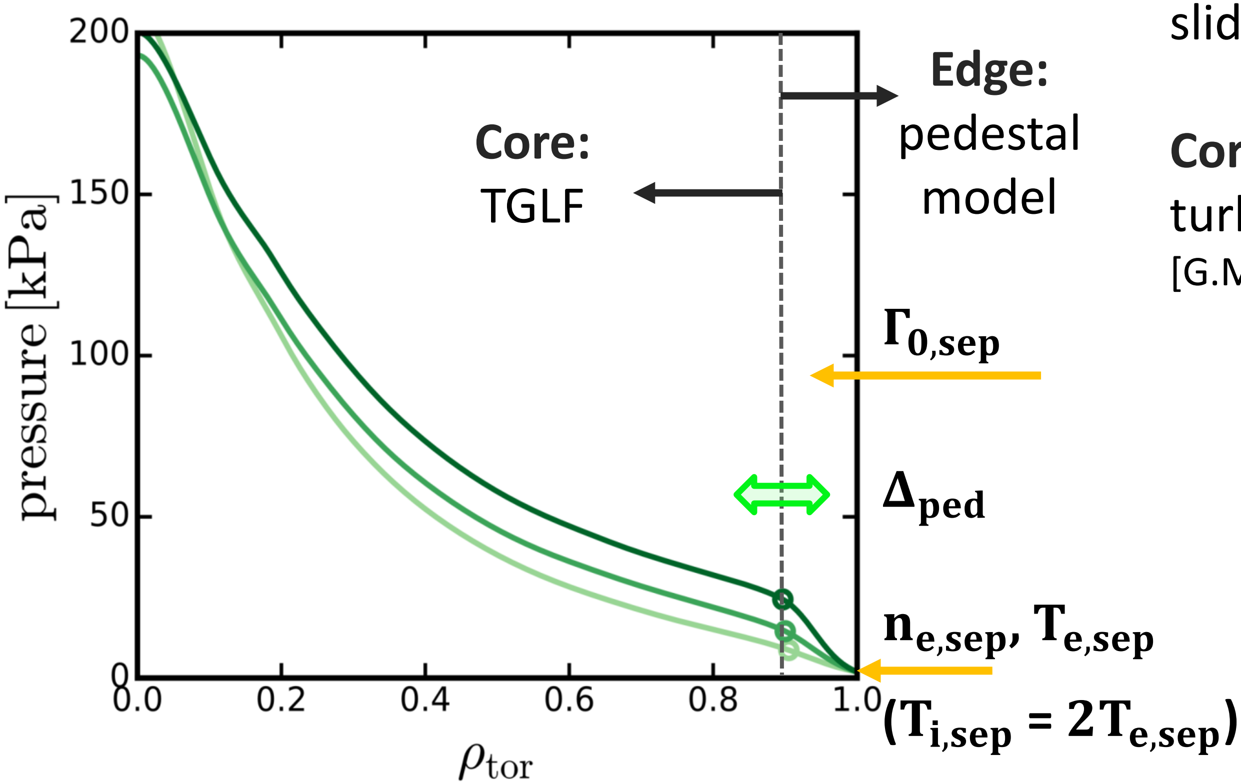
Confined plasma profiles prediction

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]



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

Pedestal transport model

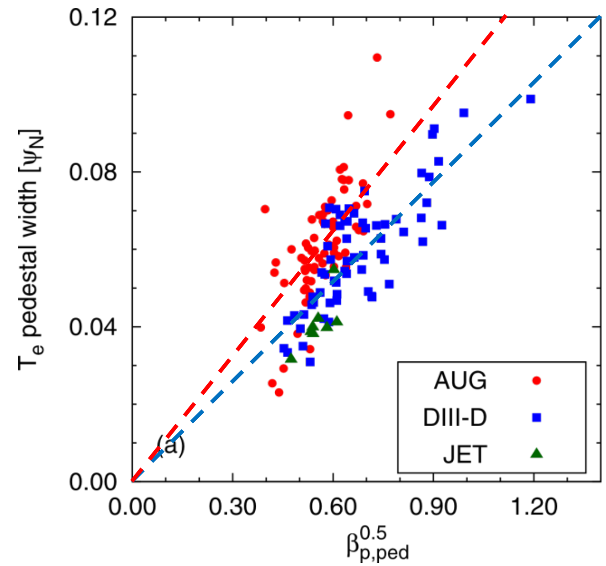
- The EPED pedestal model: [P. B. Snyder *et al* 2009 *PoP*]
  - assumes: $\Delta\Psi_N \sim (0.076, 0.11)\beta_{p,ped}^{0.5}$
  - requires $n_{e,top}$ as input
  - assumes $T_{e,top} = T_{i,top}$

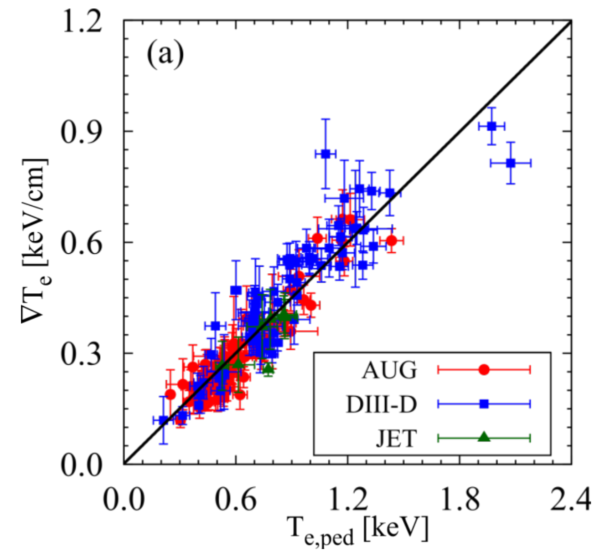
- JET data: small subset selected with the pre-ELM pedestal near the PB boundary

