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Core tungsten transport of internal transport barrier scenarios in JET with Be/W wall

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See the author list of C. F. Maggi et al. 2024 Nucl. Fusion **64 112012*
[$]*See the author list of N. Vianello et al. 2026 Nucl. Fusion in press [https://doi.org/10.1088/1741-4326/ae71ec]*

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Motivation

- Tungsten (W) is a leading candidate for plasma-facing components in next generation tokamaks

- However, it is also one of the most efficient radiators in the temperature range relevant for burning plasmas [*Pütterich NF 2019*]

- Avoiding W accumulation in the core plasma will be vital for successful operations

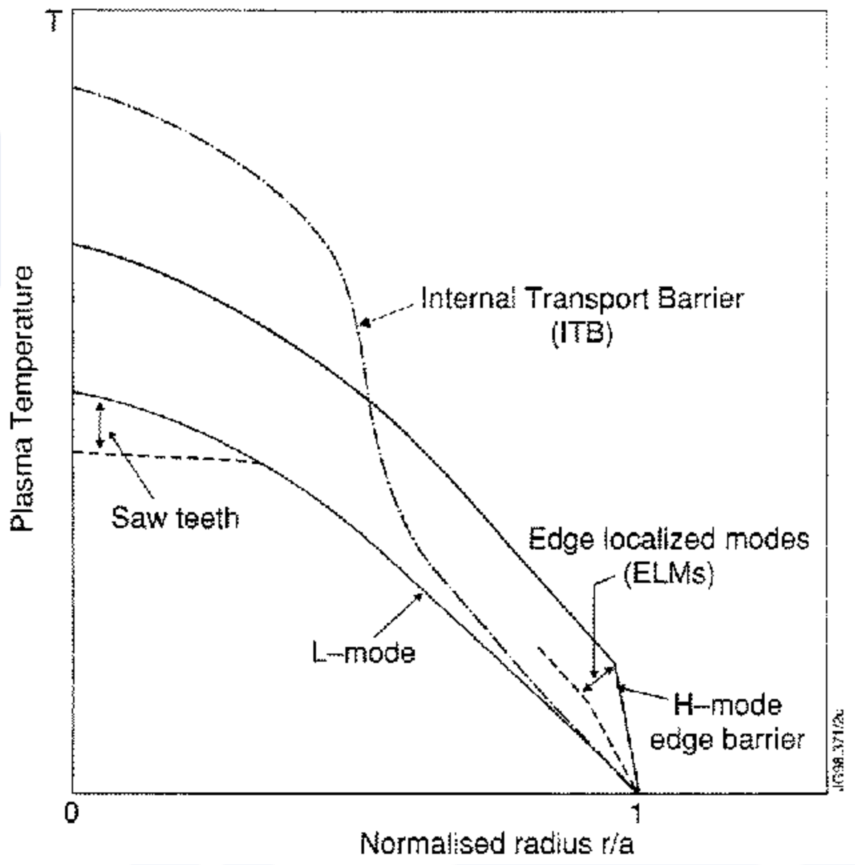
- Previous analysis of JET-ILW (Be/W wall) hybrid scenarios demonstrated peripheral W screening in D/D-T plasmas [*Field NF 2023, Field NF 2026*]

For detailed overview of W transport in tokamaks, **see C. Angioni plenary talk Thursday PM**

Motivation – Internal transport barriers

Spontaneous ITB formation may occur in burning plasma scenarios → Motivates investigation of the impact of ITBs on core W transport in JET-ILW

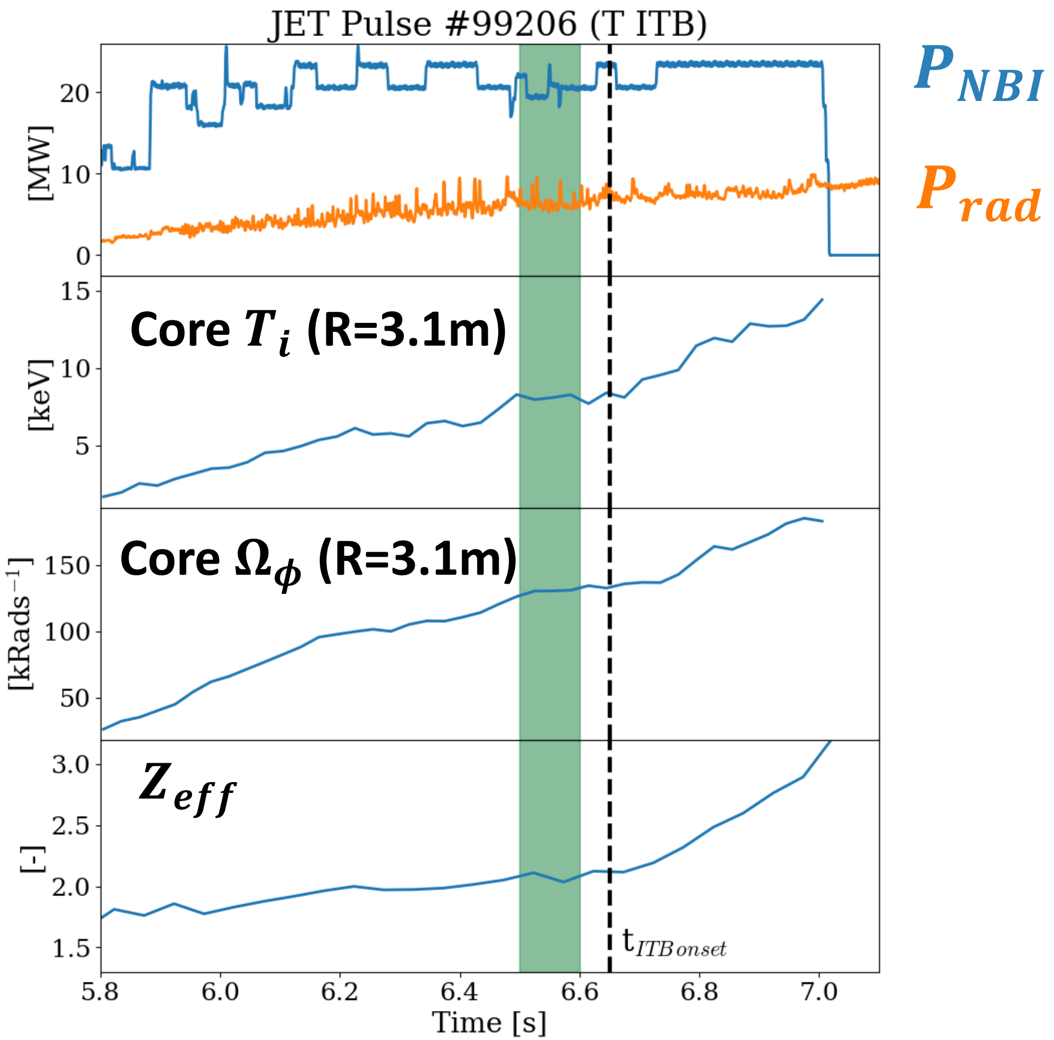
- An internal transport barrier (ITB) refers to localised regions in the core plasma where a strong reduction in transport is observed, improving core confinement [*Connor NF 2004*]
- Studies in JET-C found core impurity accumulation with ITB plasmas due to inward impurity pinch inside ITB [*Chen NF 2001, Dux NF 2004*]
- Impurity peaking found to increase with impurity charge (C, Ne, Ni)

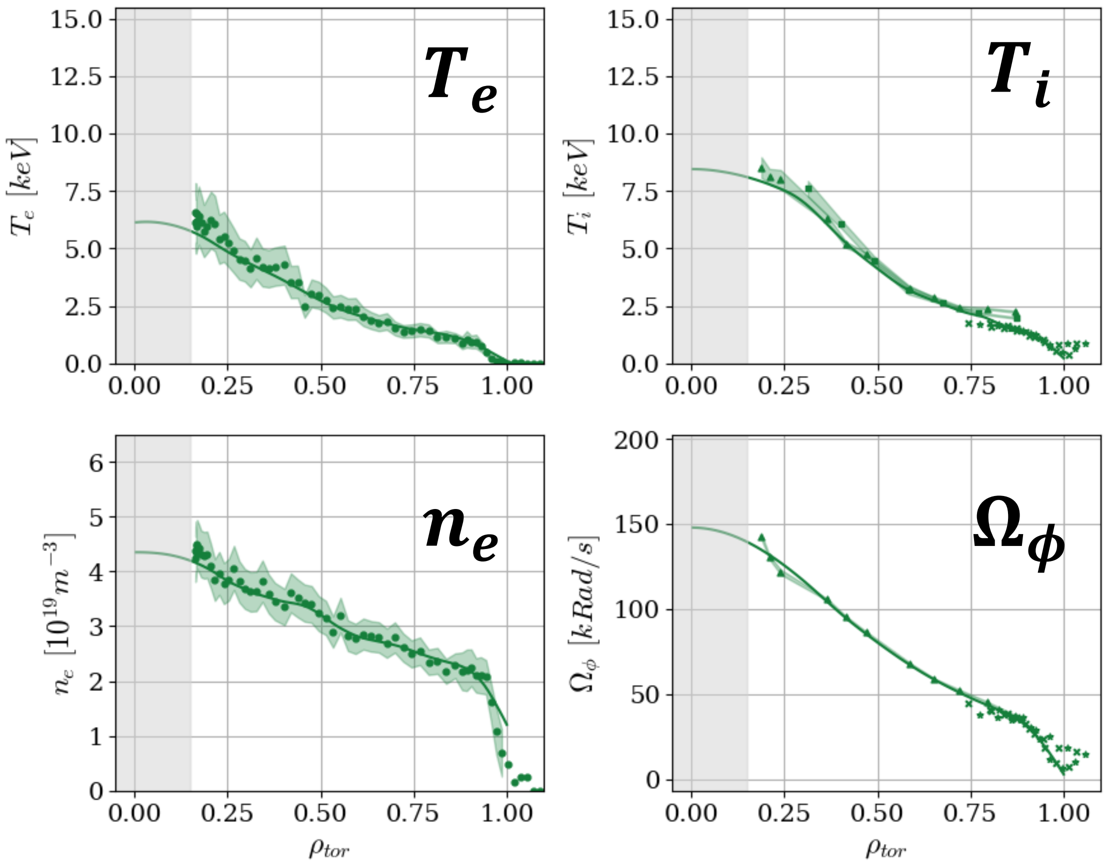


[*Jacquinot PPCF 1999*]

