Theory-based integrated modelling of tungsten transport

Validation in present-day tokamaks and predictions for ITER

30th IAEA Fusion Energy Conference

Daniel Fajardo

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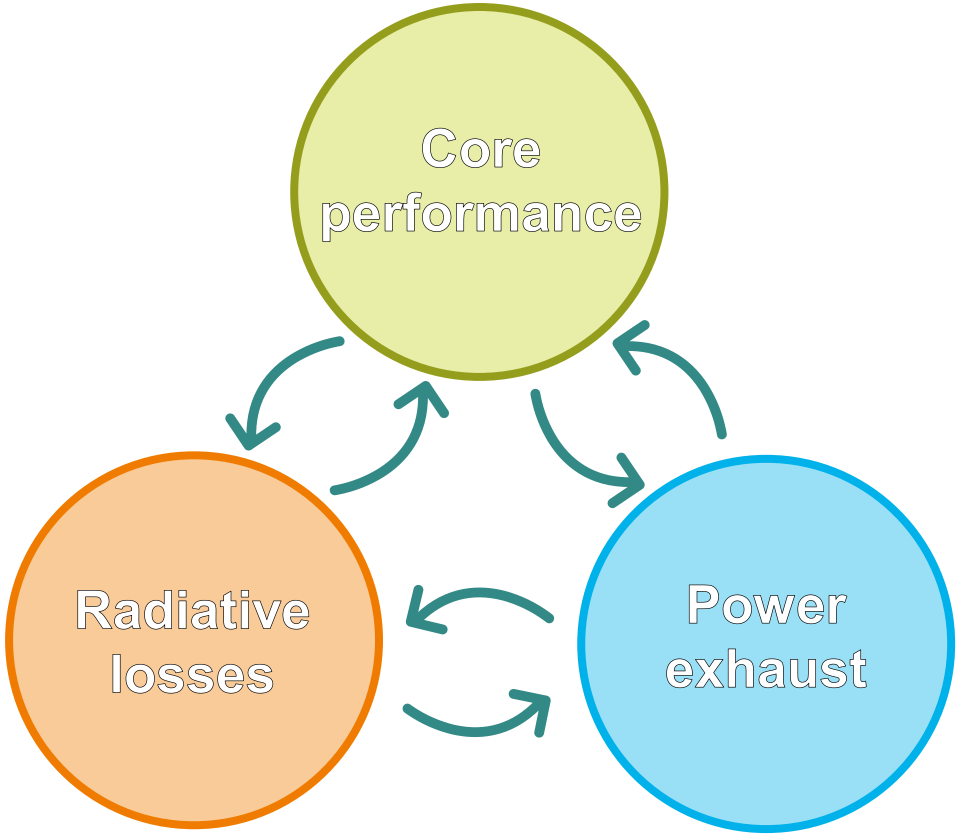
Impurities are critical in the operation of a fusion reactor



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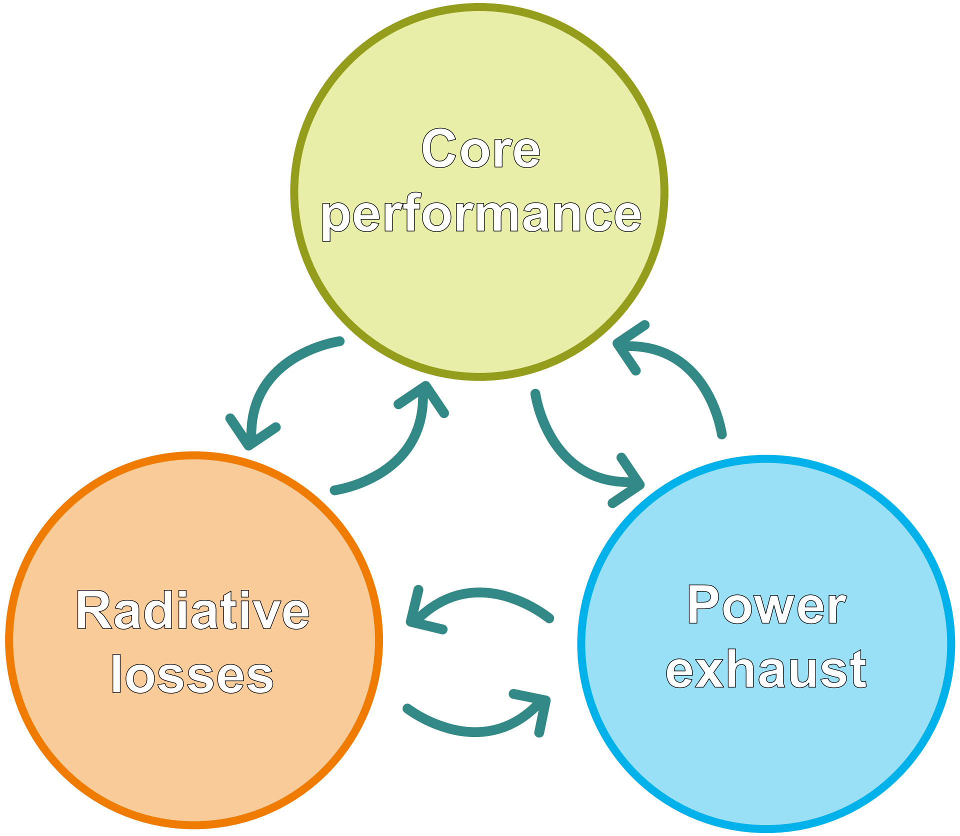

In this talk:

- Theory-based modelling workflow

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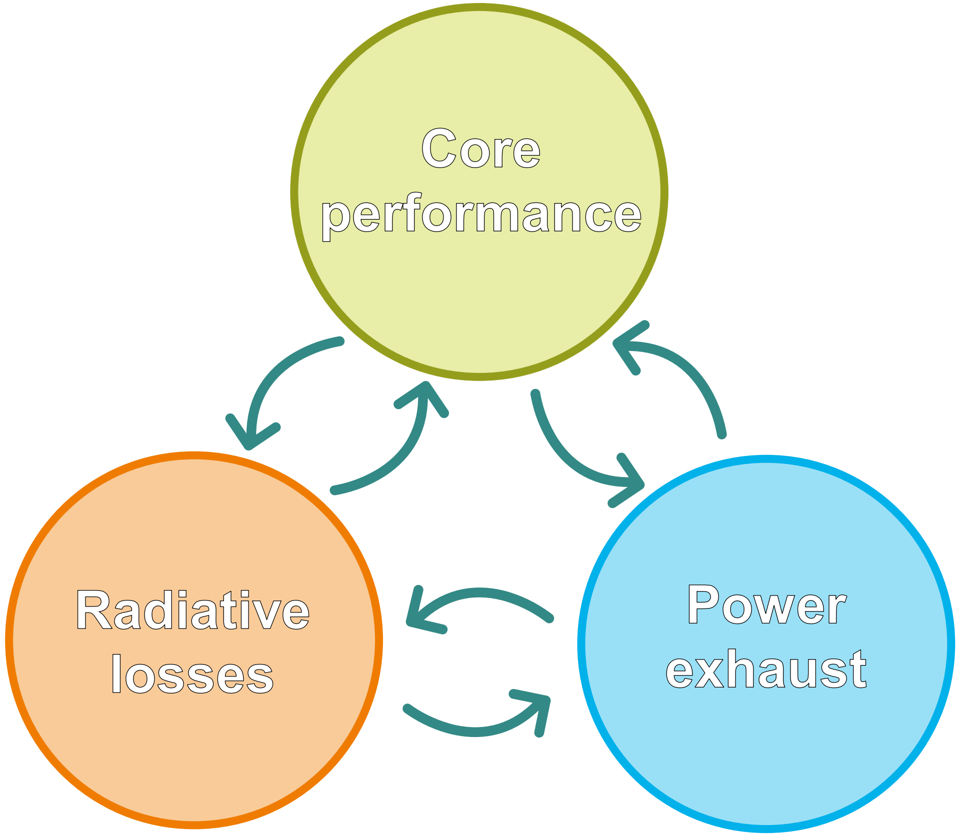

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- Validation in AUG and JET

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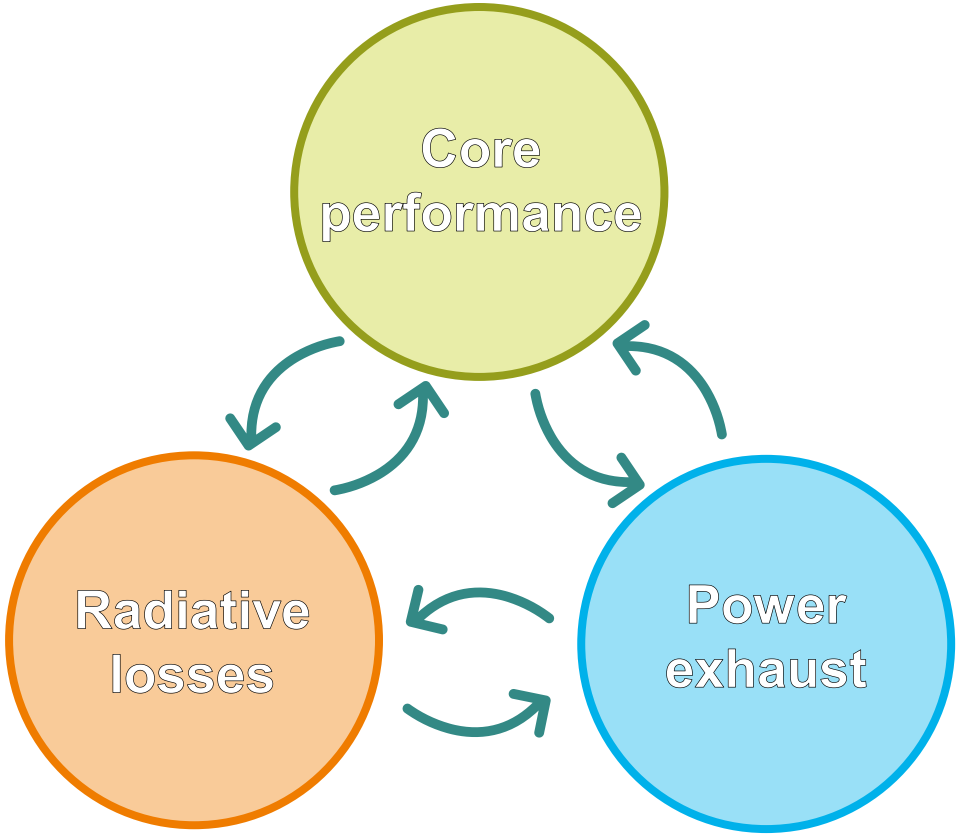

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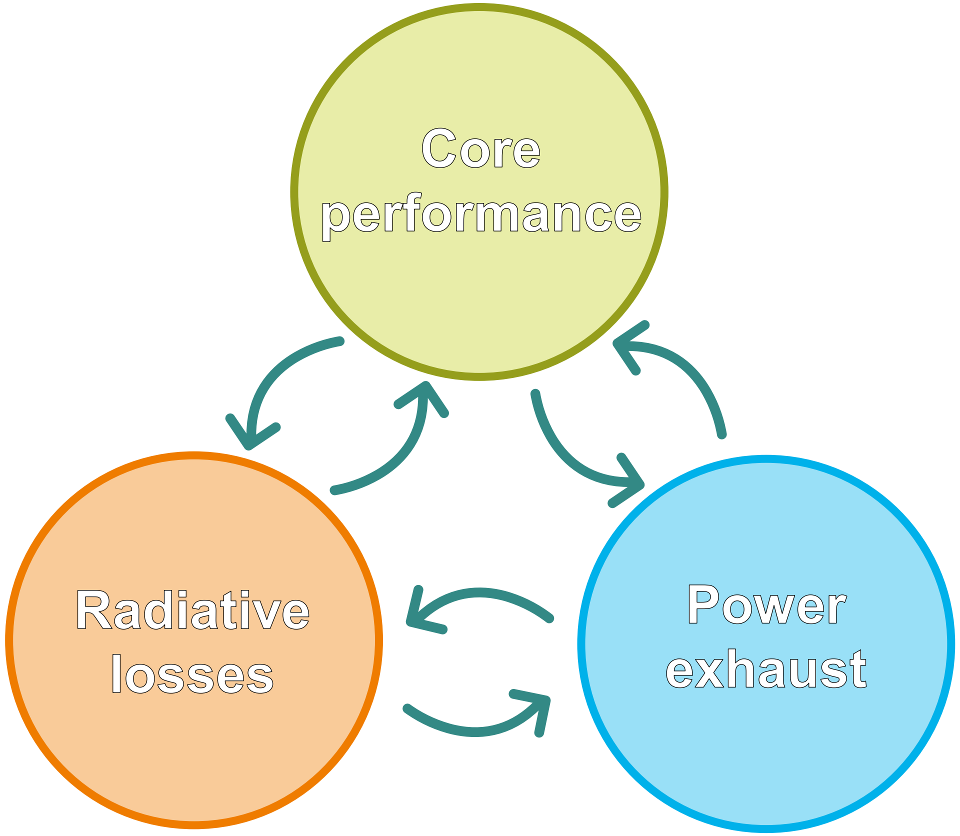