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

- We **implemented in IMEP** the condition

$$\frac{< \nabla \mathbf{T_e} >}{T_{e,top}} = -0.5\ [1/\mathrm{cm}]$$

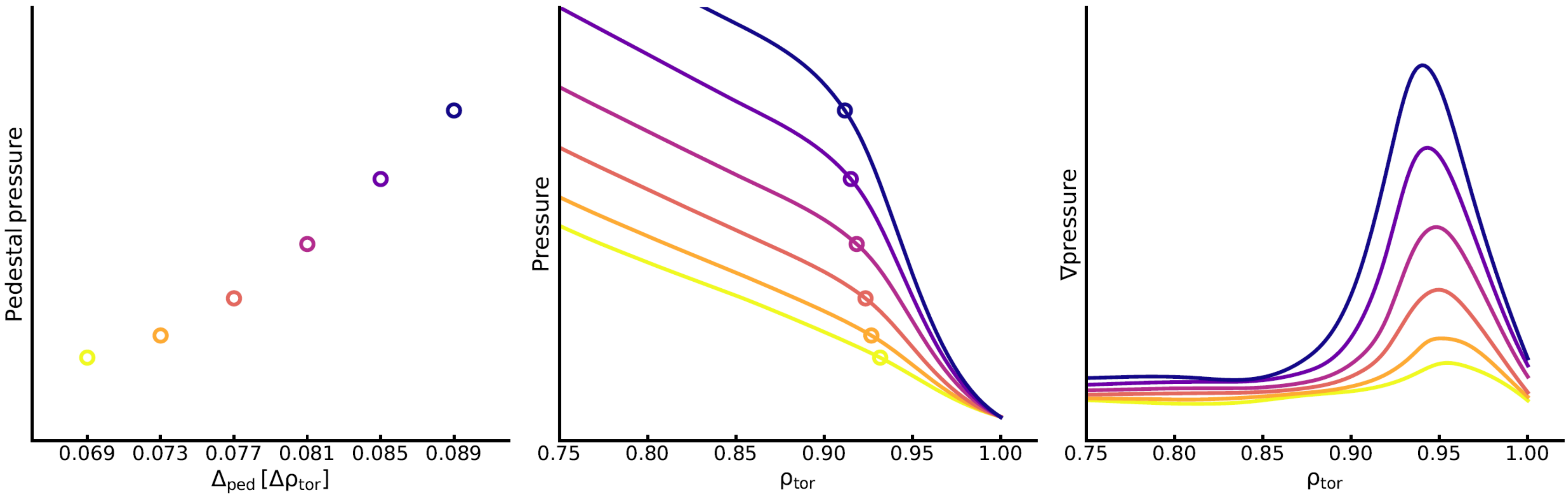




JET PB limited pedestal

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

- For every Δ_{ped} of the scan, ASTRA changes $\boldsymbol{\chi_{e,ped}}$ until $\frac{\mathbf{<\nabla T_e>}}{\mathbf{T_{e,top}}} = -0.5$ 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