#99206: JET-ILW ITB scenario in T plasma

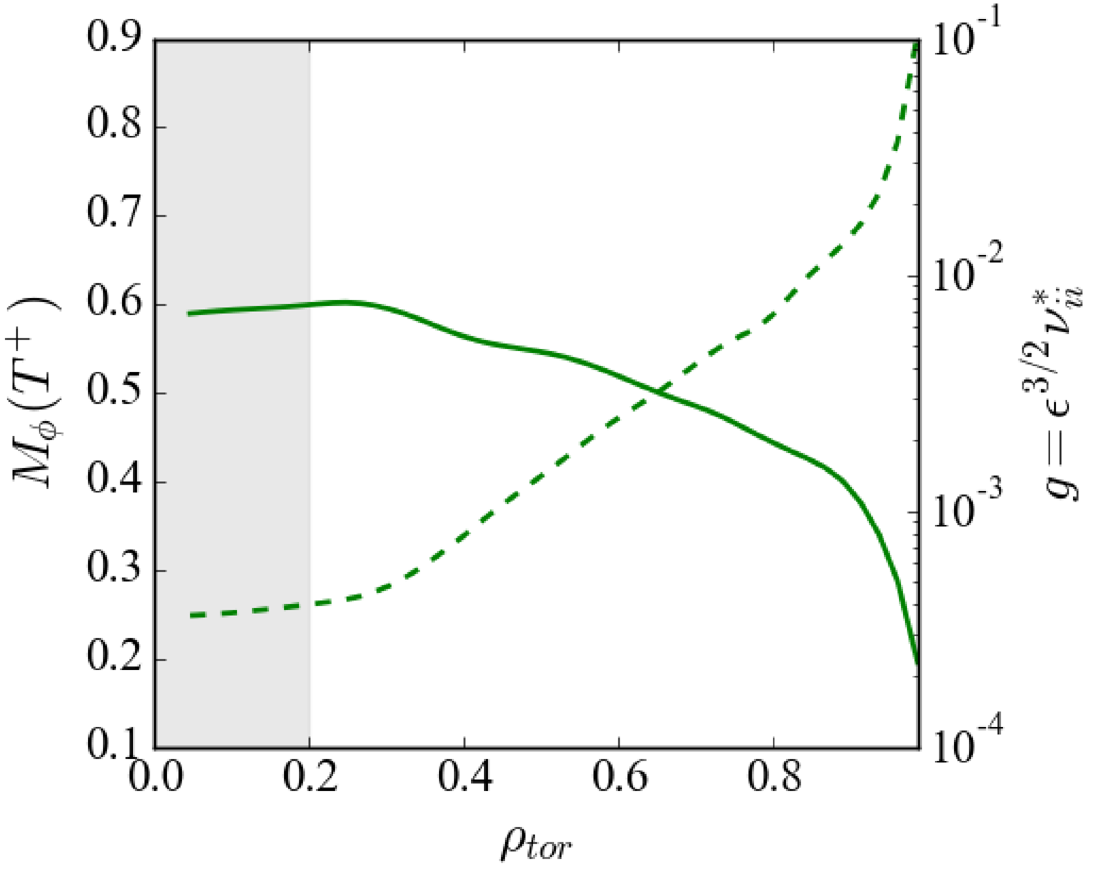
ITB scenario in T plasma, NBI heating only ~23MW (3.4T/2.8MA) *[Maggi FEC 2025]*

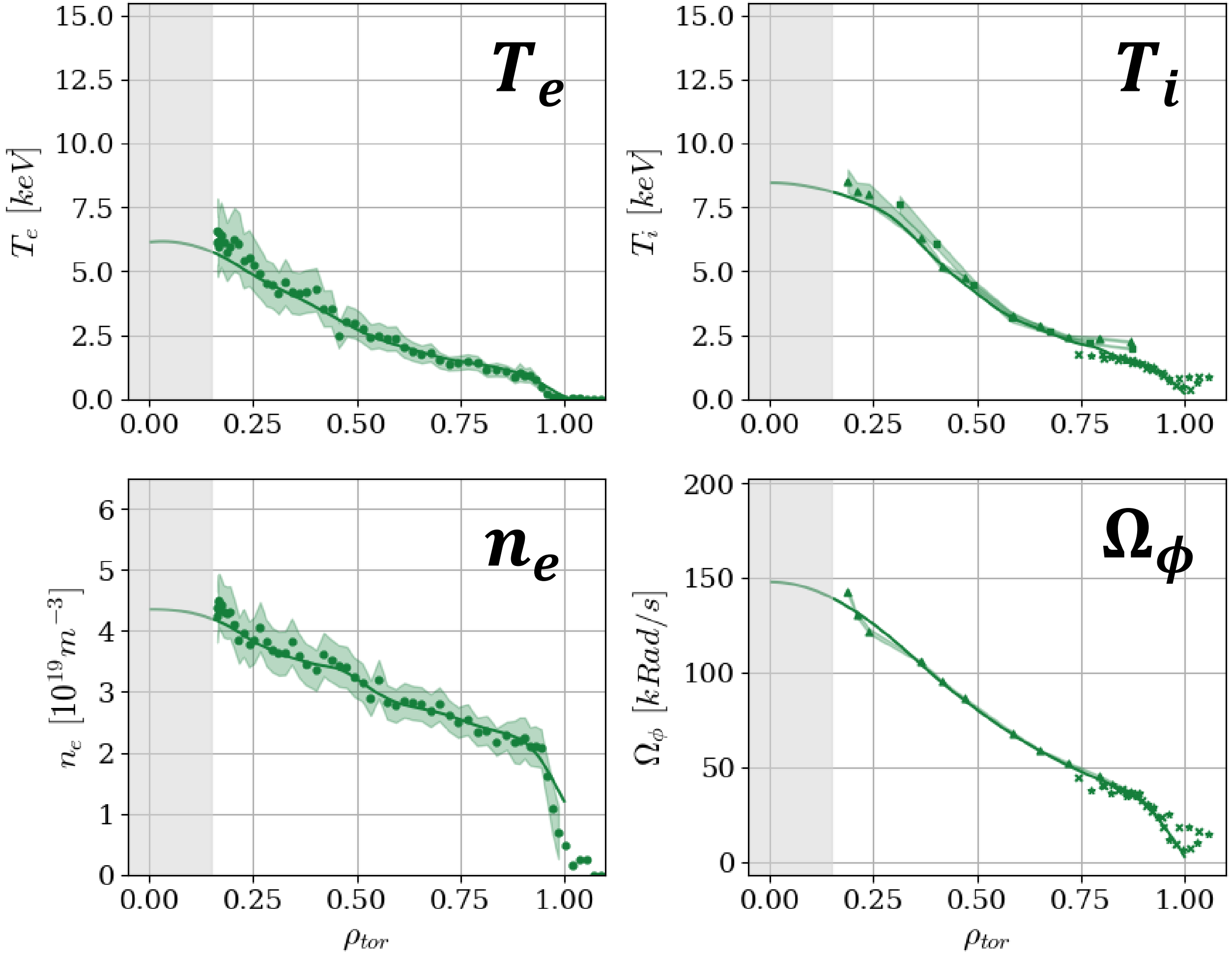




No ITB phase→ 6.5 – 6.6s

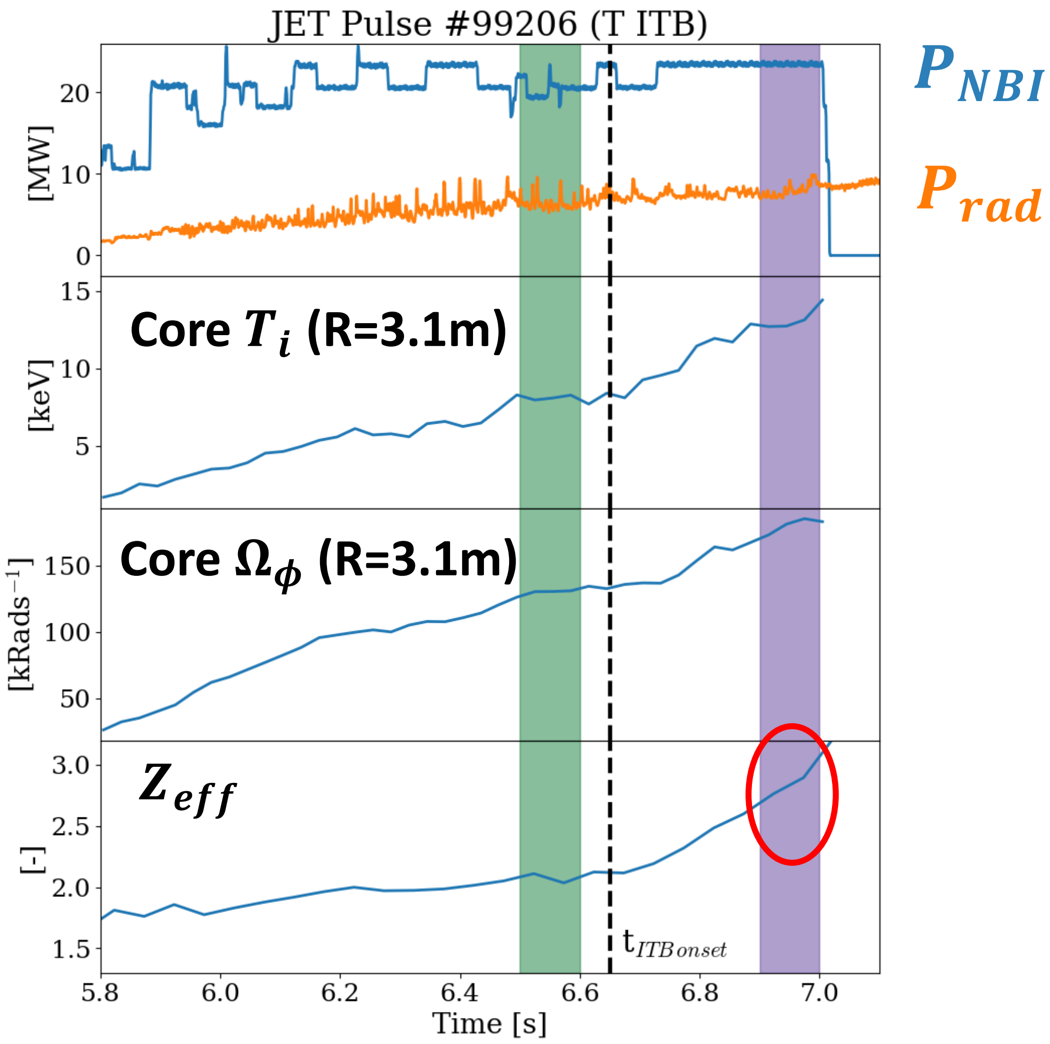
#99206 – no ITB phase: Plasma with high Mach number, low collisionality