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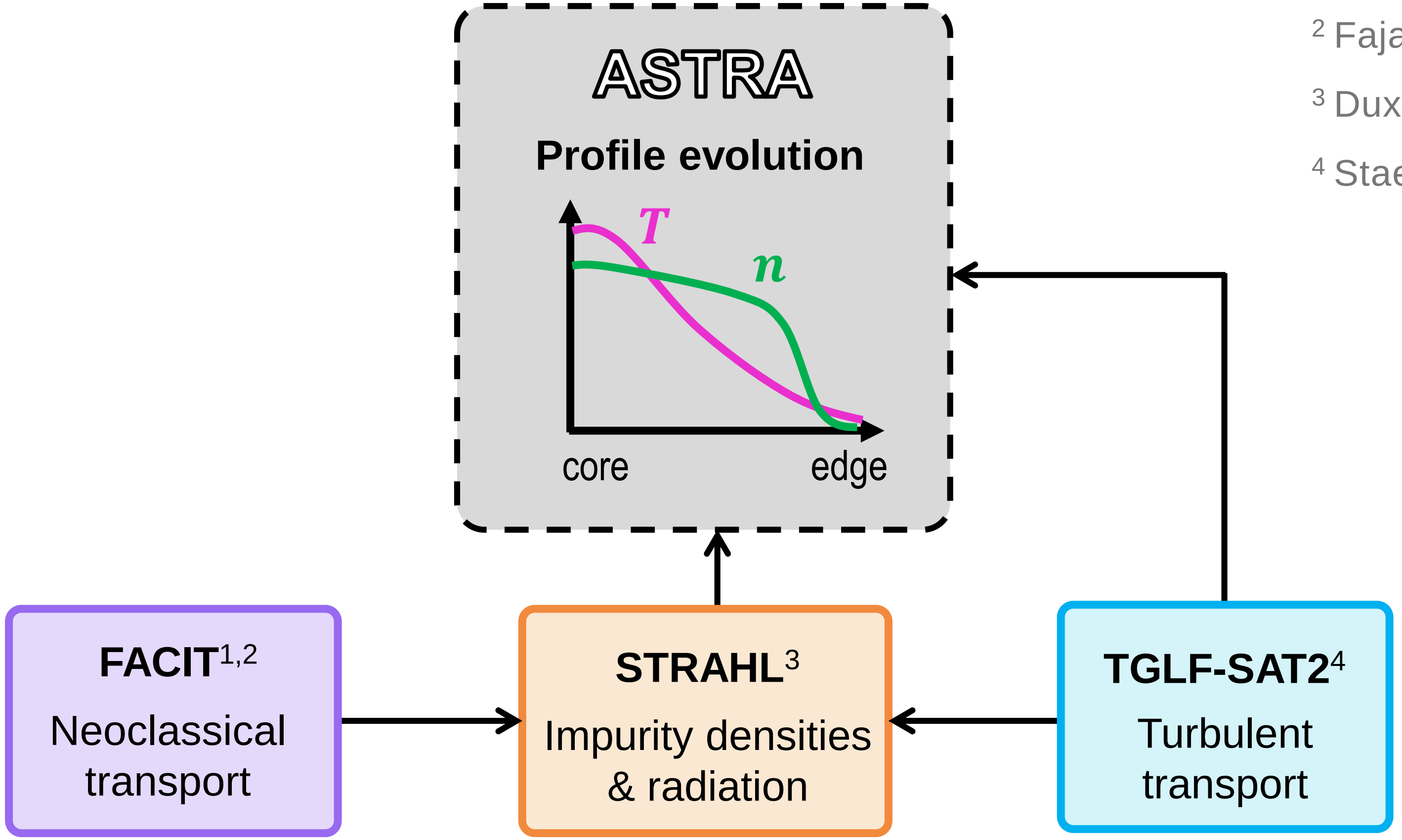
- **Theory-based** modelling workflow
- Validation in AUG and JET
- Predictions of ITER plasmas

Transport regime might not be the same

Theory-based modelling workflow

Modelling workflow with impurities

scenario to be modelled is summarized in this box



[1] Maget 2020 PPCF 62 105001
[2] Fajardo 2023 PPCF 65 035021
[3] Dux 2006 IPP report
[4] Staebler 2022 NF 61 116007

Modelling workflow with impurities

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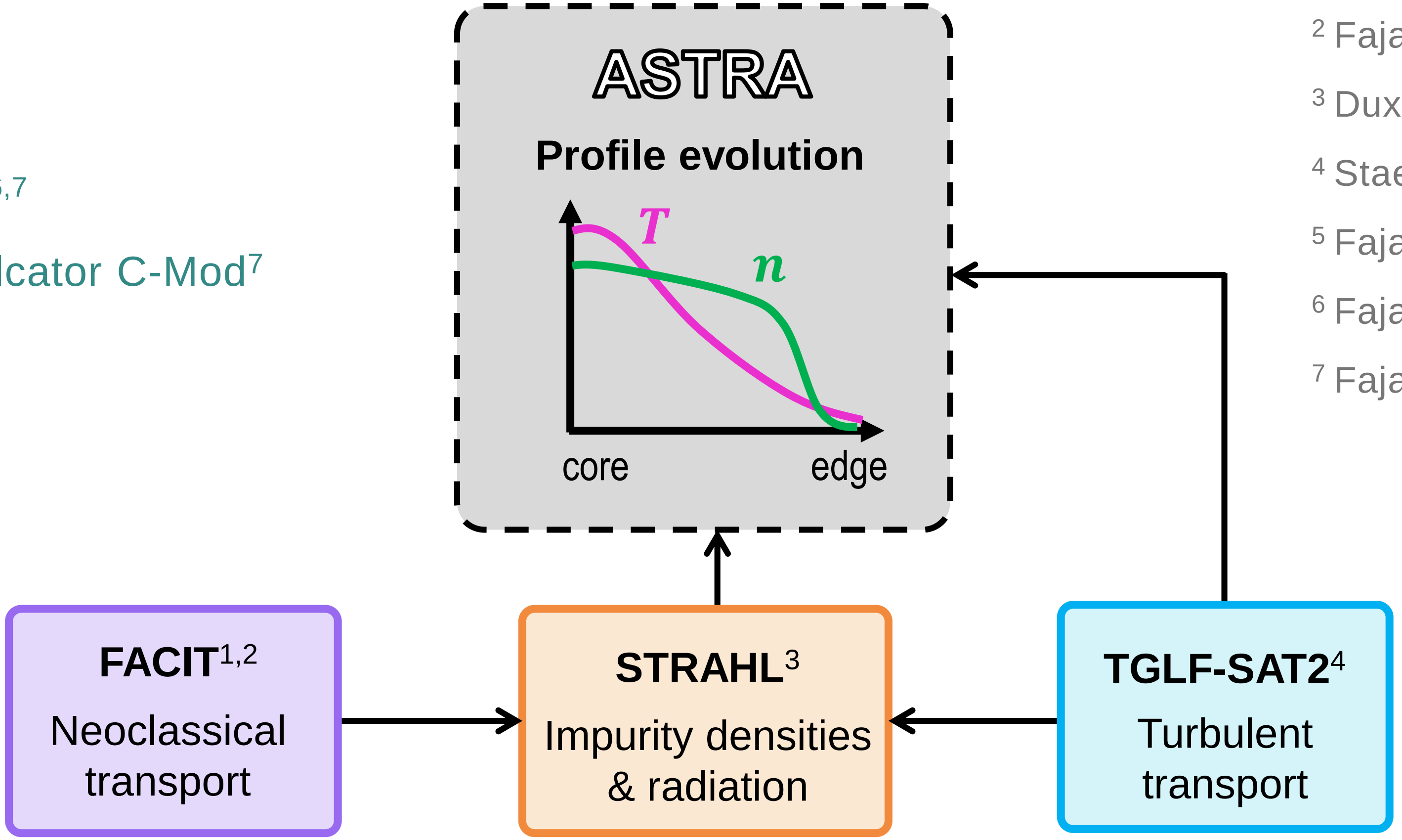
Validated on

- ✓ AUG L-modes[5]
- ✓ AUG H-modes[6,7]
- ✓ JET-ILW and Alcator C-Mod[7]



[1] Maget 2020 PPCF 62 105001

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[5] Fajardo 2024 NF 64 046021

[6] Fajardo 2024 NF 64 104001

[7] Fajardo subm. to NF

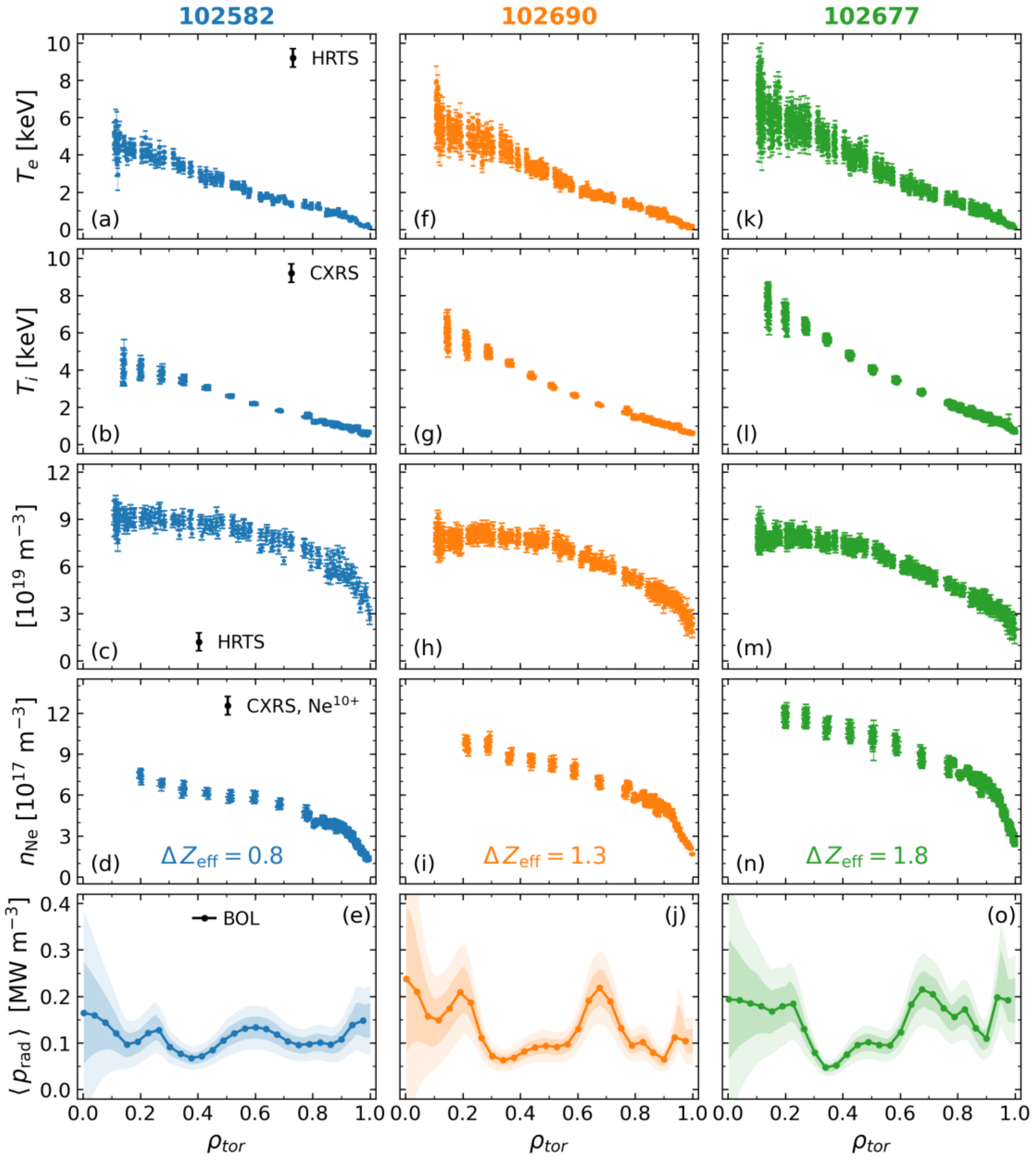
Full-radius modelling of high-power seeded discharges in JET-ILW

Full-radius modelling of JET high power Ne seeded plasmas

JET-ILW 3.2 MA
32 MW with Ne

- High current I_p = 3.2 MA at B_t = 3.45 T (q_{95} ~ 3.3) in deuterium
- 28 MW of NBI, 4 MW of ICRH
- Neon seeding: low, intermediate, high

[see C. Giroud EX-C 2924 on Wed.]



