Investigation of impurity transport in SPARC H-mode scenarios

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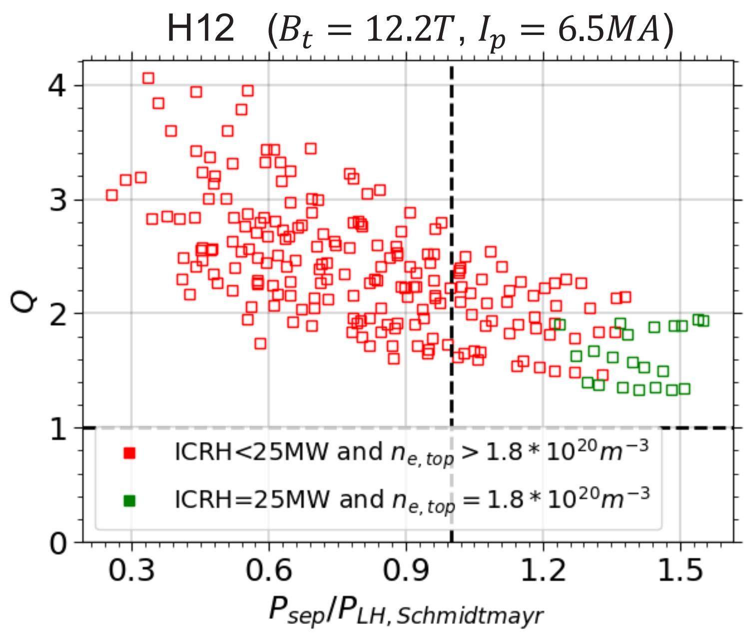
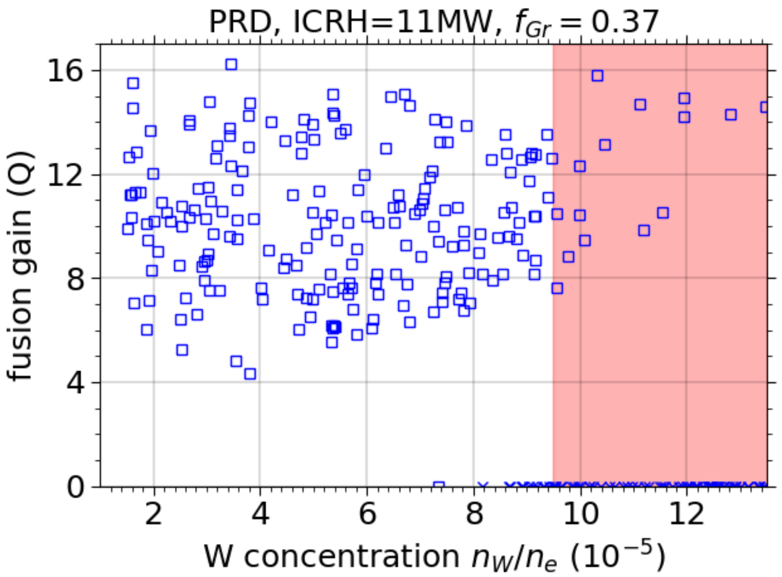
And the SPARC team

[1] MIT PSFC, [2] Max Planck IPP, [3] Columbia University, [4] CFS

Motivation: Impurities impact confinement, radiation and H-mode access

- Experimental scaling laws [1, 2] → H-mode access probability increases with P_{sep} → is reduced by P_{rad}
- $\boldsymbol{P_{rad}}$ **depends on impurity density profiles** → fixed radial concentrations assumed in previous work
- Broad scoping of several SPARC H-mode scenarios → high P_{ICRH} and low $\langle n_e \rangle$ are optimal conditions to optimize performance and H-mode access [3]
- **Needs for impurity transport simulations to validate this approach (are impurities peaking near-axis?)** → **Extensive study on impurity transport**





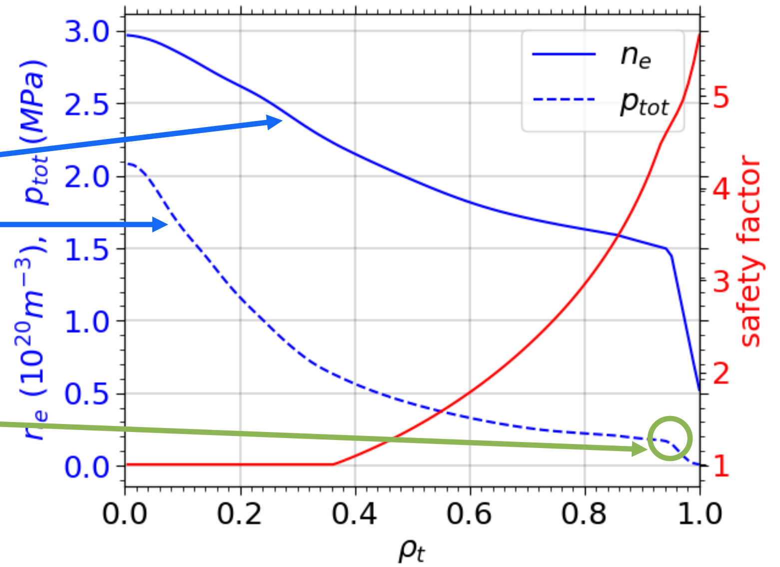
[1] Martin, J. Phys.: Conf. Ser. 2008
[2] Schmidtmayr, NF 2018
[3] Muraca, NF 2025

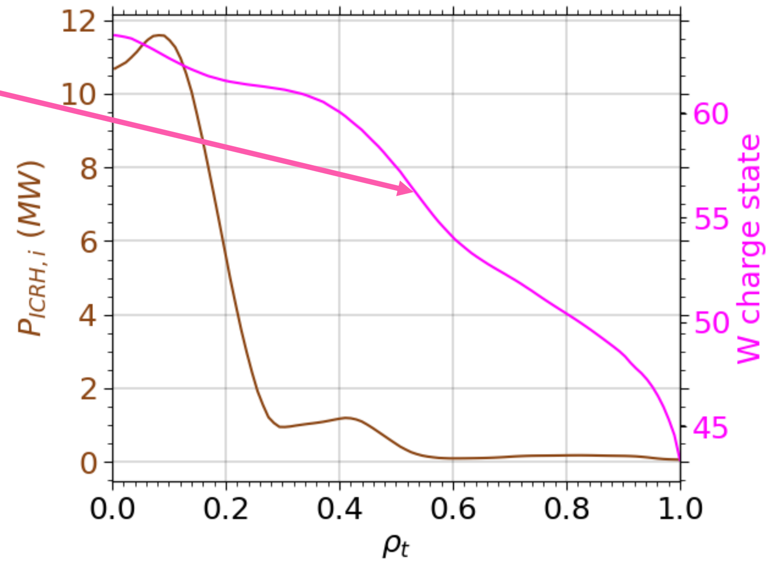
Outline of the update

- Simulations framework
- Benchmark of previous results
- Impact of uncertainties
- Effect of rotation on transport

Simulations framework

- **ASTRA** [4] flux-driven transport solver, coupled with:
  - **TGLF** [5] → turbulent transport
  - **FACIT** [6] → neoclassical transport
  - **EPED-NN** → pedestal structure
  - **STRAHL** [7] → atomic processes (e.g. recombination/ionization), charge state equilibrium and radiation





- Simulated impurities:
  - **W** → from ICRH antenna and PFCs
  - **Ar** → from seeding
  - **He3** → for ICRH absorption (treated here as thermal species)

[4] Pereverzev, IPP report 5/98 [5] Staebler NF 2021 [6] Fajardo, PPCF 2022 [7] Dux, IPP report 10/30