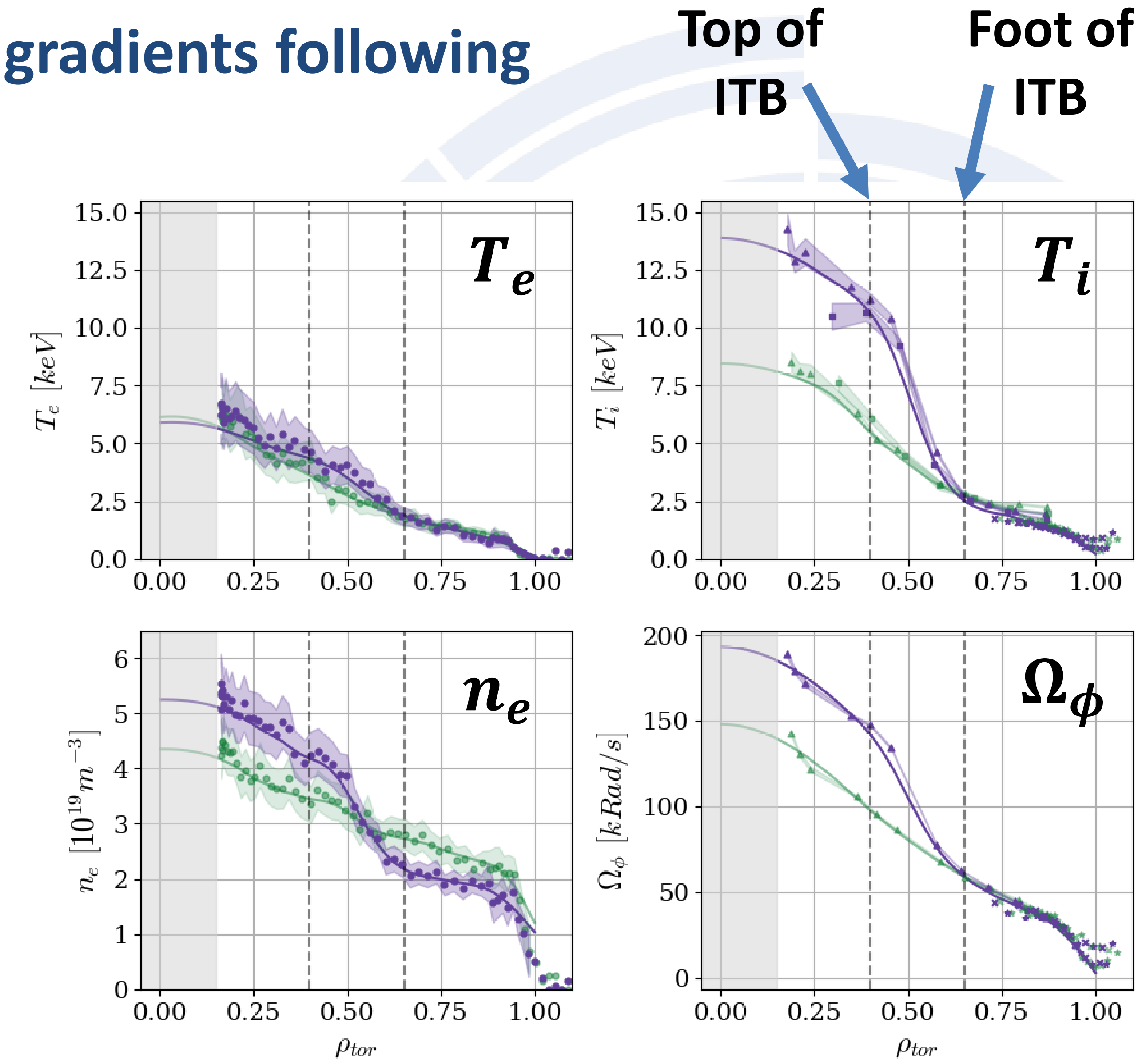




No ITB phase→ 6.5 – 6.6s

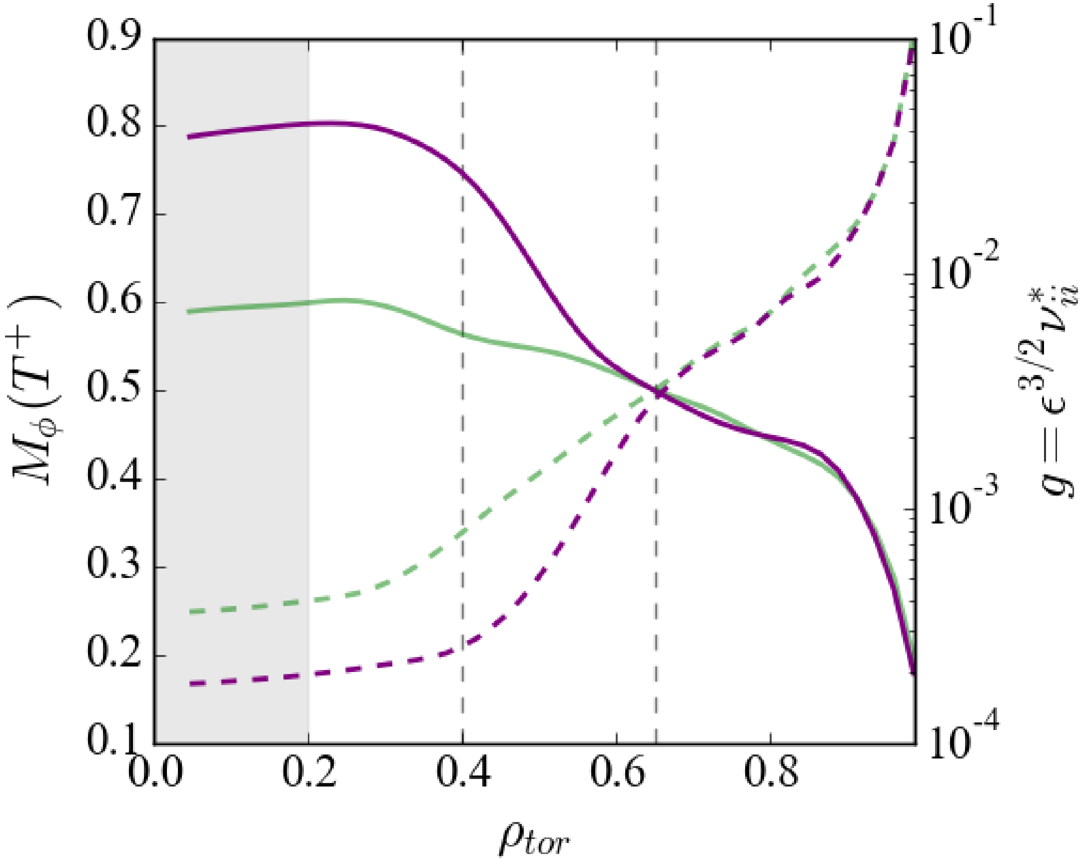
#99206 – strong ITB phase: Steep gradients following ITB formation





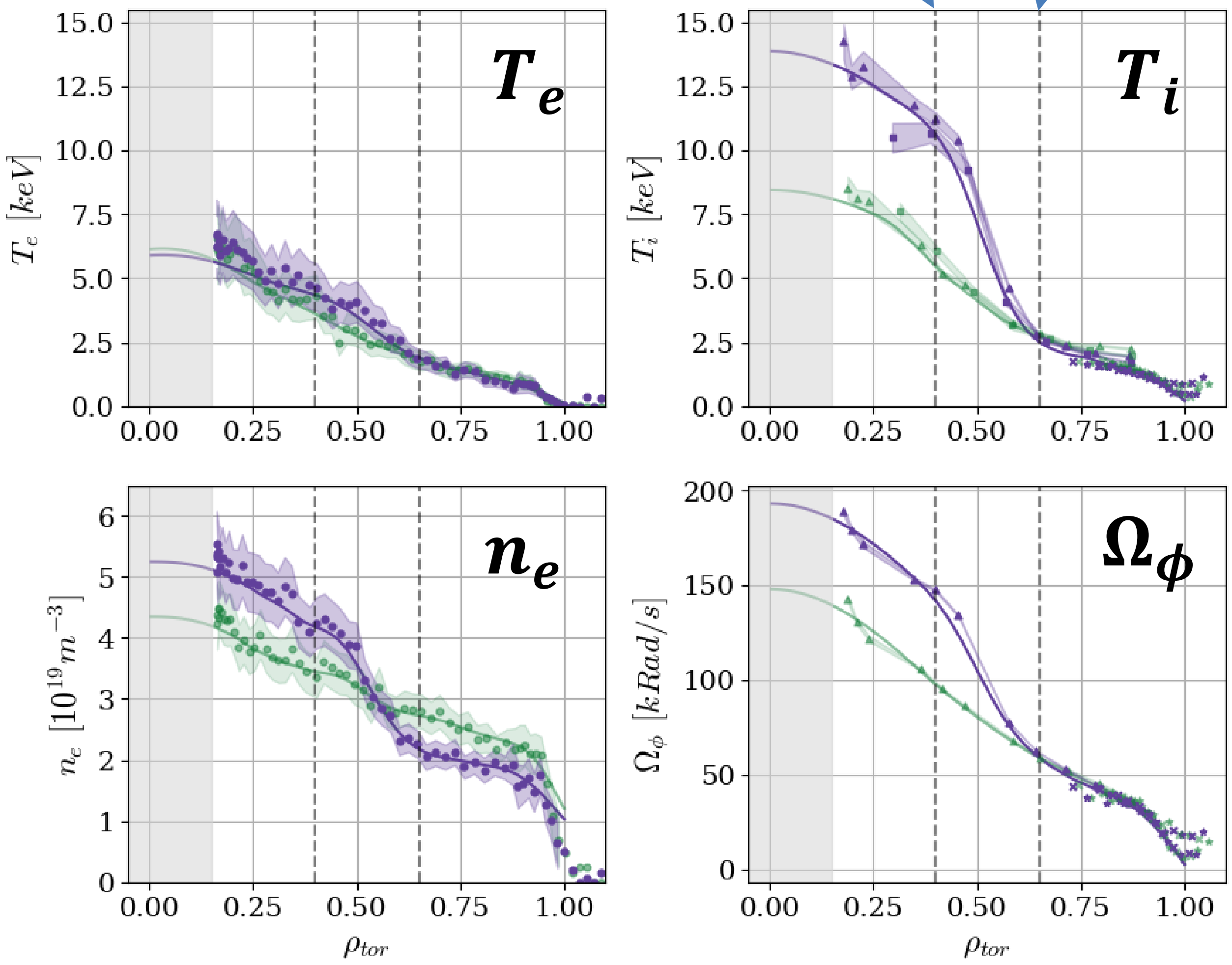
Strong ITB phase → 6.9 – 7.0s

#99206 – strong ITB phase: Further increase to Mach number and decrease in collisionality