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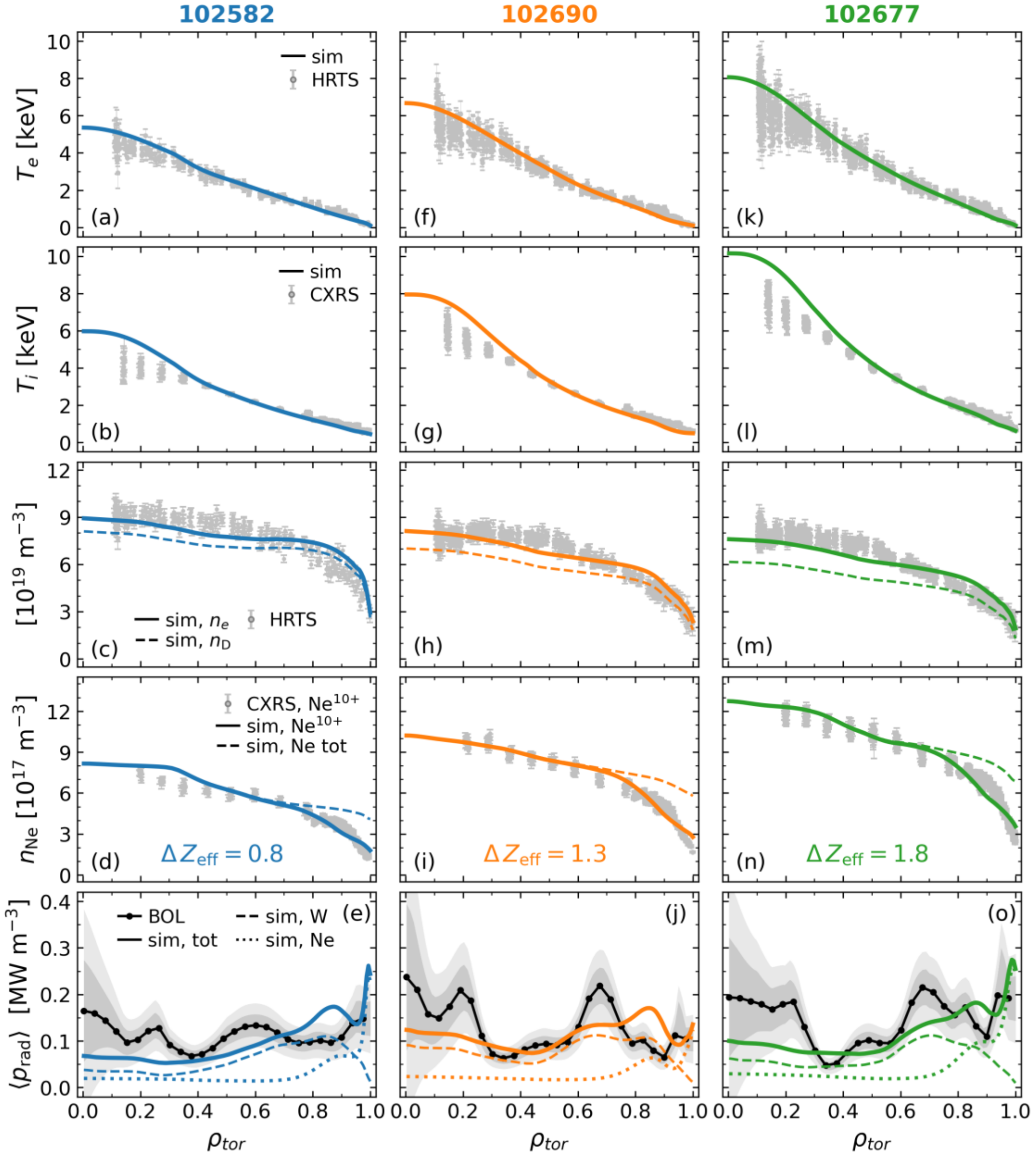
- 28 MW of NBI, 4 MW of ICRH
- Neon seeding: low, intermediate, high

  [see C. Giroud EX-C 2924 on Wed.]

- Excellent agreement with experiment across all transport channels[1]
- Including neon is necessary to reproduce the main profiles and global confinement in the simulations
- Flat radiation profiles by W and Ne

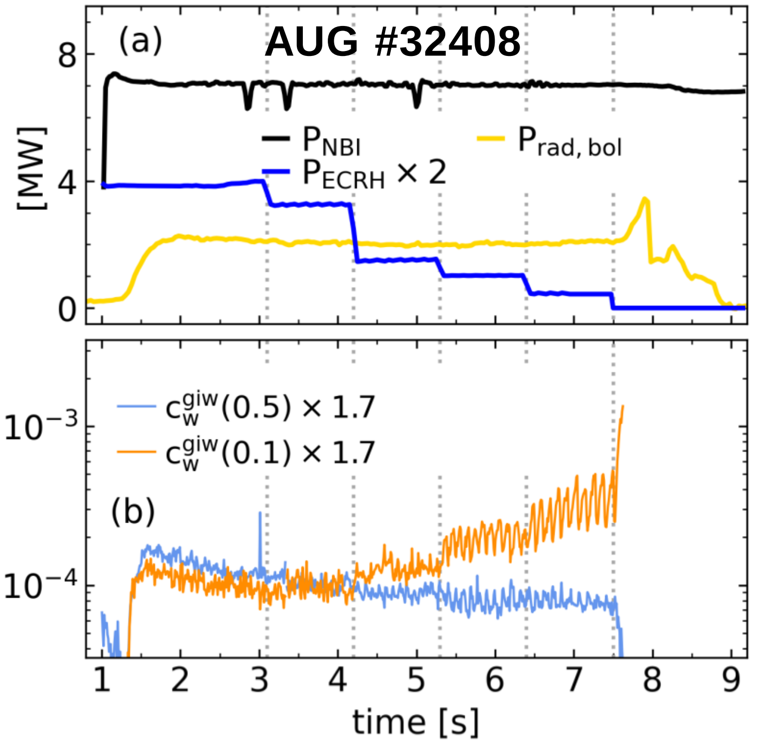


[1] Fajardo subm. to NF

Modelling the control of W accumulation with central ECRH

Dynamical modelling of AUG H-mode with NBI + ECRH steps

AUG 1.0 MA H-mode



- W accumulation as central ECRH is decreased[1]
- Central wave heating controls W accumulation because it increases W diffusivity and decreases W pinch

[1] Angioni 2017 NF 57 056015

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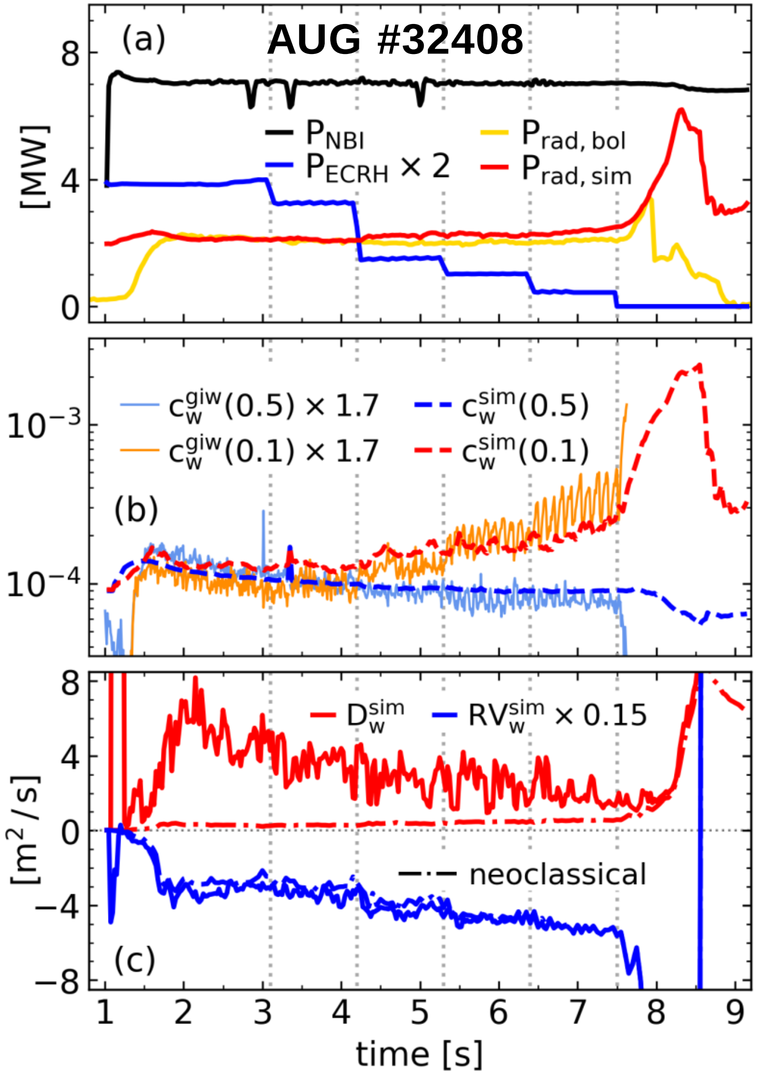
H-mode



- W accumulation as central ECRH is decreased[1]
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- ASTRA-TGLF-FACIT modelling of entire flattop **quantitatively** reproduces experimental W behavior[2]
- Competition between neoclassical convection and turbulent diffusion

[1] Angioni 2017 NF 57 056015
[2] Fajardo 2024 NF 64 104001

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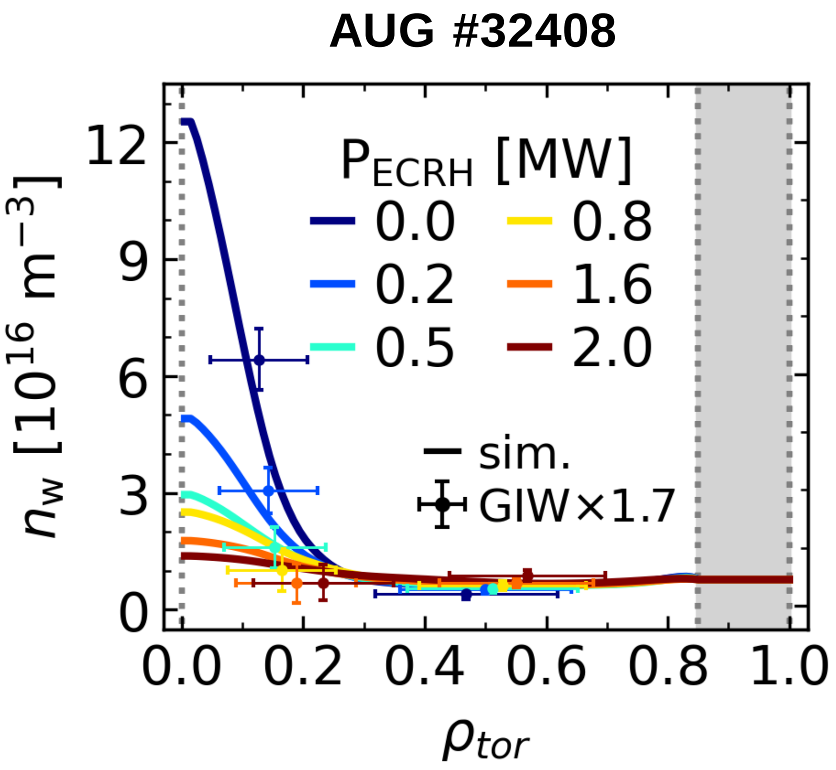
AUG 1.0 MA
H-mode



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- Central wave heating controls W accumulation because it increases W diffusivity and decreases W pinch
- ASTRA-TGLF-FACIT modelling of entire flattop **quantitatively** reproduces experimental W behavior[2]
- Competition between neoclassical convection and turbulent diffusion → different W profiles at different ECRH

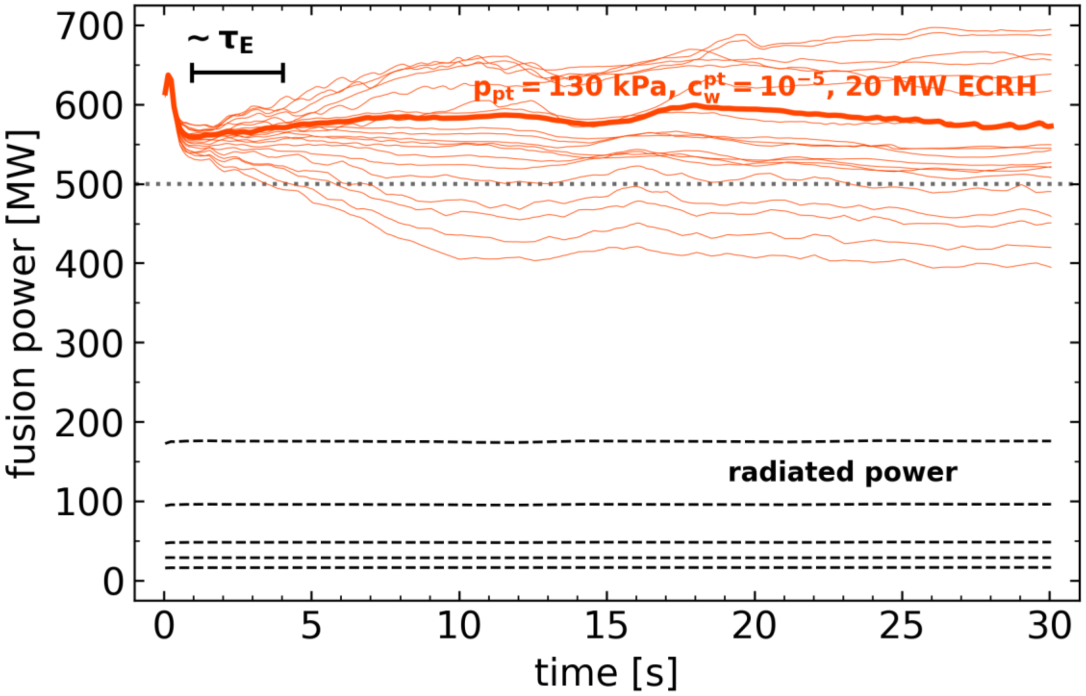
[1] Angioni 2017 NF 57 056015
[2] Fajardo 2024 NF 64 104001

ITER 15 MA baseline scenario

Modelling the 15 MA baseline scenario including tungsten

ITER 15 MA
H-mode in DT

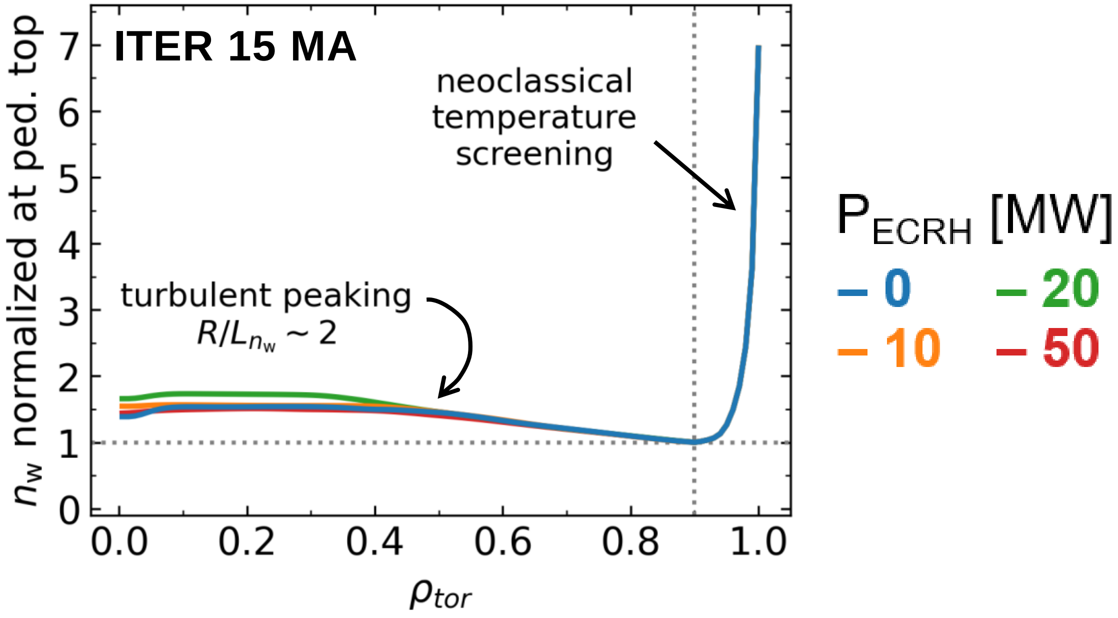
- B_t = 5.3 T, 50/50 D-T mix
- Boundary condition at pedestal top
- Pedestal calculated with **IMEP**[1]
- 30 MW of NBI
- Scan in ECRH power: 0, 10, 20, 50, 70 MW
- Scan in pedestal top W concentration: 10^{-5} to 10^{-4}



