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Increasing the predictive capability of impurities and their effects in tokamak plasmas

ASDEX Upgrade

27th Joint EU-US Transport Taskforce meeting

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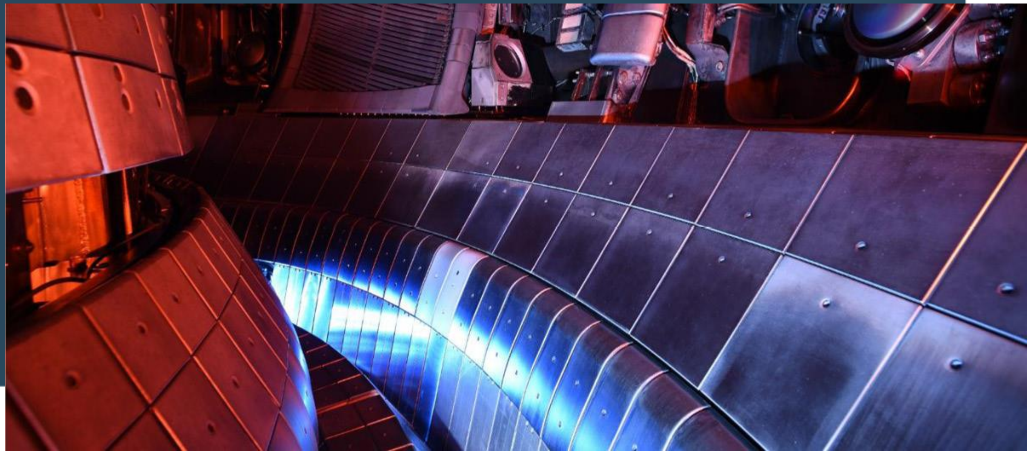

EUROfusion

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Elements needed to simulate impurities in a tokamak plasma

- Neoclassical transport
- Turbulent transport
- Impurity code for sources and radiation
- Coupled evolution in transport solver

Outline

- Neoclassical transport
- Turbulent transport → 1. **Validation of TGLF and QuaLiKiz for impurities**
- Impurity code for sources and radiation
- Coupled evolution in transport solver → 2. **Full radius modelling of a high confinement radiative L-mode**

TGLF-SAT2 → Staebler *et al* 2021 *Nucl. Fusion* **61** 116007

QuaLiKiz → Citrin *et al* 2017 *Plasma Phys. Control. Fusion* **49** 124005

Validation of impurity transport in quasilinear models

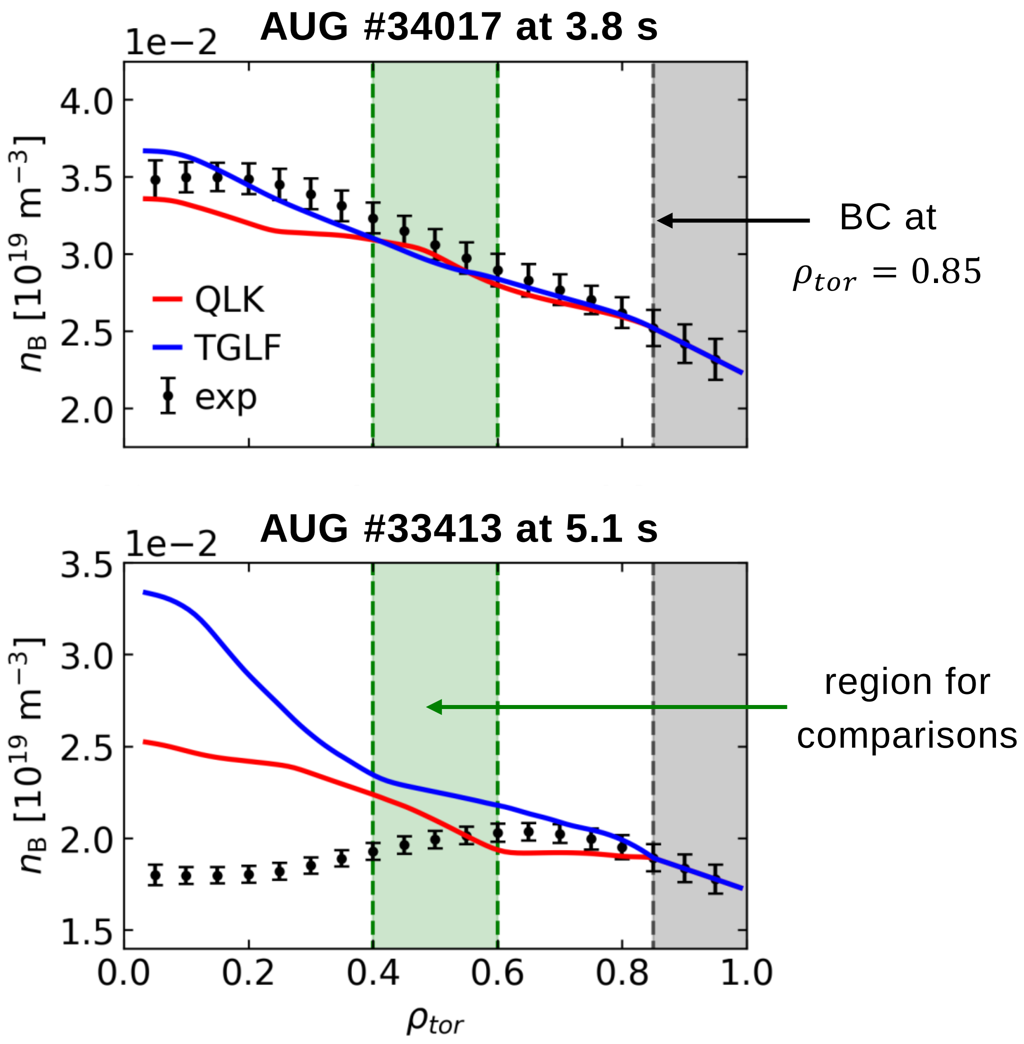
Light impurity transport: boron database

- Turbulent transport is dominant for boron (B) in both diffusion (D_z) and convection (V_z)

$$\Gamma_z = -D_z \nabla n_z + n_z V_z$$

- Database of 42 AUG H-modes with CXRS measurements of B profiles [1]

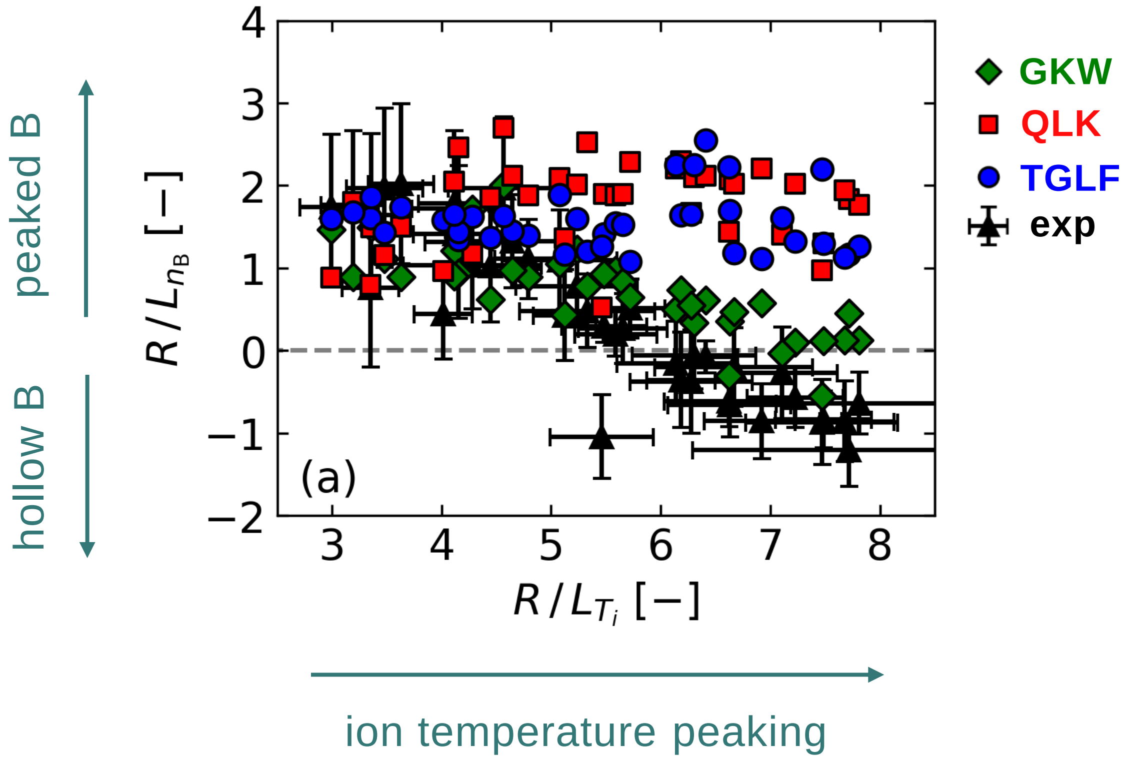
- TGLF and QuaLiKiz match the experimental gradient in some cases but not in others



[1] McDermott *et al* 2022 *Nucl. Fusion* **62** 026006

Boron gradient correlations

impurity gradient: $\frac{R}{L_{n_z}} = -\frac{RV_z}{D_z}$



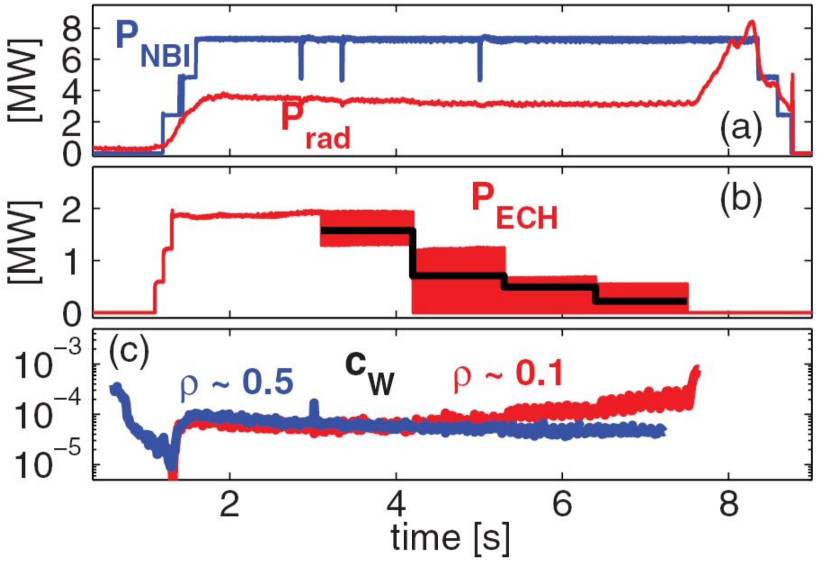
- Quasilinear models struggle at high R/L_{T_i}, low R/L_{n_e}; issues in turbulent convection?

- GK simulations (GKW linear) are better (but not hollow). Nonlinear and linear results are similar [P. Manas, this conference]

Heavy impurity transport: validating the turbulent diffusion

- For tungsten (W), diffusion is mostly turbulent and convection is mostly neoclassical
- Core W accumulation can be controlled with central wave heating

AUG H-mode (#32408) with decreasing ECRH ladder [2]



[2] Angioni *et al* 2017 *Nucl. Fusion* **57** 056015

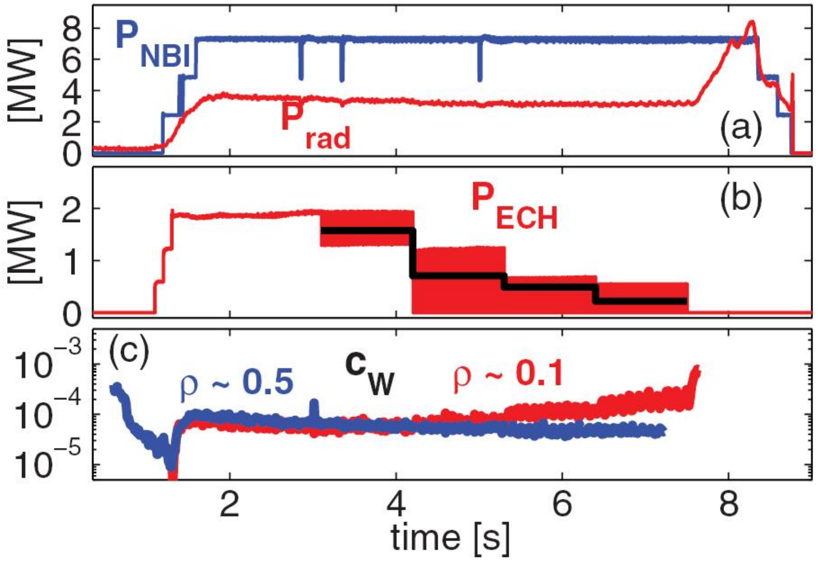
Can we reproduce this effect with integrated modelling?