Top of ITB

Foot of ITB

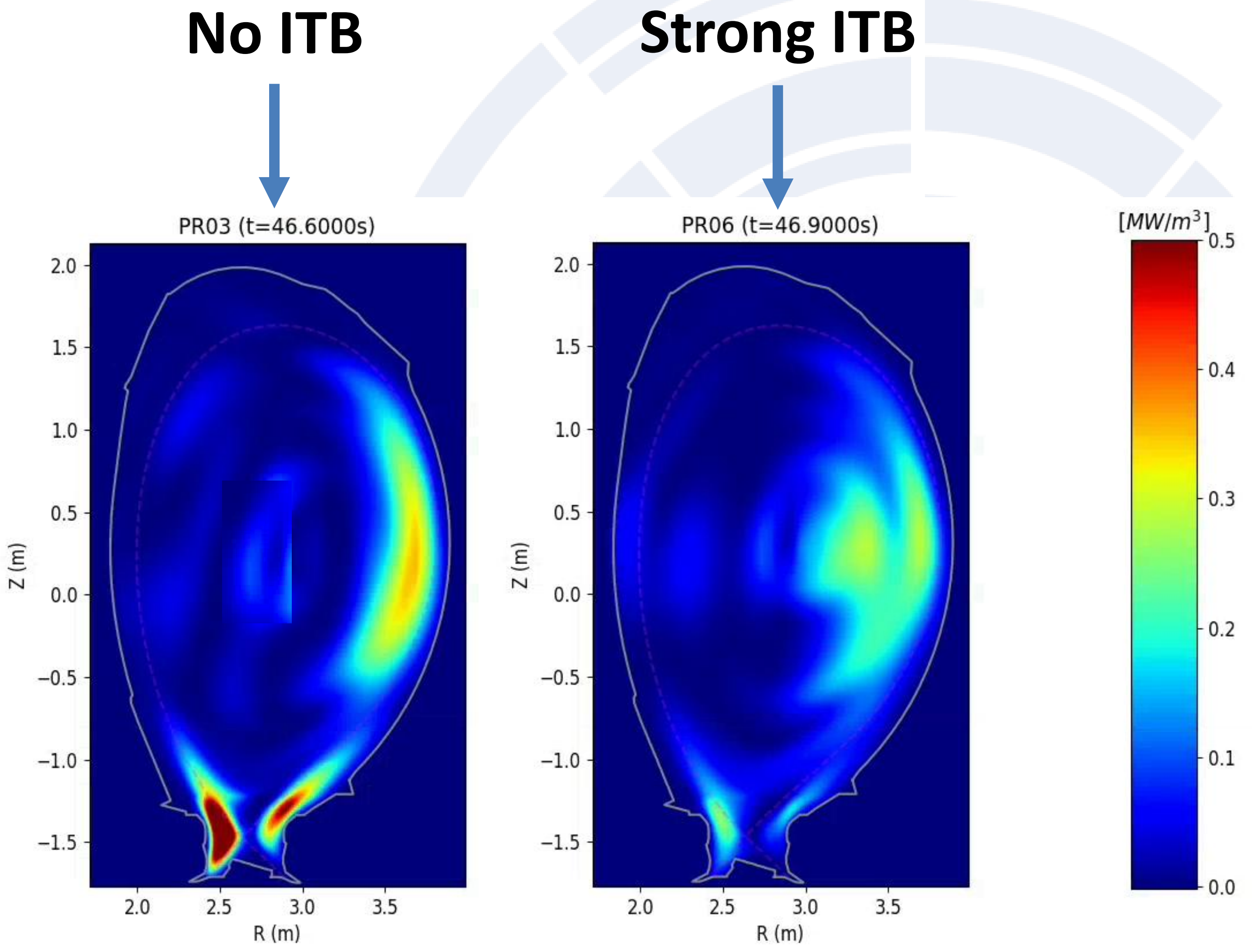


Strong ITB phase → 6.9 – 7.0s

99206 – Bolometry tomographic reconstruction

- **No ITB** – Prominent radiation peak on LFS, highlighting poloidal asymmetries of W transport [*Casson NF 2020*]
- **Strong ITB** – Second radiation peak grown radially inwards, inside foot of ITB
- Analysis of VUV spectra indicates W dominates emissivity

  $\rightarrow \; \epsilon_{tot} \sim \epsilon_W$



99206 – Total bolometry emissivity ϵ_{tot} at LFS midplane

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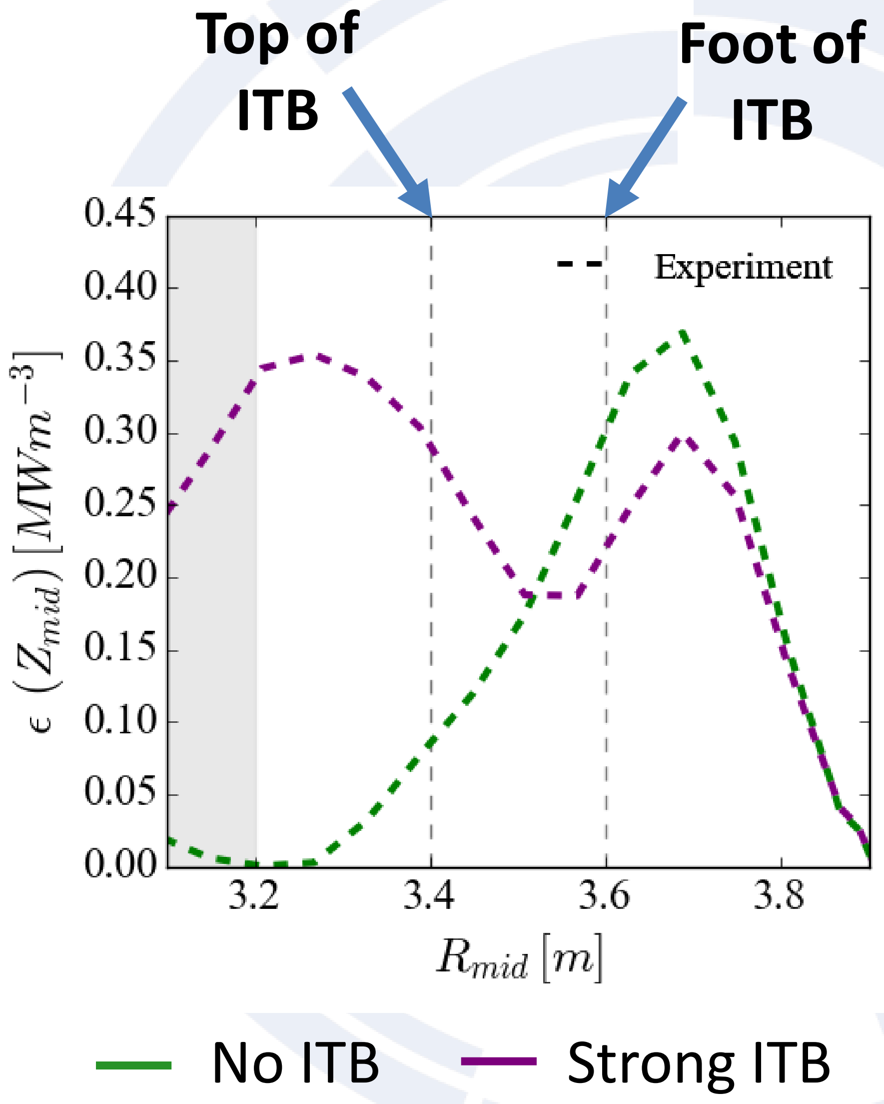


Neoclassical Transport

- Neoclassical transport is expected to dominate inside the ITB, where turbulent transport is supressed
- Literature often quotes $C_{TS} \sim 0.5$ → i.e. main ion collisionless, impurities collisional
- Recent studies have found the value of C_{TS} to vary in **both magnitude and sign** depending on the collisionality regime and toroidal rotation of the plasma *[Fajardo PPCF 2023]*
- This analysis uses the drift kinetic code NEO, which contains this important physics *[Belli & Candy PPCF 2008, 2009, 2012]*

Diffusive term — Convective terms

$$\frac{\Gamma_Z}{n_Z} = -\frac{D_Z}{L_{n_Z}} + \frac{H_Z}{L_{T_i}} + \frac{K_Z}{L_{n_i}}$$

$$V_Z \propto C_{TS}\left(\frac{R}{L_{T_i}}\right) - \frac{R}{L_{n_i}}$$

Screening parameter

$$C_{TS} = -\frac{H_Z}{K_Z}$$

NEO modelling setup

Unique aspect of this pulse is high line averaged Z_{eff} measured from visible Bremsstrahlung

→ Plasma composition, impurity-impurity collisions becomes important

However, obtaining accurate concentrations profiles of low Z (Be) and mid Z (Ni, Mo) impurities in the plasma has proved quite challenging

→ Assume flat Z_{eff} profile, with $Z_{eff} \sim 2.2$ (no ITB) and $Z_{eff} \sim 2.7$ (Strong ITB)

Investigate two extremities where ΔZ_{eff} from impurities is either dominated by low Z or mid Z impurity

- Low Z impurity: Beryllium (Be), enters plasma through erosion of PFCs
- Mid Z impurity: Molybdenum (Mo), interlayer beneath W coated divertor tiles

→ Mo was identified in VUV spectra as 2nd highest radiator behind W for this discharge

No ITB – Outward W convection predicted

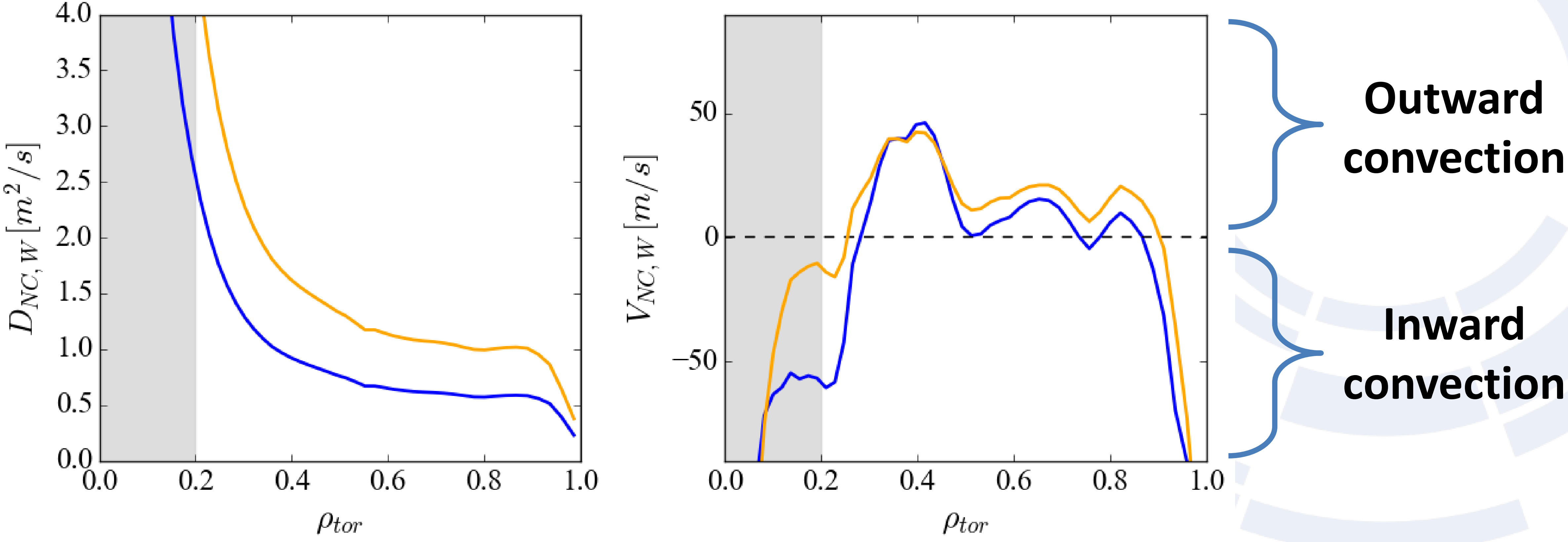
Background impurity assumption:

Low Z

Mid Z

No ITB:

- Difference in $D_{NC,W}$ profiles due to Z dependence
- $V_{NC,W}$ is directed outward for most of the plasma

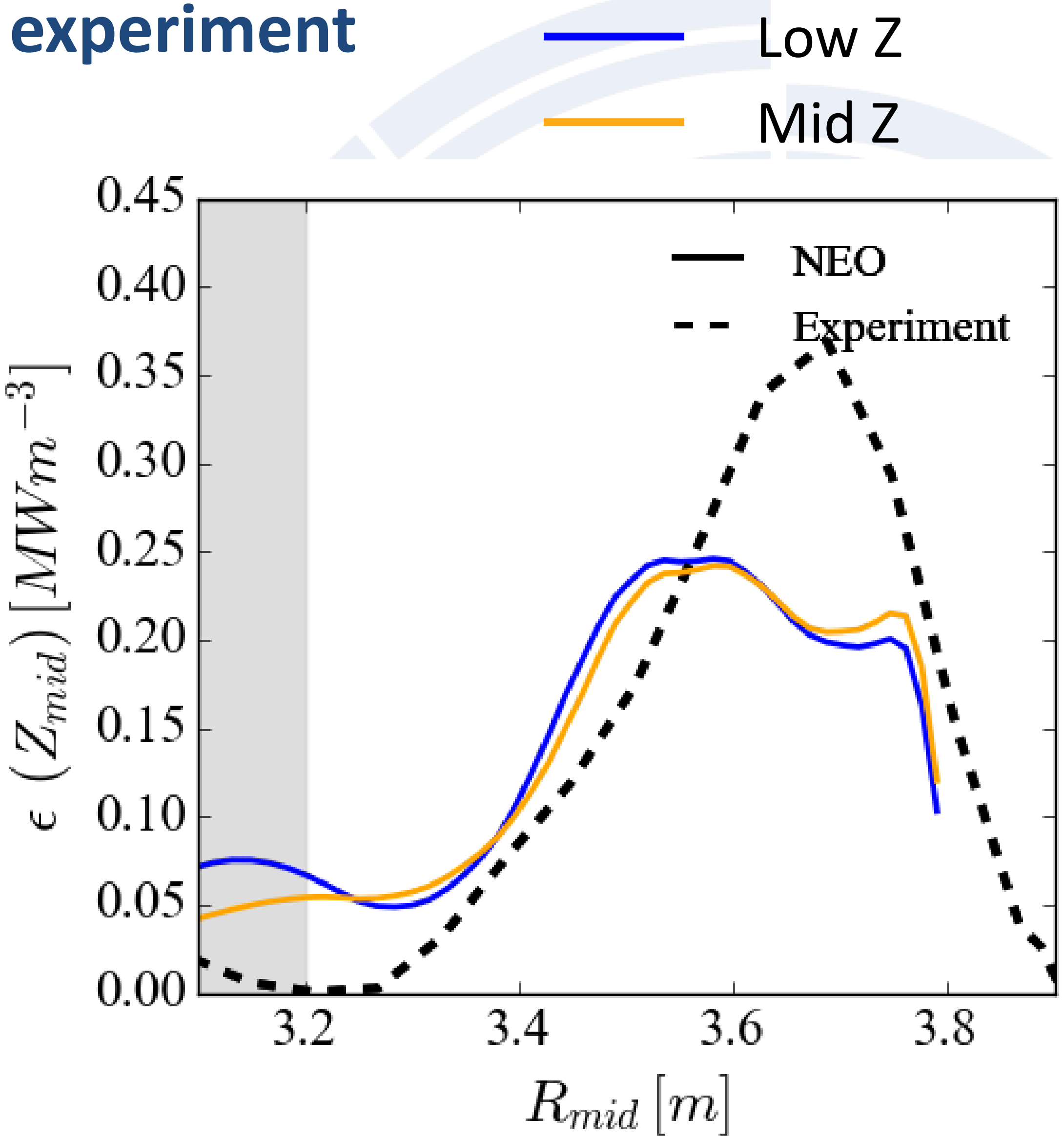


No ITB – Reasonable agreement with experiment

No ITB:

- NEO predicts emissivity profile peaks towards plasma edge

- No significant difference when changing between impurity composition of Z_{eff}



NEO ϵ_W profiles are normalised so that P_{rad} matches experiment ϵ_{tot} from bolometry

Strong ITB/Higher Z_{eff} – Larger separation in convection profiles

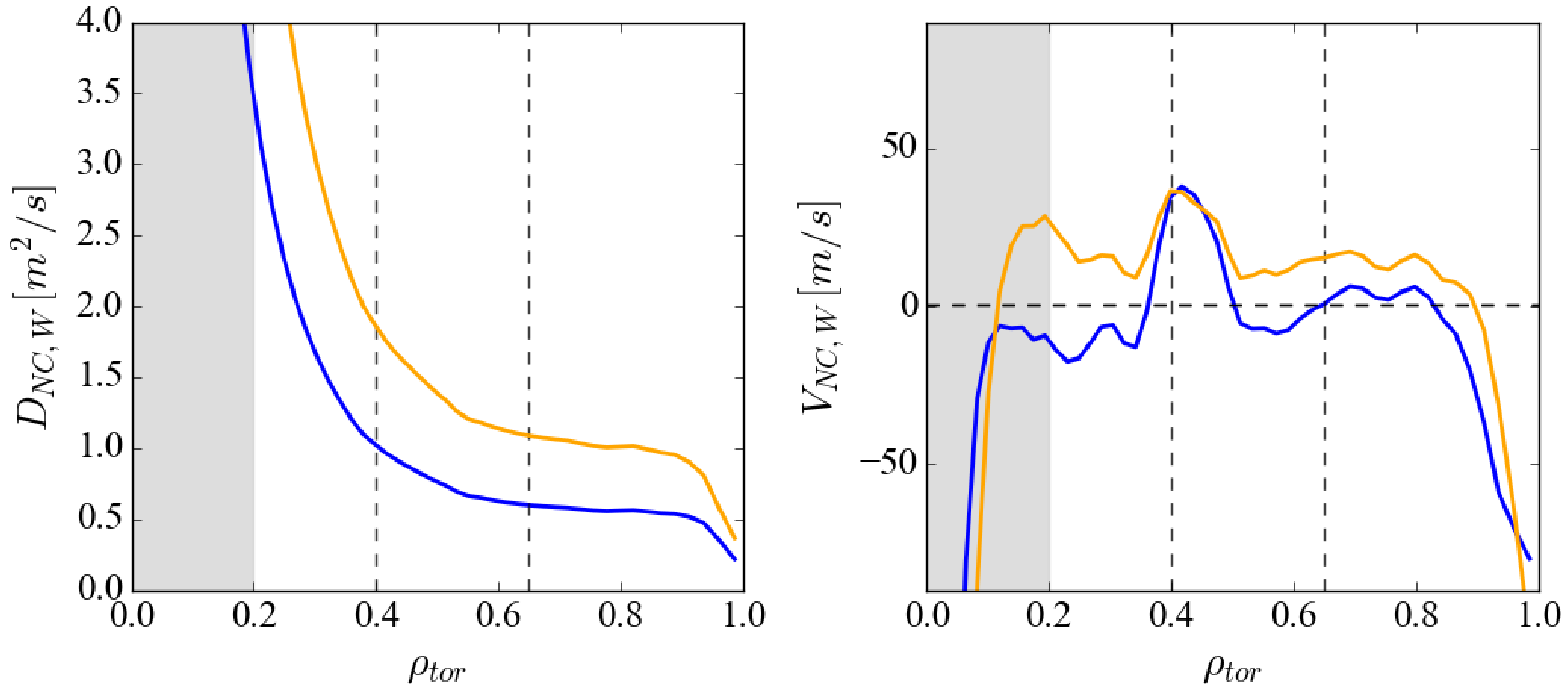
Strong ITB:

- Larger separation in $V_{NC,W}$ between cases with Z_{eff} dominated by low Z impurity vs mid Z impurity