[1] Luda 2025 NF 65 072001

W profile shape & radiation are independent of ECRH power

ITER 15 MA
H-mode in DT



- W density profile shape is practically not affected by ECRH[1]
- As a consequence, the radiated power losses are also independent of ECRH

[1] Fajardo 2024 NF 64 104001

W profile shape & radiation are independent of ECRH power

ITER 15 MA
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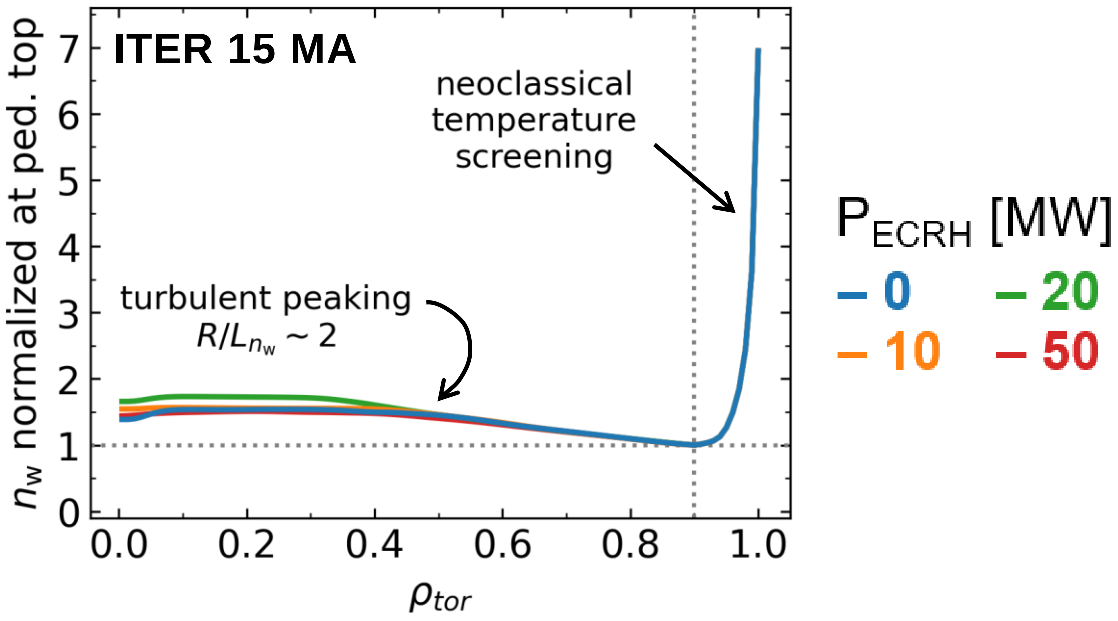

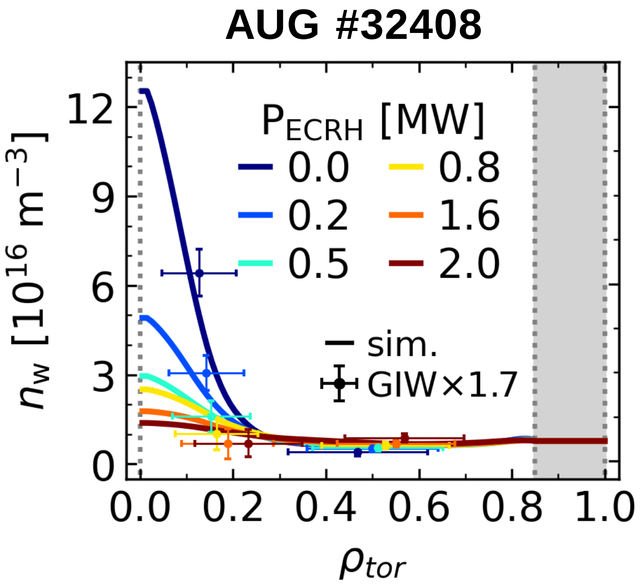

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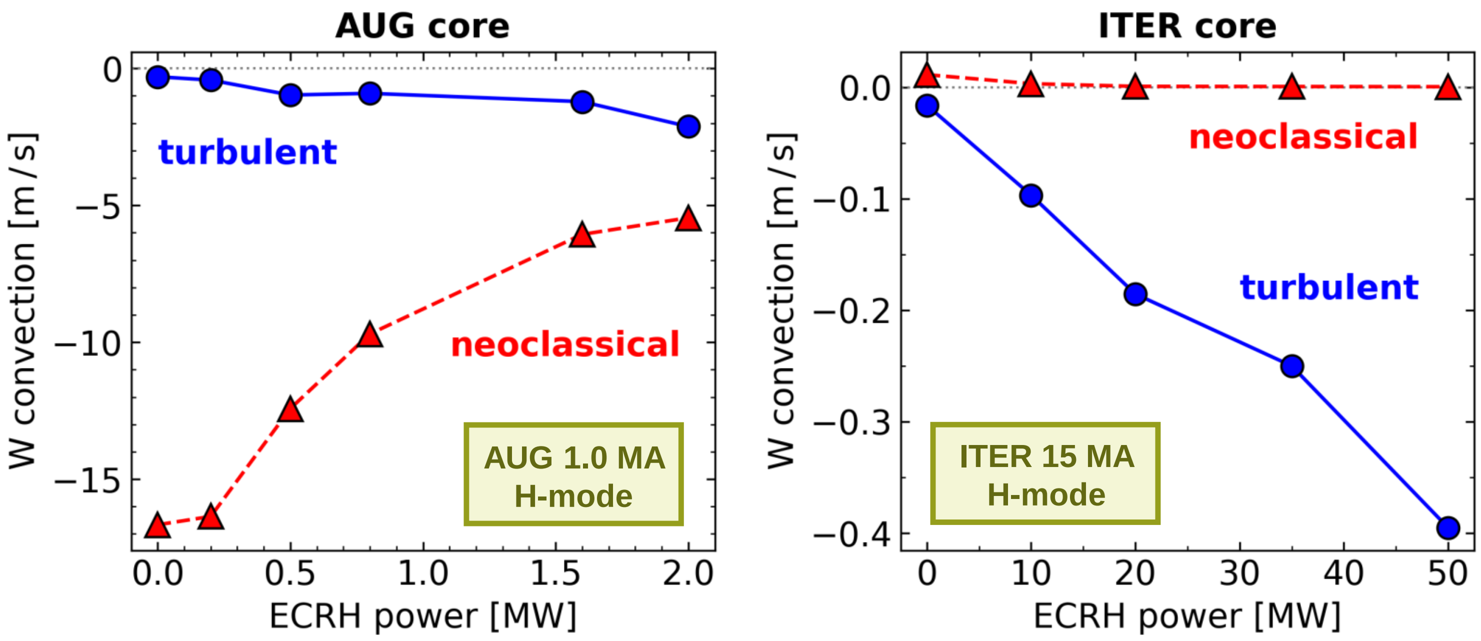
[1] Fajardo 2024 NF 64 104001

Turbulent transport is dominant for W in ITER core

- In the core of ITER, the much lower collisionality and lower rotation (compared to present-day devices) cause the **neoclassical** transport to be almost negligible compared to **turbulent** transport



(+ 8 MW of NBI)

(+ 30 MW of NBI)

- Turbulent transport does not lead to strong accumulation[1]
- Core W densities are flat regardless of ECRH power[2]

[1] Angioni 2021 PPCF 63 073001

[2] Fajardo 2024 NF 64 104001

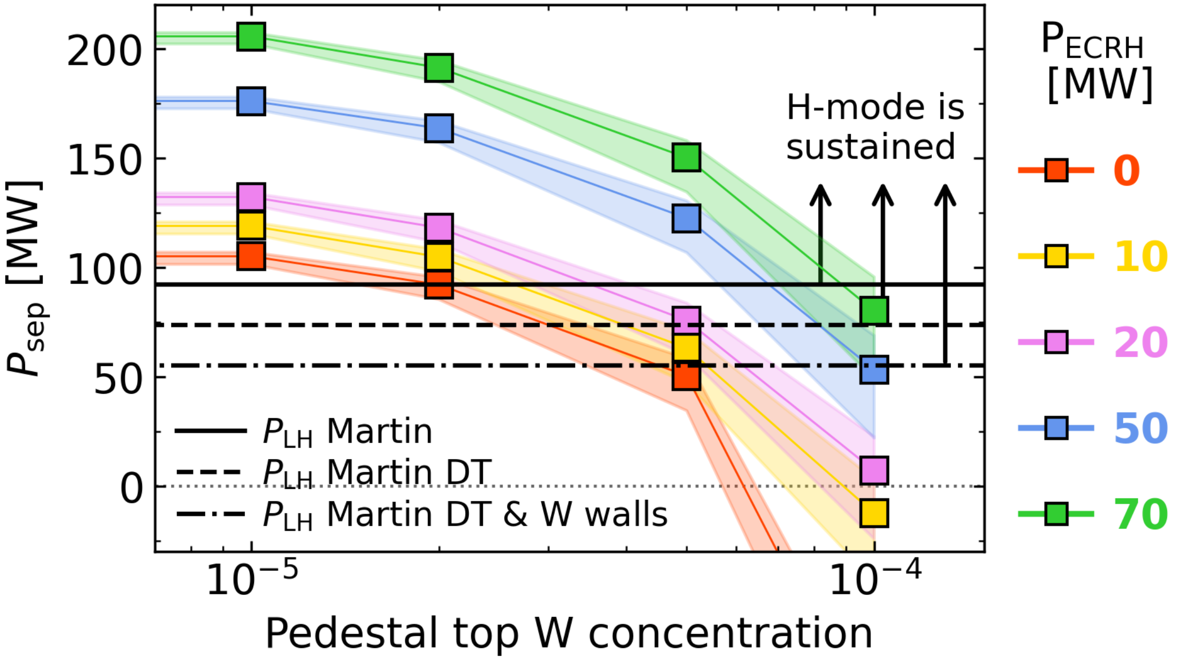
Operational limits by W are given by H-mode sustainment

ITER 15 MA
H-mode in DT

- Global condition of $P_{\mathrm{sep}} < P_{\mathrm{LH}}$ is reached before the central power balance is negative locally[1]

- Depending on the W content, auxiliary heating must be adjusted to offset global radiative losses

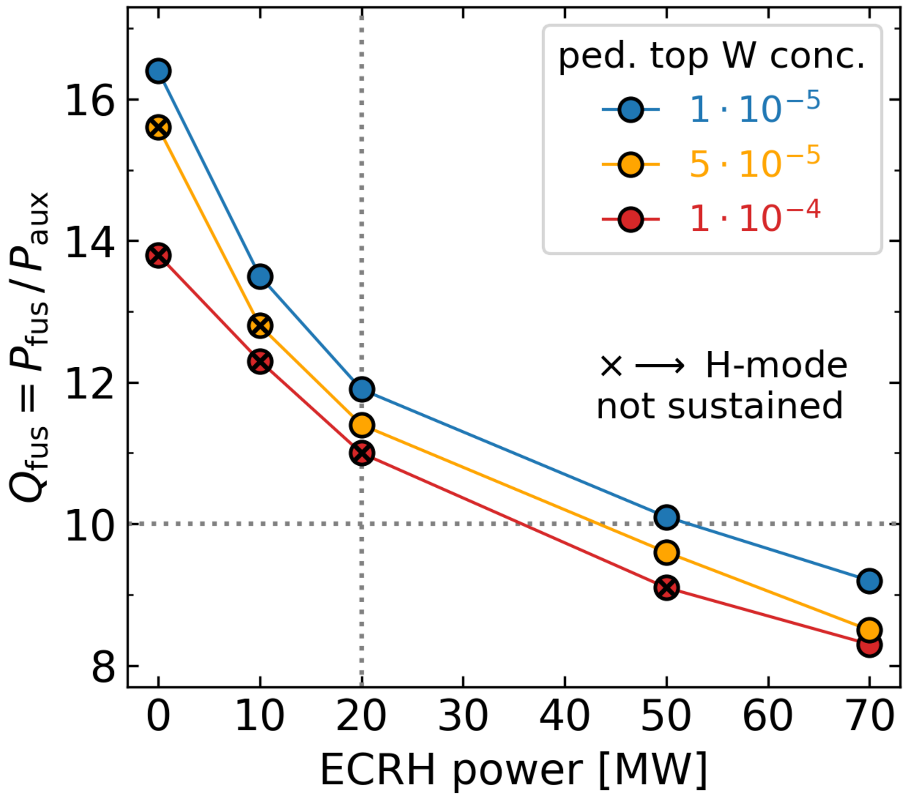
- The W concentration limited by H-mode sustainment: $\mathbf{c_w < 5 \times 10^{-5}}$ at P_{ECRH} = 20 MW