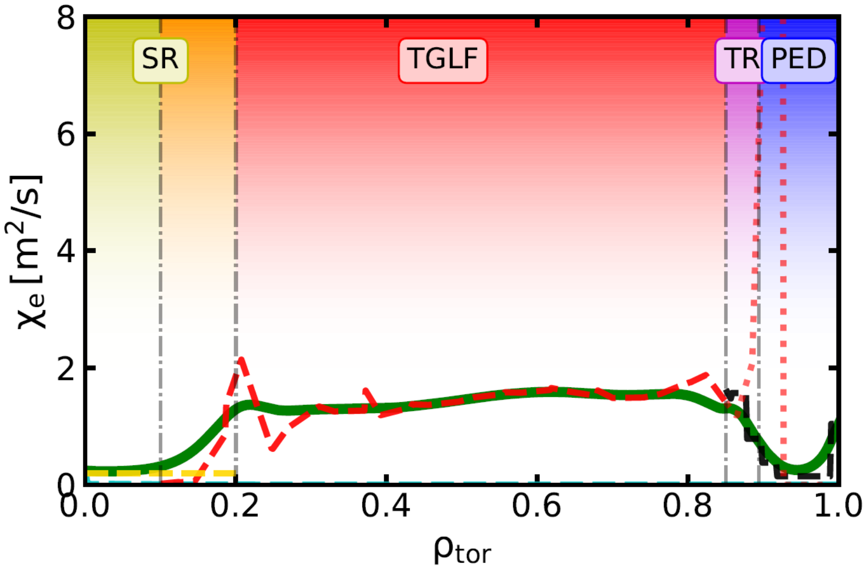


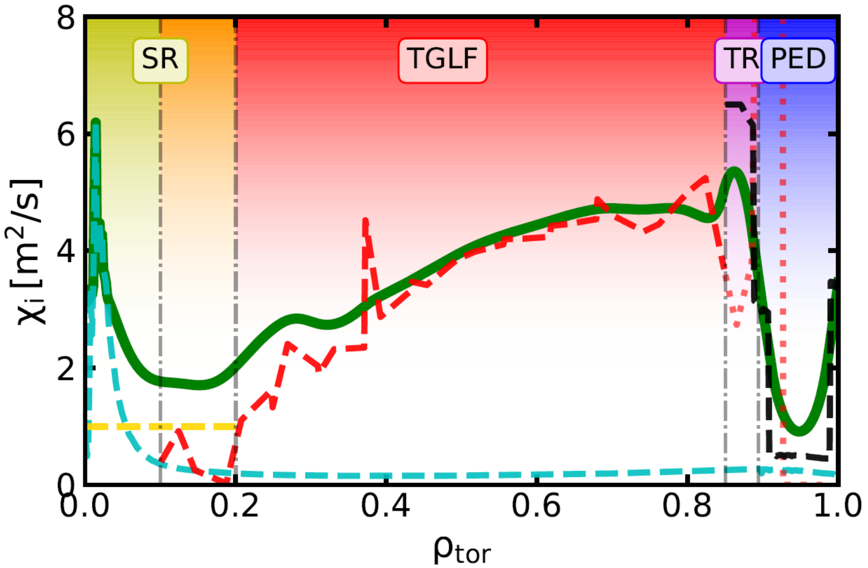
Connection of the different regions

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

- - - Before smoothing

—— After smoothing





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

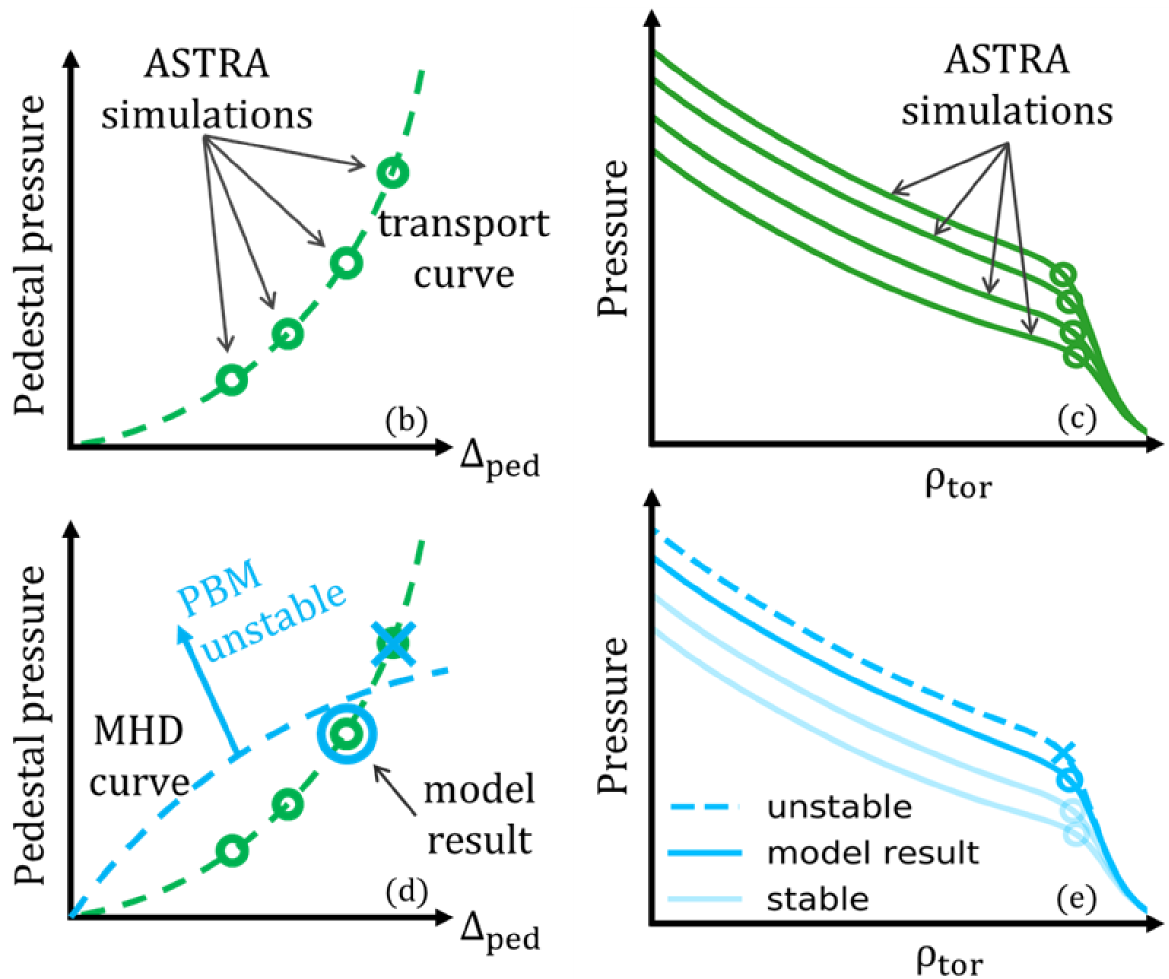
diffusivities in the **pedestal** and **transition** regions

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

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



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:

B_t = 1.5 - 2.8 [T] **I_p** = 0.6 – 1.2 [MA]

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

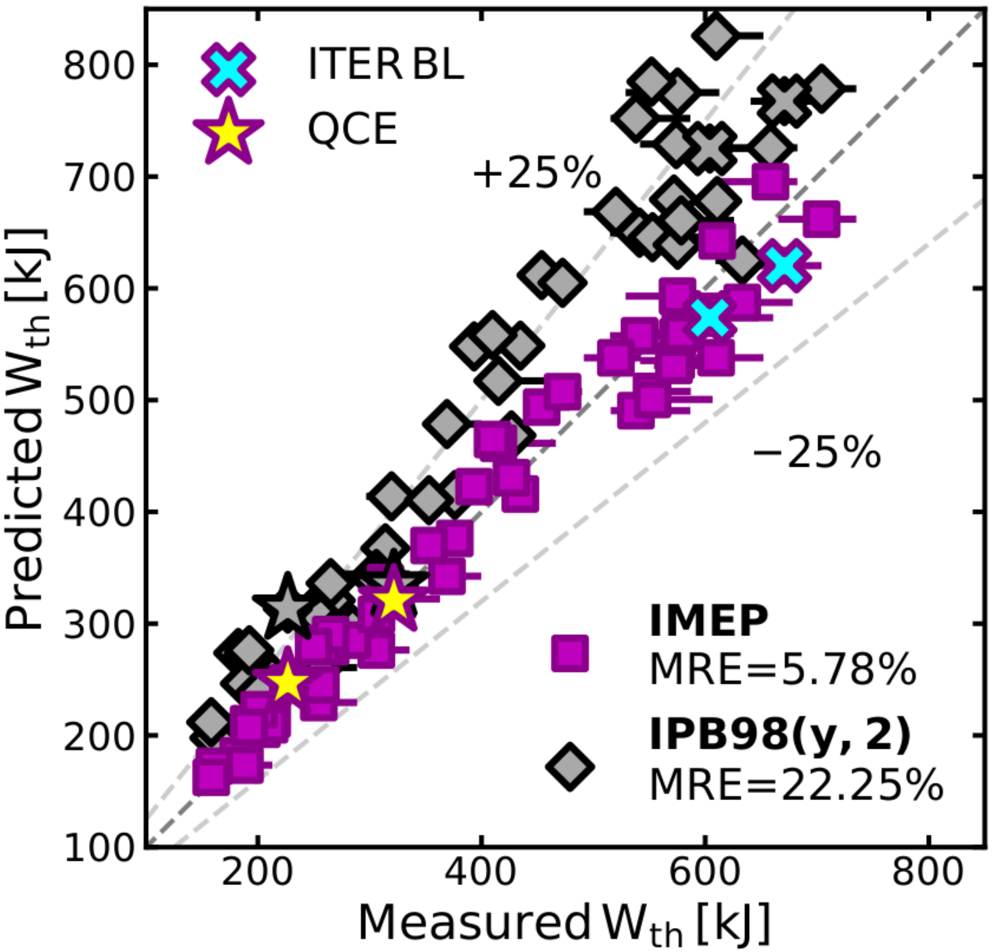
Γ_D = 0 – 8 x 10^{22} [e/s]

δ = 0.19 – 0.42

V_{NBI} = 42 - 92 [kV]

IMEP:

- ✓ 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

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]