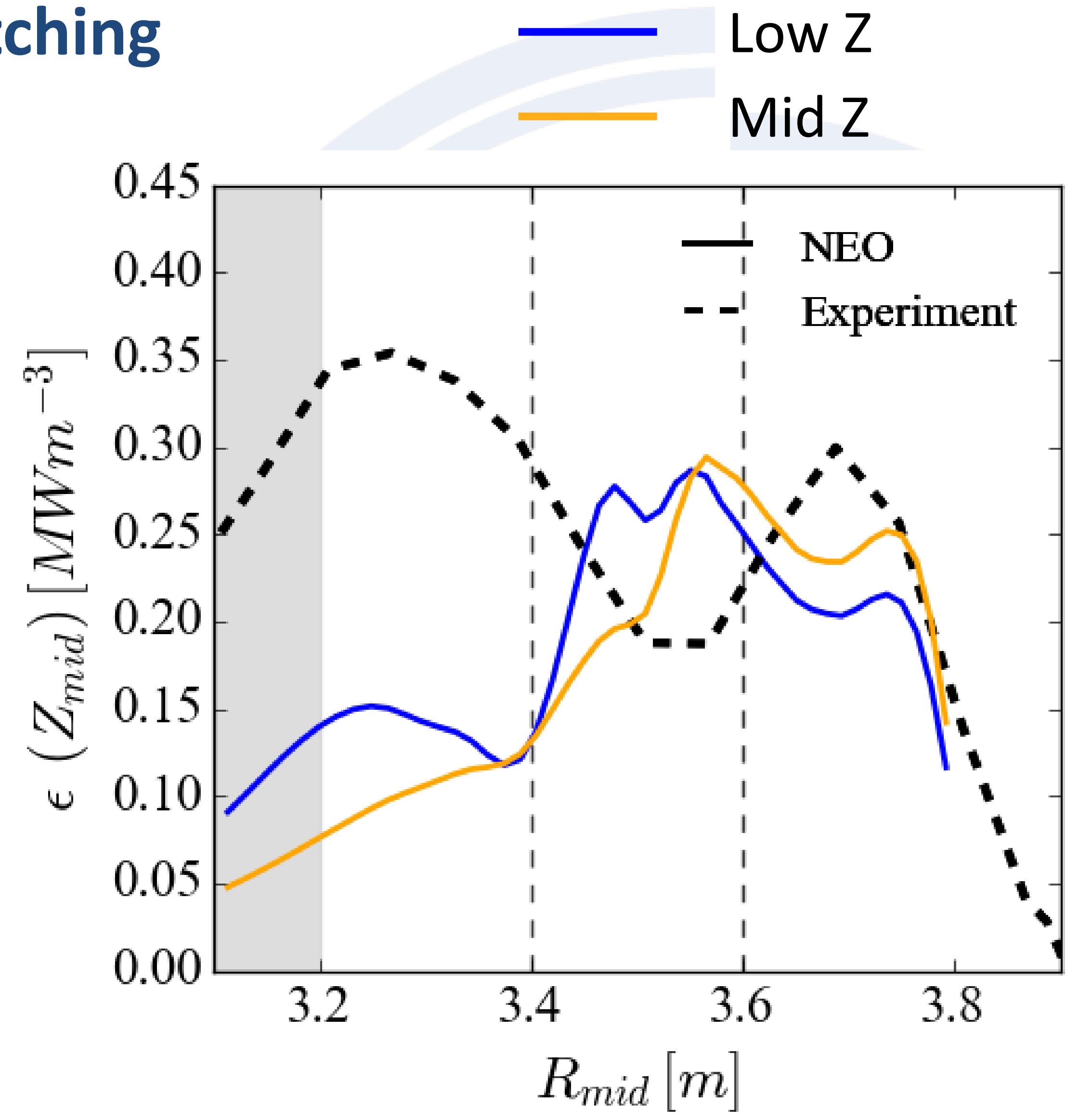
Background impurity assumption:

Low Z

Mid Z



Strong ITB/Higher Z_{eff} – Difficulty matching NEO predictions with experiment



NEO ϵ_W profiles are normalised so that P_{rad} matches experiment ϵ_{tot} from bolometry

Strong ITB:

- Neither variant can capture the formation of 2nd emissivity peak in plasma core

- Other sensitives? → **Profile gradients**

$$V_Z \propto C_{TS}\left(\frac{R}{L_{T_i}}\right) - \frac{R}{L_{n_i}}$$

Strong ITB/Higher Z_{eff} – Difficulty matching NEO predictions with experiment

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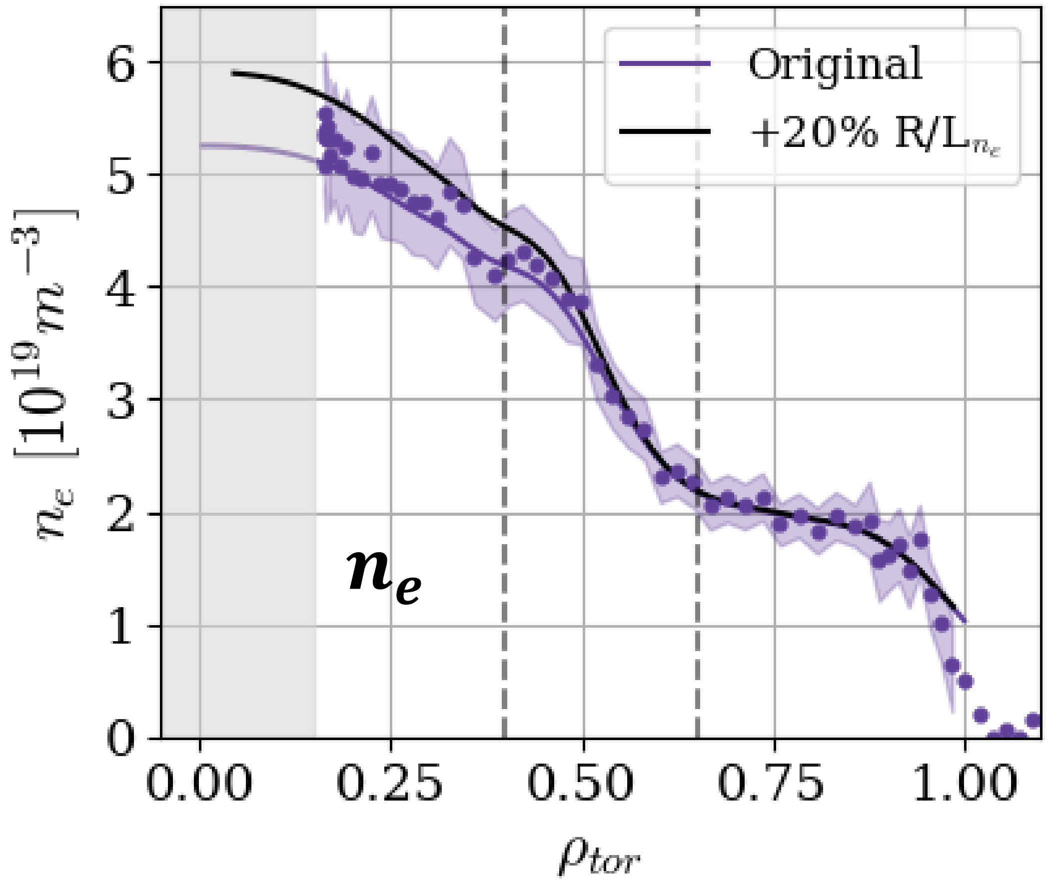
$$V_Z \propto C_{TS}\left(\frac{R}{L_{T_i}}\right) - \frac{R}{L_{n_i}}$$

Sensitivity test:

- Increase $\frac{R}{L_{n_e}}$ by 20% from foot of ITB inwards

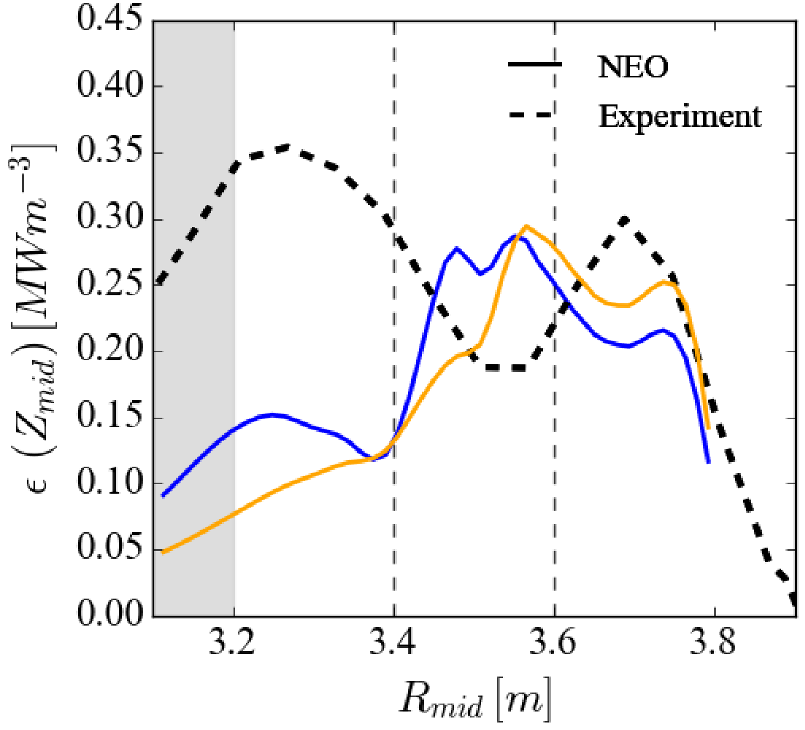
→ Pushes profile fit to upper limit of data uncertainty



Strong ITB/Higher Z_{eff} – Larger variation in predictions seen with stronger density gradient