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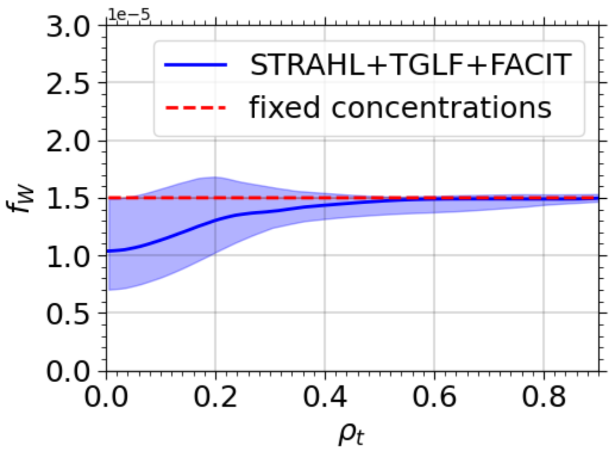
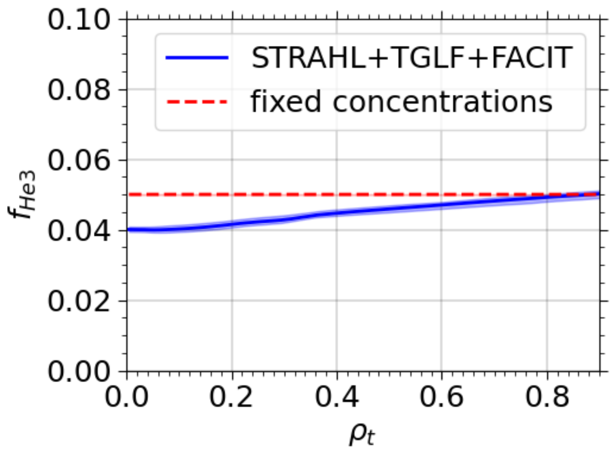
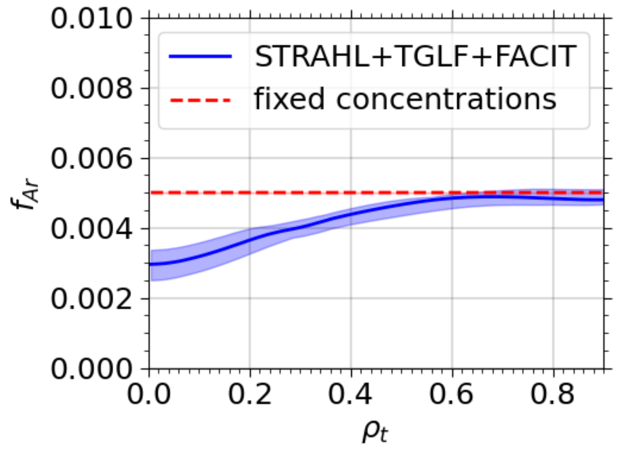
Impurity transport validates simulations with fixed concentrations

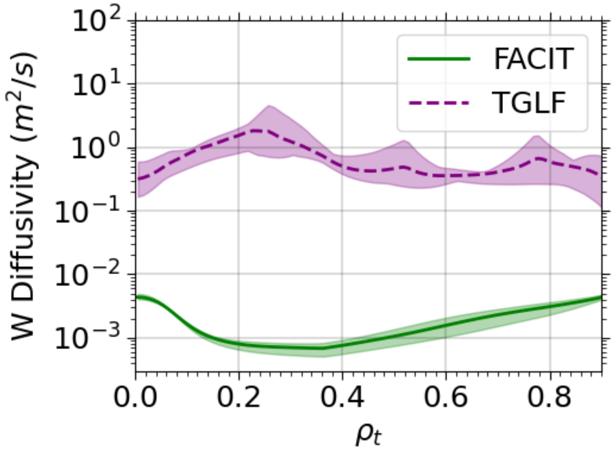
- ~ flat impurity concentrations, varying n_{top} and P_{ICRH}
- **Good penetration of He3** → 4% near-axis
- Ar hollowed profiles → lower radiation with STRAHL + impurity transport → higher P_{sep}
- **Good agreement of Q, more optimistic $f_{LH} = {}^{P_{sep}}/_{P_{LH}}$**
- **W impurity transport is dominated by turbulence** (consistent with ITER predictions[8]). Same for Ar.
- **→ similar picture for the other H-modes, spanning different I_p and B_t**

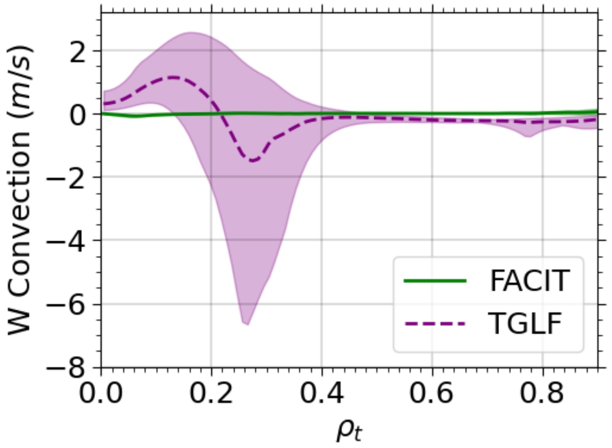
H12 $(B_t = 12.2T, I_p = 6.5MA)$











$\langle \Delta Q \rangle \sim 2\%$ $\quad \Delta Q_{max} \sim 10\%$

$\langle \Delta f_{LH} \rangle \sim 14\%$ $\quad \Delta f_{LH,max} \sim 30\%$

[8] Fajardo PPCF 2025

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Scan of Ar concentration shows competitive effects on core and pedestal

- W concentration scan has minimal impact on performance and impurity peaking
- Ar concentration scan has an effect on:
  - Z_{eff}
  - Pedestal pressure
  - **Main ion dilution**
  - **ITG/TEM equilibration → density peaking**
  - Radiation
- The lower dilution and density peaking counteract the higher pedestal pressure →
  - **roughly constant Q**
  - **slightly lower f_{LH}**

$$\frac{P_{rad}}{P_{input}} = [0.15 - 0.4]$$

W scan

$f_{W,top}$	$\langle T_i \rangle\ (keV)$	$P_{rad}\ (MW)$	Q	$f_{LH,Schmidt}$
$0.6 * 10^{-5}$	8	10.7	1.43	1.58
$2 * 10^{-5}$	8.05	12	1.43	1.57
$3.3 * 10^{-5}$	8.1	13.5	1.45	1.55
$4.6 * 10^{-5}$	8.18	15	1.45	1.51
$6 * 10^{-5}$	8.2	15.7	1.52	1.51

Ar scan

$f_{Ar,top}$	$\langle Z_{eff} \rangle$	$p_{top}\ (kPa)$	$\langle f_{DT} \rangle$	ν_n	$P_{rad}\ (MW)$	Q	$f_{LH,Schmidt}$
$0.5 * 10^{-3}$	1.34	256	0.87	1.66	5.8	1.54	1.61
$1.8 * 10^{-3}$	1.7	272	0.85	1.59	7.7	1.55	1.6
$3.2 * 10^{-3}$	2.1	290	0.82	1.53	9	1.51	1.59
$4.6 * 10^{-3}$	2.5	304	0.79	1.47	11	1.53	1.59
$6 * 10^{-3}$	2.9	320	0.77	1.37	12	1.43	1.57
$7.2 * 10^{-3}$	3.3	337	0.75	1.38	13	1.49	1.57
$8.6 * 10^{-3}$	3.8	358	0.72	1.38	15	1.52	1.56