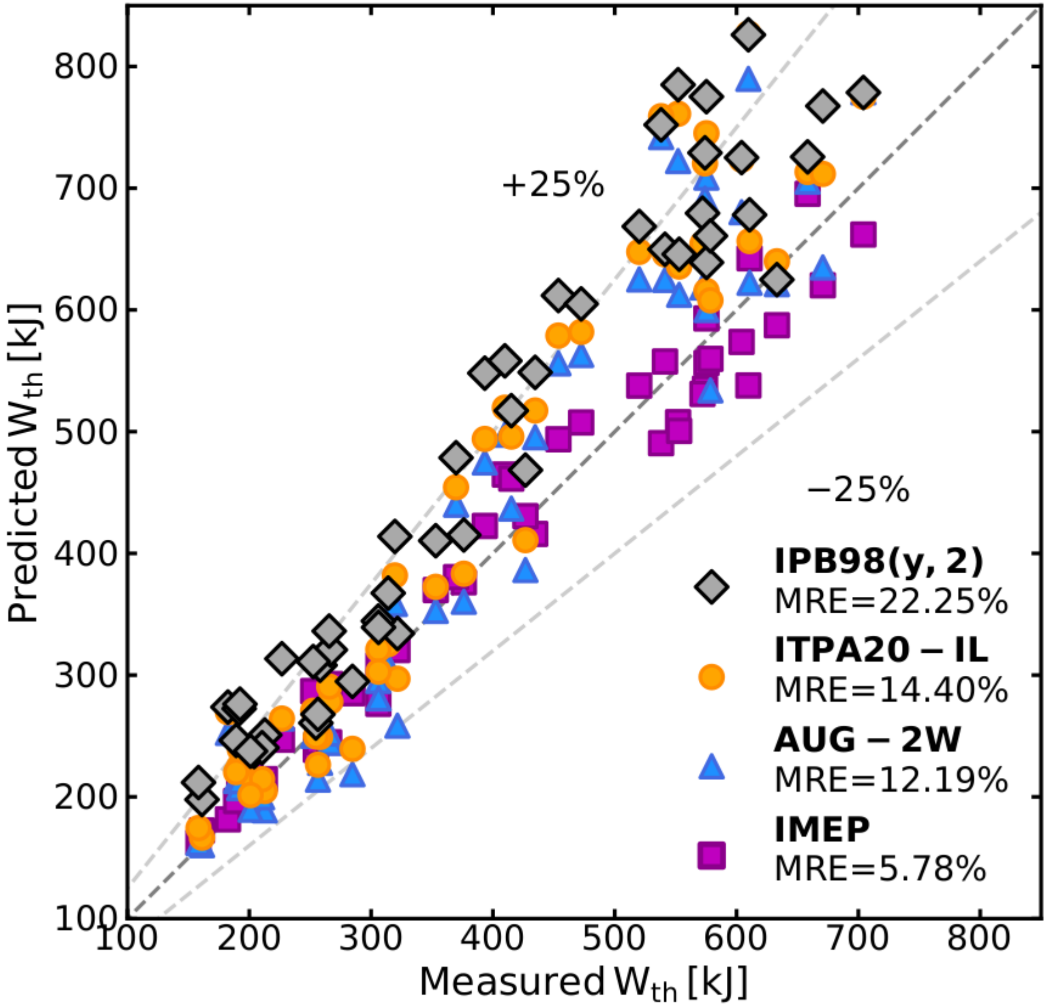
P_{net} = 2 – 14 [MW]   **q_{95}** = 3 - 8

Γ_D = 0 – 8 x 10^{22} [e/s]

δ = 0.19 – 0.42

V_{NBI} = 42 - 92 [kV]

IMEP 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:

B_t = 1.5 - 2.8 [T] I_p = 0.6 – 1.2 [MA]

P_{net} = 2 – 14 [MW] q_{95} = 3 - 8

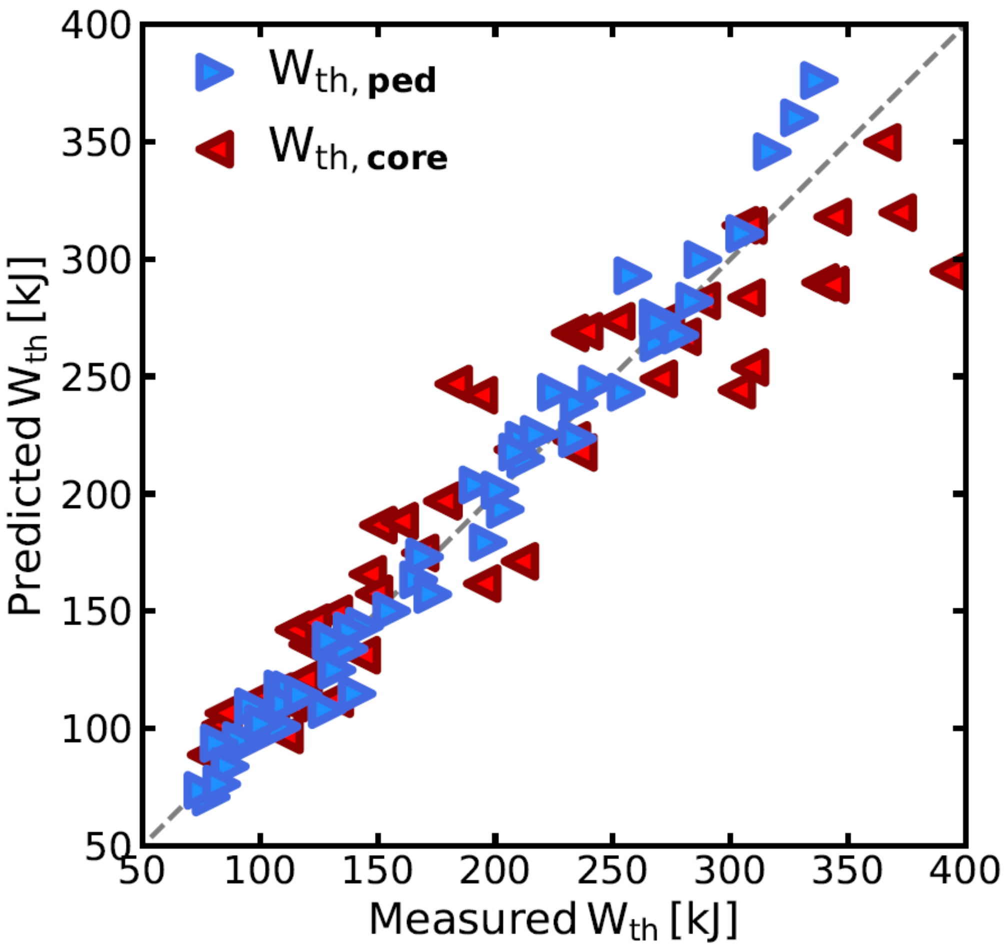
Γ_D = 0 – 8 x 10^{22} [e/s]

δ = 0.19 – 0.42

V_{NBI} = 42 - 92 [kV]

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:

$\mathbf{B_t}$ = 1.5 - 2.8 [T] $\mathbf{I_p}$ = 0.6 – 1.2 [MA]