[1] Fajardo 2024 NF 64 104001

Interplay between plasma performance, heating and W content

ITER 15 MA
H-mode in DT



(+ 30 MW of NBI)

- Auxiliary heating can be raised to tolerate more W (lower Q) or lowered to reach higher Q
- Little sensitivity of pedestal pressure to ECRH power in ITER[1] and stiff core profiles

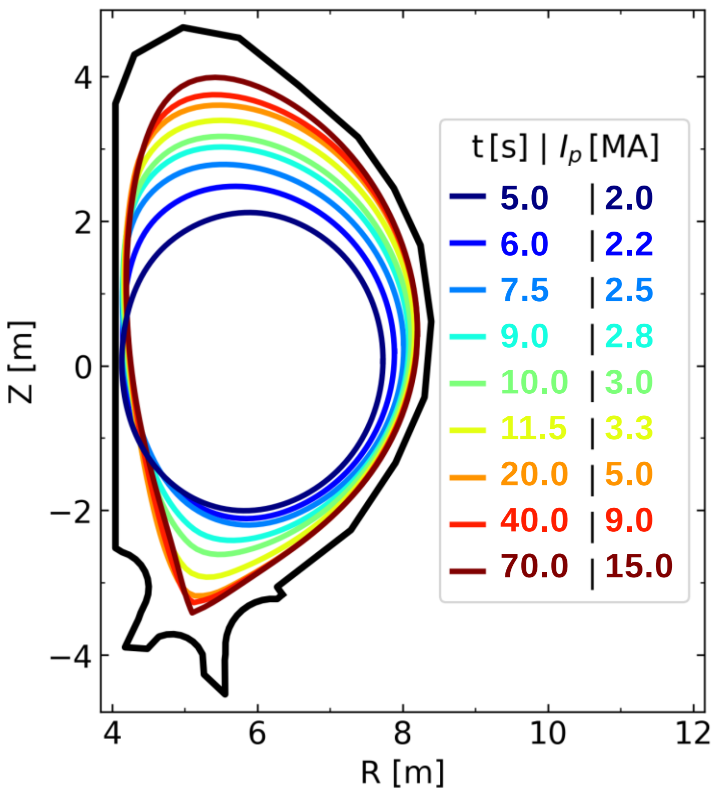
✓ ITER targets are satisfied, as long as c_W is low enough[2]

[1] Luda 2025 NF 65 072001
[2] Fajardo 2025 PPCF 67 015020

Full-radius modelling of the current ramp-up in ITER

ITER current ramp-up simulations

ITER L-mode ramp-up in D



- New ITER full-W wall[1] brings particular interest to limiter phase [see J. Hobirk EX-C 3308 today at 17:30]
  [see A. Loarte TEC-ITR 2766 on Wed.]
- Dynamical modelling of limiter to diverted plasmas during I_p ramp over 65 seconds
- Full-radius L-mode simulations, motivated by previous modelling of ITER electron-heated L-modes[2]
- Scan W source to assess limits on W concentration

[1] Loarte 2025 PPCF 67 065023
[2] Fajardo 2025 PPCF 67 015020

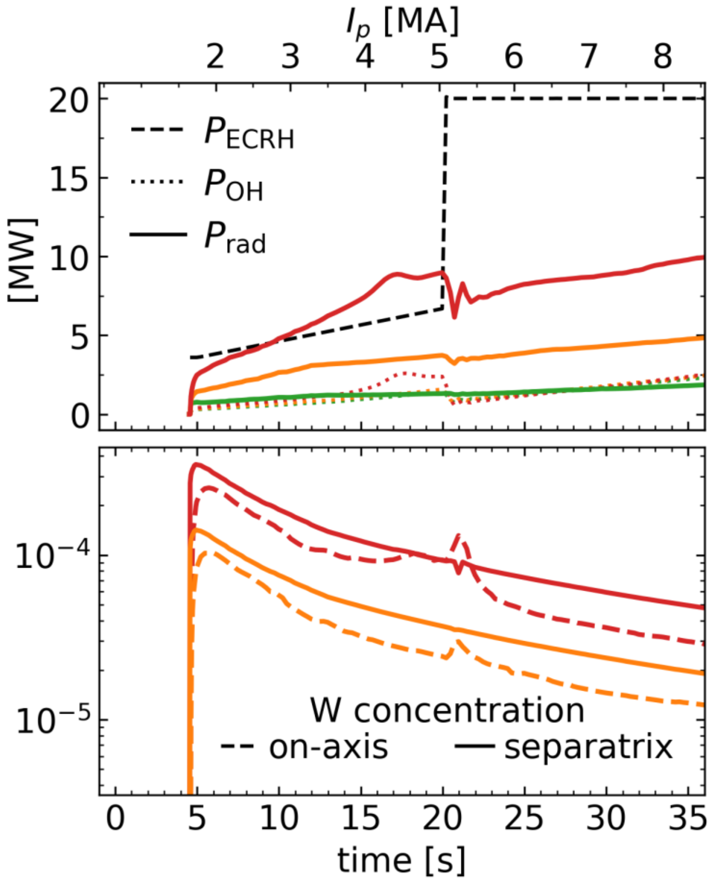
Limits of W content for plasma survival

ITER L-mode ramp-up in D

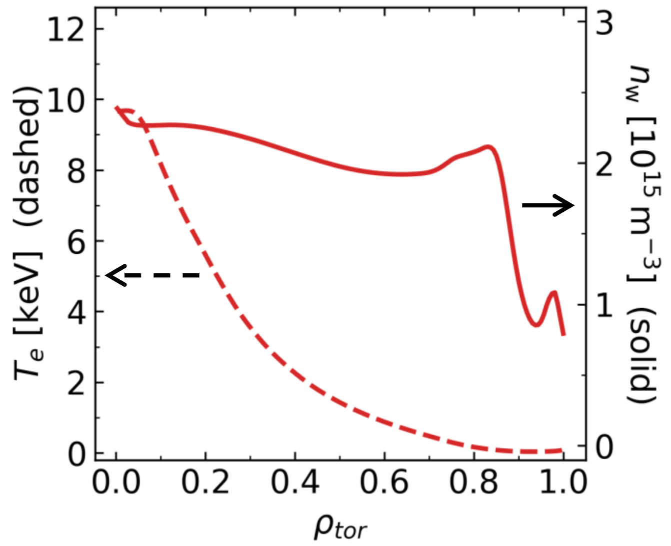
without W

intermediate W

maximum W



maximum W source, profiles before EC step



- W concentration during limiter phase of 10^{-4} is tolerable, 3×10^{-4} is problematic[1]
- Plasma marginally survives at highest W source, but edge T_e collapses and W pedestal develops

[1] Fajardo 2025 PPCF 67 015020

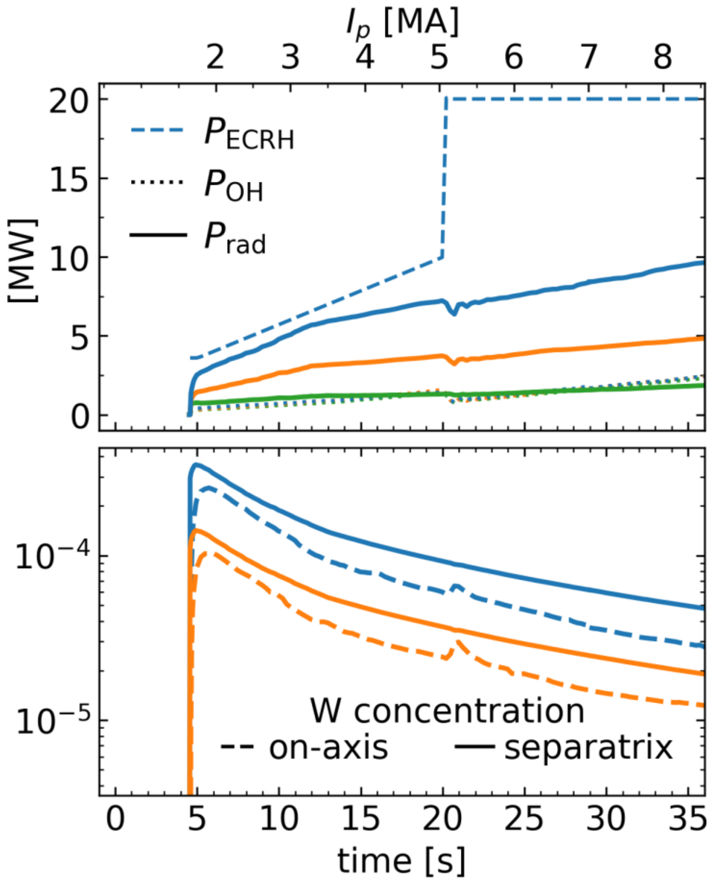
Slightly modified ECRH ramp alleviates problems at high W

ITER L-mode ramp-up in D

without W

intermediate W

maximum W with faster ECRH ramp



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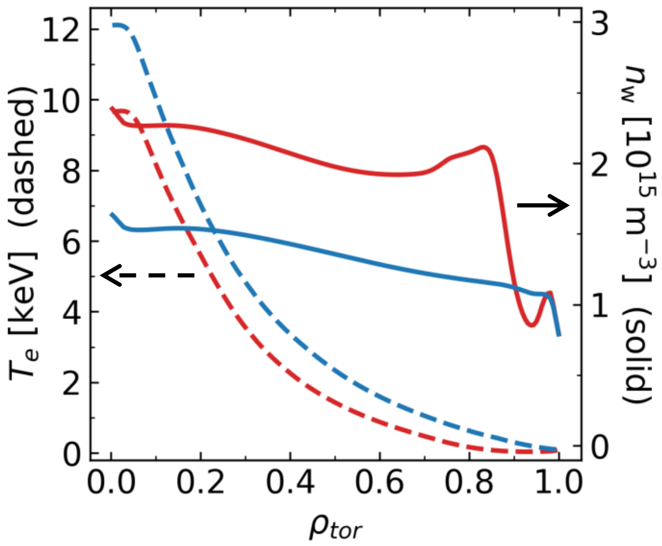


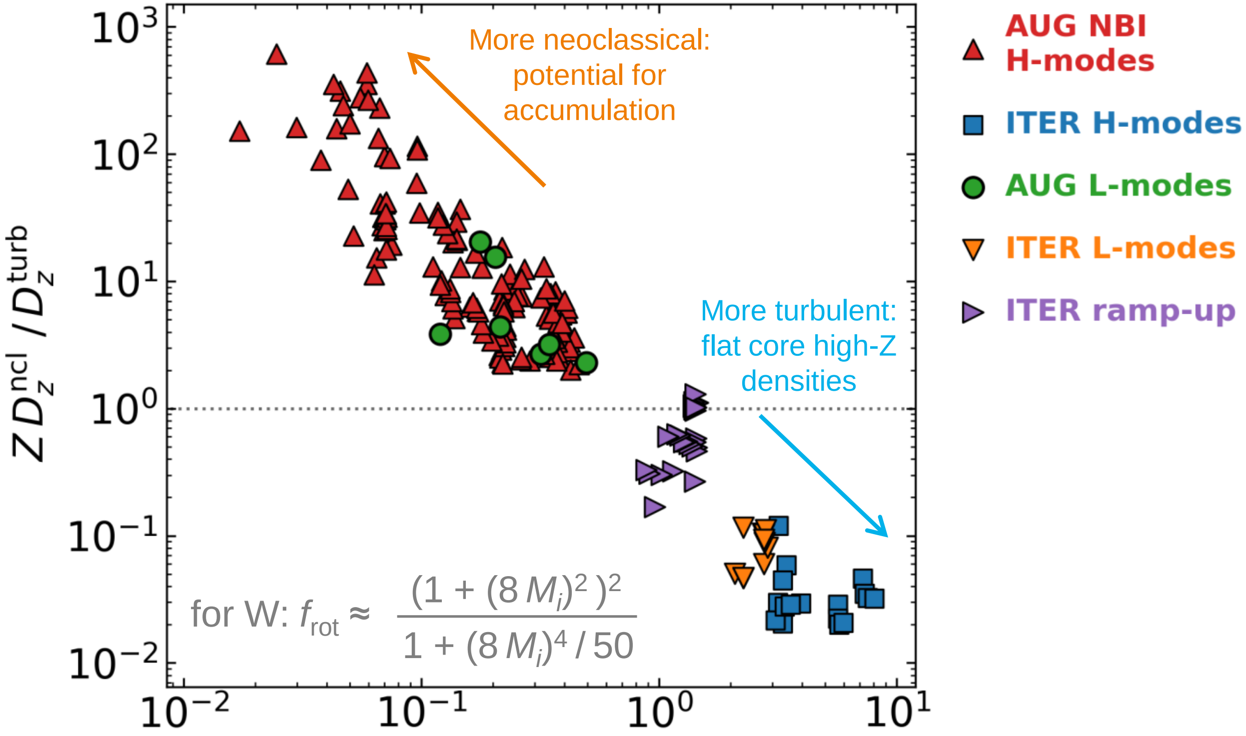
- Optimized heating trajectory avoids transient increase of W radiation at high W source
- Higher W concentrations can be tolerated by slightly modifying the ECRH ramp[1]

[1] Fajardo 2025 PPCF 67 015020

Summary and conclusions

Key takeaway points

- Theory-based integrated modelling with impurity transport → validated on present experiments → allows quantitative predictions
- Transition from dominant neoclassical to turbulent W transport towards reactors
- In ITER, auxiliary heating power is required to keep the plasma in H-mode, not to control central W accumulation
- Predictive modelling allows optimization of heating trajectories in transient phases like current ramps



$$\frac{D_{gB}}{D_{ncl}} \sim \frac{(v_{ti}^2/\Omega_{ci})(\rho_i/a)}{Z_{eff}\,\nu_Z\,\rho_Z^2\,f_{rot}} \sim \frac{T_i^2}{n_i\,a\,Z_{eff}\,f_{rot}}$$