Core W progressively increases as ECRH decreases

Enhanced turbulent D_w & reduced neoclassical V_w with ECRH

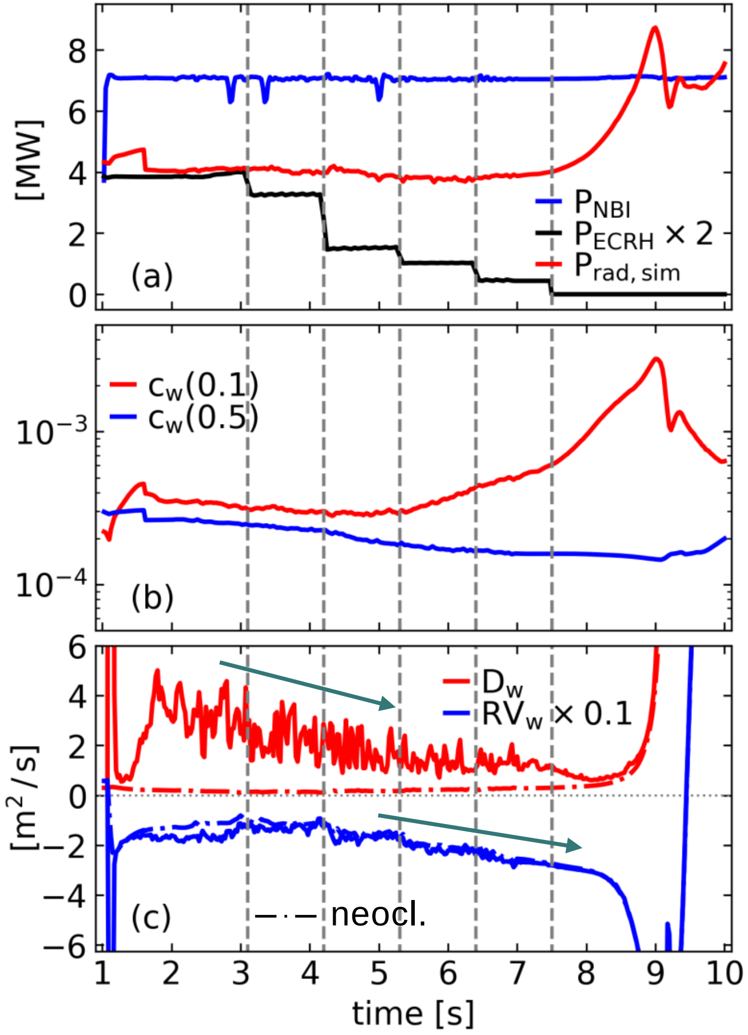
- ASTRA + TGLF-SAT2 + FACIT simulations of T_e, T_i, n_e, j, n_w obtain this effect

AUG H-mode (#32408) with decreasing ECRH ladder [2]



[2] Angioni *et al* 2017 *Nucl. Fusion* **57** 056015

Dynamical simulation of entire flattop

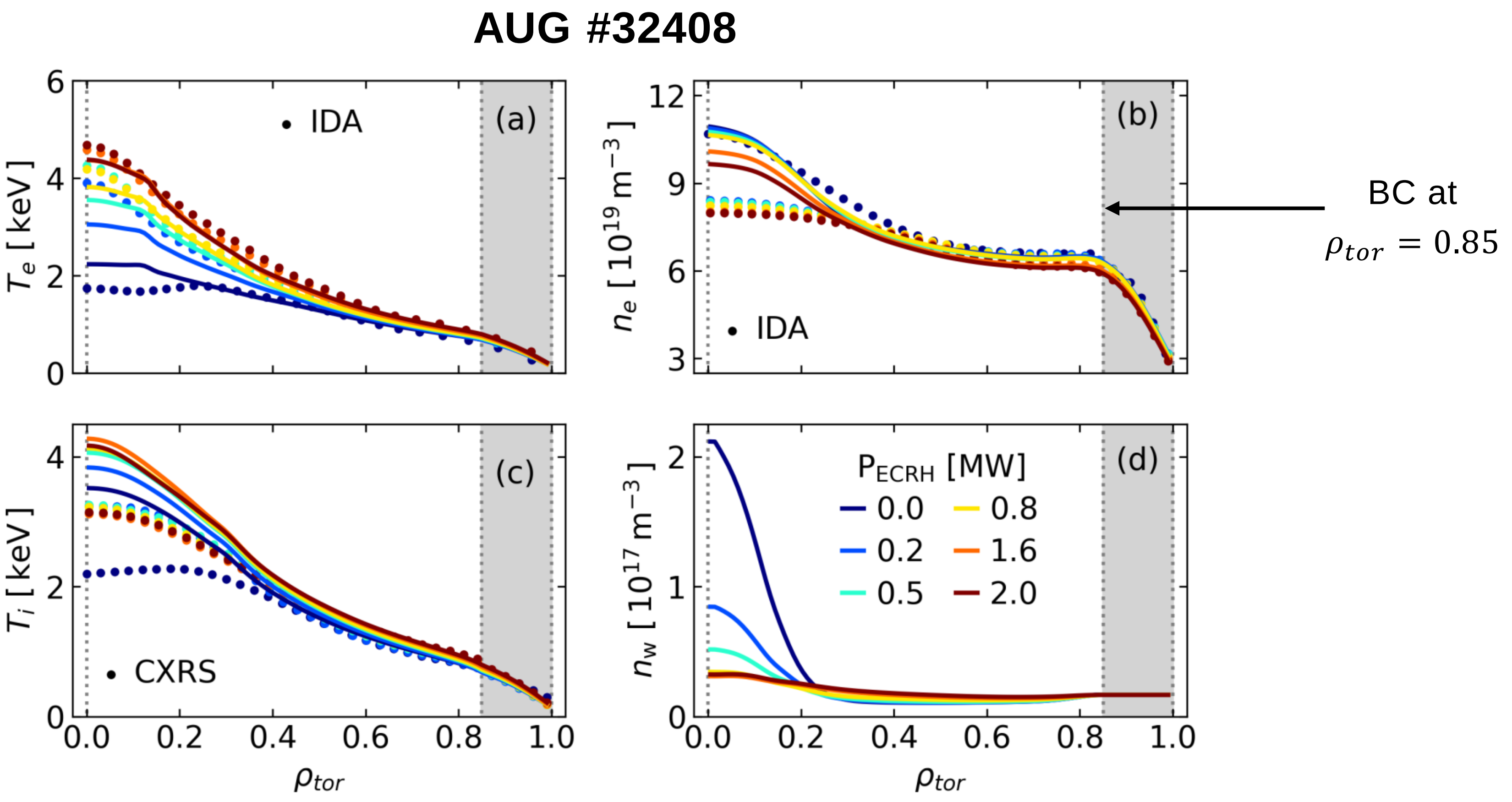


BC at $\rho_{tor} = 0.85$

Central W transport ($\rho < 0.3$)

FACIT → Fajardo *et al* 2023 *Plasma Phys. Control. Fusion* **65** 035021
Maget *et al* 2020 *Plasma Phys. Control. Fusion* **62** 105001

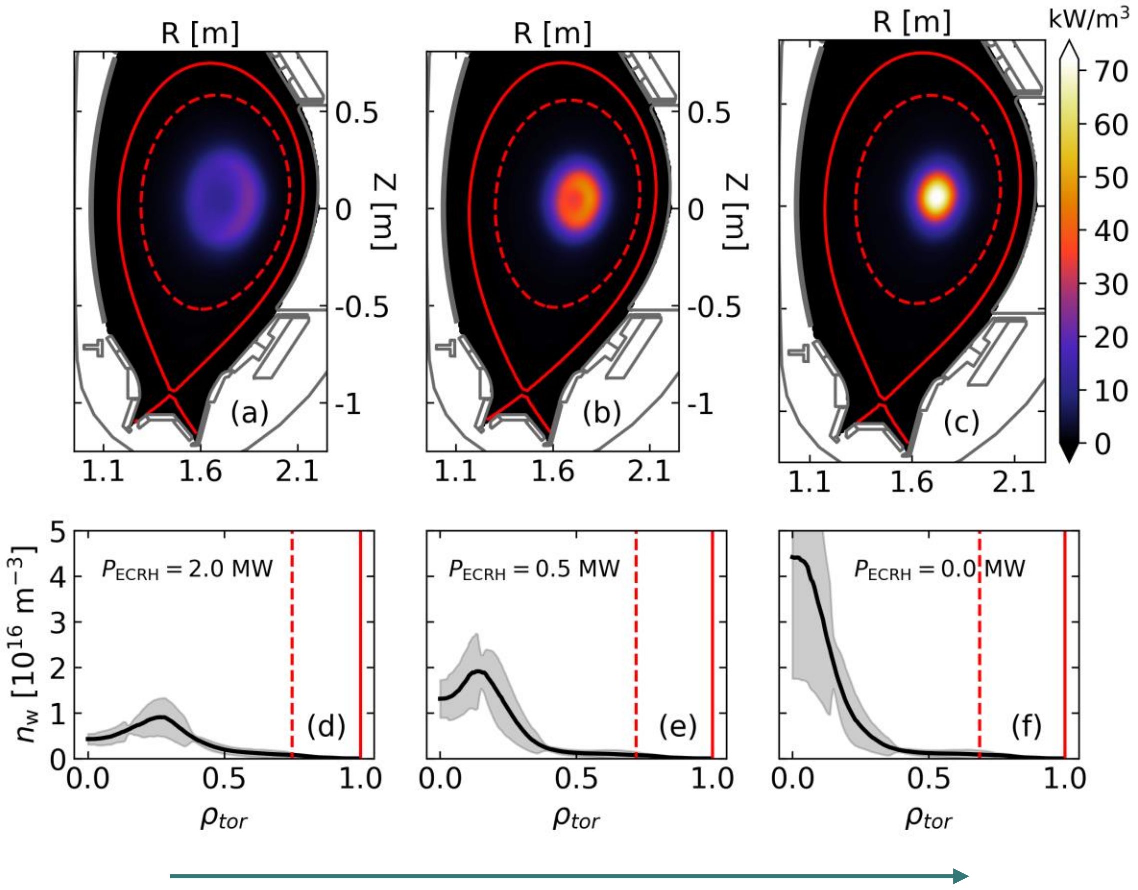
Effect on simulated T_e, T_i, n_e, n_w profiles



- Role of reduced n_e peaking for reduced neoclassical pinch [P. Manas *et al* 2020 IAEA FEC]