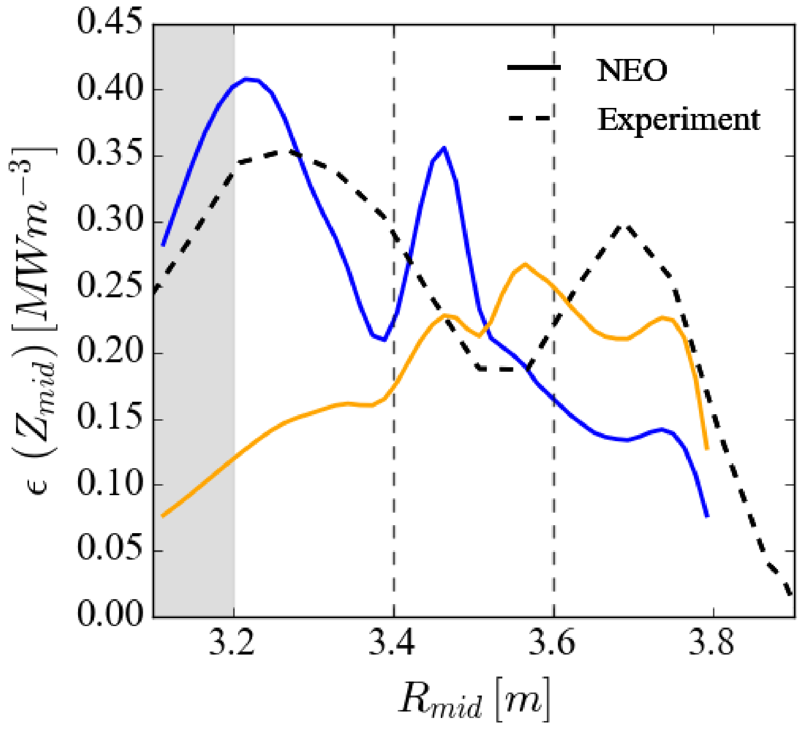
Low Z
Mid Z

Original profiles



$+20\%\ \frac{R}{L_{n_e}}$ inside ITB

Stronger n_e gradient

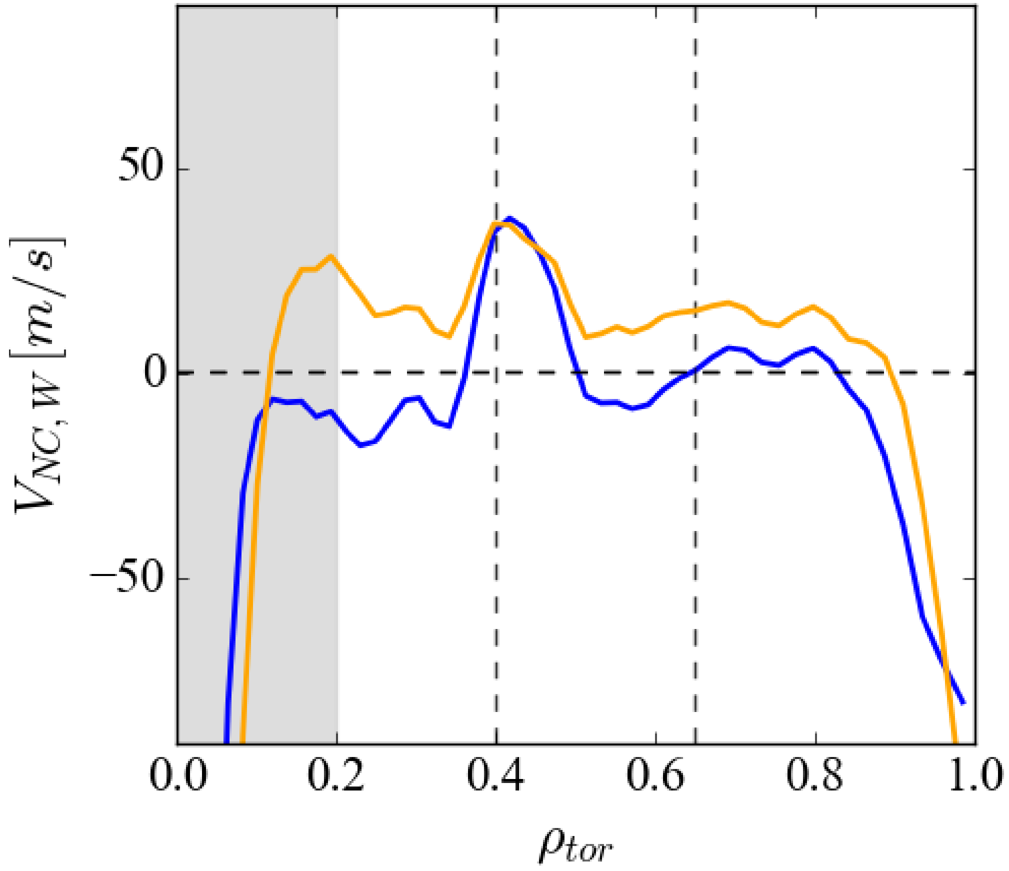


- With stronger density gradient → Larger difference in core emissivity predictions when changing background impurity composition

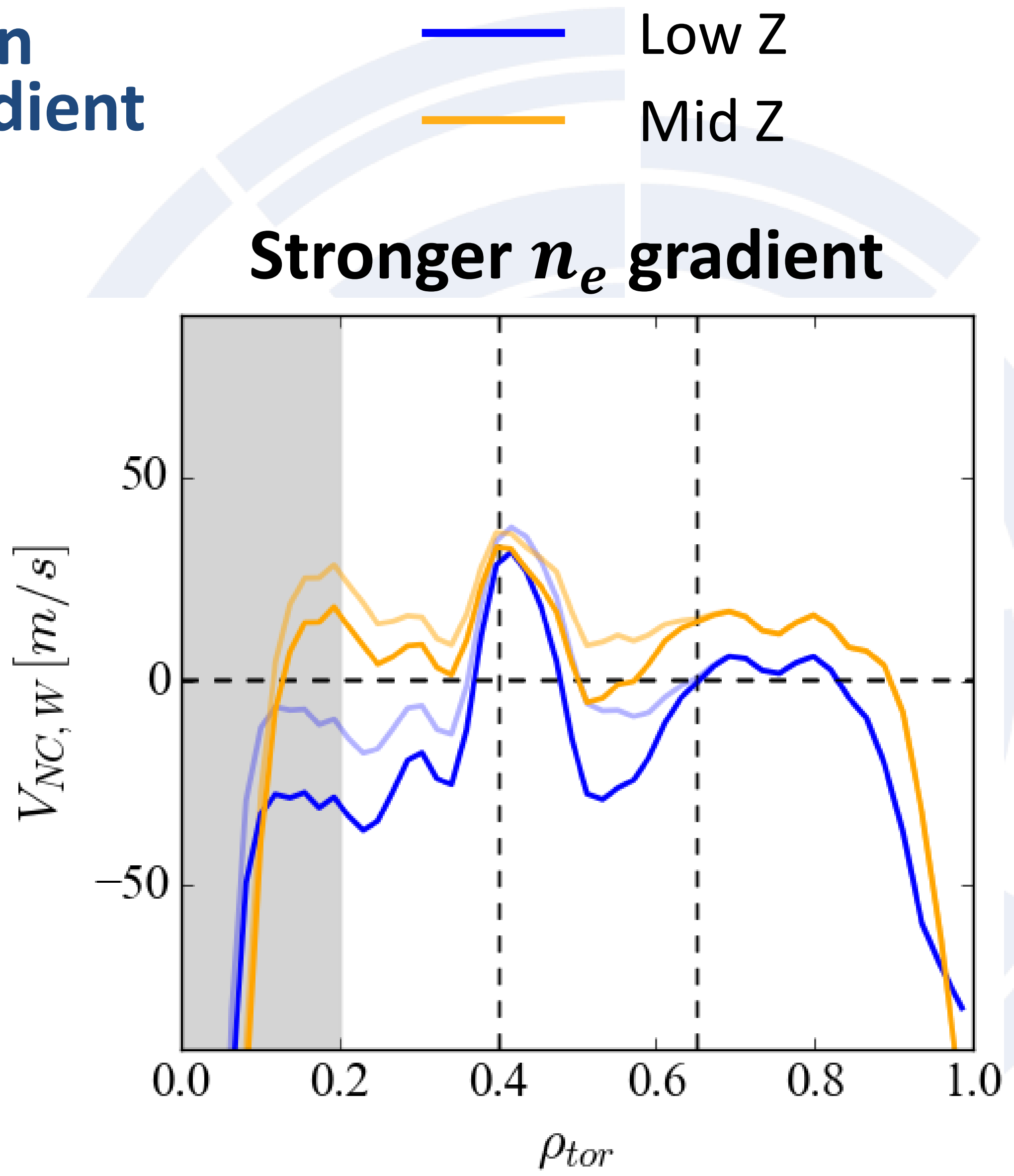
Strong ITB/Higher Z_{eff} – Larger variation in predictions seen with stronger density gradient

Low Z
Mid Z

Original profiles



Strong ITB/Higher Z_{eff} – Larger variation in predictions seen with stronger density gradient



- Larger density gradient gives desired effect of larger inward convection

Difference in $V_{NC,W}$ profiles due to changes in C_{TS} when varying impurity compositions

- $\nu_{W\rightarrow Z} \propto n_z {Z_Z}^2$
- At fixed $Z_{eff} \rightarrow n_z {Z_Z}^2$ for low Z is $\sim \frac{1}{3}$ larger

$\rightarrow$ Higher collisionality $\rightarrow$ Reduction in C_{TS}

Future fusion devices are expected to operate at higher Z_{eff} :

- Burning plasmas → High concentrations of He
- Seeded impurities (core and edge)

Summary

- Spontaneous ITB formation may occur in burning plasma scenarios
  → Essential to understand core W transport during these transient events

- Bolometry reconstruction of JET-ILW T ITB plasma with low collisionality, high Mach number and high Z_{eff} shows W content moving radially inwards following ITB formation

- NEO prediction of NC core W transport in this pulse proves challenging due to the complex interplay between strong gradients, high toroidal rotation, low collisionality and high Z_{eff}

- Sensitivity analysis highlights the impact of having different assumptions for background impurity composition

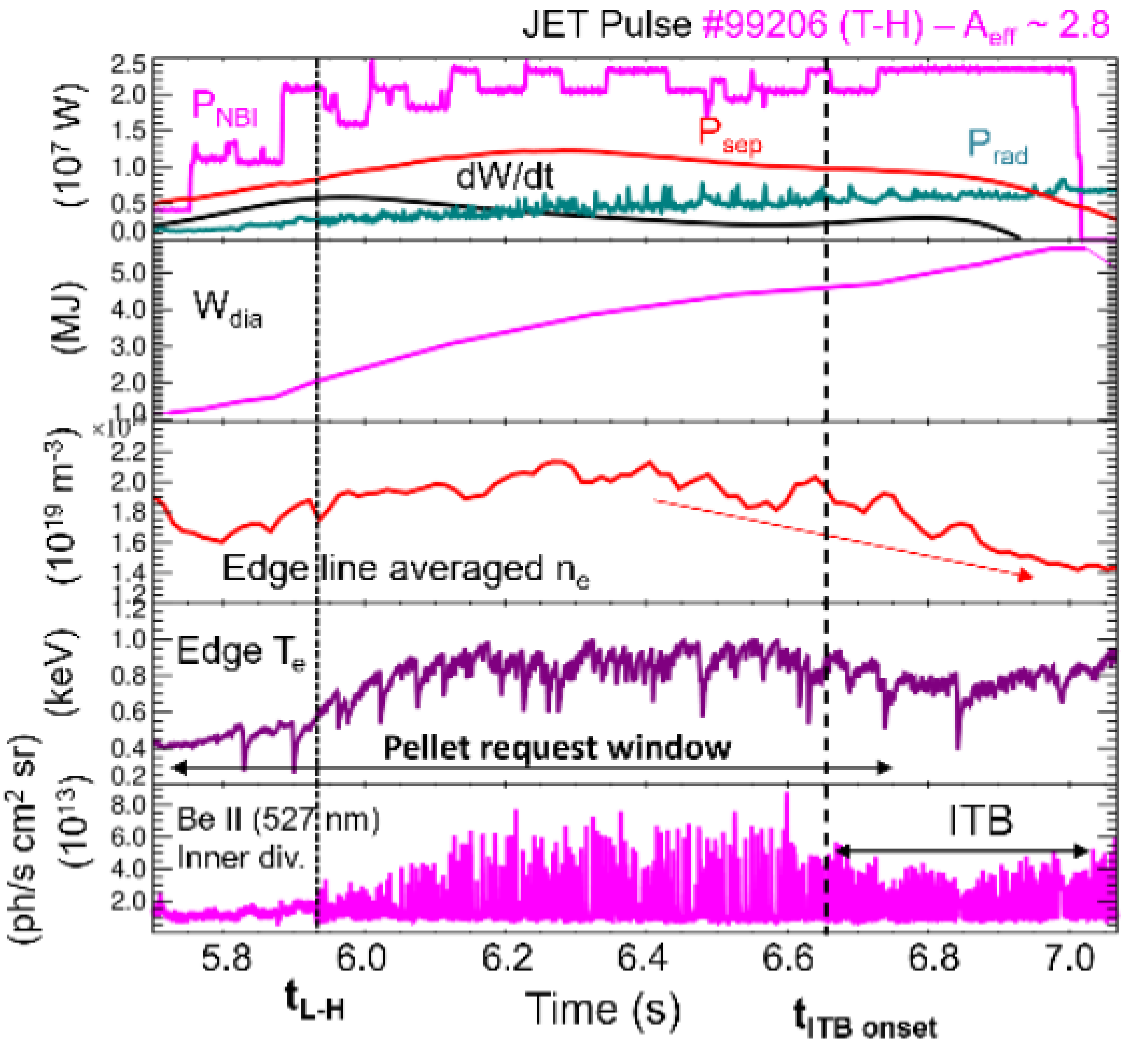
- Accurate impurity concentration profiles may become more important when modelling W transport in high Z_{eff} plasmas
  → Important to retain impurity-impurity collisions (NEO)