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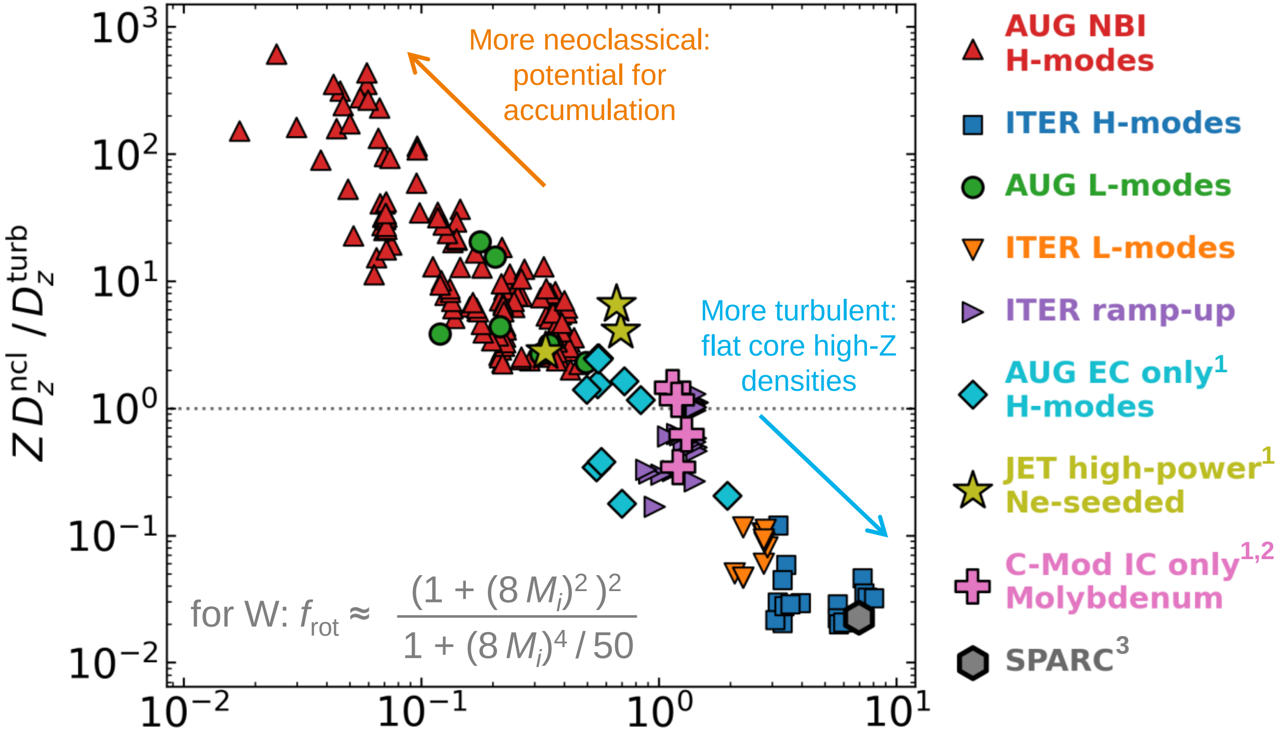

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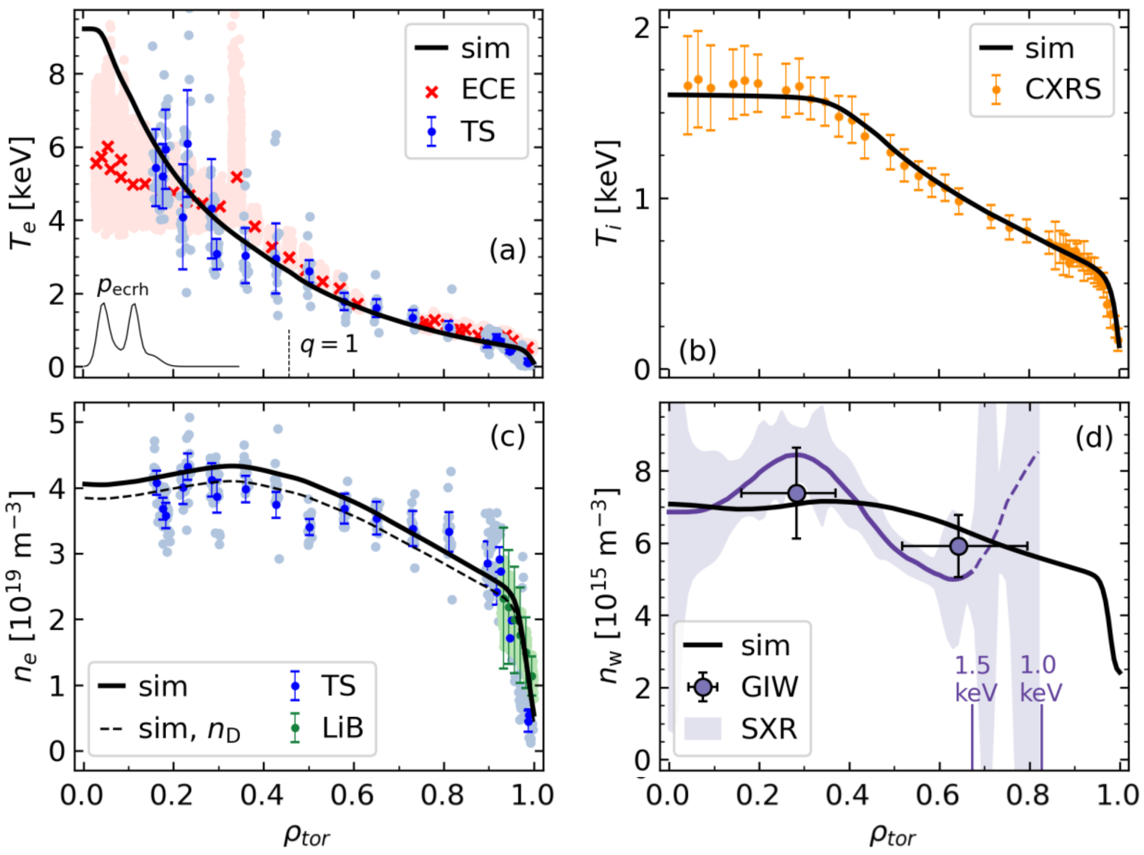
[1] Fajardo subm. to NF [2] Perks subm. to NF [3] Muraca 2025 EU-US TTF

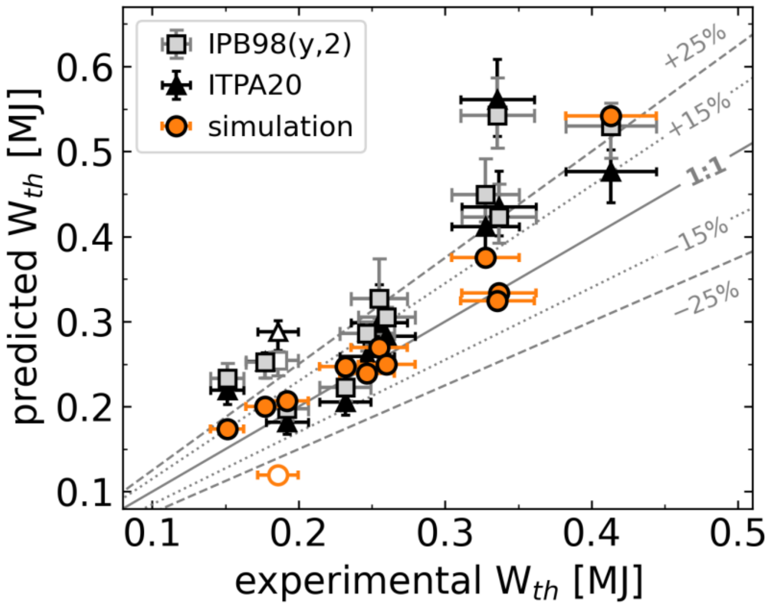
Additional material

Simulations of ECRH-only AUG H-modes

AUG #37909



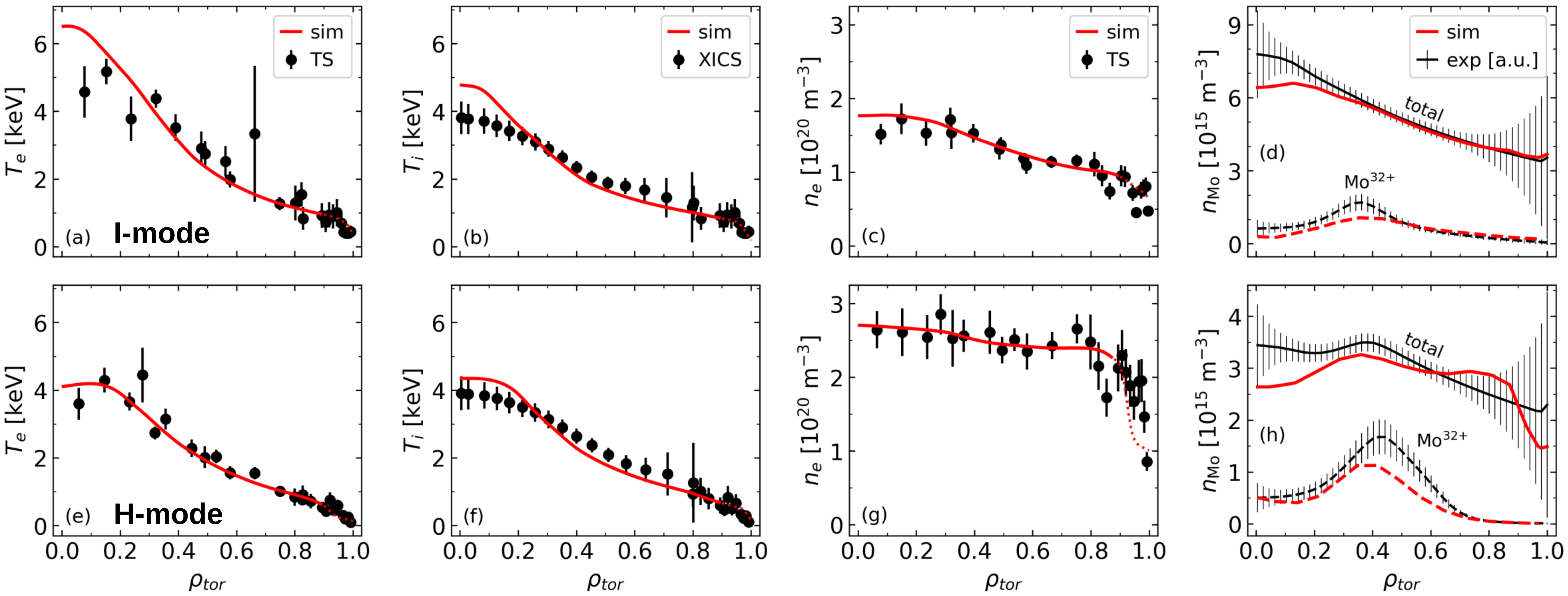
- Database of 12 AUG H-modes spanning $P_{ECRH} \in \{0.7 – 4.3\}$ MW, $I_p \in \{0.6 – 1.2\}$ MA, $n_e \in \{1.9 – 8.4\}$ 10^{19} m^{-3}
- Overall flat W profiles: low intrinsic rotation
- Better confinement prediction than scalings



[Fajardo subm. to NF]

Simulations of Alcator C-Mod plasmas with Molybdenum

C-Mod H-,I- & L-modes in D

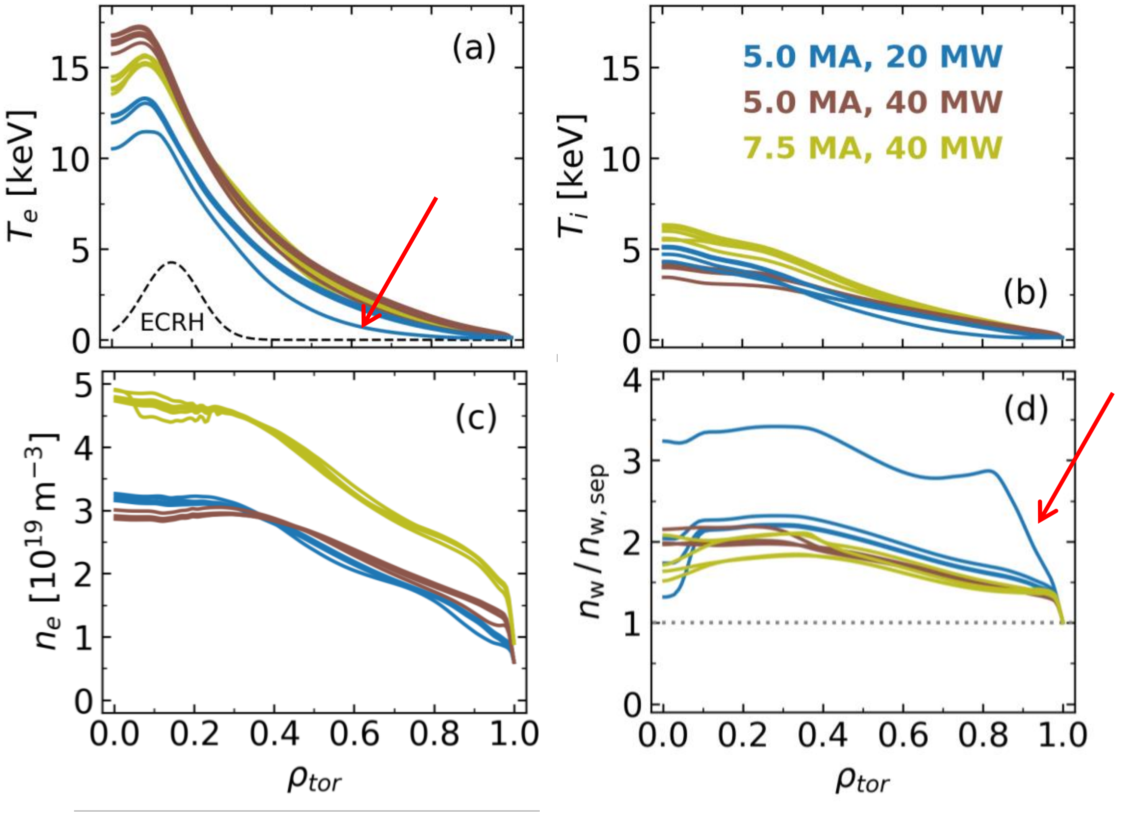


[Fajardo subm. to NF]