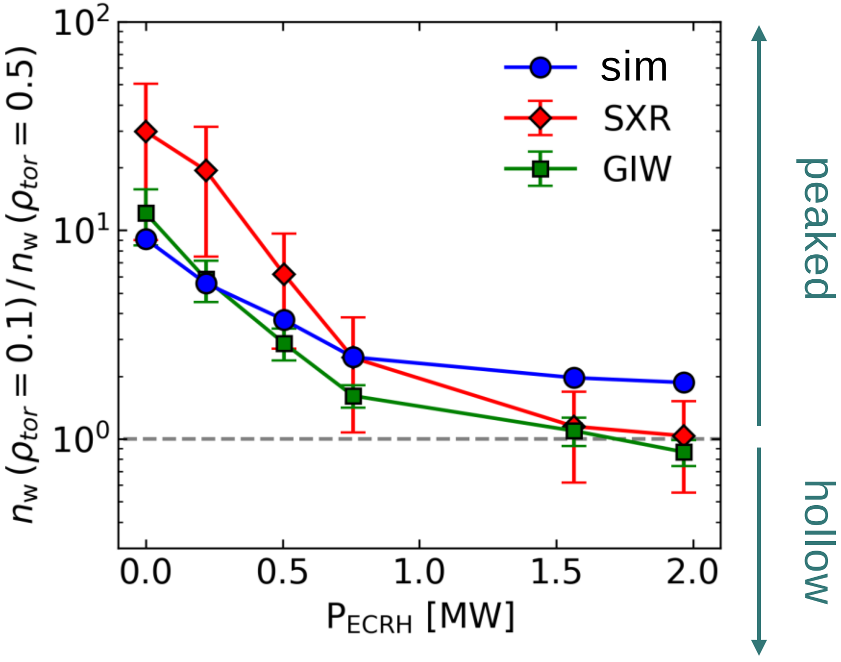
Simulated W peaking vs diagnostics

Soft X-ray measurements

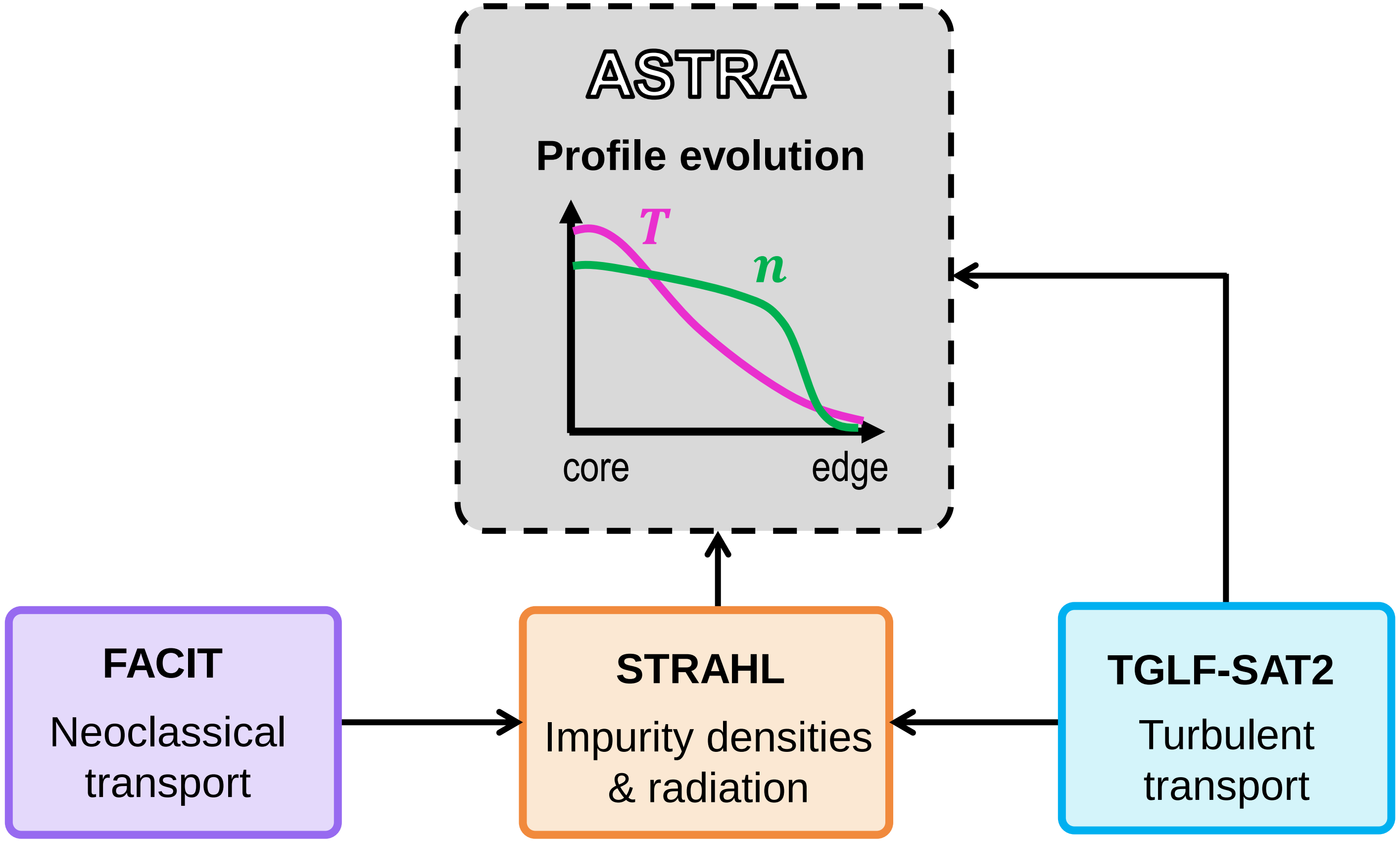


less ECRH power

Tungsten peaking



Full radius integrated modelling of L-modes with impurities

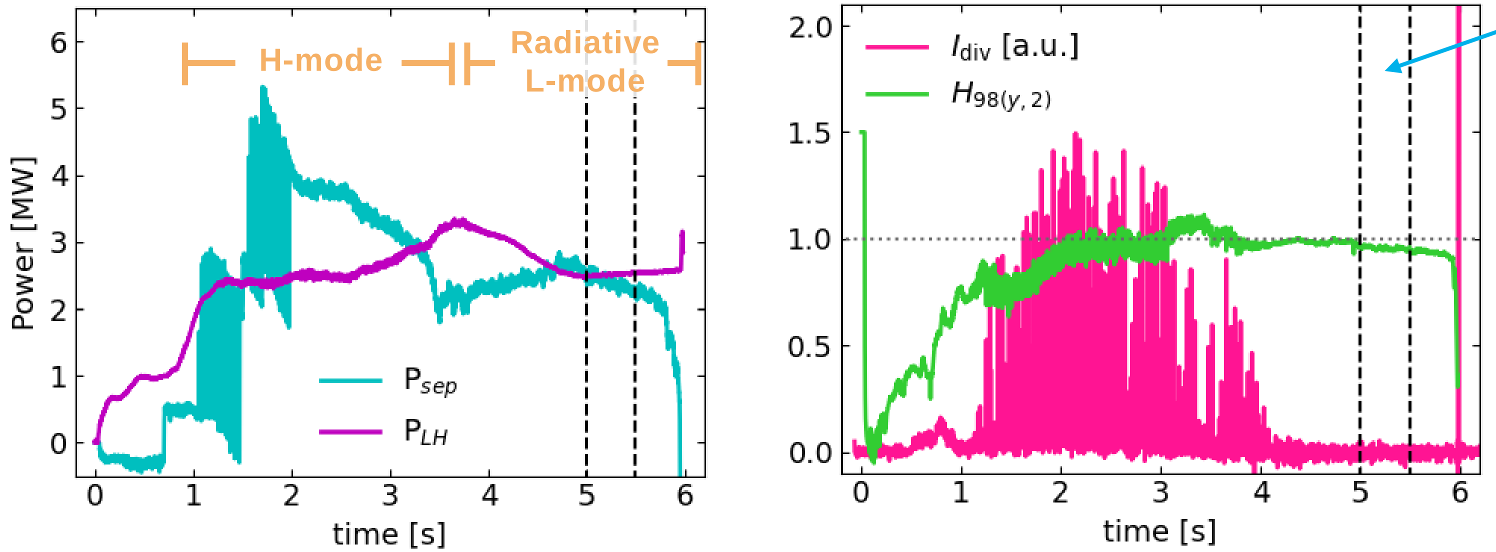


Radiative L-mode with X-point radiation

- Experiment with P_{aux} ~ 7.5 MW but feedback on P_{rad} with Ar seeding for $P_{sep} < P_{LH}$ [4]

$$P_{\text{sep}} = P_{\text{aux}} - P_{\text{rad}}$$

AUG #37041



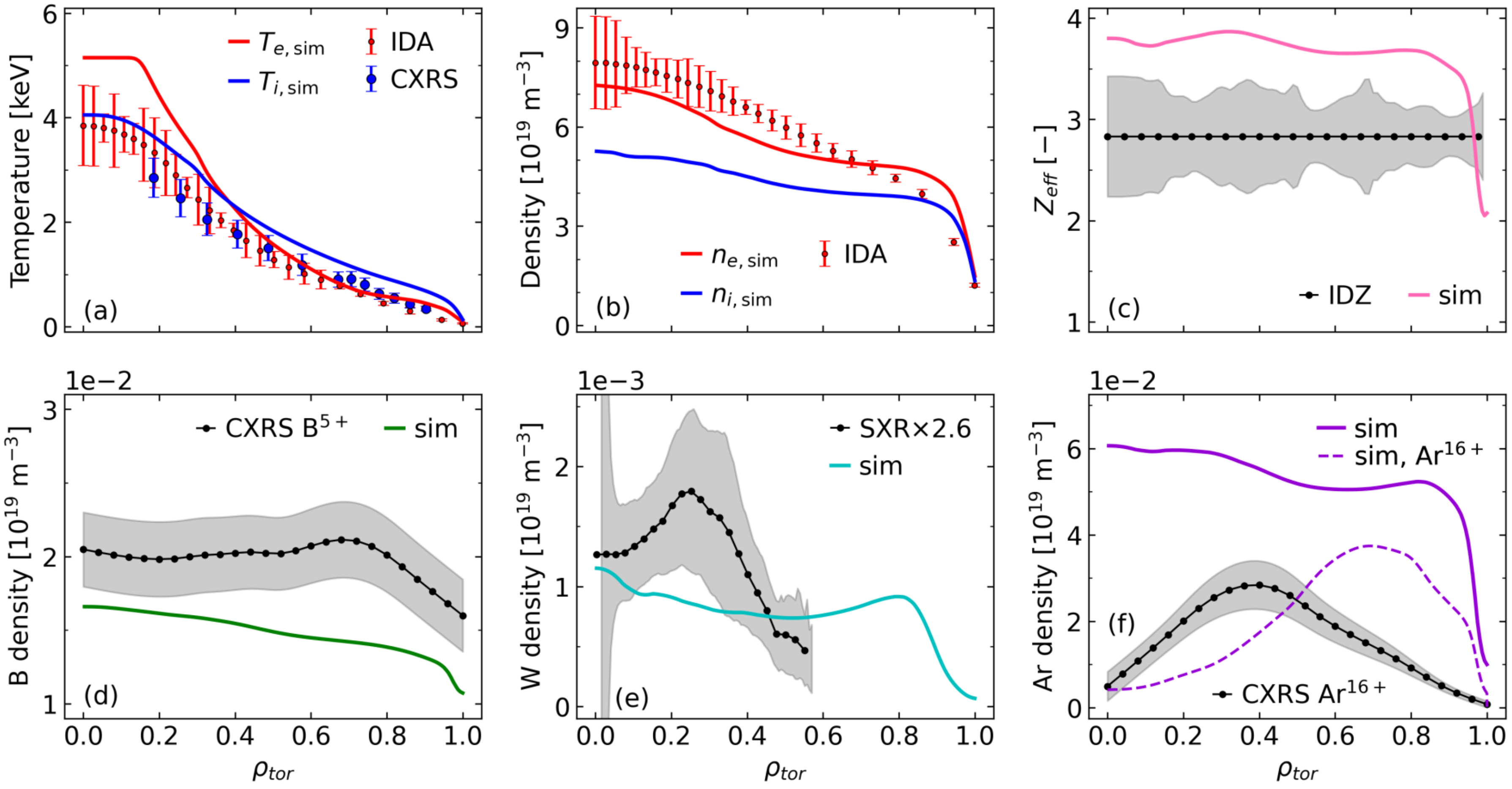
phase to analyze

[4] Fable *et al* 2022 *Nucl. Fusion* **62** 024001

- Three impurity species (B, W, Ar), high P_{rad} (70% P_{aux}) and Z_{eff}, high confinement, and well diagnosed
- Can we simulate this plasma, without a radiative collapse?

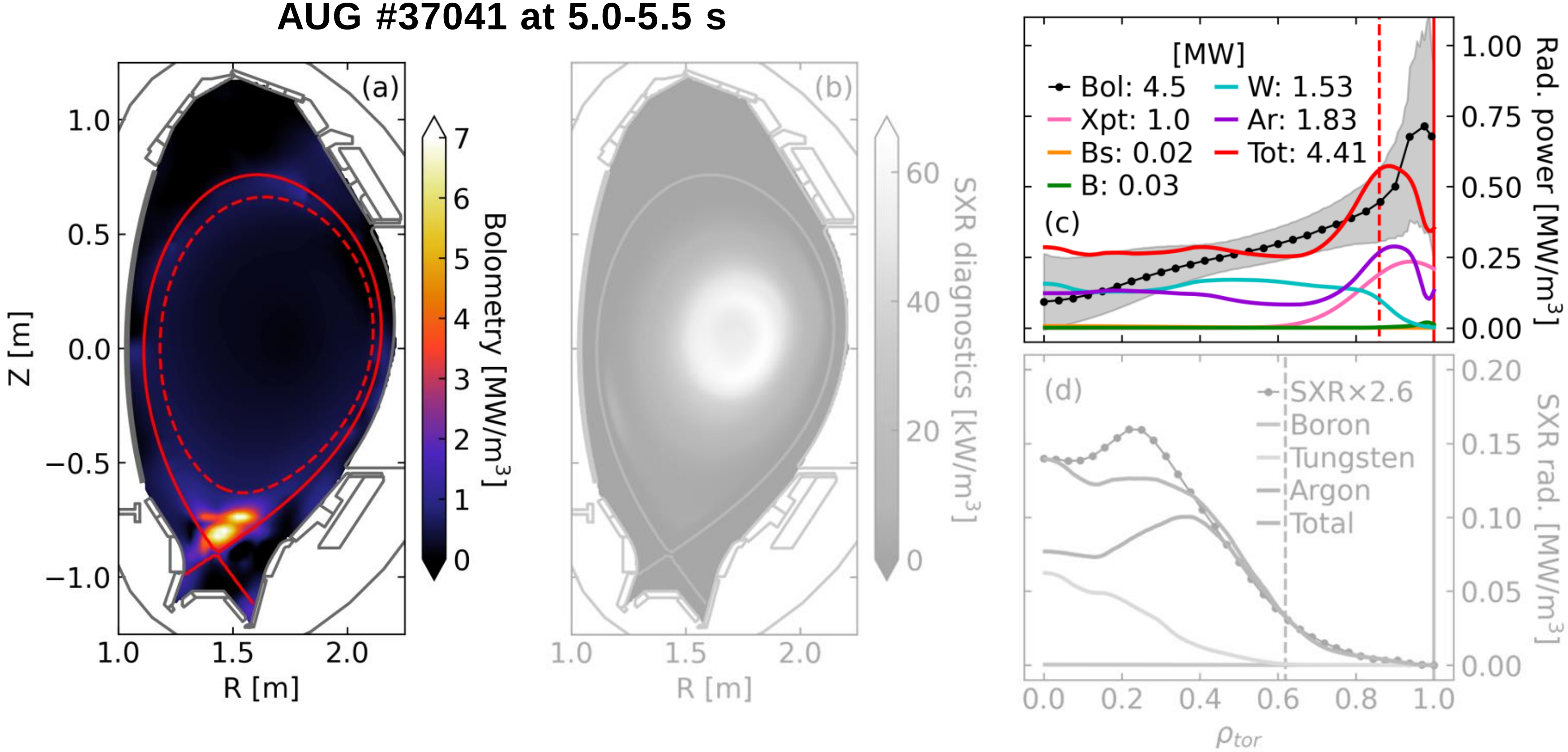
Coupled evolution of $T_e, T_i, n_e, j, n_\mathrm{B}, n_\mathrm{w}, n_\mathrm{Ar}$ with $\rho_\mathrm{BC} = 1$

