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

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Introduction

For the upcoming generation of tokamaks, tungsten (W) is widely considered as a leading candidate for plasma facing components (PFCs) due to its ability to withstand high heat fluxes while maintaining low tritium (T) retention. However, W is also among the most efficient radiators in the temperature range relevant to burning plasma conditions. For successful operations, avoiding core W accumulation will be vital for achieving steady-state, high-performance plasmas. A further challenge arises from transient events such as the formation of internal transport barriers (ITBs), which may occur spontaneously in a burning plasma. A strong reduction in turbulent transport is observed inside the ITB following formation, that typically generates steep gradients in the ion temperature (T_i) and electron density (n_e) channels. These gradients are key drivers of neoclassical transport, which is expected to dominate inside the ITB where turbulence is supressed. Previous analysis of ITB plasmas on JET-C found core impurity accumulation following ITB formation due to an inward impurity pinch inside the ITB [1], with impurity peaking observed to increase with impurity charge [2]. This motivates the need to better understand the impact of ITBs on core W transport, which strongly depends on neoclassical transport.

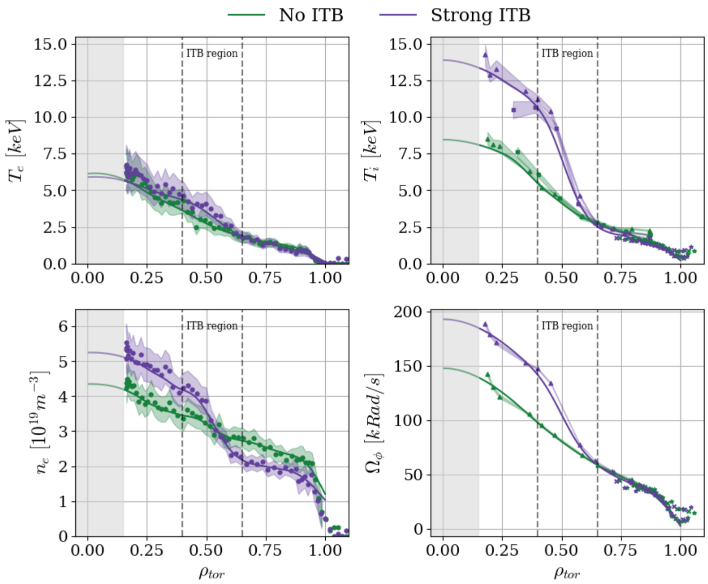

Figure 1: *Kinetic profiles for JET-ILW pulse 99206 before ITB onset (green) and when the ITB is fully formed (purple). For profile fits: HRTS diagnostic data is used for n_e, T_e; both core and edge CXRS data on Ne^{+10} is used for T_i, Ω_ϕ. The region between the top and foot of the ITB is indicated by the vertical grey dashed lines.*

Modelling setup and theory

The analysis shown in this report investigates core W transport for JET-ILW (Be/W wall) discharge #99206, an ITB scenario in T plasma at 3.4T/2.8MA with NBI heating only (~23MW). The ITB forms at low n_e, generating high core T_i and toroidal rotation (Ω_ϕ). There is also a sharp increase in effective charge (Z_{eff}) following ITB onset. Core W transport is analysed at two distinct phases: before ITB onset and after full ITB formation. These analysed phases will be referred to as "no ITB" and "strong ITB" in this report, and their respective kinetic profiles are shown in figure 1. These profiles correspond to low main ion collisionality (g) values and high main ion toroidal Mach numbers (M_ϕ), as seen in figure 2, both of which are key parameters that influence neoclassical transport. It is possible to obtain the following relation for neoclassical impurity convection velocity: $V_{NC,Z} \propto C_{TS}\left(\frac{R}{L_{T_i}}\right) - \frac{R}{L_{n_i}}$, where ${L_x}^{-1} = -\frac{d \ln x}{dr}$. In recent studies, the screening parameter C_{TS} has been found to vary in both magnitude and sign depending on the collisionality regime and toroidal rotation of the plasma [3]. To ensure that this important physics is captured in our analysis, the drift kinetic code NEO [4] is used to model core W transport. An input that can be provided to NEO is an estimate of any low Z (Be) or mid Z (Ni, Mo) impurities that make up the plasma composition. A unique aspect of this pulse is the high line averaged Z_{eff} measured from visible Bremsstrahlung, particularly during the strong ITB phase. However, obtaining accurate concentrations of any background impurities has so far proved quite challenging for this pulse.