Full-radius simulations of electron-heated ITER L-modes

ITER 5 & 7.5 MA L-modes in D

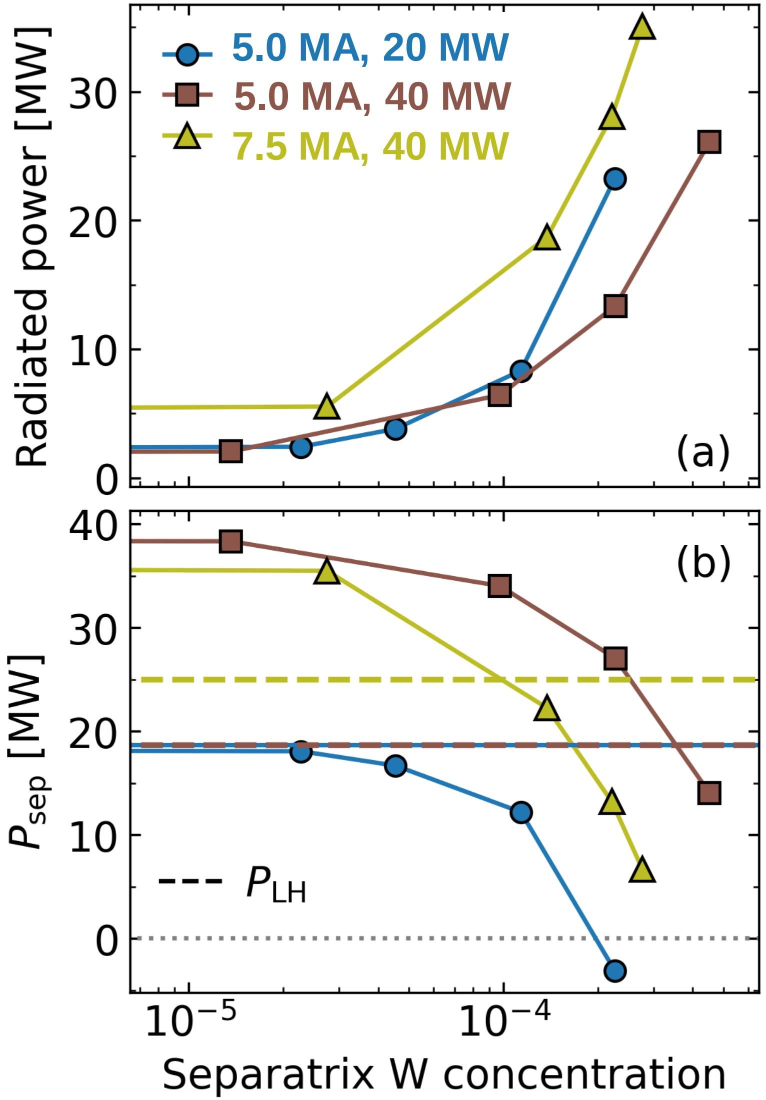
- 5.0 MA with **20 MW** and **40 MW** of ECRH
- **7.5 MA** with **40 MW** of ECRH
- B_t = 2.65 T, D plasmas, constant GW fraction



[Fajardo 2025 PPCF 67 015020]

Radiation and access to H-mode

ITER 5 & 7.5 MA
L-modes in D



- With our modelling assumptions, **20 MW** of ECRH do not allow access to H-mode

- 40 MW of ECRH enables H-mode operation in D provided the separatrix W concentration remains below: **3×10^{-4}** at **5MA**, **1.5×10^{-4}** at **7.5MA**

[Fajardo 2025 PPCF 67 015020]

Neoclassical and turbulent impurity transport

- Neoclassical flux components strongly depend on charge, collisionality and rotation

diffusion

convection

$\sim \frac{1}{2}$

$$\frac{R\,\Gamma_z^{\mathrm{ncl}}}{\langle n_z\rangle} = D_z^{\mathrm{ncl}}\left(\boxed{\frac{R}{L_{\langle n_z\rangle}}} - \boxed{\frac{Z}{Z_i}\frac{R}{L_{\langle n_i\rangle}}} + \boxed{\frac{Z}{Z_i}\frac{H_z}{K_z}\frac{R}{L_{T_i}}}\right)$$

inward pinch

temperature screening

can lead to central accumulation

- Turbulent flux components do <u>not</u> scale strongly with charge or mass

diffusion

convection

$$\frac{R\,\Gamma_z^{\mathrm{trb}}}{\langle n_z\rangle} = \boxed{D_z^{\mathrm{trb}}\frac{R}{L_{\langle n_z\rangle}}} + \boxed{V_{T_z}\frac{R}{L_{T_z}}} + \boxed{V_{uz}u'_z} + \boxed{V_{pz}}$$

thermo-diffusion

pure pinch

roto-diffusion

does not cause strong peaking

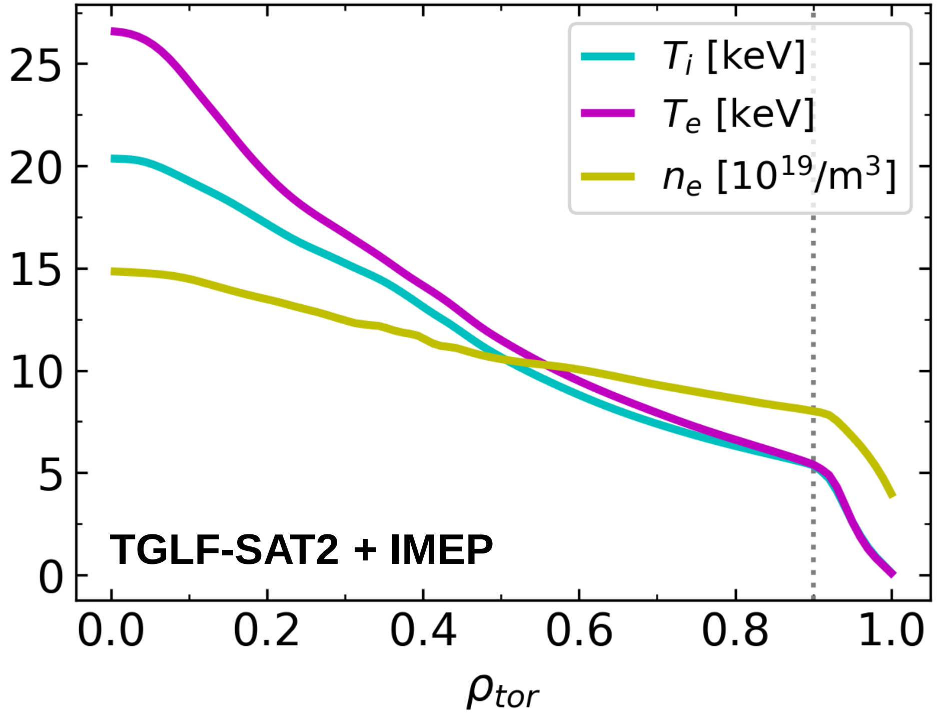
Main plasma profiles

ITER 15 MA
H-mode in DT

- Pedestal calculated with IMEP[1], kept fixed across the scans in ECRH power and W concentration

- Core profiles evolved using TGLF-SAT2

- Rotation profile from previous predictions[2,3] was kept fixed, fusion power might be sensitive to it[1]



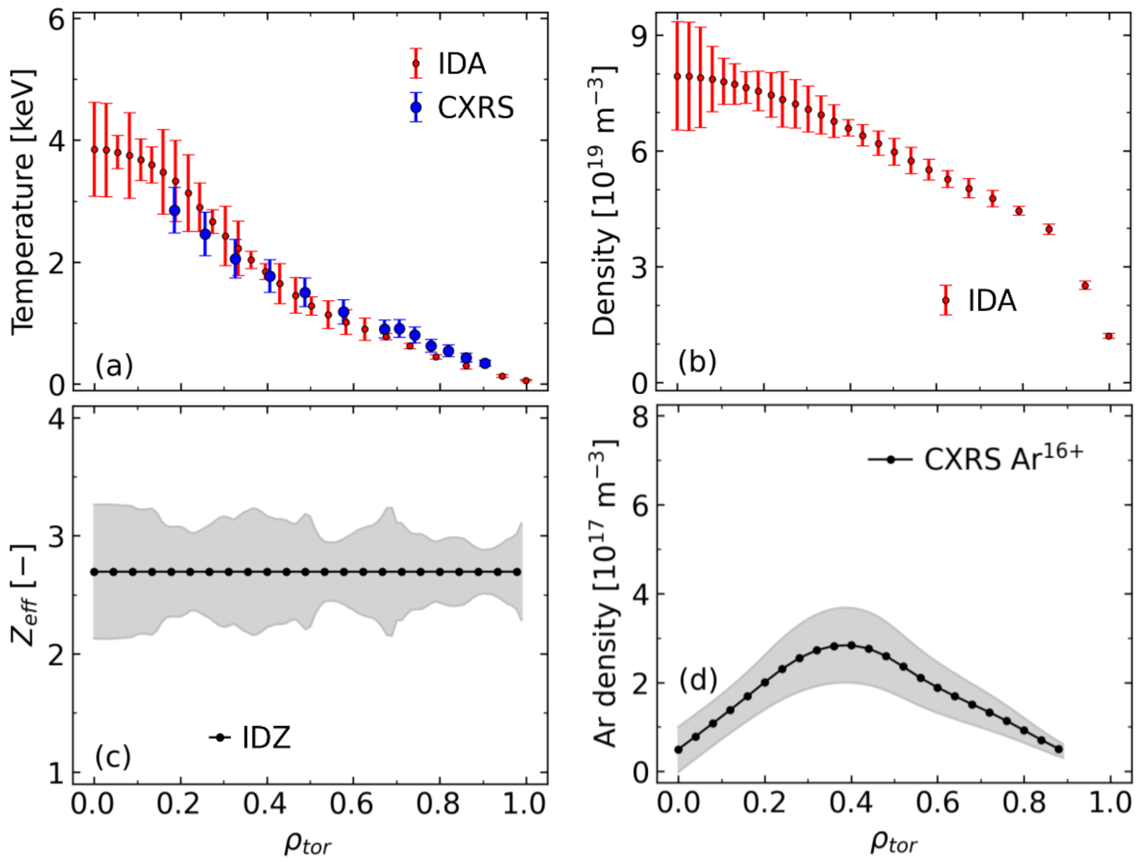
[1] Luda 2025 NF 65 072001
[2] Singh 2017 NJP 19 055004
[3] Chrystal 2020 NF 60 036003

Full-radius modelling of AUG Ar seeded radiative L-mode

AUG 0.8 MA with Ar

- Experiment with P_{aux} ~ 7.5 MW but $P_{sep} < P_{LH}$: feedback with **Ar** seeding[1]
- High $P_{rad} / P_{aux} \approx 70\%$
- $H_{98} \approx 0.95$ without ELMs

AUG #37041 at 5.0-5.5 s



[1] Fable 2022 NF 62 024001

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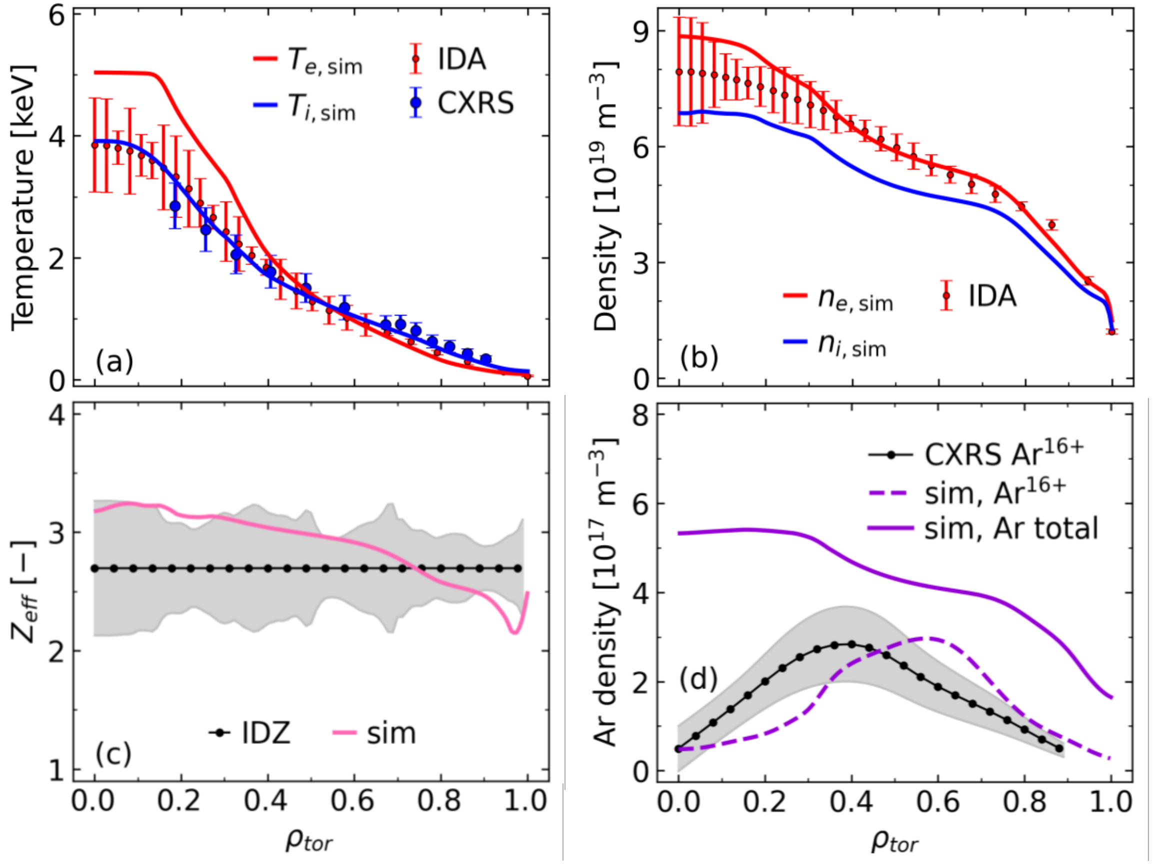
- High P_{rad} / $P_{aux} \approx 70\%$
- $H_{98} \approx 0.95$ without ELMs