AUG #37041 at 5.0-5.5 s



Radiation profiles are well matched

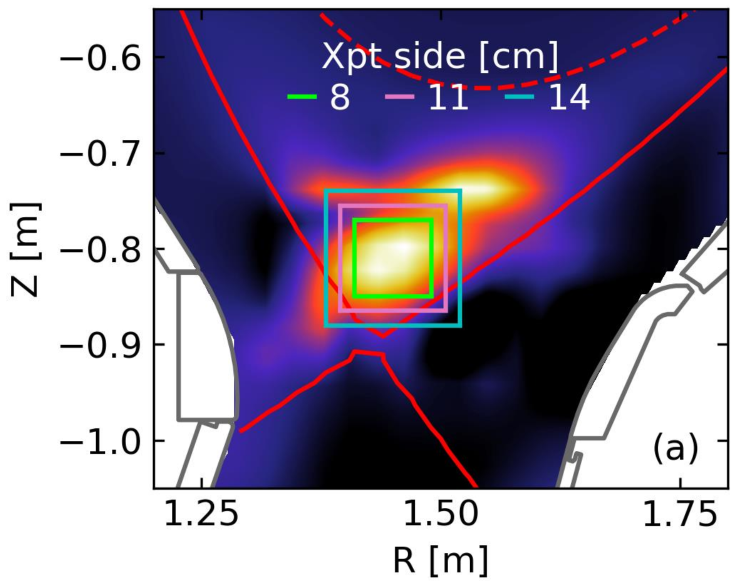
AUG #37041 at 5.0-5.5 s

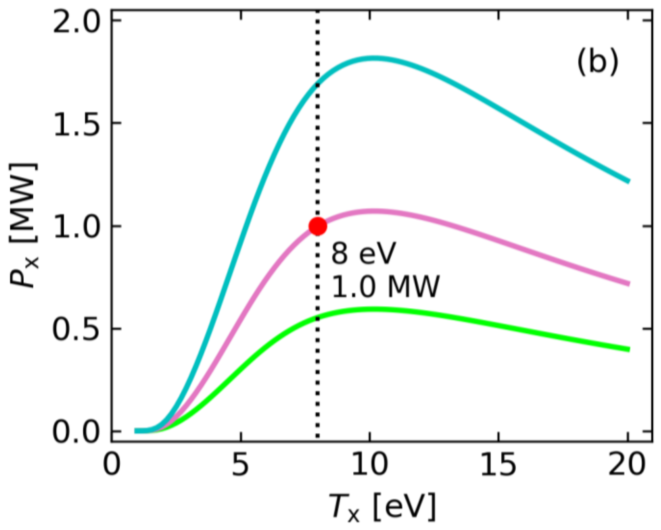


- Semi-empirical radiated power added at the edge to model the X-point radiation seen in bolometry
  - ➢ Additional edge radiation from X-point cannot be fully compensated with core radiation

Simple model for X-point radiation

- 2D radiation pattern at the edge is impossible to model with ASTRA
- Simplified model based on pressure balance from upstream (*u*) to X-point (*x*)





$$n_x \approx \frac{n_u T_u}{T_x}$$

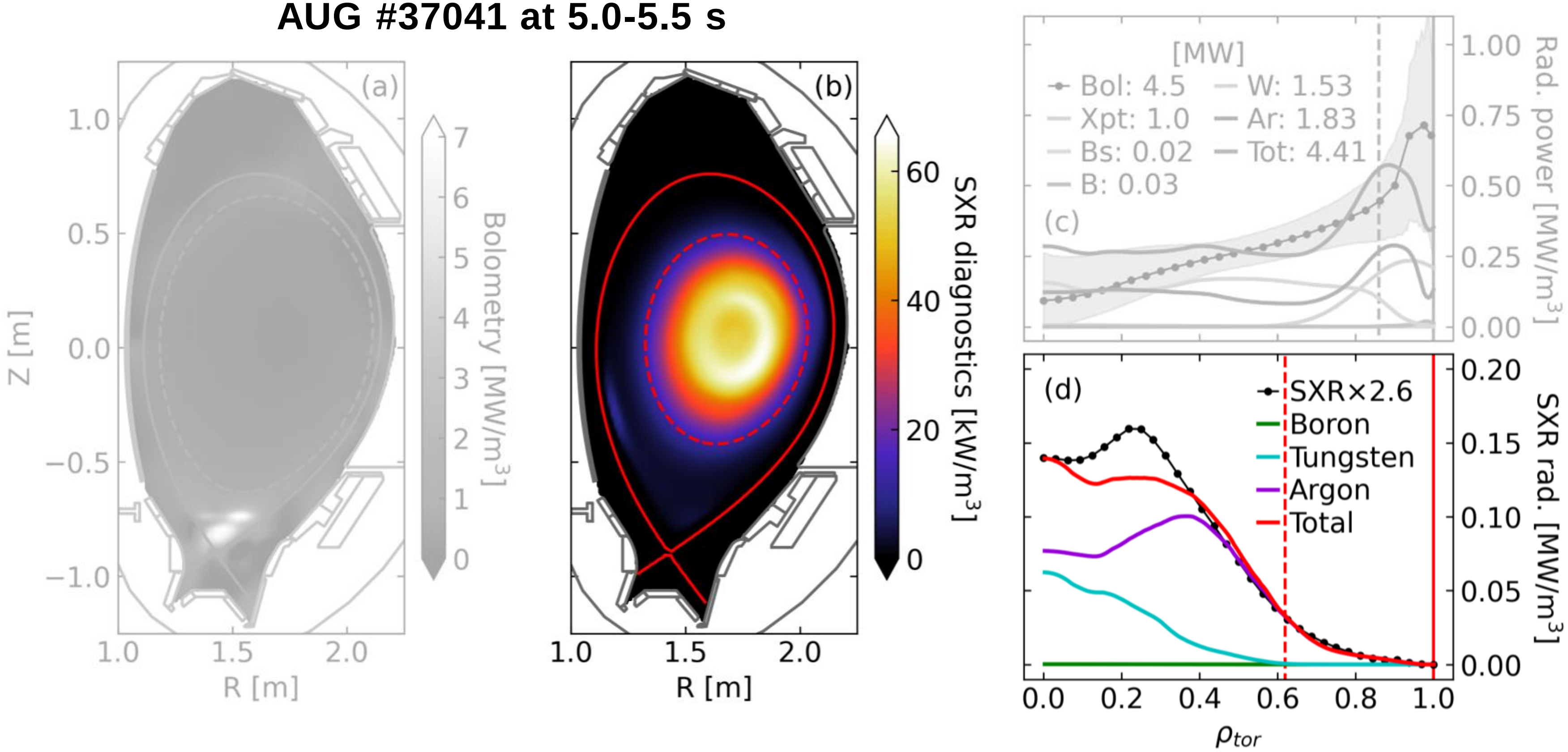
$$c_{zx} \approx c_{zu}$$

$$P_x \approx L_z(T_x)\, c_{zx}\, n_x^2\, V_x$$

- Choice of free parameters (T_x, V_x) from typical AUG XPR conditions: modelling [Stroth NF 2022], SOLPS simulations [Pan NF 2022] and measurements [Cavedon NF 2022]

Radiation profiles are well matched

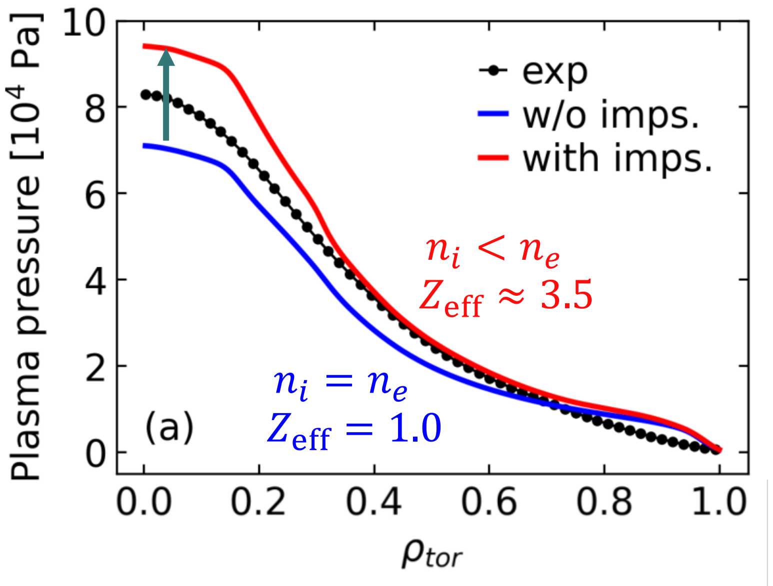
AUG #37041 at 5.0-5.5 s

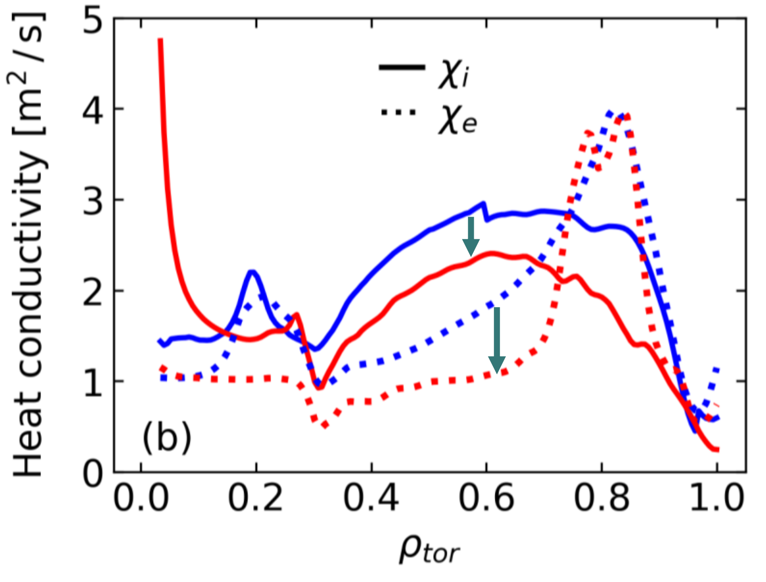


- SXR range more accurately diagnoses core profile shapes

High confinement of the radiative L-mode

- Are impurities related to the good (H-mode like) confinement of this discharge?





- Reduced heat transport in TGLF-SAT2 with impurities leads to higher main plasma confinement (+30%)

Summary & outlook

Summary & outlook

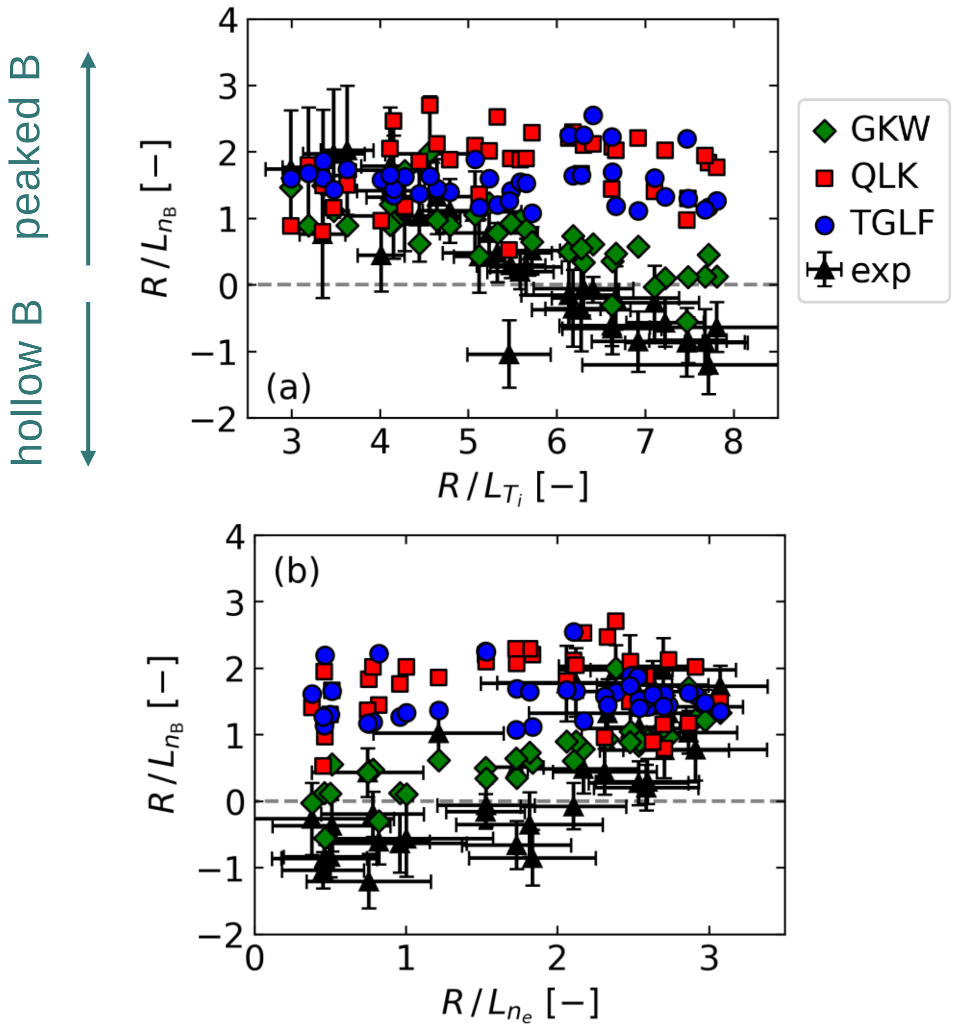
- Quasilinear models predict more peaked light impurity profiles
- Heavy impurities are better modelled because neoclassical transport dominates the pinch
- Successful full radius L-mode modelling including impurity transport and radiation
- Extend applicability to full radius simulations of seeded **H-mode** scenarios with IMEP [5], possibly applying the model for X-point radiation