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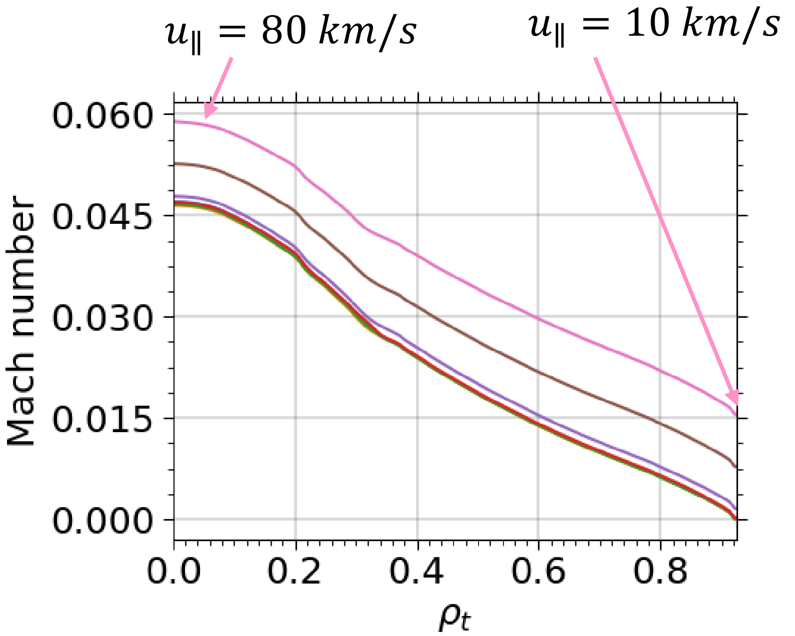
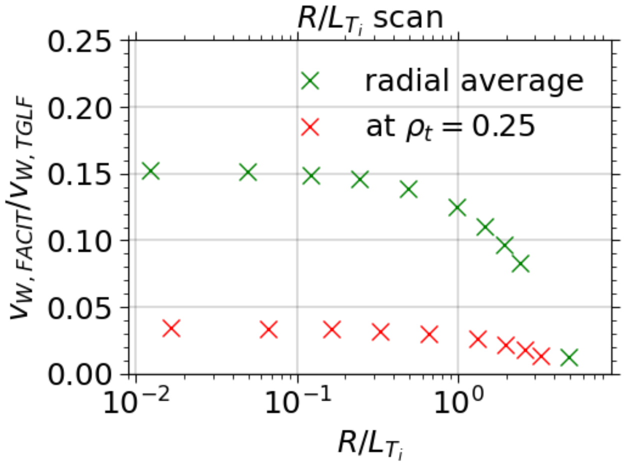
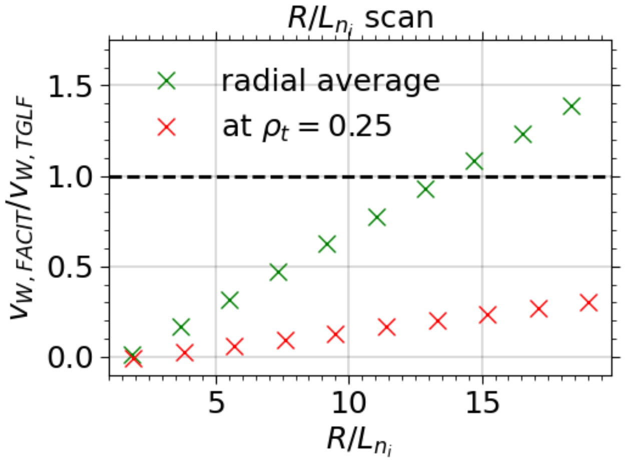
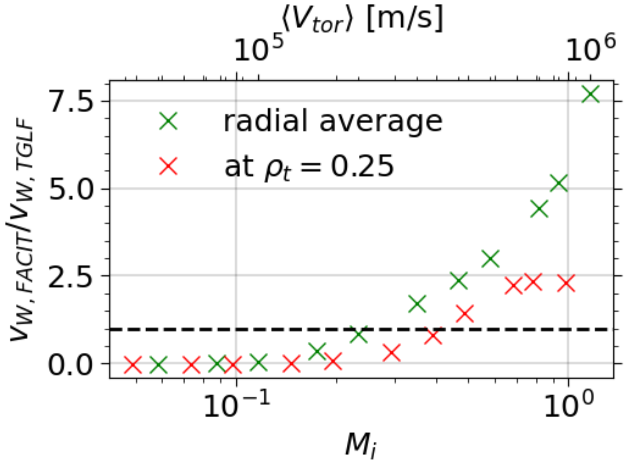
Found small impact of rotation on transport for SPARC H-mode scenarios

- Rotation affects turbulent and neoclassical transport
- → Reduced analytical model for core momentum transport [9] in ASTRA → scan of edge rotation ($v_{tor} = [0 - 10]\ km/s$)
- **Negligible effect on turbulent transport** (via E_r modification)
- **No effect on neoclassical transport** → unexpected, maybe due to low collisionality?
- → sensitivity of neoclassical D and V, scanning v_{tor}, $\frac{R}{L_{T_i}}$ and $\frac{R}{L_{n_i}}$
- $\langle v_{W,NC} \rangle_{\rho_t} \ll \langle v_{W,turb} \rangle_{\rho_t}$ **for every ∇T_i and reasonable ∇n_i and v_{tor}**









[9] Zimmermann PoP 2024

Conclusions and Outlook

CONCLUSIONS

- Turbulence dominates impurity transport for a variety of SPARC H-modes
- Fixed-fraction impurities can be used to lower cost, without significant loss of accuracy
- He3 can reach ~4-5% concentration near-axis → efficient ICRH heating
- H-modes plasma performance is roughly independent on Ar concentrations
- Rotation levels predicted in SPARC do not affect the core turbulent and neoclassical transport

OUTLOOK:

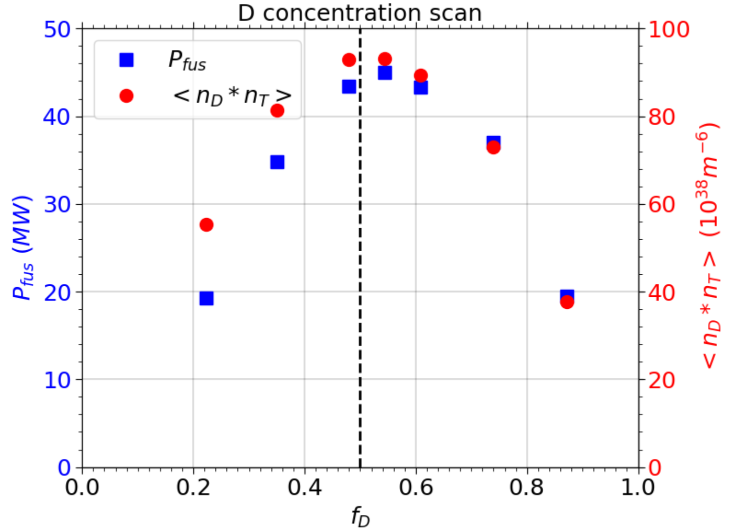
- Inclusion of Lengyel model for consistent exhaust solution
- Simulate reactor class future devices
- Inclusion of self-consistent ICRH generated fast particles
- Simulate different scenarios (e.g. L-mode, QCE, I-mode)

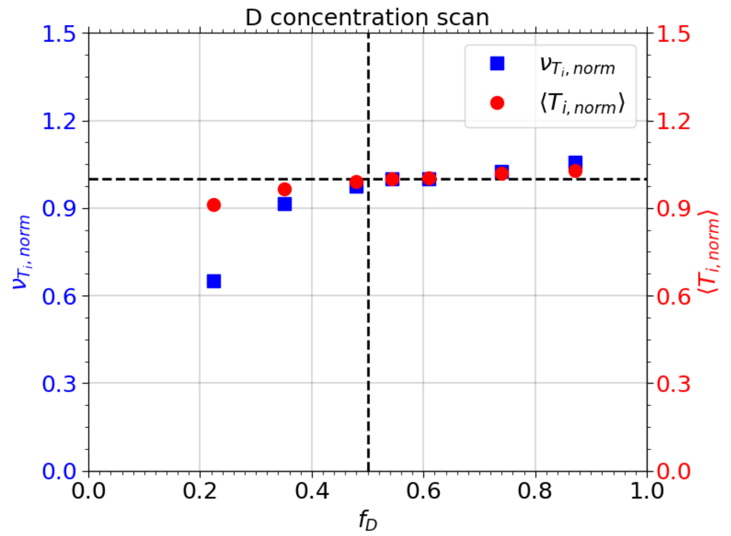
Not shown: ~50-50% DT fuel mix composition maximizes P_{fus}, with an asymmetric distribution with respect to the D concentration