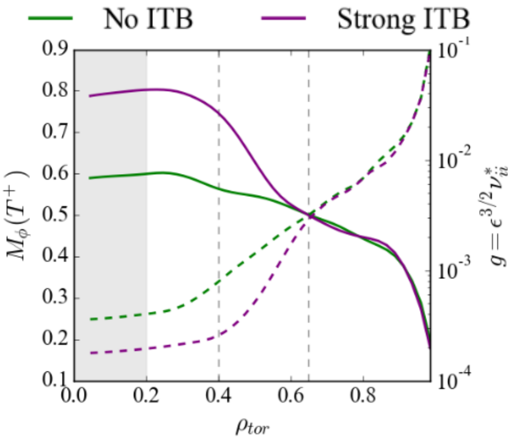

Figure 2: *Profiles during both analysed phases of main ion collisionality parameter g (dashed) and main ion toroidal Mach number M_ϕ (solid).*

For this study, a flat Z_{eff} profile is assumed, using experimental data to assume $Z_{eff}{\sim}2.2$ at the no ITB phase and $Z_{eff}{\sim}2.7$ at the strong ITB phase. Then two extremities are investigated, where the ΔZ_{eff} contribution from impurities is assumed to be dominated by either a low Z or mid Z impurity. The representative low Z impurity is Beryllium (Be) that enters the plasma through erosion of PFCs. Molybdenum (Mo) is used for the mid Z impurity, which is used as an interlayer beneath the W coated divertor tiles and was identified in Vacuum Ultra-Violet (VUV) spectra as the 2nd highest radiator for this discharge. As expected, W was identified as the dominant radiator during both phases of interest. Bolometry tomographic reconstruction during the no ITB phase shows a prominent radiation peak on the plasma Low Field Side (LFS), highlighting the poloidal asymmetries of W transport which is commonly seen on JET-ILW experiments [5]. During the strong ITB

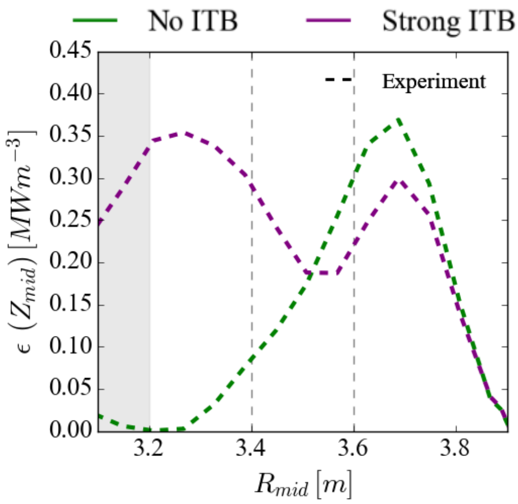

Figure 3: *Profiles of total emissivity at the low field side midplane taken from bolometry tomographic reconstruction, corresponding to measurements before (green) and after (purple) ITB formation.*

phase, bolometry reconstruction shows the formation of a second radiation peak, that has grown radially inwards inside the foot of the ITB. These experimental findings are more clearly seen in figure 3, which shows a slice at the LFS midplane of the total emissivity (ϵ_{tot}) taken from bolometry reconstruction. This suggests that following ITB formation, the W transport has changed such that core W accumulation occurs due to inward neoclassical convection. The goal of this analysis is to validate these observations from experimental measurements with predictions from the NEO code. Assuming trace W concentration, NEO predicts neoclassical W particle flux Γ_W which can be used to calculate neoclassical diffusivity ($D_{NC,W}$) and $V_{NC,W}$ for W. The W density can then be calculated using $\frac{R}{L_{n_W}} = \frac{V_{NC,W}}{D_{NC,W}+D_{anom,W}}$, where the anomalous W diffusivity $D_{anom,W}$ is inferred from TRANSP results. The anomalous convection ($V_{anom,W}$) term is dropped since it is assumed that $V_{anom,W} \ll V_{NC,W}$. Finally, using ADAS [6] data we can obtain a prediction for W emissivity (ϵ_W) that can be compared to the experimental measurements of ϵ_{tot}.