[5] Luda *et al* 2020 *Nucl. Fusion* **60** 036023

Additional material

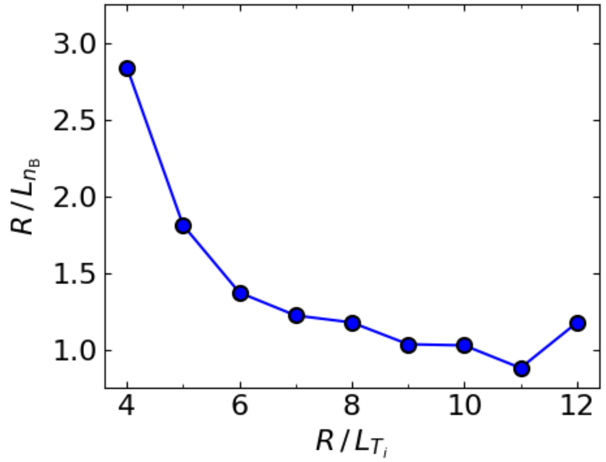
Boron gradient correlations

- Quasilinear models struggle at high R/L_{T_i}, low R/L_{n_e}

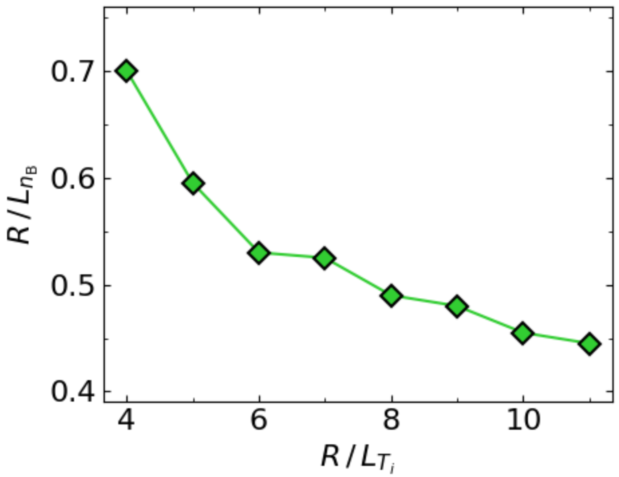


- Standalone TGLF and GKW (gyrokinetic) scans

TGLF standalone



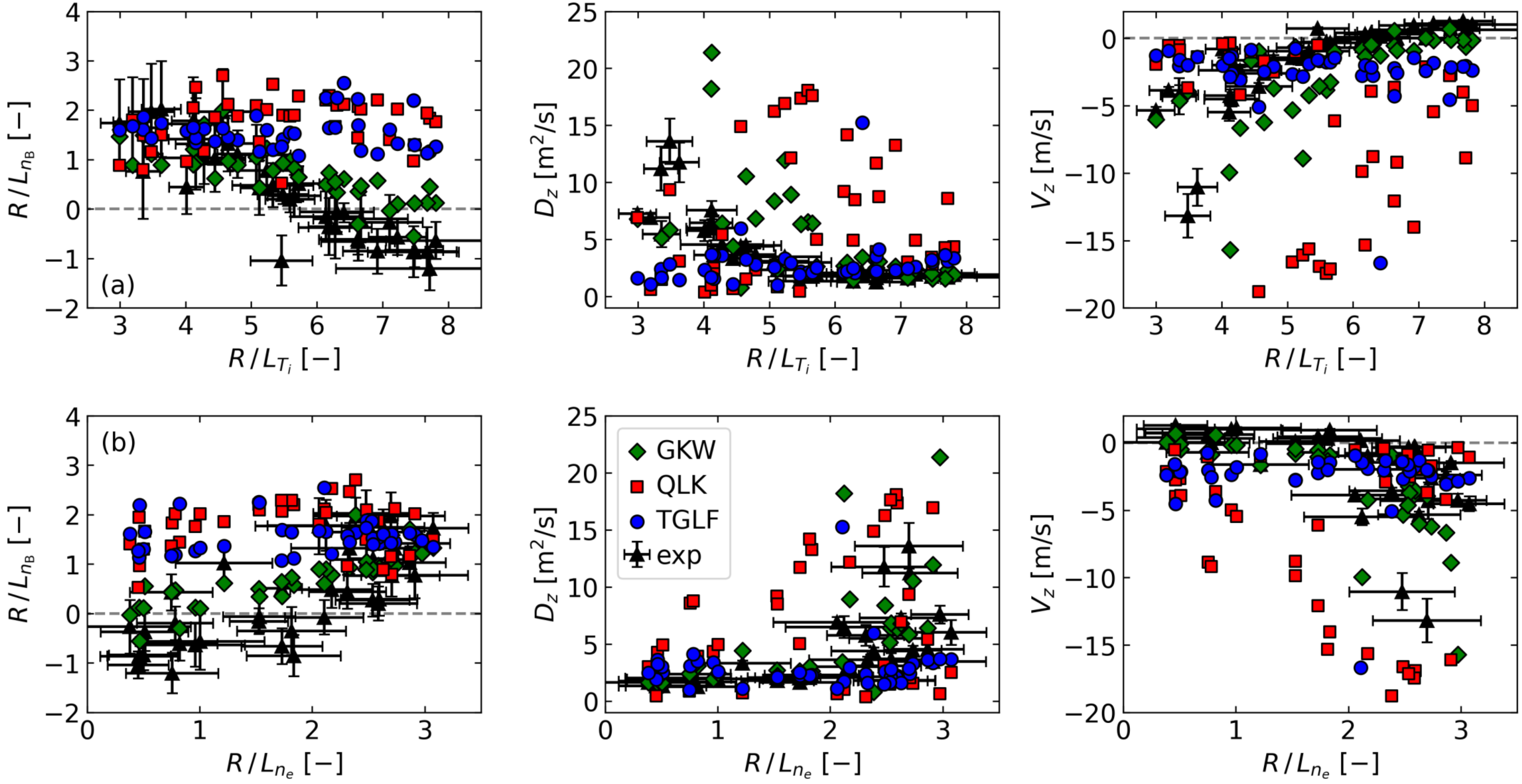
GKW



  - Good trend of increasing outward thermodiffusion, but higher magnitude

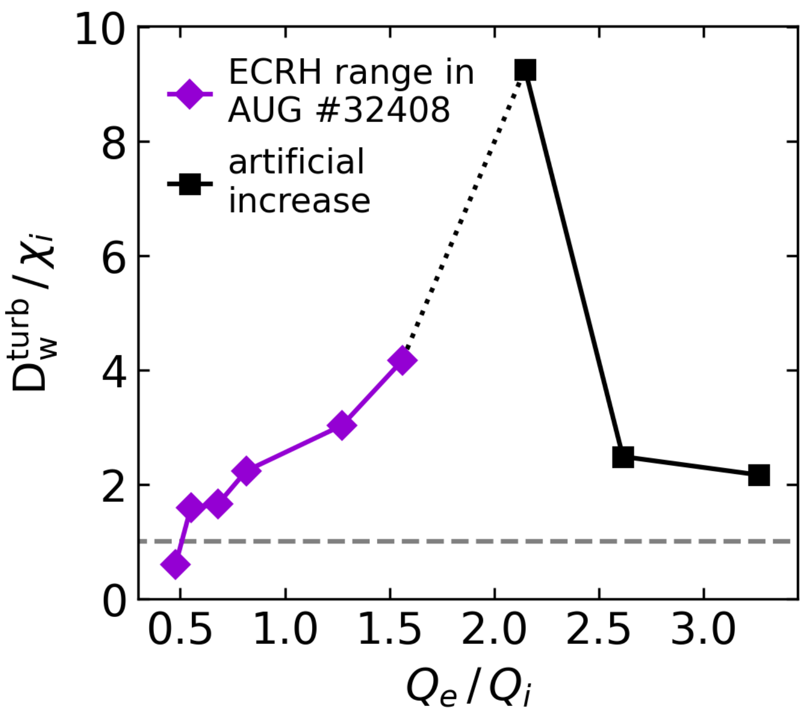
Boron gradient correlations

- Quasi-linear models seem to struggle at high R/L_{T_i}, low R/L_{n_e}: why?