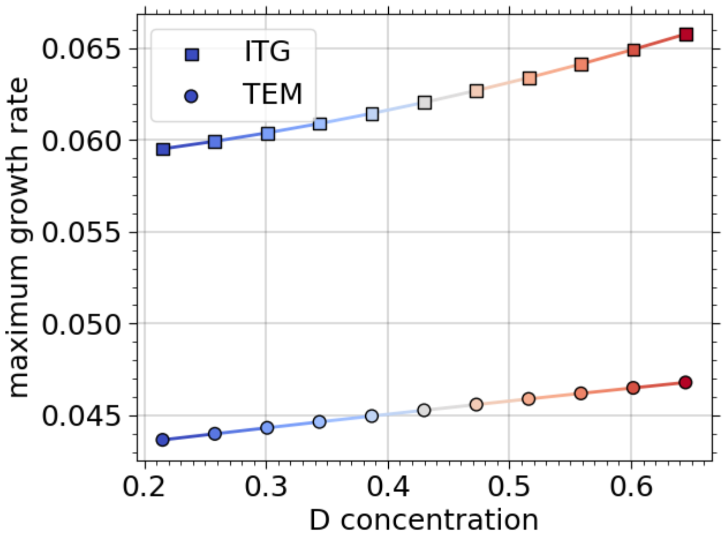
BACKUP

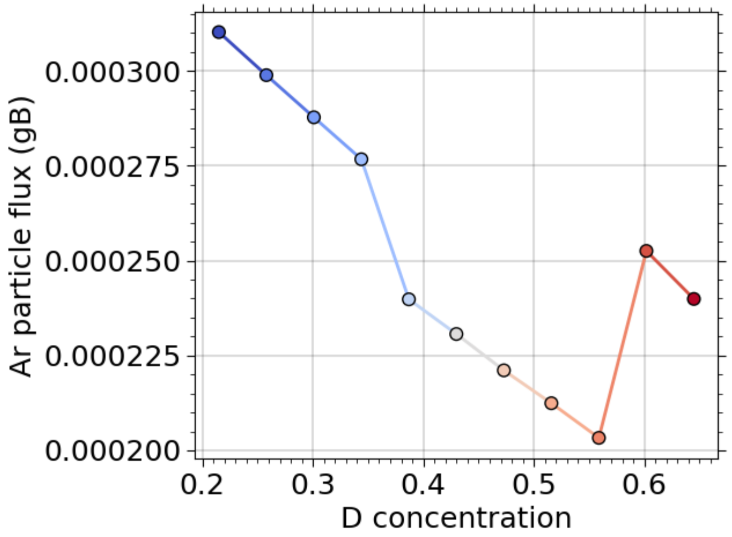
DT fuel mix gives maximum P_{fus} around 50-50%, with asymmetric distribution

- As expected, the maximum fusion power is around 50-50% DT fuel mix composition
- However, the distribution of P_{fus} with $f_D = \frac{n_D}{n_D+n_T}$ is asymmetric (more optimistic at higher D concentrations). Why?
- → higher D percentage → higher growth rate (ITG dominated) → higher Ar particle pinch → higher Z_{eff} → higher T_i → higher P_{fus}
- TGLF standalone simulations confirmed the trend



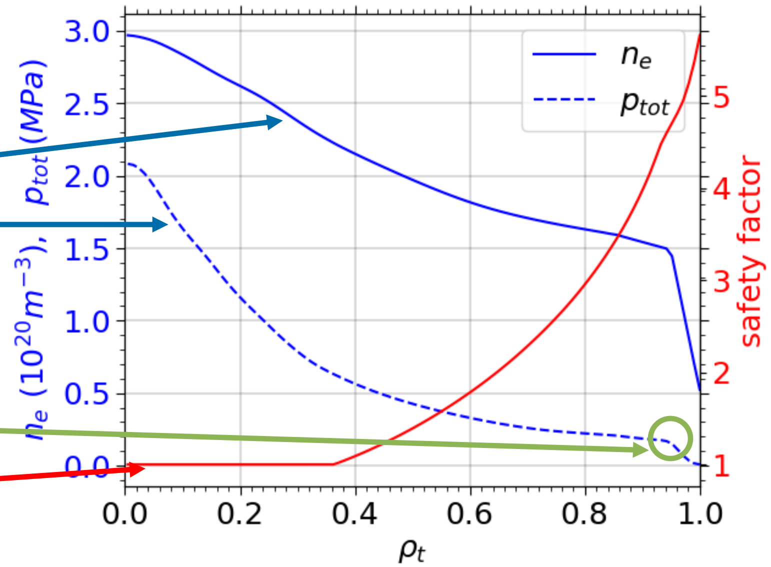


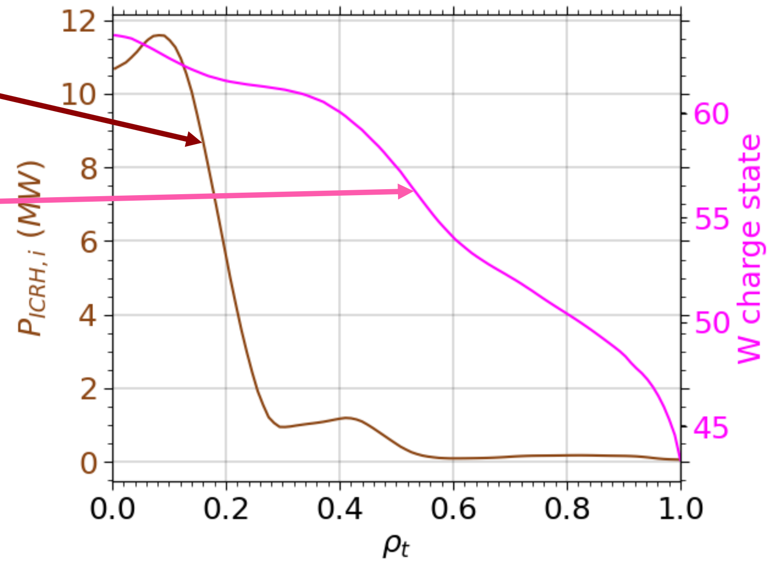




Simulations framework

- ASTRA [4] flux-matching transport solver, coupled with:
  - TGLF [5] → turbulent transport
  - FACIT [6] → neoclassical transport
  - EPED-NN → pedestal stability
  - TRANSP+Porcelli model → sawtooth period
  - TRANSP+TORIC+CQL3D → ICRH deposition
  - STRAHL [7] → atomic processes (e.g. recombination/ionization), charge state equilibrium and radiation





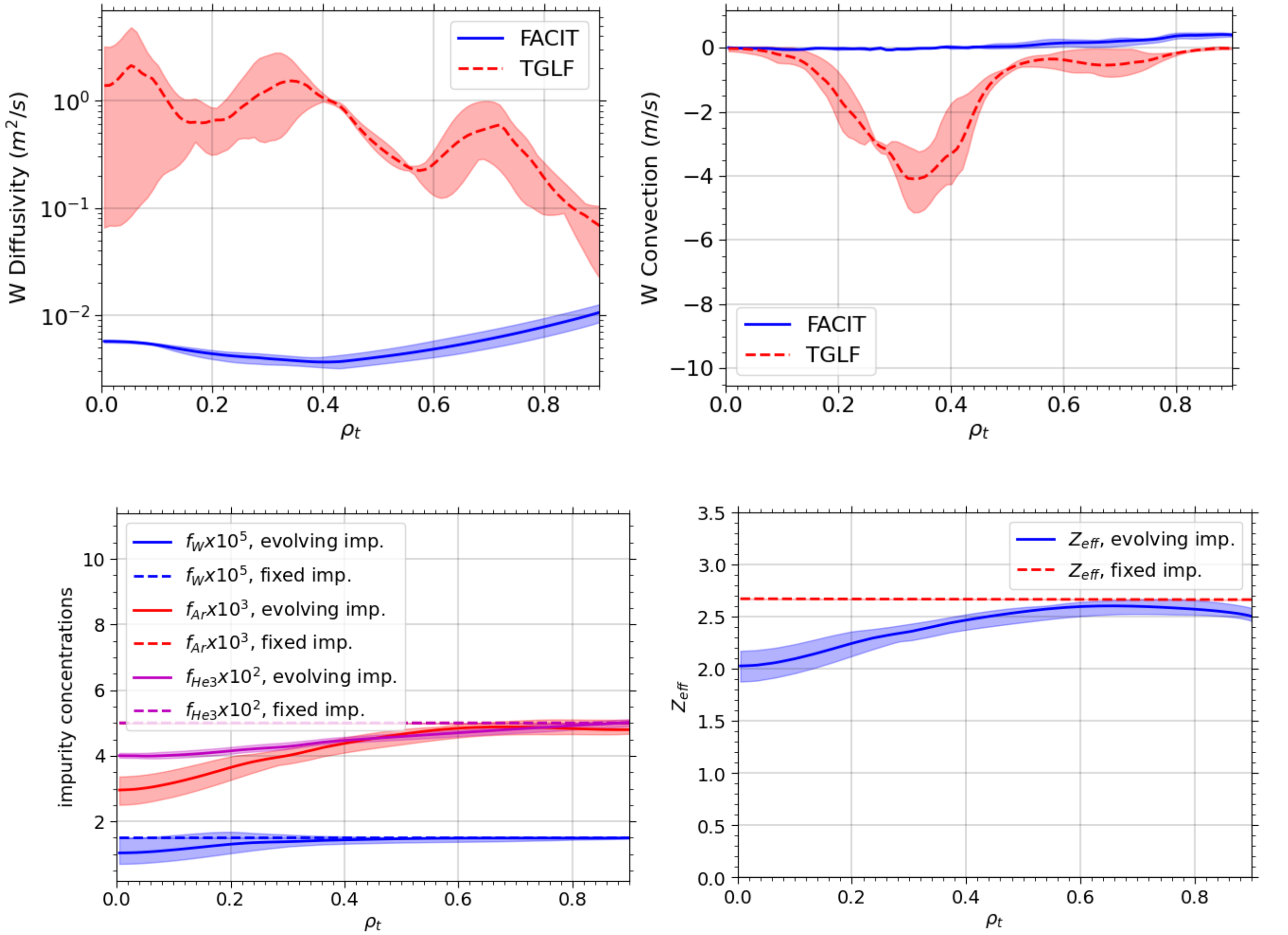
- Simulated impurities:
  - **W** → from ICRH antenna and PFCs
  - **Ar** → from seeding and to reach target Z_{eff}
  - **He3** → for ICRH absorption (treated here as thermal species)