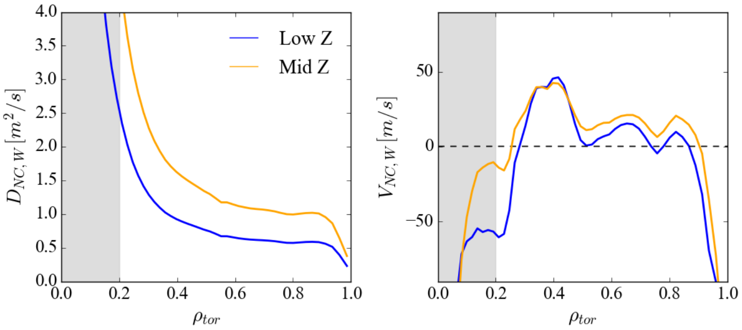

Figure 4: Profiles during no ITB phase of $D_{NC,W}$ (left) and $V_{NC,W}$ (right) predictions from NEO for two varying assumptions on background impurity composition.

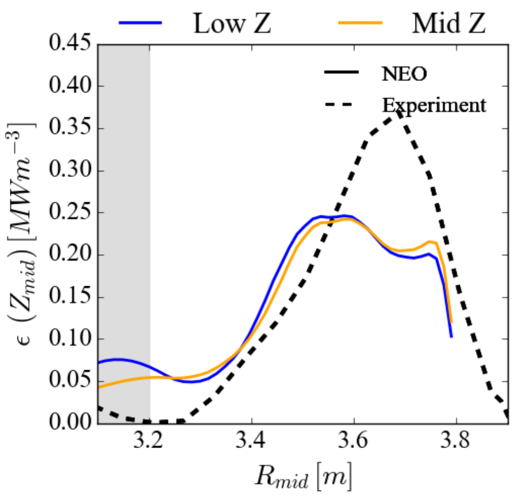

Figure 5: Profiles during no ITB phase of predicted ϵ_W from NEO (solid) compared against experimental bolometry measurements (dashed) for two varying assumptions on background impurity composition.

NEO modelling results and discussion

For the no ITB phase, predictions from NEO for the $D_{NC,W}$ and $V_{NC,W}$ profiles for both the low Z and mid Z background impurity assumptions are shown in figure 4. The dependance of $D_{NC,W}$ on Z is highlighted by the increase when moving from the low Z to mid Z assumption. For both cases, outward convection ($V_{NC,W} > 0$) is predicted across a significant portion of the plasma. The corresponding LFS ϵ_W is compared against experimental measurements in figure 5. Both impurity composition assumptions predict the emissivity profile to peak towards the plasma edge, giving reasonable agreement with the experiment. Repeating the analysis for the strong ITB phase, there is a similar trend in the dependance of $D_{NC,W}$ on Z seen in the profiles. For the low Z assumption, a larger portion of the $V_{NC,W}$ profile is directed outwards, whereas the mid Z assumption continues to mostly have outward $V_{NC,W}$. However, when looking at the predicted LFS ϵ_W profiles from NEO shown in figure 6, neither can capture the formation of a second emission peak in the core plasma as is seen in the bolometry data. When considering what sensitivity tests could be explored that might increase the inward convection, the profile gradients are a prime candidate. Since the ion density gradient contributes to inward convection, the NEO analysis was repeated with an increase of 20% in $\frac{R}{L_{n_e}}$ from the foot of the ITB inwards, pushing the n_e profiles towards the upper limit of the uncertainty in the experimental data. Figure 7 highlights that with the stronger n_e gradient, the low Z assumption sees a significant increase in core emissivity, whereas the mid Z assumption only has minor changes. Whilst the stronger n_e gradient had the desired effect of increasing the inward convection, there is a clear difference in the NEO predictions when changing the background impurity composition. One possible explanation could be a change in C_{TS} parameter due to the different impurity compositions assumed for the given Z_{eff}. Since collision frequency $\nu_{W\rightarrow Z} \propto n_Z Z_Z{}^2$ and the value of $n_Z Z_Z{}^2$ with the low Z assumption is $\sim\frac{1}{3}$ larger for the given Z_{eff}, this likely causes a reduction in C_{TS} due to the higher collisionality. This highlights the importance of including accurate low or mid Z impurity concentrations when modelling core W transport. It also emphasizes the value of using codes such as NEO that include impurity-impurity collisions so that this physics relevant to high Z_{eff} conditions can be captured. This may become more relevant for modelling predictions of future fusion devices, which are expected to operate at higher Z_{eff} values due to the presence of seeded impurities and higher concentrations of Helium (He) expected in burning plasmas. Further analysis is planned to unravel these findings, as well as investigating whether similar results are found in other JET-ILW ITB plasmas.