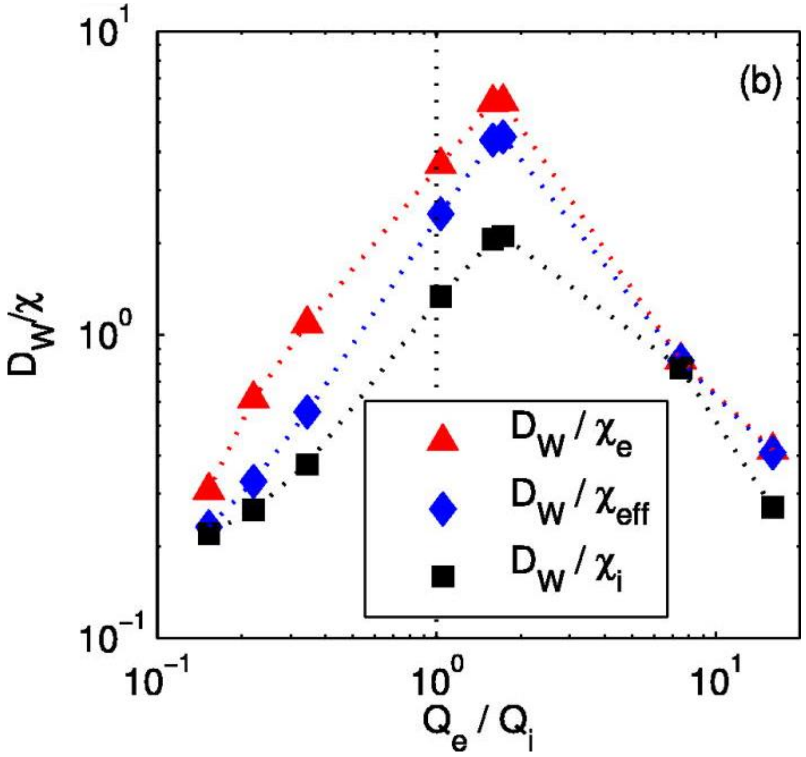


Dynamical simulations of W peaking with ECRH power ramp

- TGLF-SAT2 seems to capture important physics too



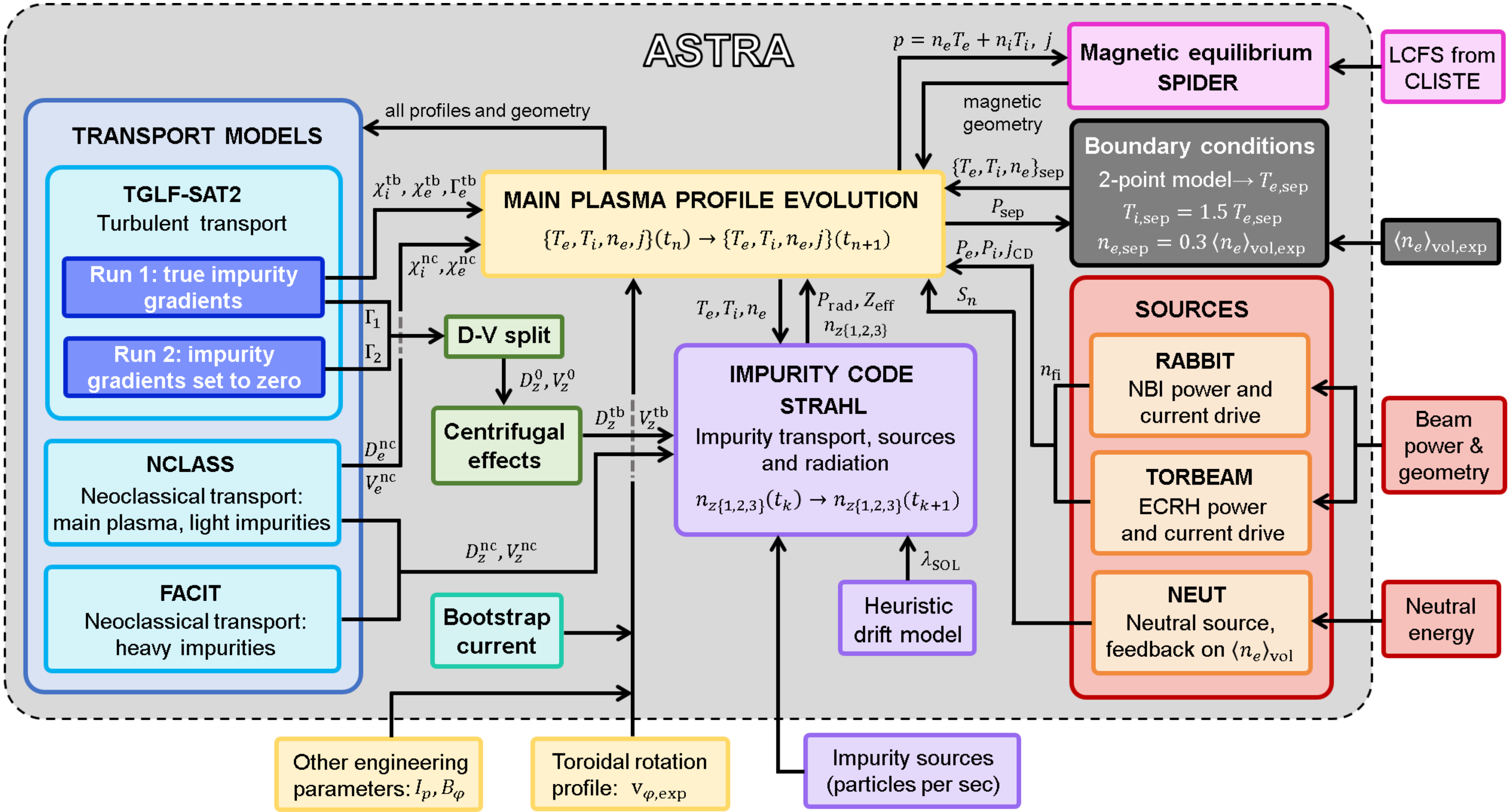
Non-linear GKW



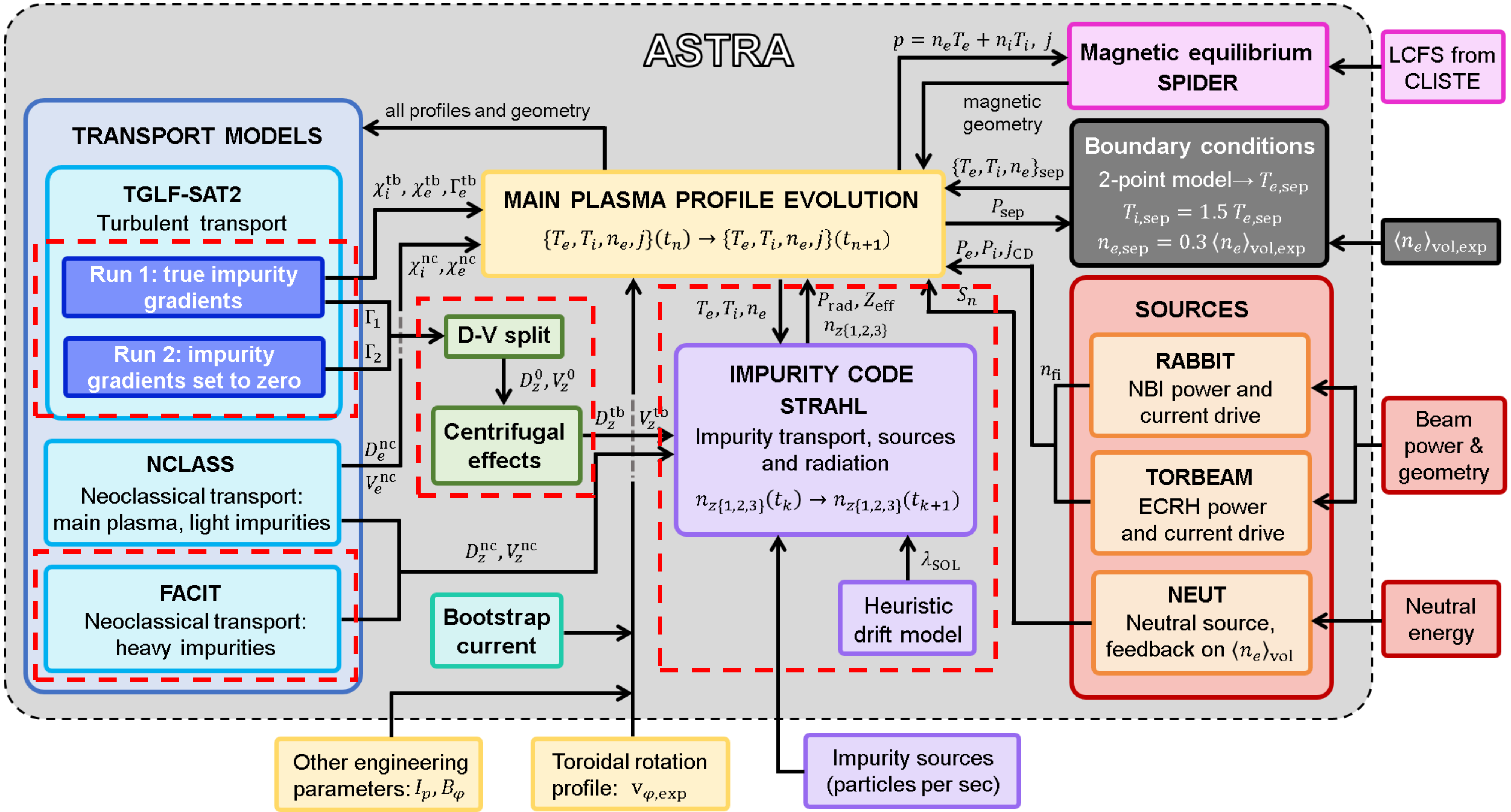
[3] Angioni 2015 *Phys. Plasmas* **22** 102501

- In general, QuaLiKiz is giving no W transport in the core, so this entire exercise is not possible…

Modelling workflow: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT

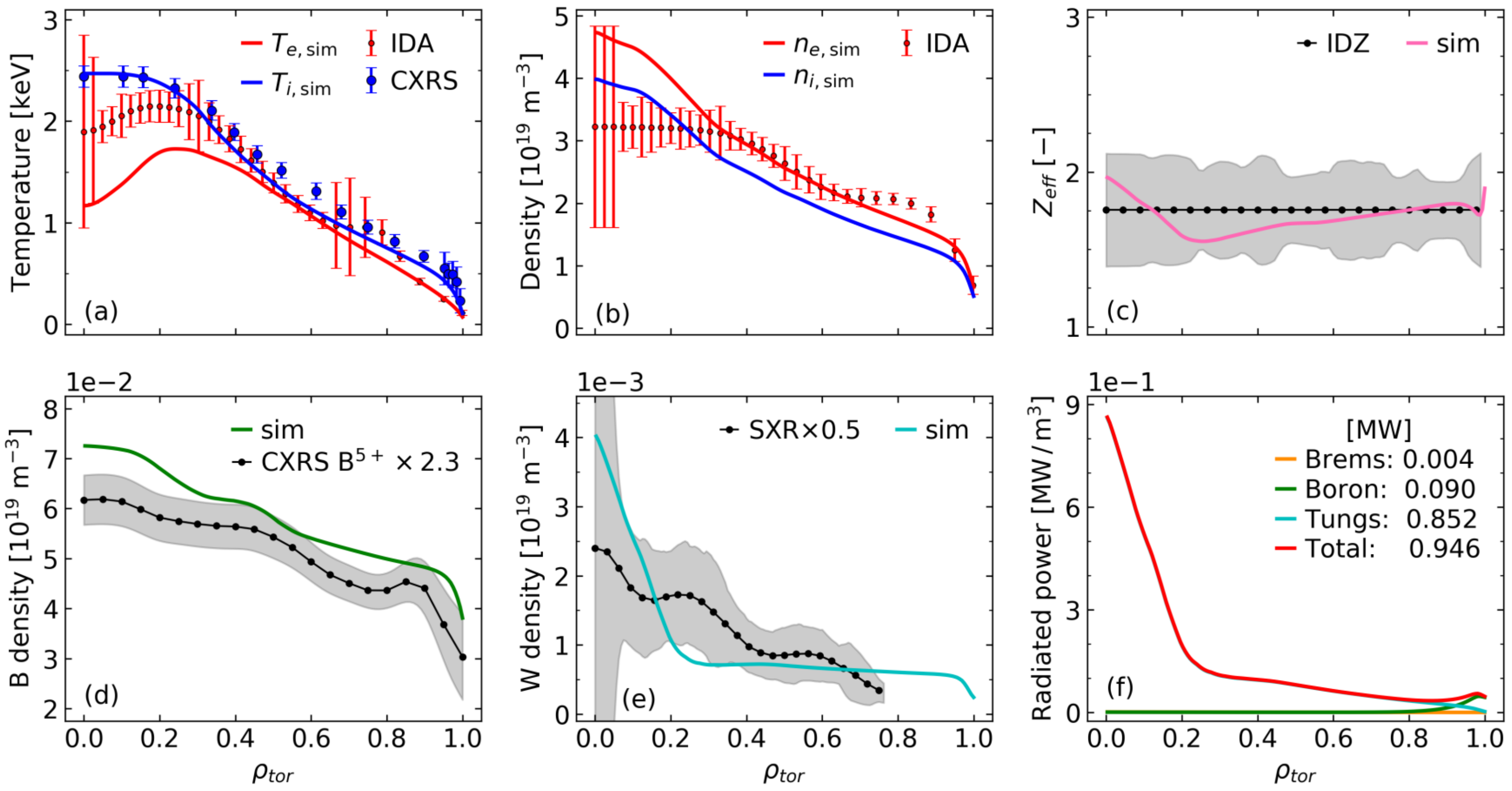


Modelling workflow: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT



AUG L-modes: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT

- Six L-modes with same $\bar{n}_e$, ~1.5 MW but different NBI/ECRH mix, $I_p \in \{0.5, 0.8, 1.2\}$ MA
- Simulated both B and W → most relevant and well-diagnosed impurities



AUG #39255 at 3.5-4.0 s

P_{NBI} = 1.50 MW

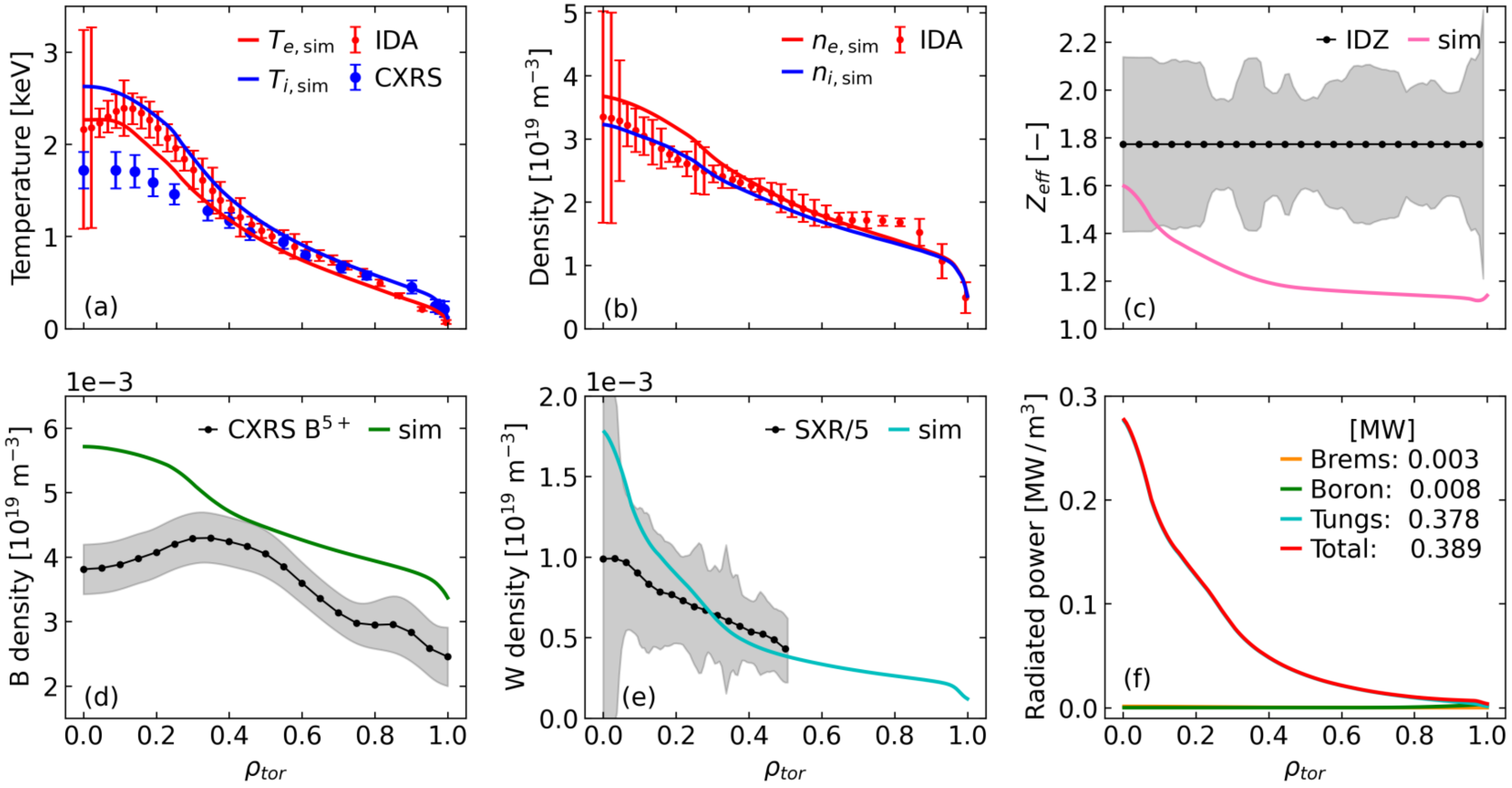
P_{ECRH} = 0.00 MW

I_p = 1.24 MA

P_{rad} = 1.0 MW

AUG L-modes: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT

- Six L-modes with same $\bar{n}_e$, ~1.5 MW but different NBI/ECRH mix, $I_p \in \{0.5, 0.8, 1.2\}$ MA
- Simulated both B and W → most relevant and well-diagnosed impurities