- Simulation of main plasma with three impurities[2]: **Ar**, **W** and **B**
- High confinement is reproduced
- Simple model for X-point radiation was included
- Removing argon from the simulation leads to 33% lower confinement

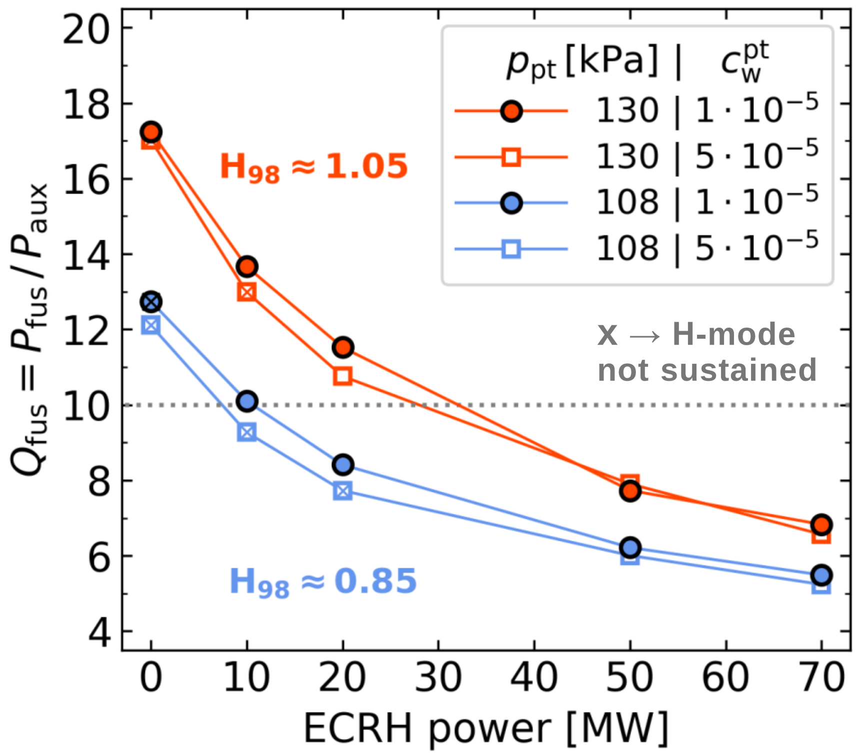
AUG #37041 at 5.0-5.5 s



[1] Fable 2022 NF 62 024001 [2] Fajardo 2024 NF 64 046021

Interplay between plasma performance, heating and W content

ITER 15 MA H-mode in DT



(+ 30 MW of NBI)

- Auxiliary heating can be raised to tolerate more W (lower Q) or lowered to reach higher Q
- Little sensitivity of pedestal pressure to ECRH power in ITER[2]
- Pedestal top pressure at IMEP (& EPED) value of **130 kPa** gives:
  - ➢ better performance in ***Q*** (+1-5 w.r.t. **108 kPa**)[1]
  - ➢ Higher margin for H-mode sustainment due to higher alpha heating (+20-30MW w.r.t. **108 kPa**)[1]

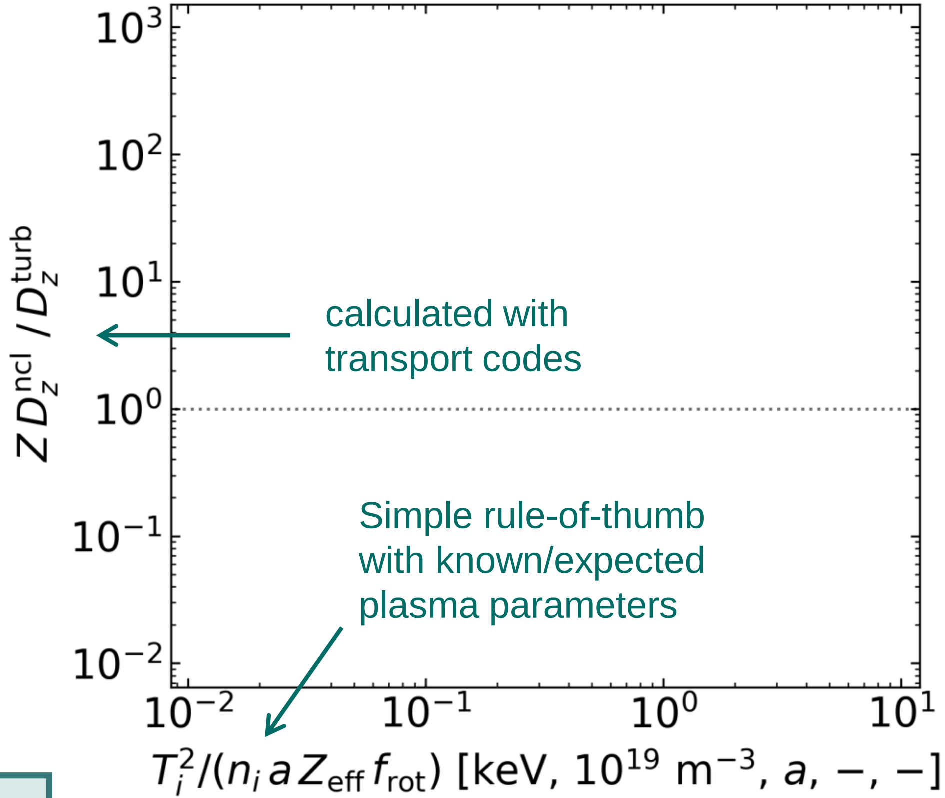
✓ ITER targets are satisfied, as long as c_w and P_{LH} are low enough

[1] Fajardo 2025 PPCF 67 015020
[2] Luda 2025 NF 65 072001

Transition from dominant neoclassical to turbulent W transport

- In present-day devices, core W convection is mostly neoclassical and diffusion is mostly turbulent

- In reactor core, much lower collisionality (and rotation) → convection is also mostly turbulent



$$\frac{D_{\mathrm{gB}}}{D_{\mathrm{ncl}}} \sim \frac{(\mathrm{v}_{\mathrm{ti}}^2/\Omega_{\mathrm{ci}})(\rho_i/a)}{Z_{\mathrm{eff}}\,\nu_Z\,\rho_Z^2\,f_{\mathrm{rot}}} \sim \frac{T_i^2}{n_i\,a\,Z_{\mathrm{eff}}\,f_{\mathrm{rot}}}$$

for tungsten: $f_{\mathrm{rot}} \approx \dfrac{(1 + (8\,M_i)^2\,)^2}{1 + (8\,M_i)^4\,/\,50}$

Transition from dominant neoclassical to turbulent W transport

- In present-day devices, core W convection is mostly neoclassical and diffusion is mostly turbulent
- In reactor core, much lower collisionality (and rotation) → convection is also mostly turbulent

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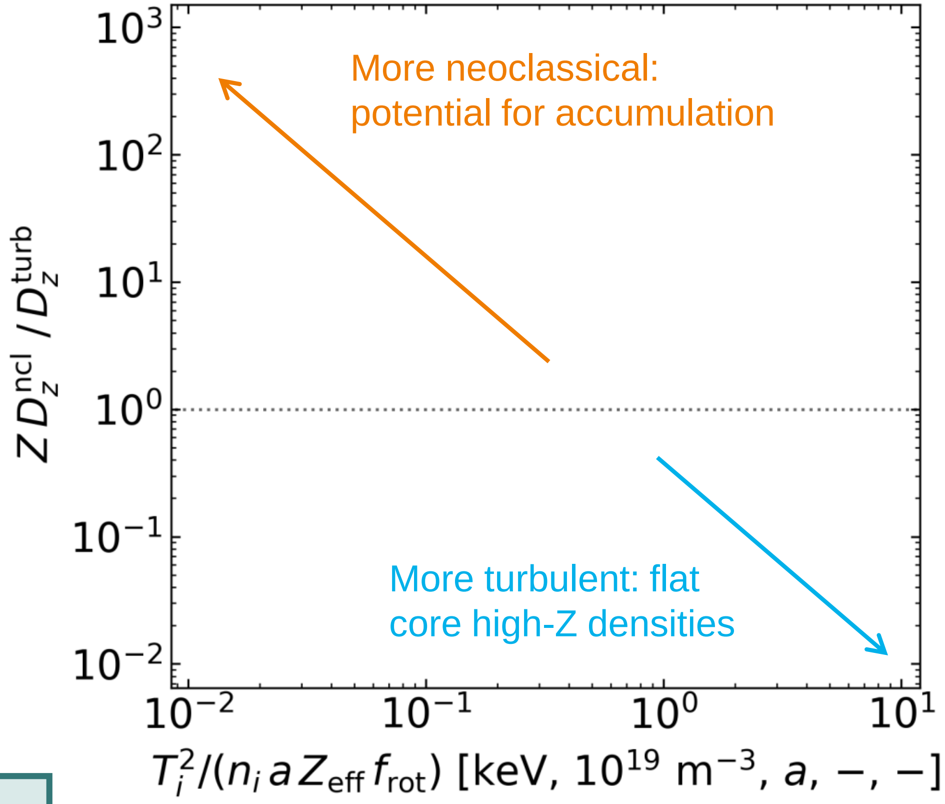

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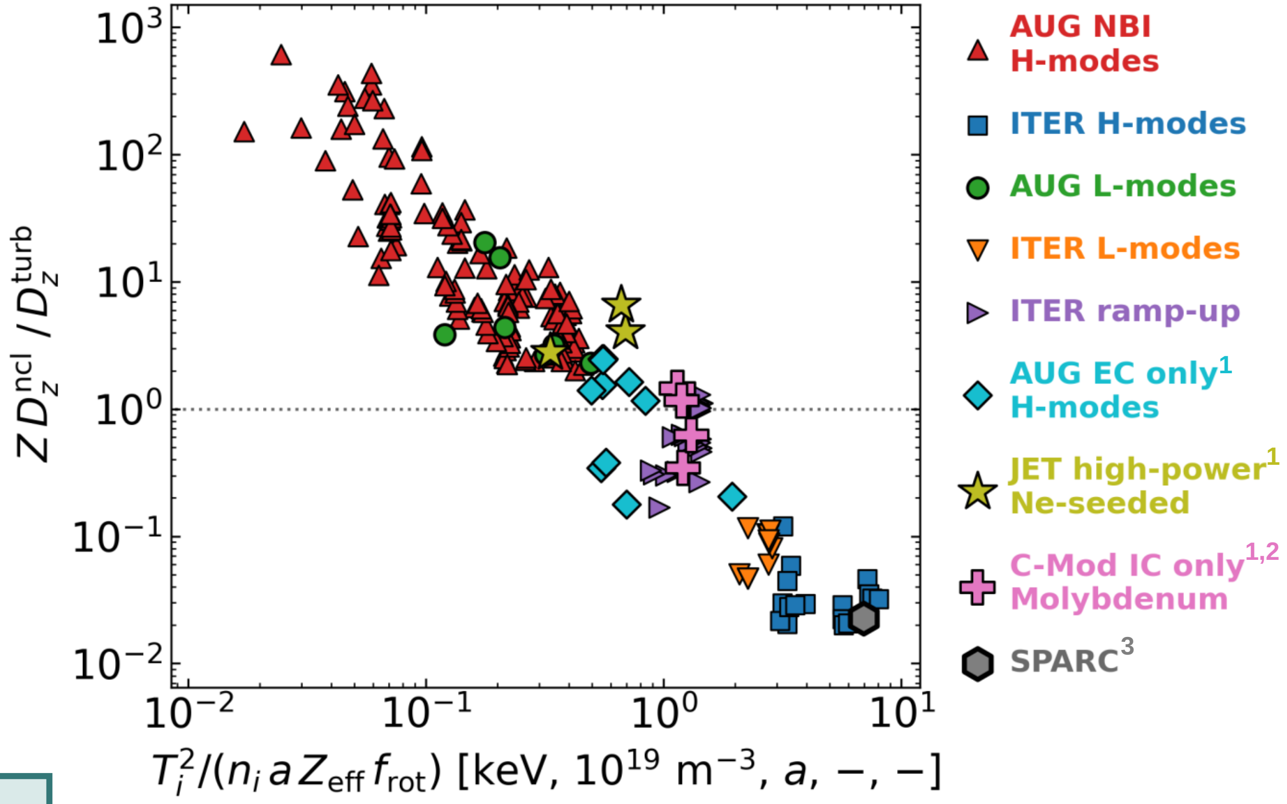

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[1] Fajardo subm. to NF
[2] Perks subm. to NF
[3] Muraca 2025 EU-US TTF