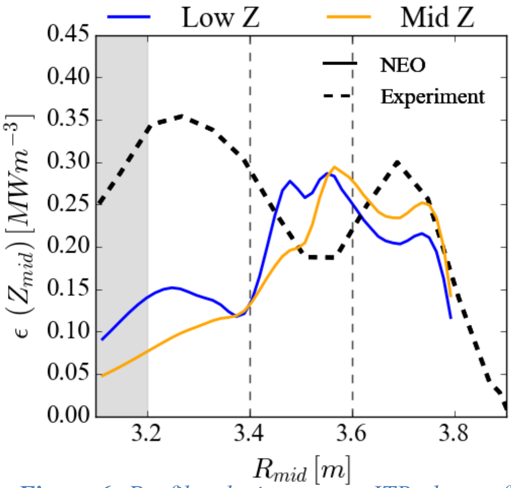

Figure 6: *Profiles during strong ITB phase of predicted ϵ_W from NEO (solid) compared against experimental bolometry measurements (dashed) for two varying assumptions on background impurity composition.*

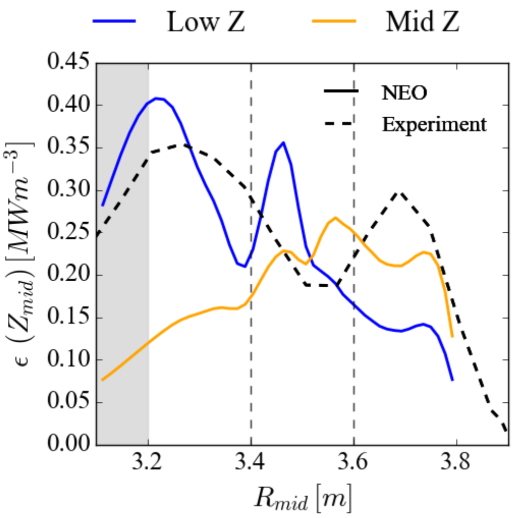

Figure 7: *Profiles during strong ITB phase with 20% increase to R/L_{n_e}, comparing predicted ϵ_W from NEO (solid) against experimental bolometry measurements (dashed) for two varying assumptions on background impurity composition.*

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References

[1] H. Chen *et al* 2001 *Nucl. Fusion* **41** 31

[2] R. Dux *et al* 2004 *Nucl. Fusion* **44** 260

[3] D. Fajardo *et al* 2023 *Plasma Phys. Control. Fusion* **65** 035021

[4] E. A. Belli and J. Candy 2012 *Plasma Phys. Control. Fusion* **54** 015015

[5] F. J. Casson *et al* 2020 *Nucl. Fusion* **60** 066029

[6] H. P. Summers 2004 The ADAS User Manual, version 2.6 http://www.adas.ac.uk