AUG #35475 at 2.8-3.3 s

P_{NBI} = 1.59 MW

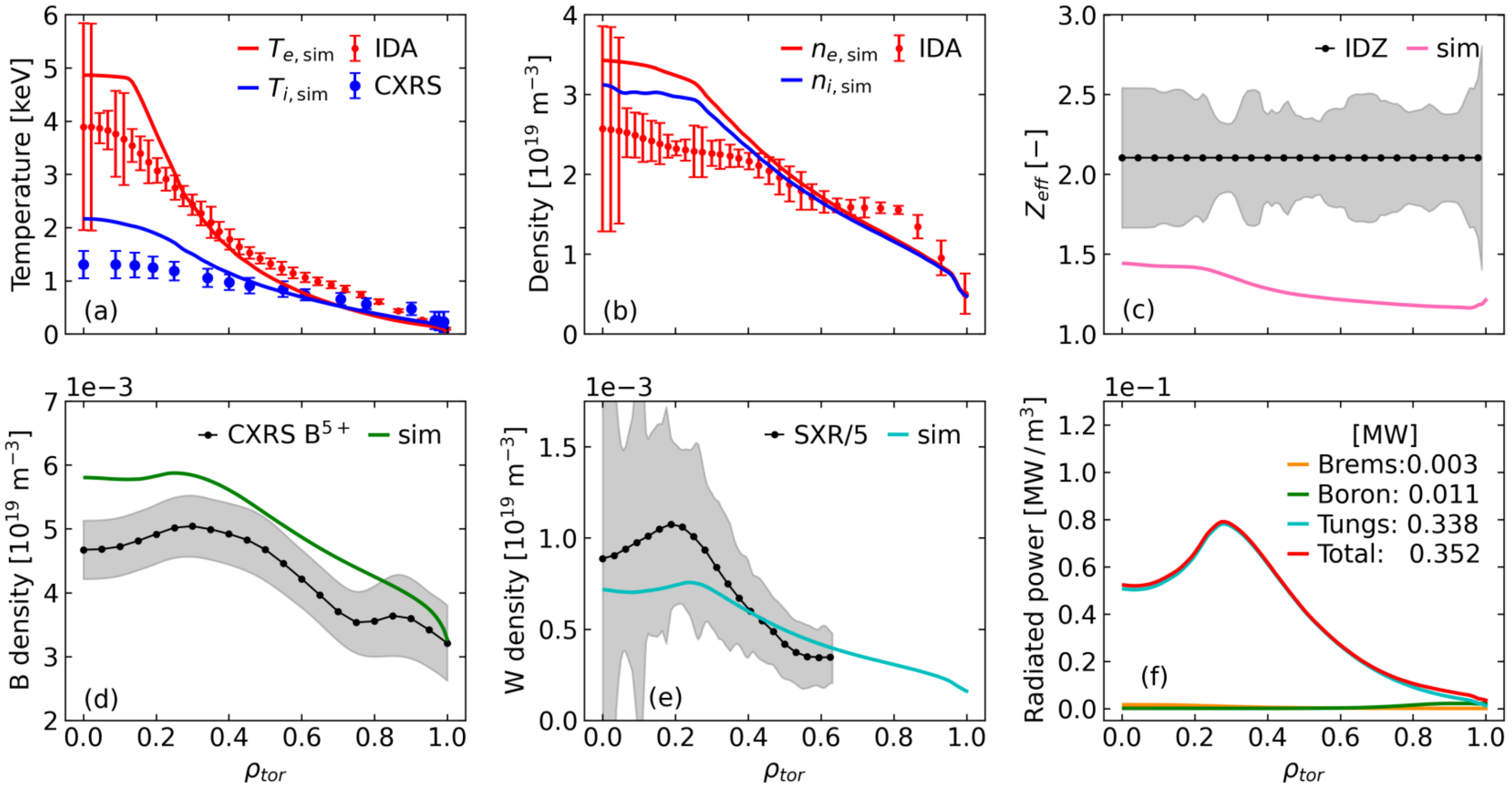
P_{ECRH} = 0.00 MW

I_p = 0.83 MA

P_{rad} = 0.30 MW

AUG L-modes: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT

- Six L-modes with same $\bar{n}_e$, ~1.5 MW but different NBI/ECRH mix, $I_p \in \{0.5, 0.8, 1.2\}$ MA
- Simulated both B and W → most relevant and well-diagnosed impurities

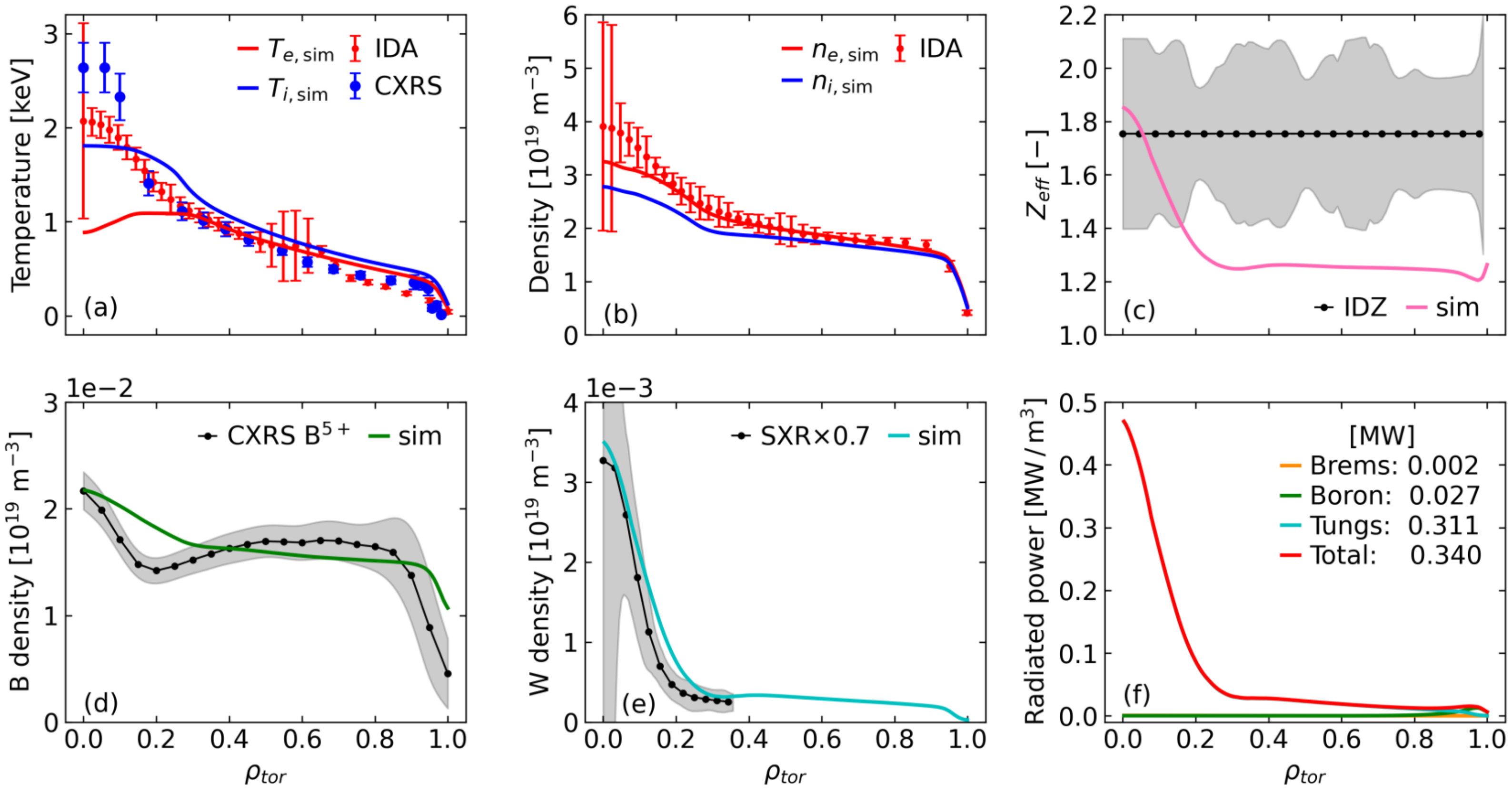


AUG #35475 at 4.3-5.0 s

P_{NBI} = 0.80 MW
P_{ECRH} = 0.72 MW
I_p = 0.83 MA
P_{rad} = 0.36 MW

AUG L-modes: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT

- Six L-modes with same $\bar{n}_e$, ~1.5 MW but different NBI/ECRH mix, $I_p \in \{0.5, 0.8, 1.2\}$ MA
- Simulated both B and W → most relevant and well-diagnosed impurities



AUG #39323 at 5.0-6.0 s

P_{NBI} = 1.50 MW

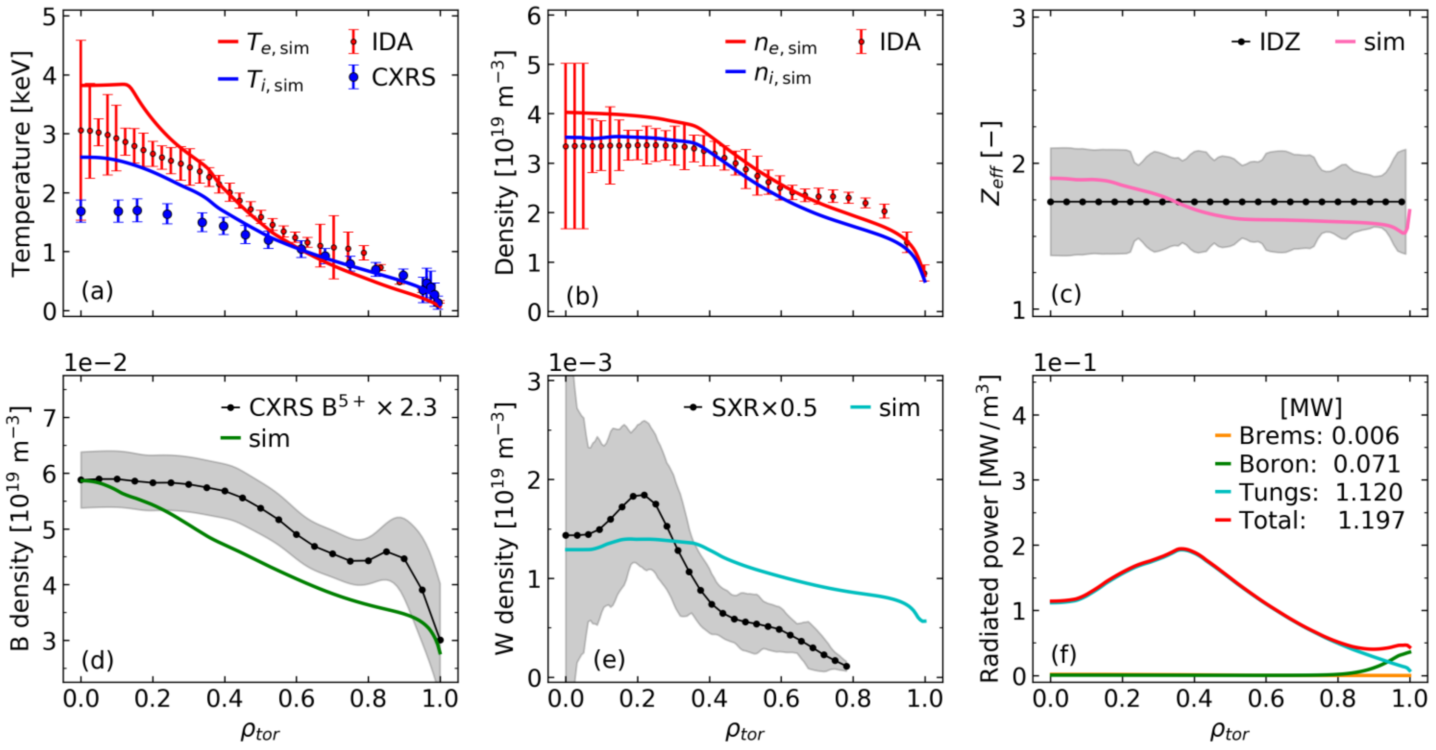
P_{ECRH} = 0.00 MW

I_p = 0.52 MA

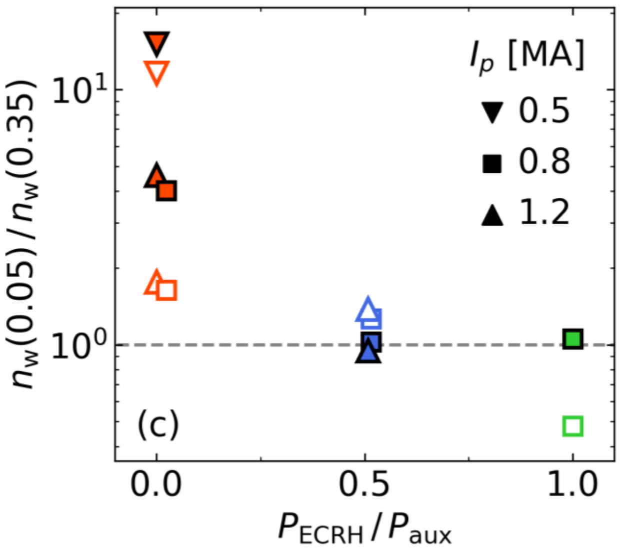
P_{rad} = 0.50 MW

AUG L-modes: full radius ($\rho_{BC} = 1$) ASTRA-STRAHL with TGLF-SAT2 & FACIT

ECRH heated case

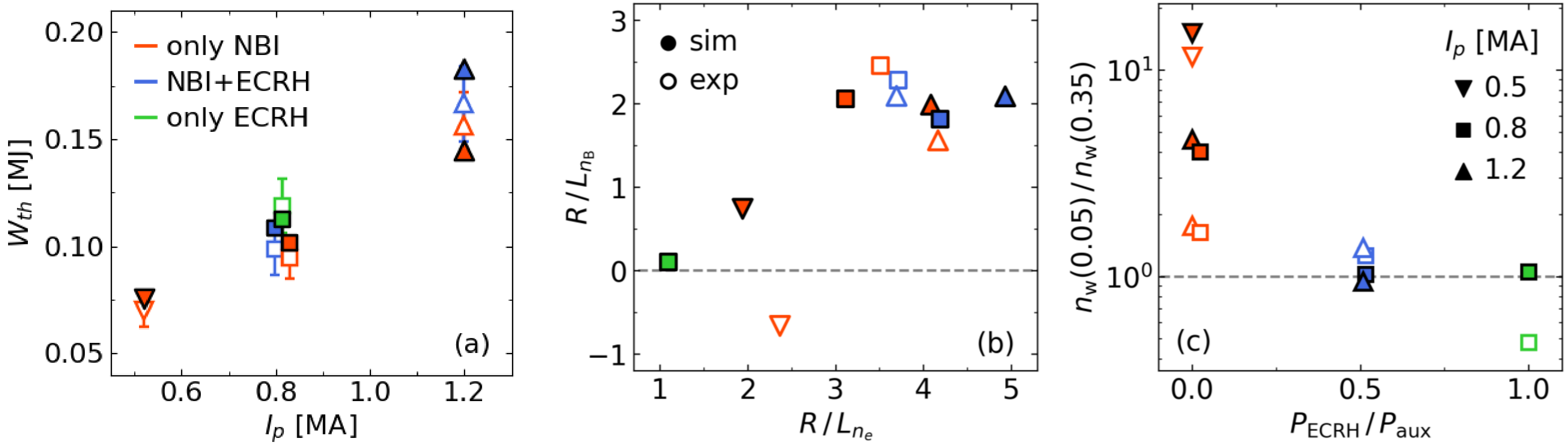


Over set of six L-modes



Unseeded L-modes in AUG: some general properties

- Six L-modes: ~1.5 MW with $P_{\mathrm{NBI}}/(P_{\mathrm{NBI}}+P_{\mathrm{ECRH}}) \in \{0.0, 0.5, 1.0\}$; $I_p \in \{0.5, 0.8, 1.2\}$ MA; same $\bar{n}_e$
- Assume only impurity species are B and W → most relevant and well-diagnosed