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

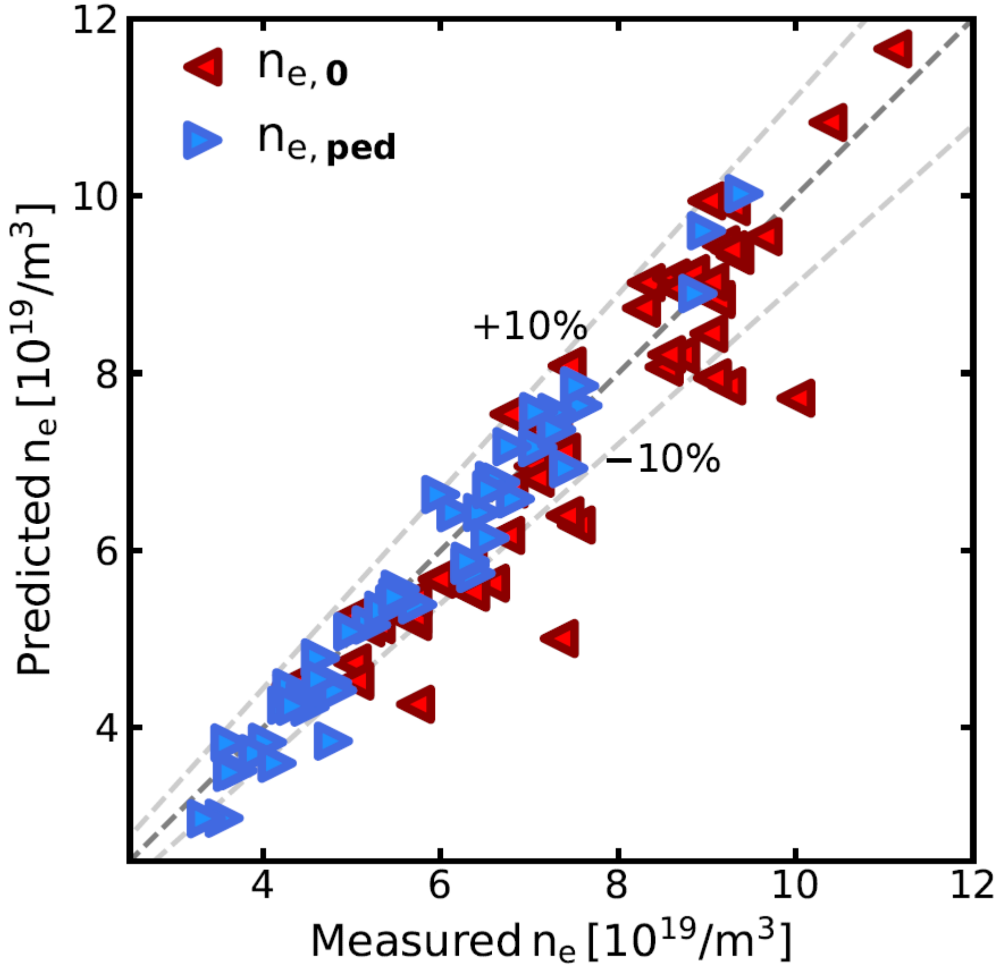
$\mathbf{\Gamma_D}$ = 0 – 8 x 10^{22} [e/s]

$\boldsymbol{\delta}$ = 0.19 – 0.42

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

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

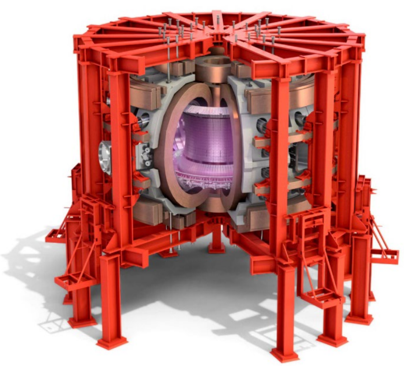
The **core density** prediction is also accurate, it might be underpredicted due to too low stabilization mechanisms (fast ions, β effects)



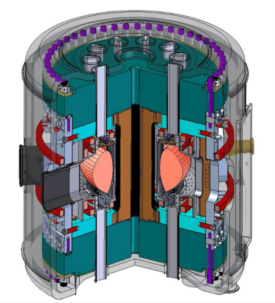
Application of the model to other devices

- The successful validation of the model on a database of AUG experiments is very promising for a more **physics based prediction** of plasma confinement

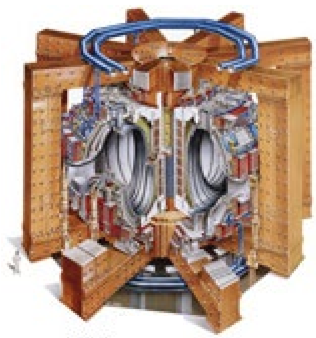
- It is important to extend the validation to **other devices** to test the validity of the assumptions and to gain confidence for the prediction of future devices



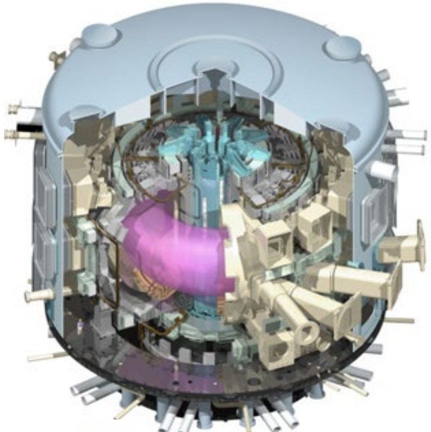
AUG



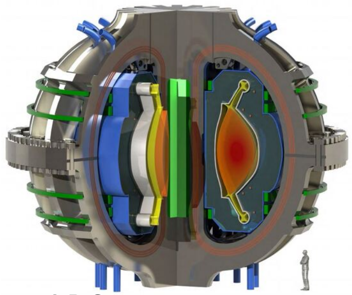
Alcator C-Mod



JET



ITER

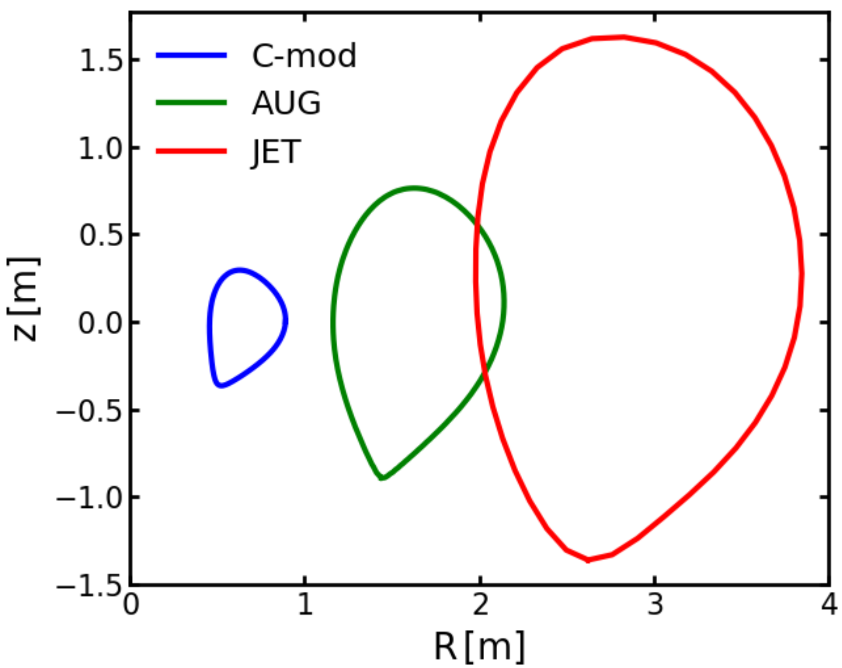


ARC

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	2.5	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 data: small subset selected with the pre-ELM pedestal near the PB boundary



Simulations setup:

- boundary conditions at separatrix (Te, Ti, ne) fixed to experimental values
- pedestal top density fixed to experimental value (via feedback on neutrals density) → **no SOL model**
- power deposition (ICRH, NBI) from TRANSP

$\frac{<\nabla T_e>}{T_{e,top}}$ = **constant also for C-Mod and JET?**

Can IMEP correctly reproduce the pedestal pressure for the other tokamaks?