Thank you for listening

Back up slides

ITB scenario in T plasma in JET-ILW (99206)

- Tritium (T) plasma with type III ELMs
- $B_T = 3.4\text{T}$, $I_p = 2.8\text{MA}$
- NBI heating only $P_{NBI} \sim 23\text{MW}$
- H pellets → No pellet triggered ELMs



NEO modelling setup

- Assuming trace W concentration, NEO predicts $\Gamma_W \rightarrow$ calculate $D_{NC,W}$ and $V_{NC,W}$

- n_W is calculated from $\frac{R}{L_{n_W}} = \frac{V_{NC,W}}{D_{NC,W}+D_{anom,W}}$, assuming $V_{anom,W} \ll V_{NC,W}$

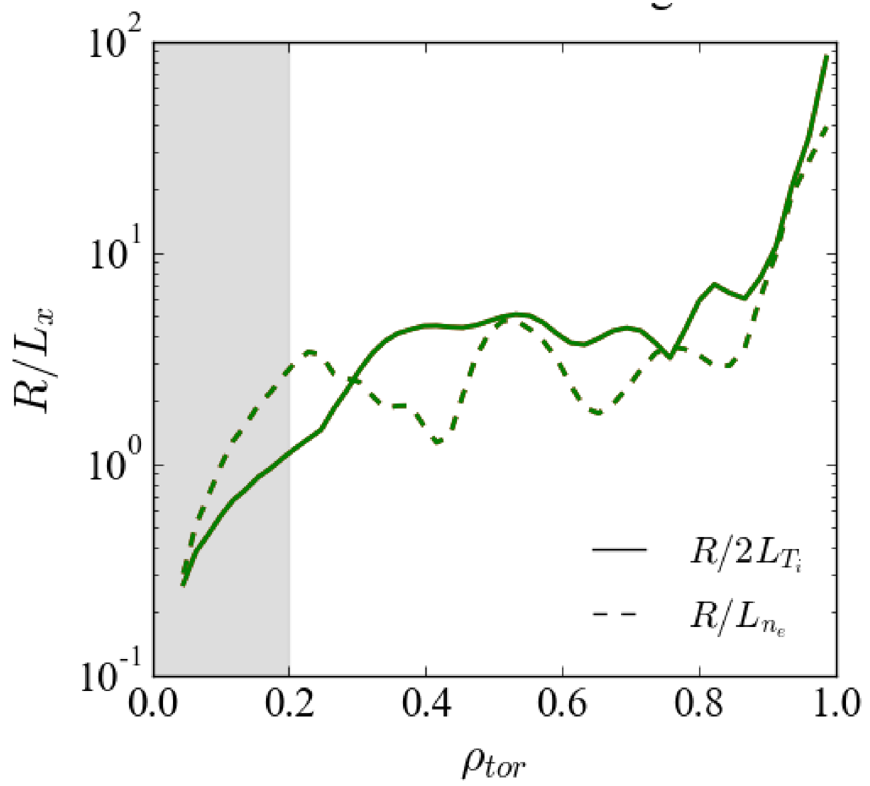
- $D_{anom,W}$ is inferred from TRANSP results

- ϵ_W can be calculated using n_W and cooling factors from ADAS

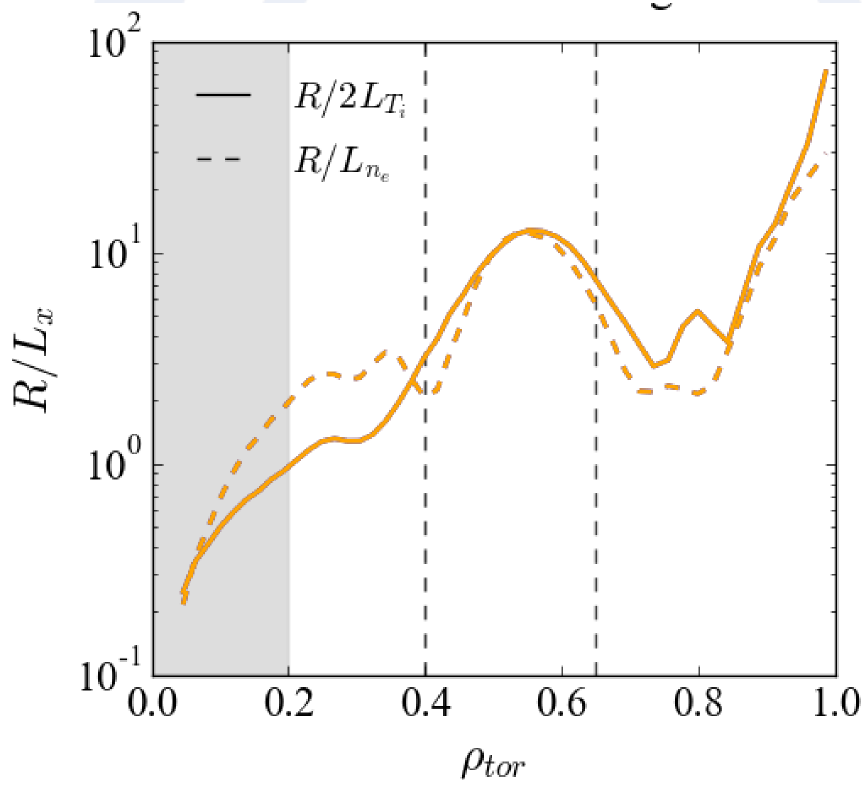
Normalised logarithmic gradients

$\frac{1}{2}\frac{R}{L_{T_i}} > \frac{R}{L_{n_e}}$ roughly equates to outward W convection ($V_{NC,W} > 0$)

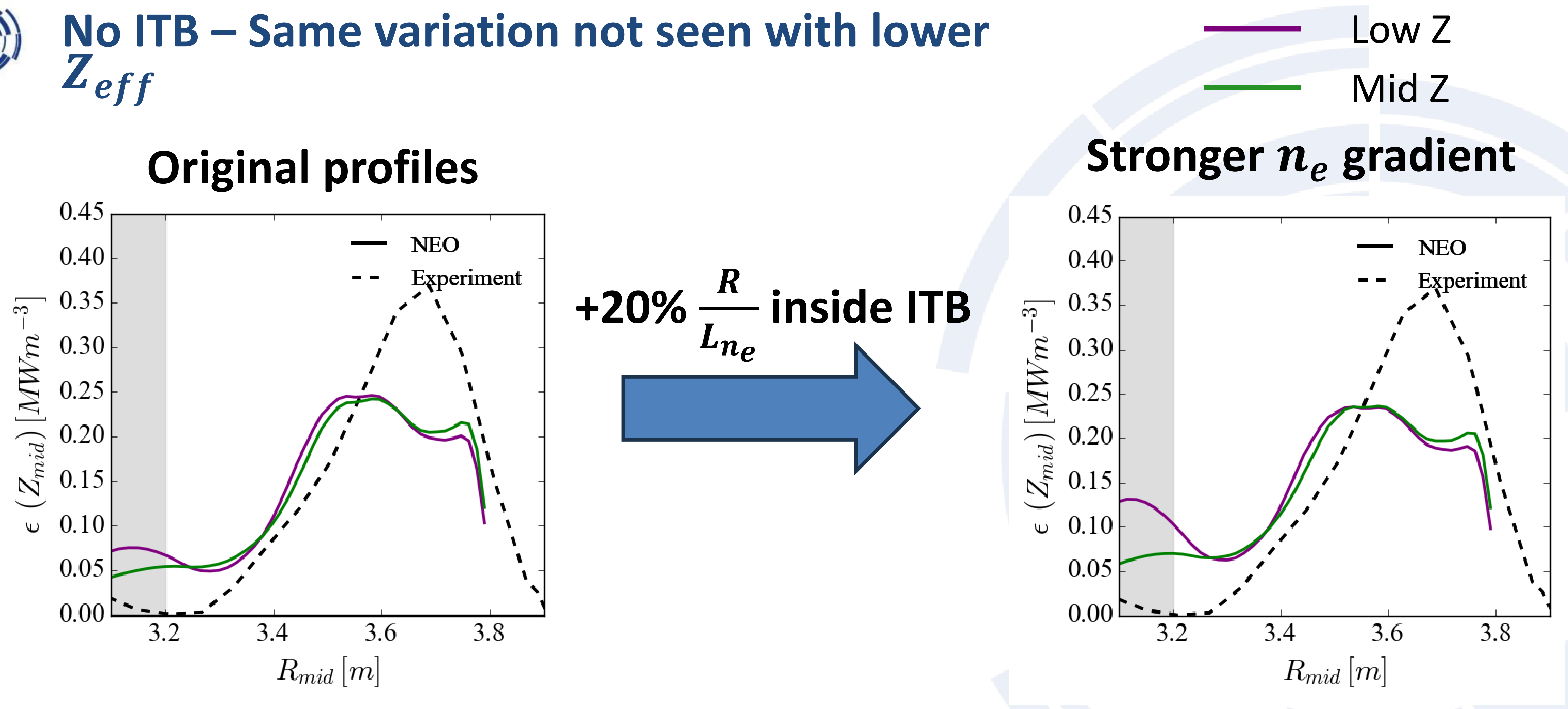
No ITB



Strong ITB



No ITB – Same variation not seen with lower Z_{eff}



- No significant changes for either variant following increased density gradient

Anomalous convection estimates

GK studies have observed that anomalous convection of W is very small when $Q_e \ll Q_i$ [*Angioni NF 2017*]

Linear GK modelling of 99206 at the same $k_y \rho_i$ (= 0.4) has calculated $\frac{Q_e}{Q_i}$ for multiple ρ_{tor} locations inside the ITB, and finds $Q_e \ll Q_i$

- $\rho_{tor} = 0.47$; $\frac{Q_e}{Q_i}$ = 0.1986
- $\rho_{tor} = 0.50$; $\frac{Q_e}{Q_i}$ = 0.1970
- $\rho_{tor} = 0.55$; $\frac{Q_e}{Q_i}$ = 0.2860