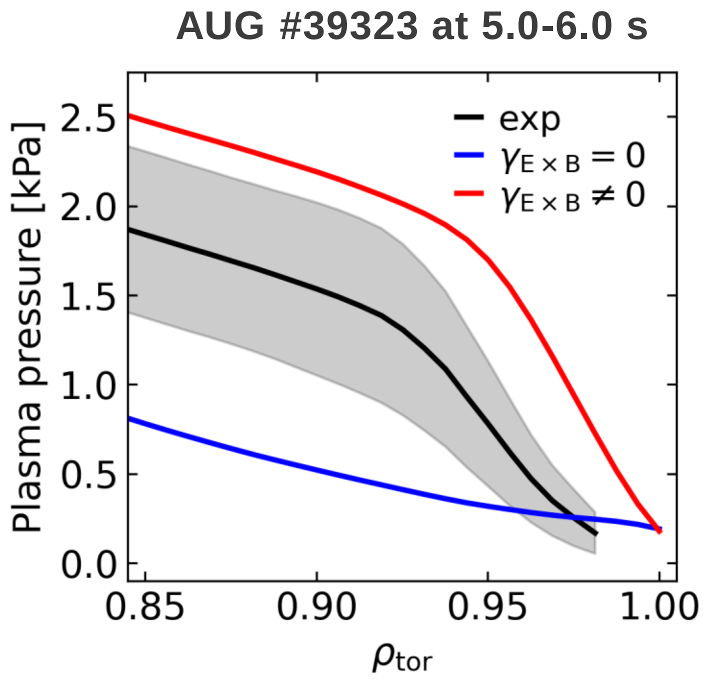


Confinement vs current | **Boron vs electron peaking** | **W peaking vs heating mix**

Unseeded L-modes: ExB shearing

- Sometimes experiment is marginally close to L-H transition

- TGLF can generate pedestal structures at the edge if a consistent E_r is used [Bonanomi EPS 2022]



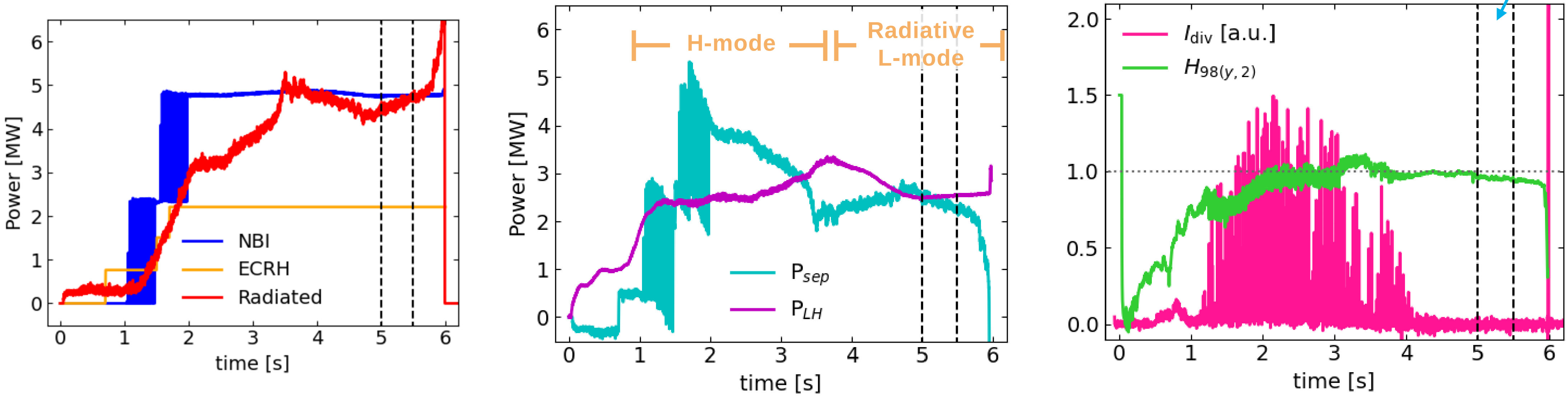
$$\gamma_{E\times B} = -\frac{r}{q}\frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta}\right)$$

Radiative L-mode with X-point radiation

- Experiment with P_{aux} ~ 7.5 MW but feedback on P_{rad} with Ar seeding for $P_{sep} < P_{LH}$ [4]

phase to analyze

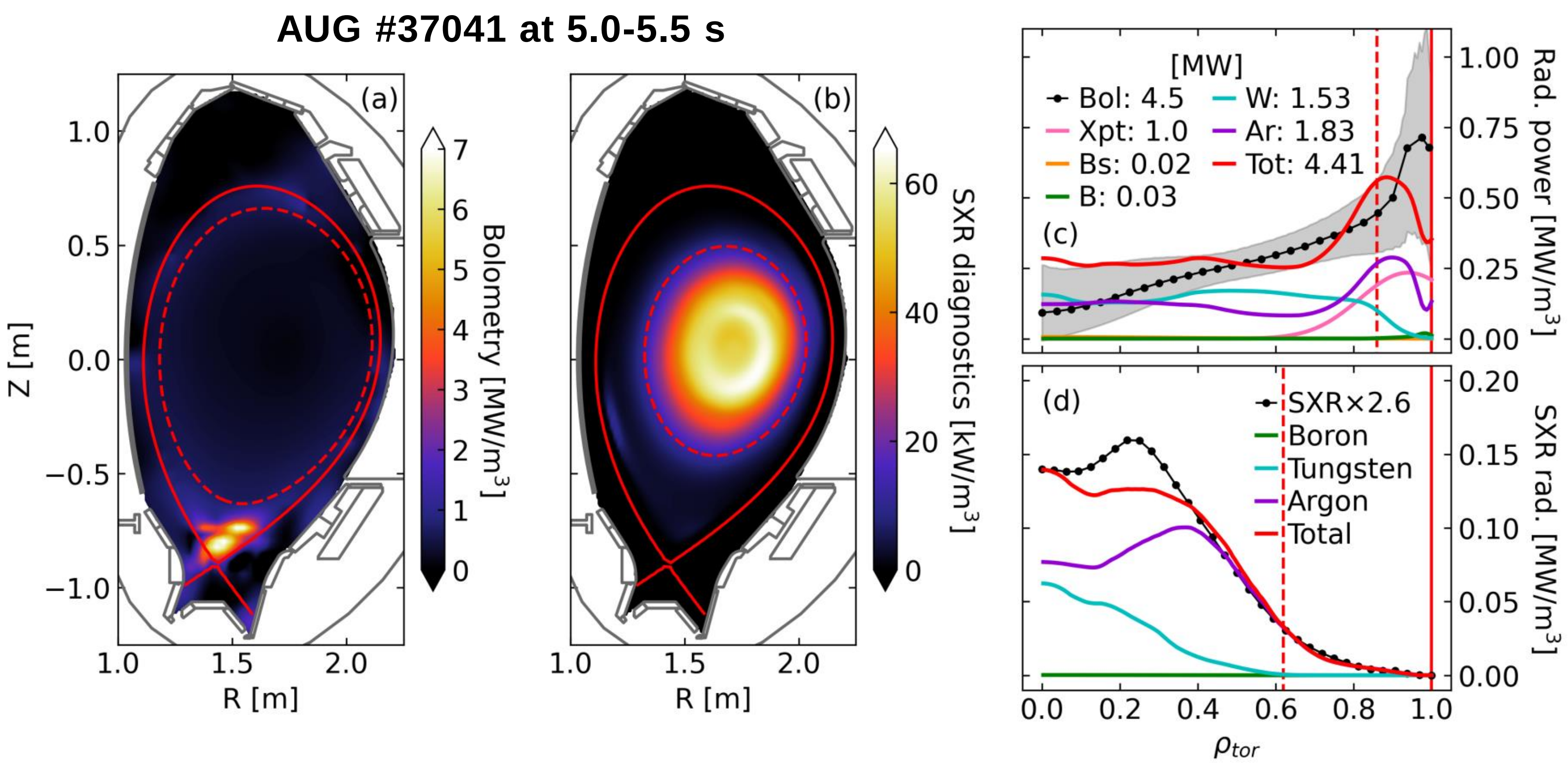
AUG #37041



[4] Fable *et al* 2022 *Nucl. Fusion* **62** 024001

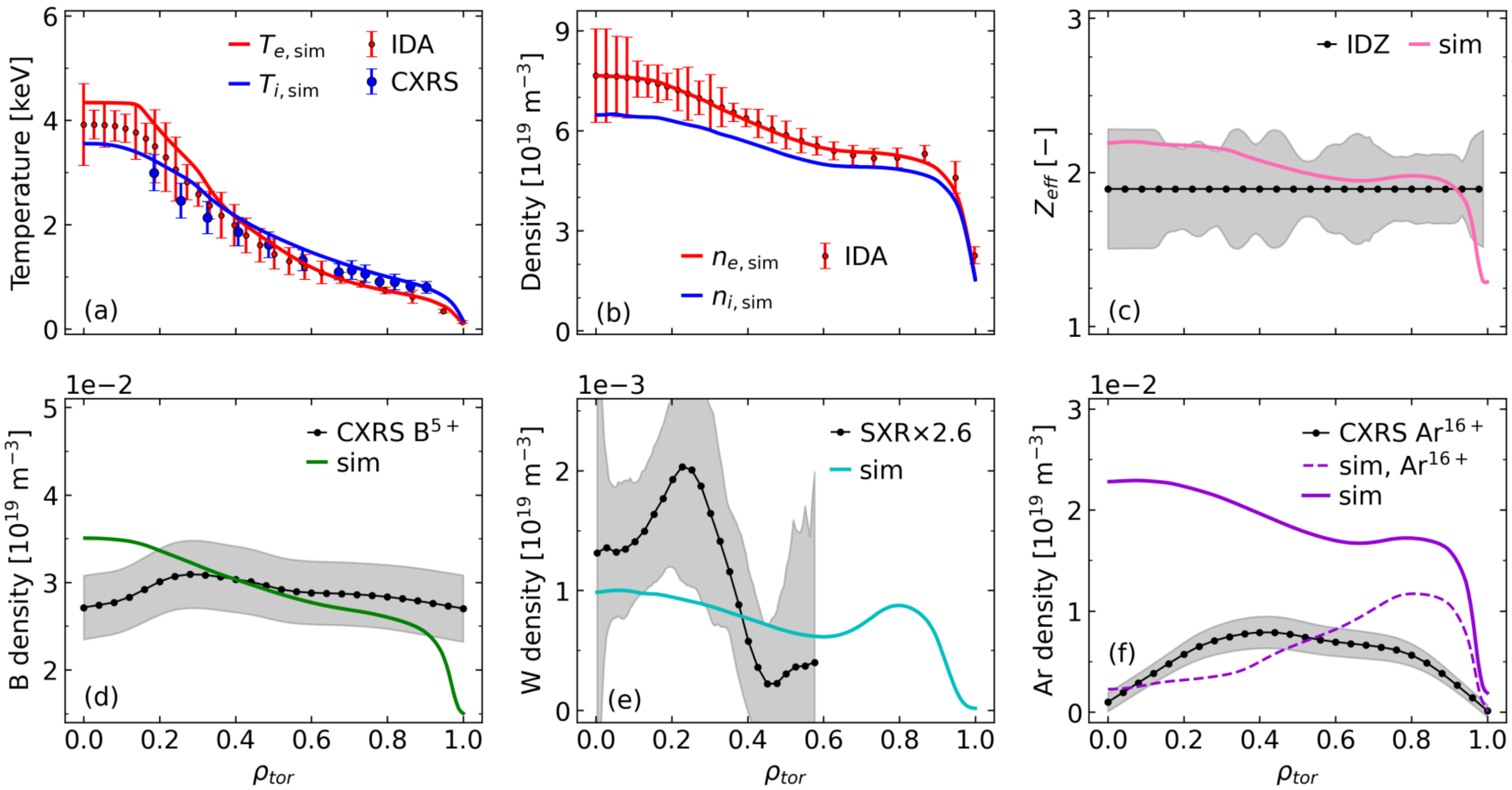
- Three impurity species (B, W, Ar), high P_{rad} (70% P_{aux}) and Z_{eff}, high confinement, and well diagnosed
- Can we simulate this plasma, without a radiative collapse?

Radiation profiles are well matched



- In WEST, recent modelling efforts of N-seeded XPR → S. Shi, this conference

Radiative L-mode: previous H-mode phase of this discharge



Radiative L-mode: previous H-mode phase of this discharge