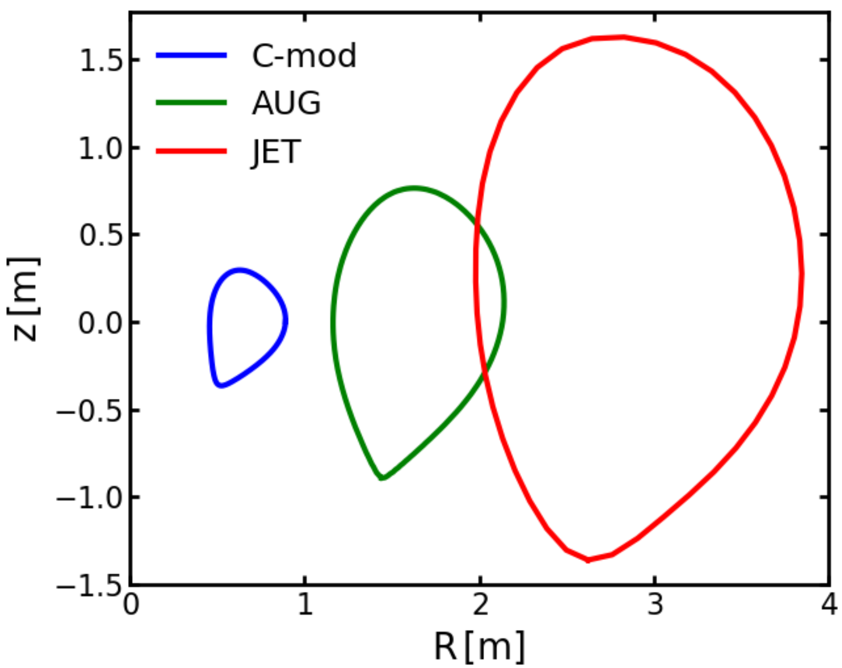
Test on C-Mod and JET-ILW ELMy H-mode

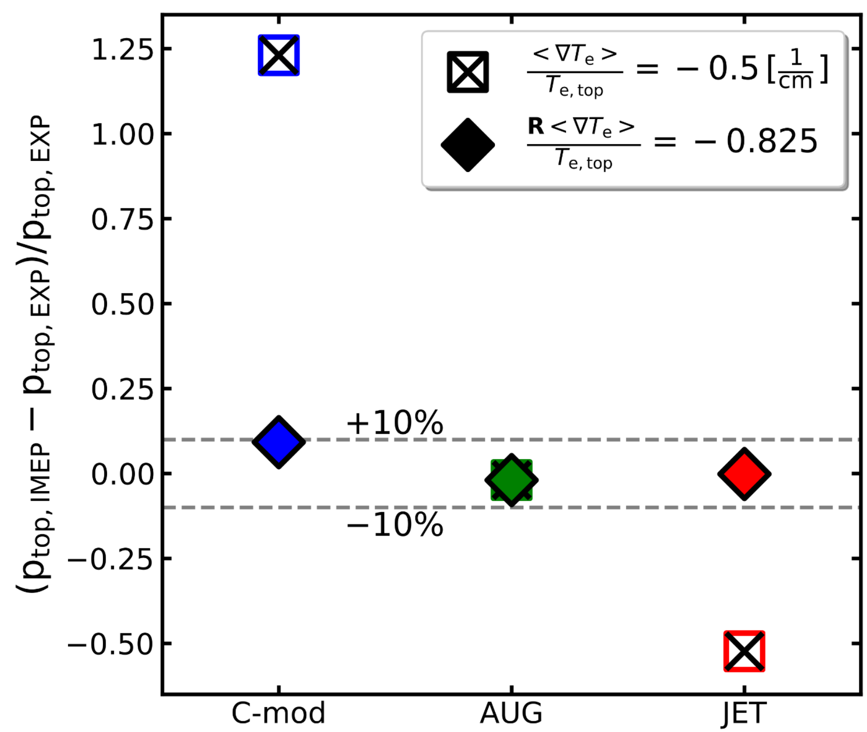
	P_{heat} [MW]	I_p [MA]	B_t [T]	q_{95}	$\overline{n_e}\,[\frac{10^{19}}{m^3}]$
C-Mod	2.5	0.9	5.5	4.3	16.5
AUG	12.0	1.0	2.5	4.0	7.0
JET	14.5	2.0	2.3	3.6	2.0

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

$$\frac{R<\nabla T_e>}{T_{e,top}} = \text{constant} \rightarrow \textbf{very accurate!}$$