[4] Pereverzev, IPP report 5/98 [5] Staebler NF 2021 [6] Fajardo, PPCF 2022 [7] Dux, IPP report 10/30

Turbulent transport prevails on neoclassical for impurities

- The W impurity transport is dominated by turbulence (consistent with ITER predictions[8]).
- → observed for all scenarios
- Valid also for Ar → slightly hollowed profiles for H12 → lower radiation with impurity transport
- Good penetration of He3 → 4% concentration near-axis possible with 5% penetration at top of pedestal

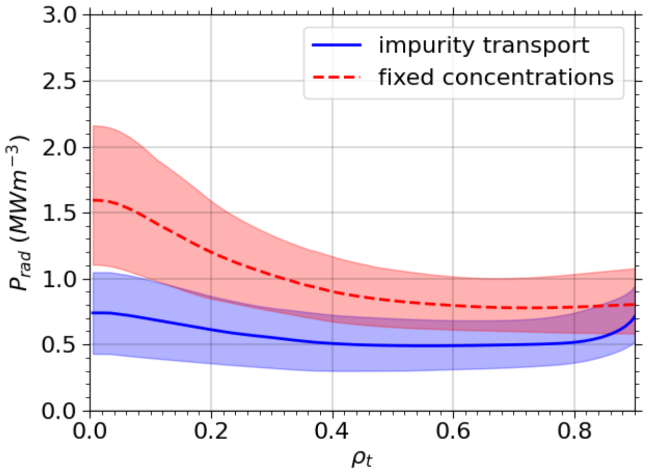
H12 $(B_t = 12.2T,\ I_p = 6.5MA)$



[8] Fajardo NF 2025

Impurity transport validates simulations with fixed concentrations

- Exceptional agreement of Q, scanning n_{top} and P_{ICRH}
- → valid for all the H-modes analyzed, spanning different I_p, B_t
- Small deviation of $f_{LH} = {}^{P_{sep}}/_{P_{LH}}$ caused by different radiation contributions, due to:
  - minor deviations of impurity densities
  - simplified formulae used in the simulations without STRAHL



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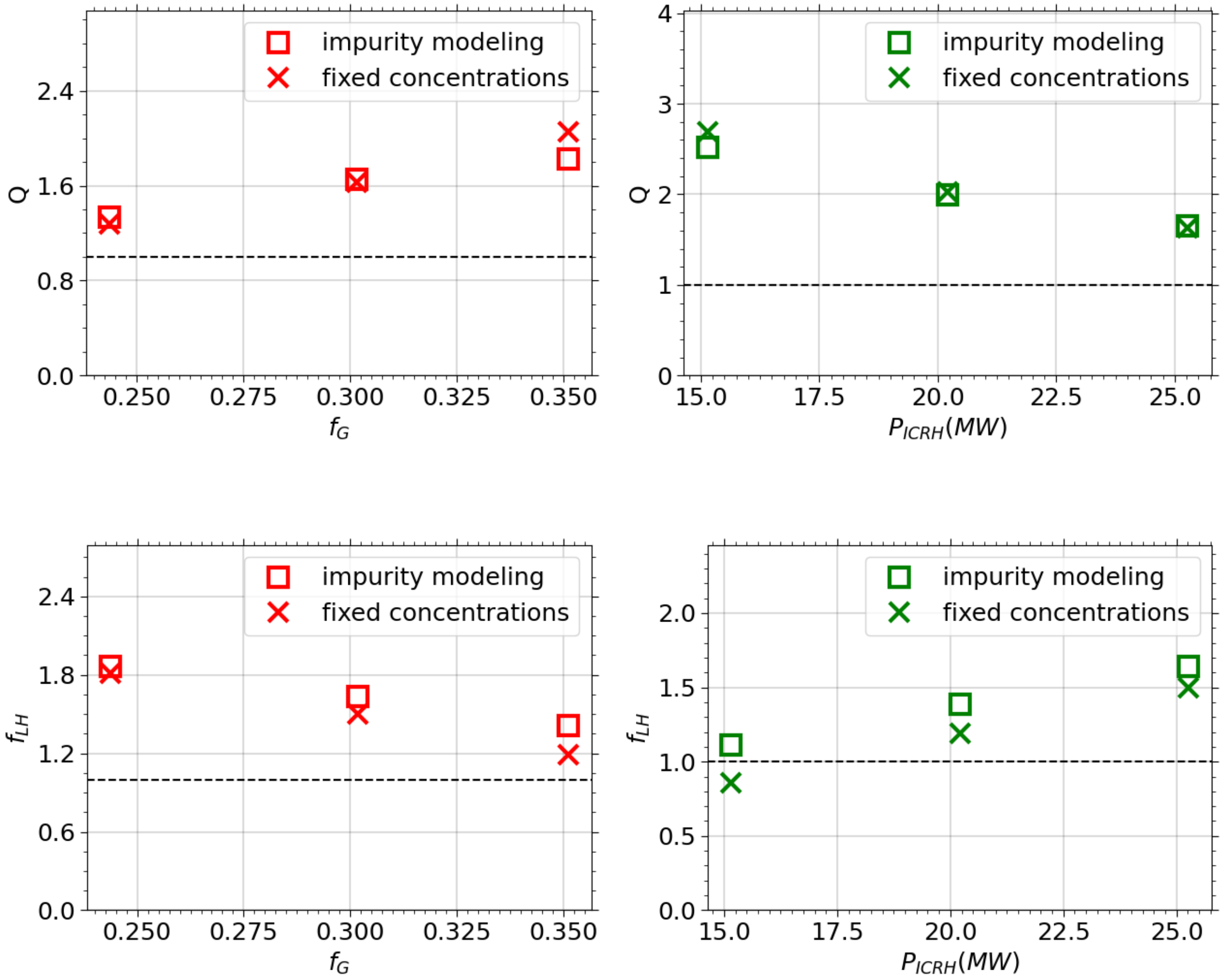
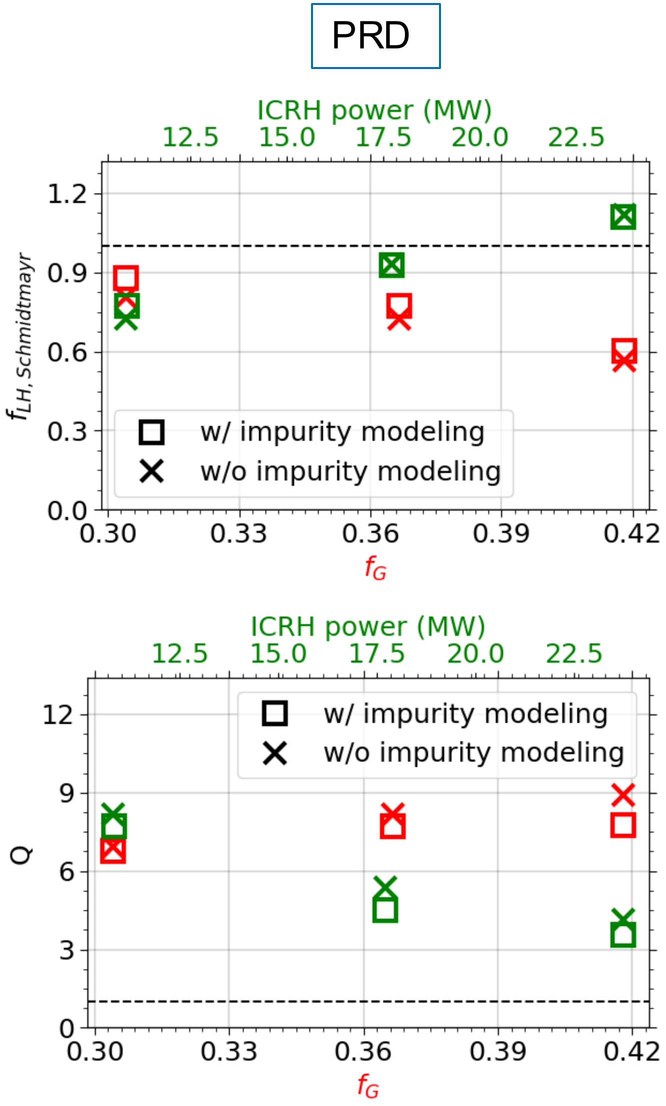
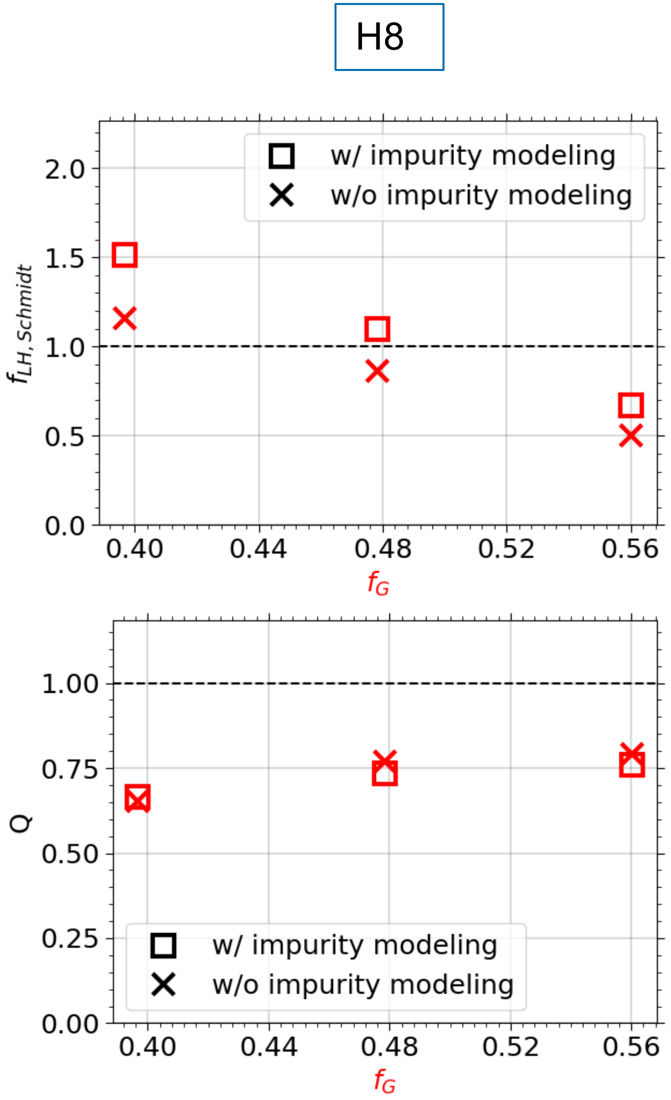
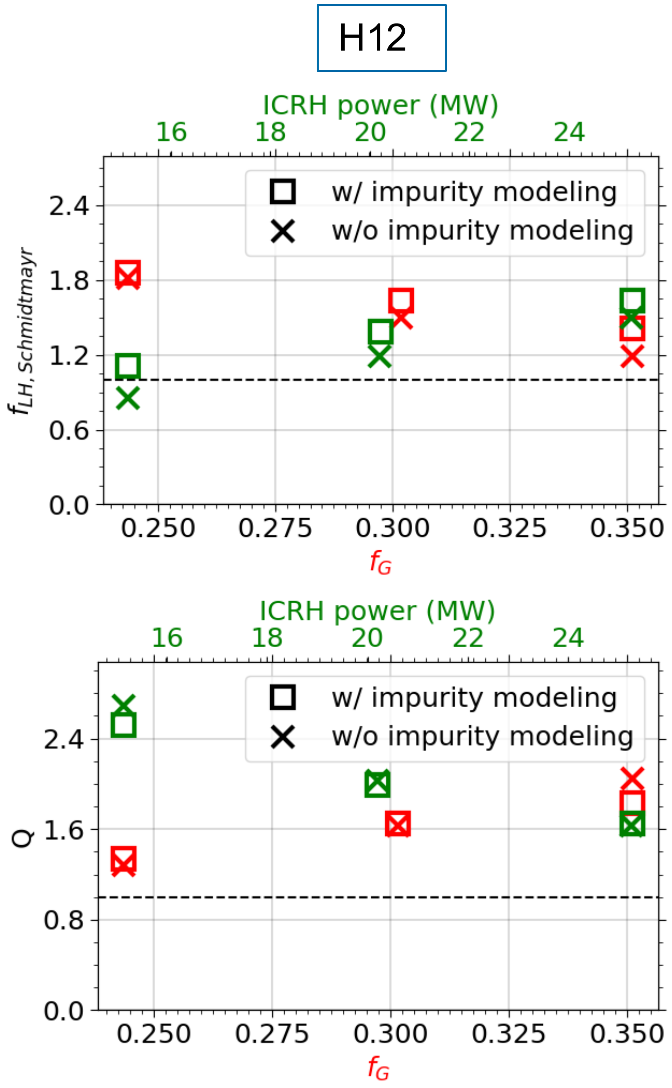