JET data: small subset selected with the pre-ELM pedestal near the PB boundary





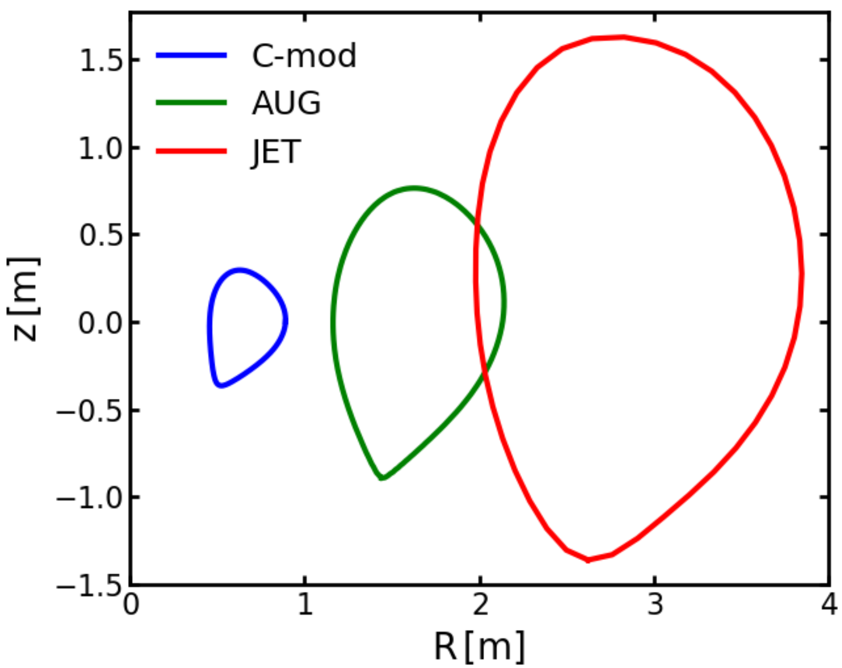
Test on C-Mod and JET-ILW ELMy H-mode

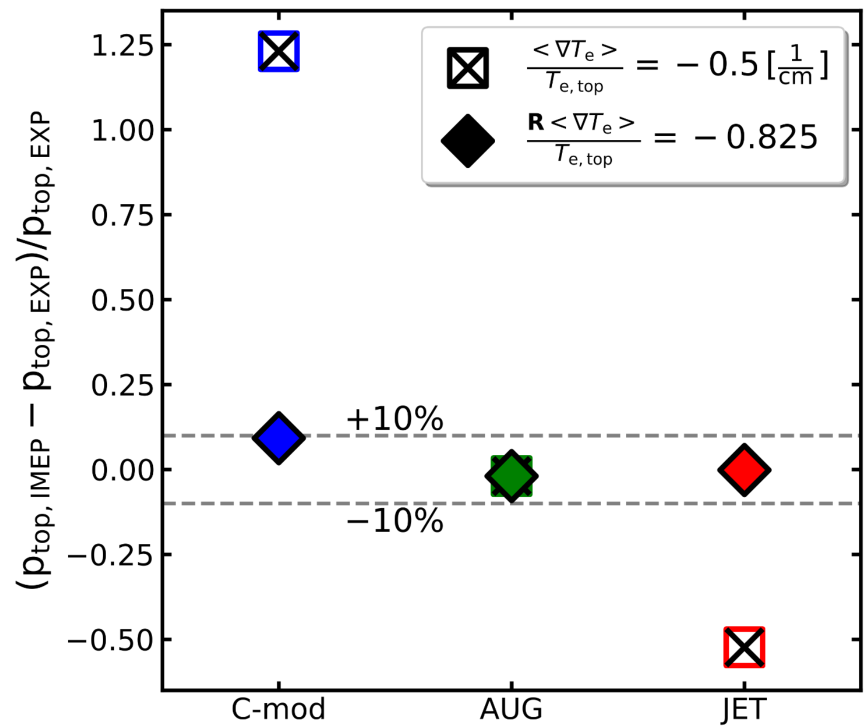
	P_{heat} [MW]	I_p [MA]	B_t [T]	q_{95}	$\overline{n_e}\,[\frac{10^{19}}{m^3}]$
C-Mod	2.5	0.9	5.5	4.3	16.5
AUG	12.0	1.0	2.5	4.0	7.0
JET	14.5	2.0	2.3	3.6	2.0

M5.1 - Heuristic pedestal transport model refined based on parameter scans performed in deliverable 1 and exp. results from machines other than AUG

D5.1 - Refined heuristic transport model ready for interfacing

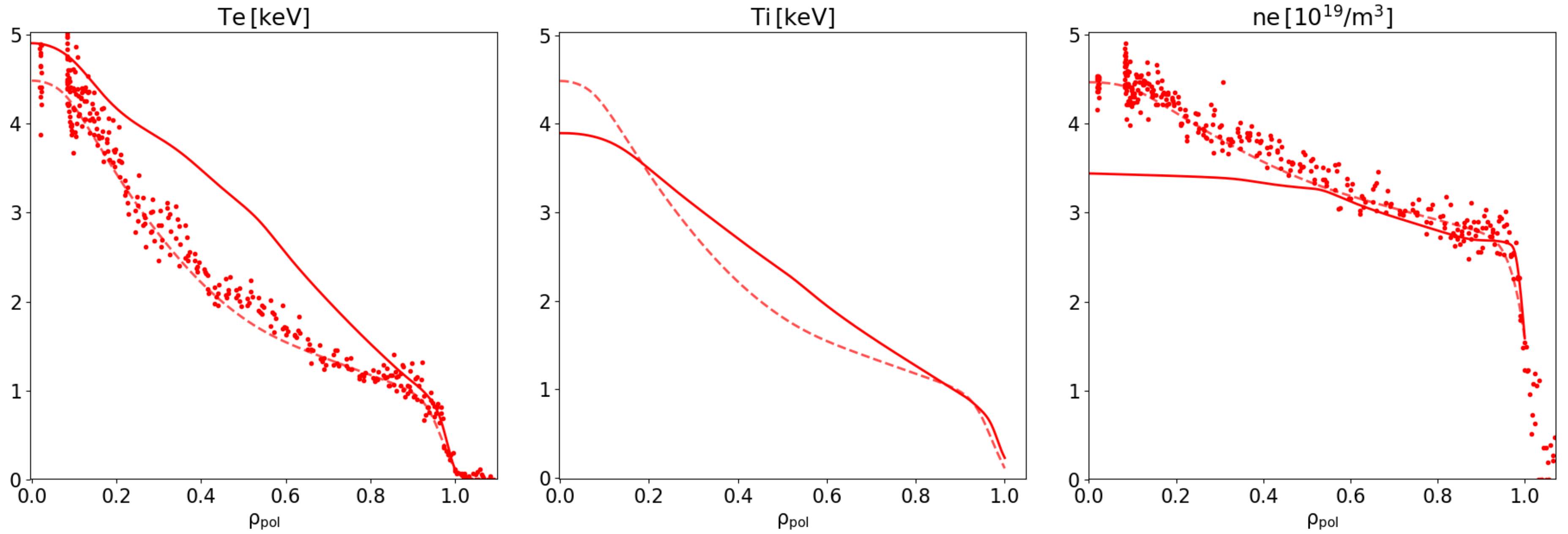
JET data: small subset selected with the pre-ELM pedestal near the PB boundary





JET-ILW simulations

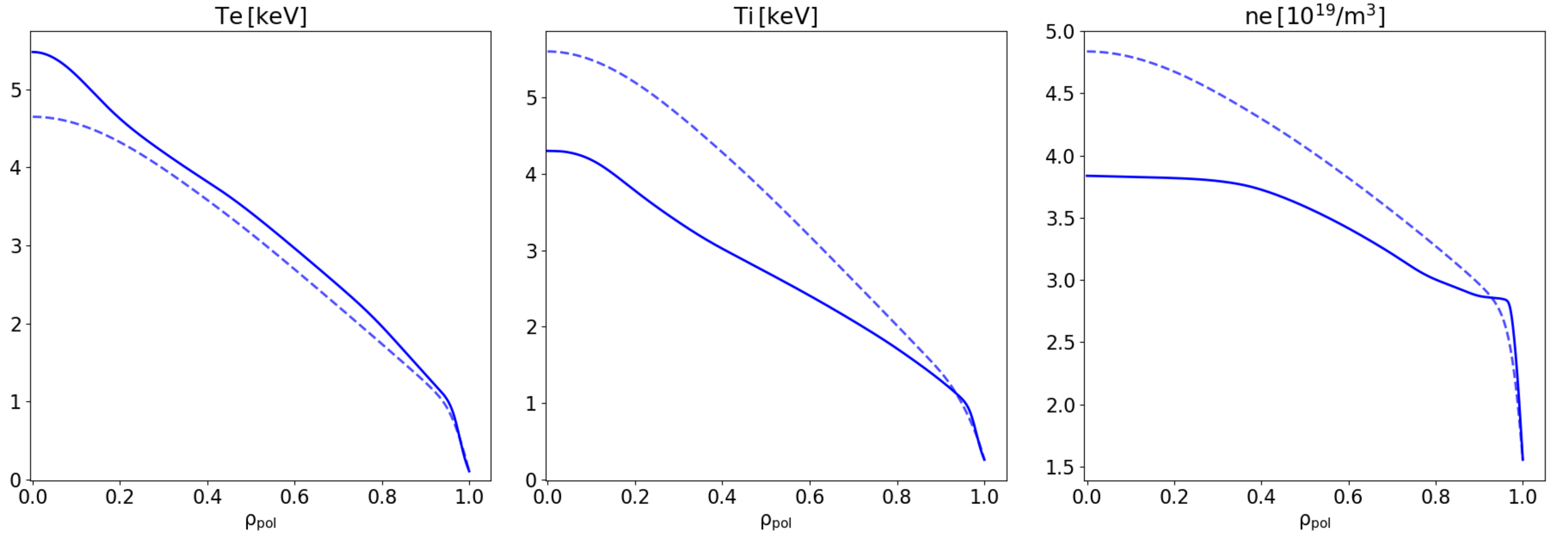
	P_{heat} [MW]	I_p [MA]	B_t [T]	q_{95}	$\overline{n_e}\,[\frac{10^{19}}{m^3}]$
JET	14.5	2.0	2.3	3.6	3.0