Benchmark of simulations including impurity transport

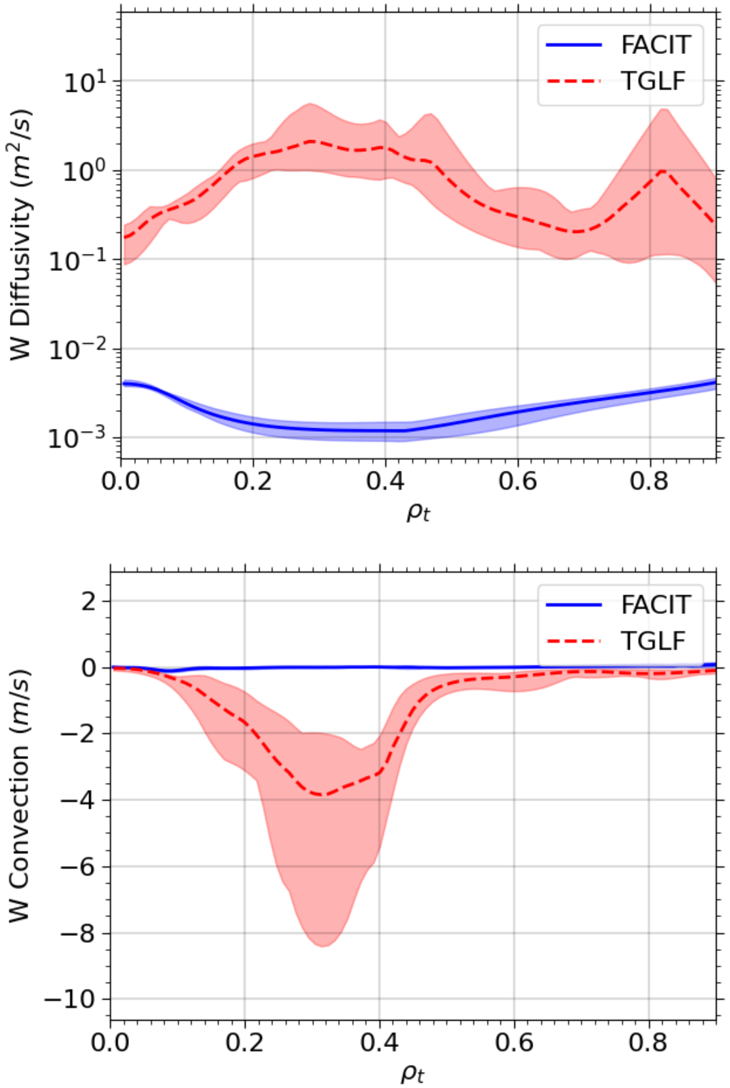




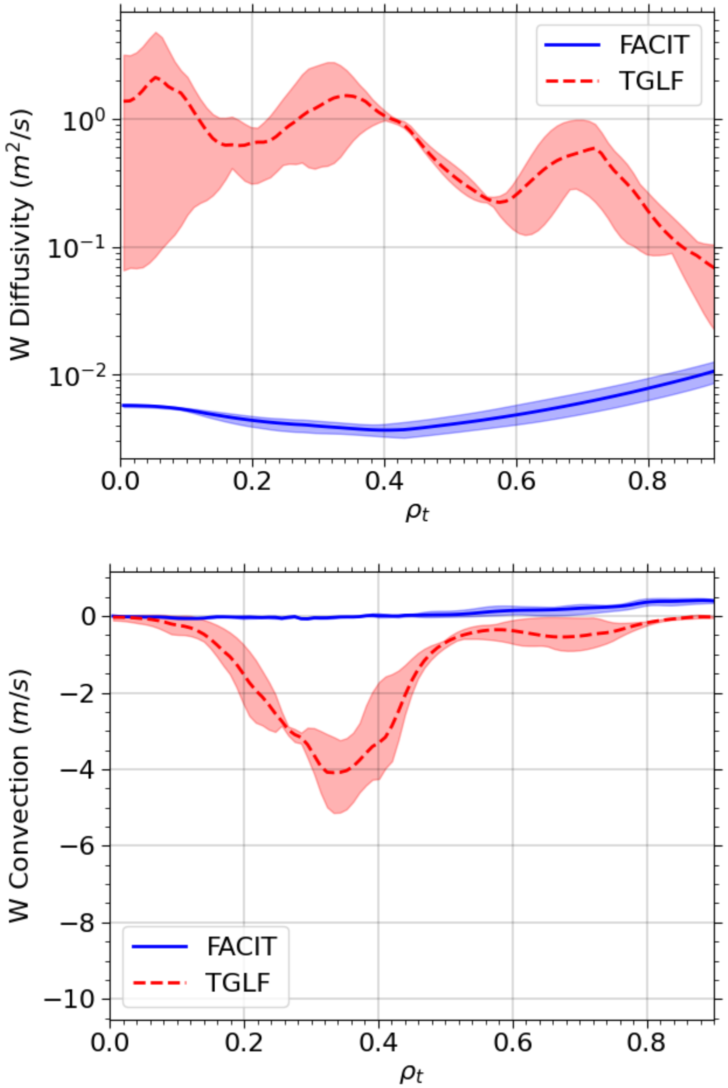


W diffusivities and convections for PRD and H8

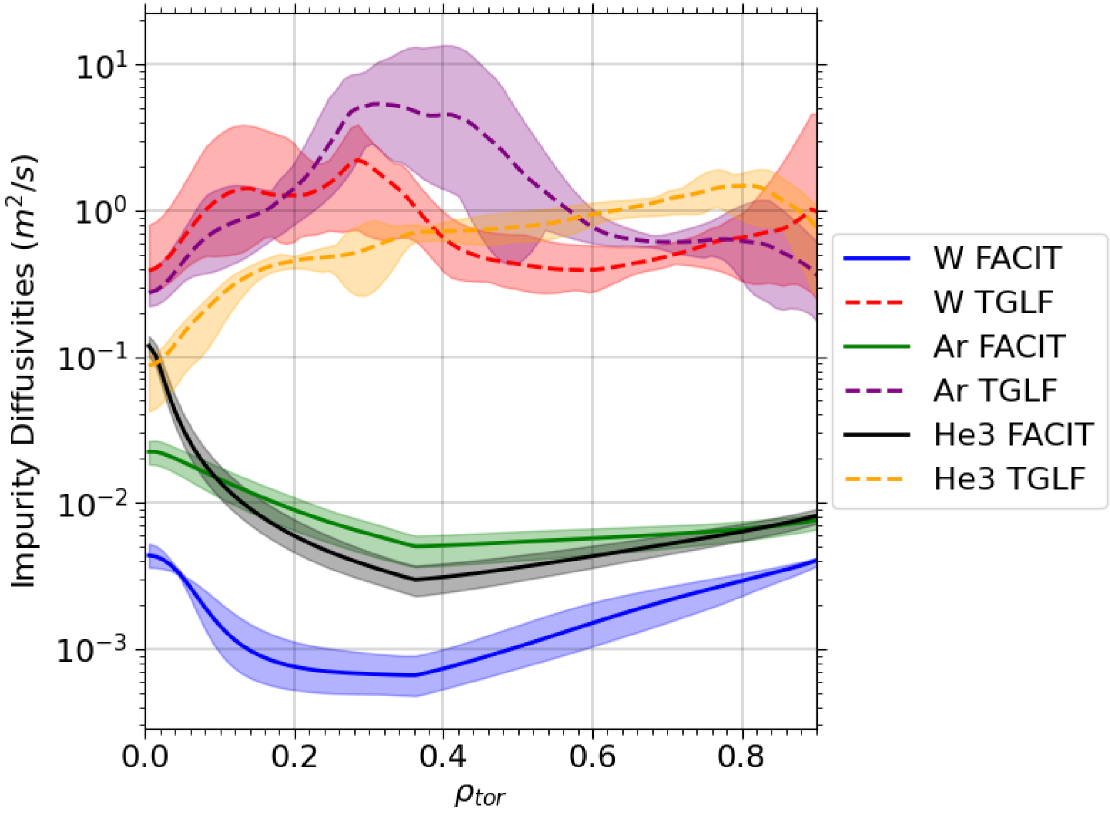
PRD

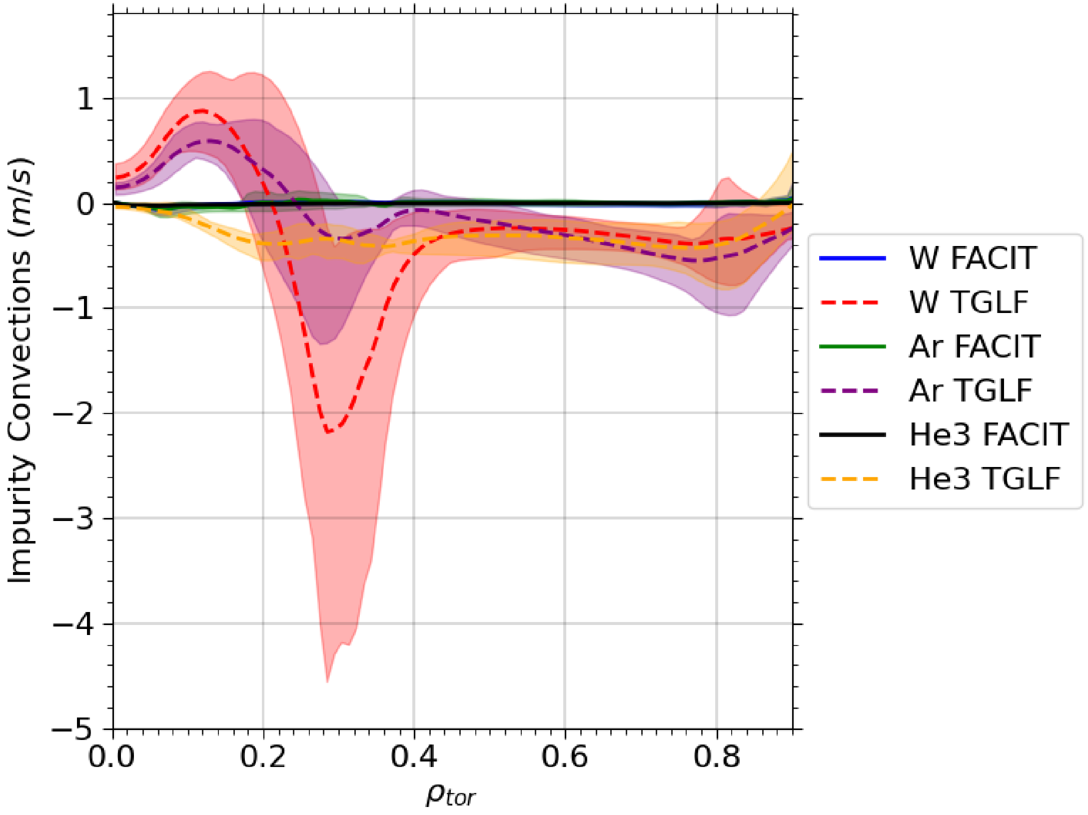


H8

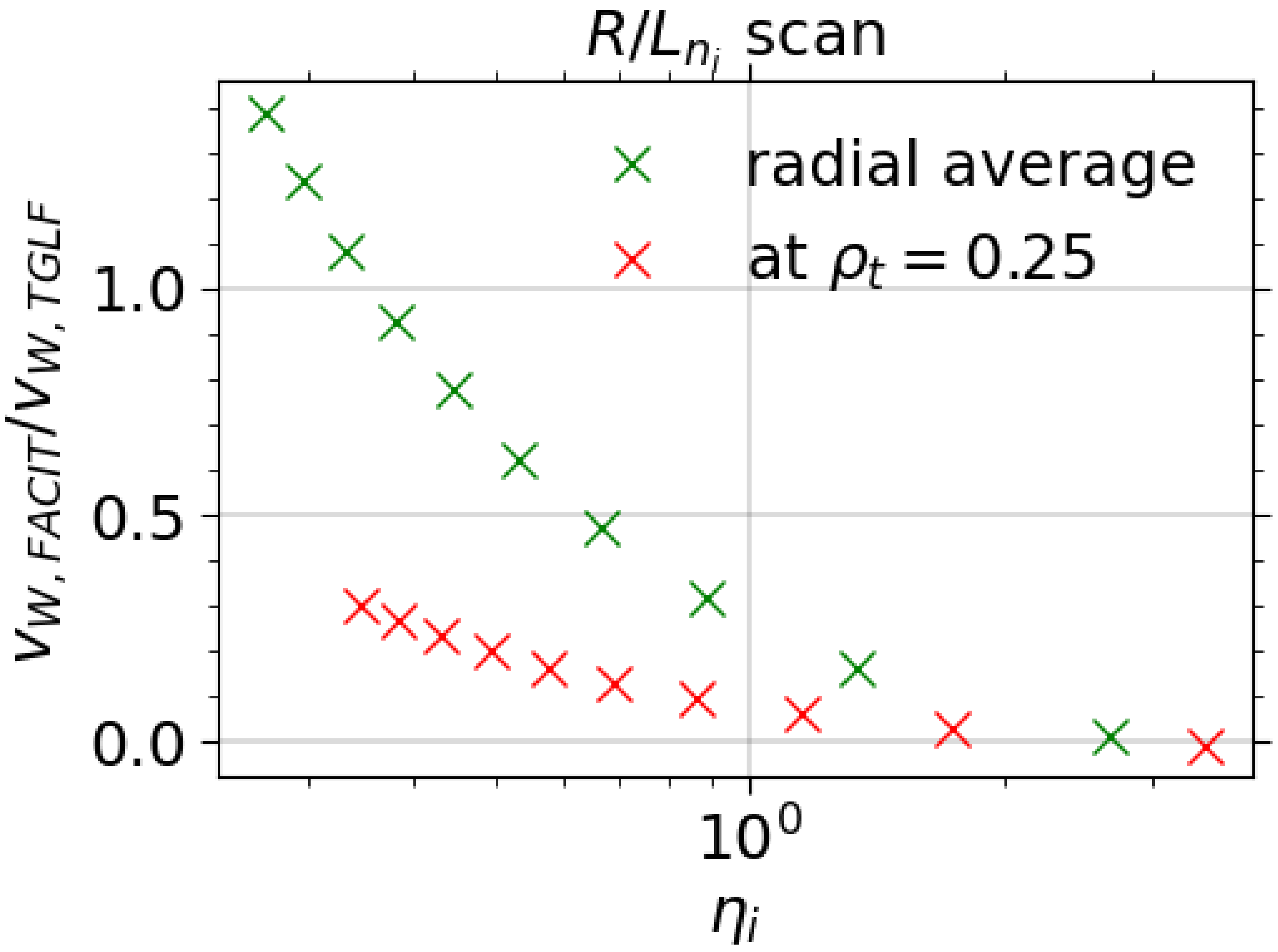


H12: diffusivities and convections of W, Ar and He3

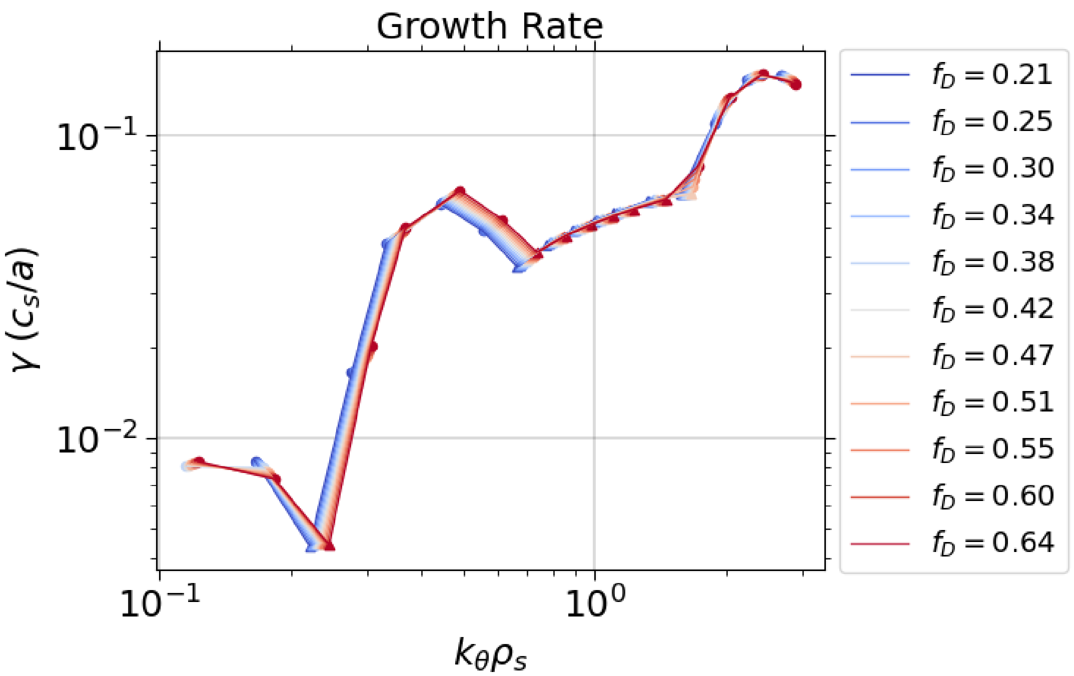


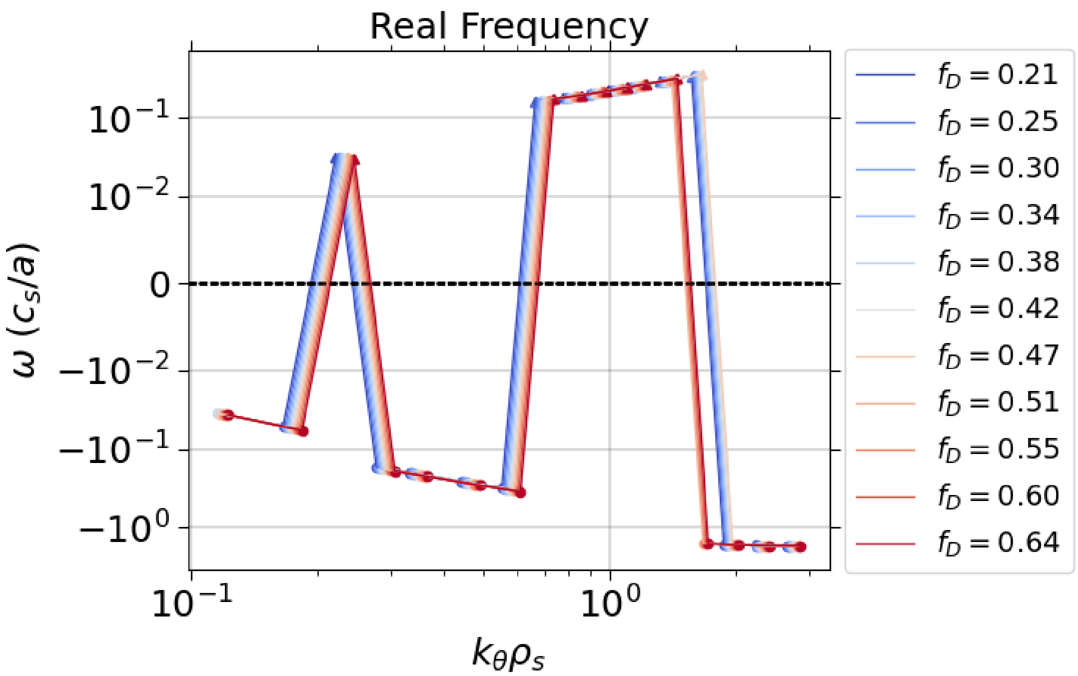


Sensitivity study of FACIT



Spectra of standalone TGLF scan in D concentration





H12: $u_{\parallel}$ profile for $u_{\parallel,edge}$ scan