Pedestal top quantities well reproduced
Core profiles not very well reproduced by QuaLiKiz-NeuralNetwork

JET-ILW simulations

	P_{heat} [MW]	I_p [MA]	B_t [T]	q_{95}	$\overline{n_e}$ [$\frac{10^{19}}{m^3}$]
JET	12	1.4	1.7	4.4	3.8



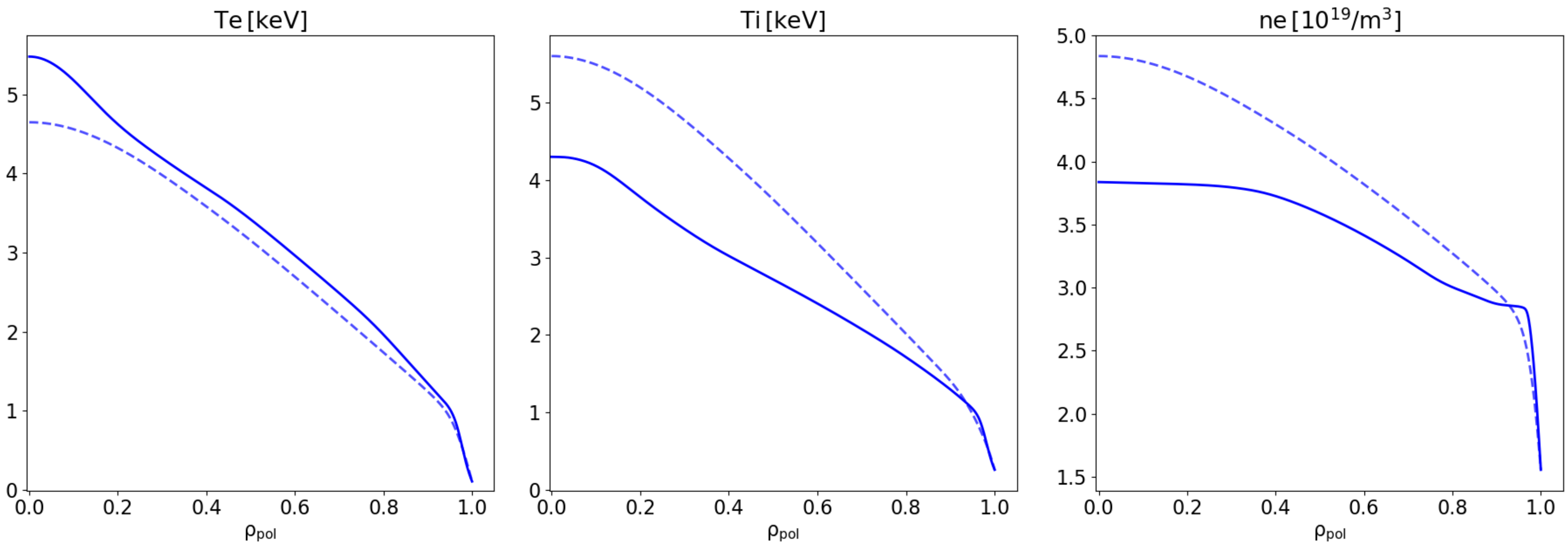
Pedestal top quantities well reproduced

Core profiles not very well reproduced by QuaLiKiz-NeuralNetwork

JET-ILW simulations

	P_{heat} [MW]	I_p [MA]	B_t [T]	q_{95}	$\overline{n_e}$ [$\frac{10^{19}}{m^3}$]
JET	12	1.4	1.7	4.4	3.8

Database will be expanded with fueling and power scans



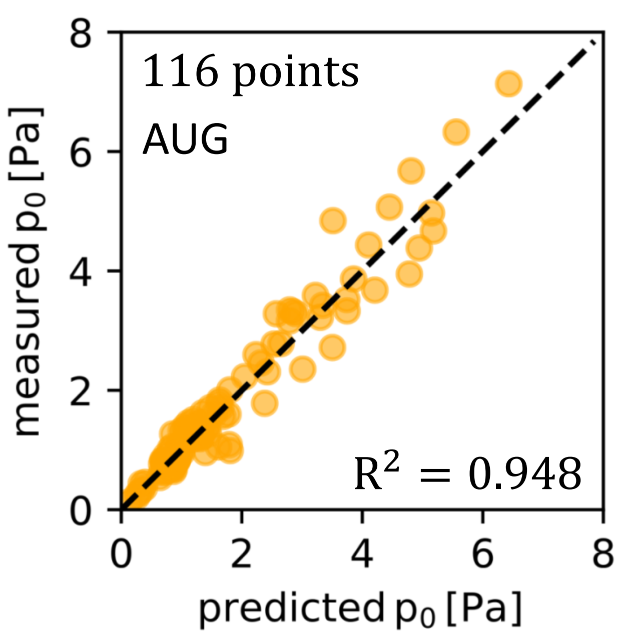
Pedestal top quantities well reproduced
Core profiles not very well reproduced by QuaLiKiz-NeuralNetwork

Summary

- **IMEP predicts entire radial profiles** of AUG H-mode plasmas, from magnetic axis to separatrix, only using global parameters as inputs
- Validation on AUG database with large variations in operational parameters demonstrates that IMEP can capture physics effects determining plasma confinement **beyond the possibilities of empirical scaling laws**
- 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
- **Dimensionless parameter** $\frac{R<\nabla T_e>}{T_{e,top}} = \text{constant}$ is shown to be promising candidate in AUG, C-Mod, and JET-ILW (PB limited pedestal) to accurately predict the pedestal pressure in different devices (with experimental b.c.)
- 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 $\mathbf{p_0}$ is AUG specific
- In the long term the model could contribute to develop and optimize ITER, DEMO, and SPARC scenarios to **reach the best fusion performance**

Scrape Off Layer model

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



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

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 ($T_0 = 5\mathrm{eV}$)