Comparative Analysis of Core Heat Transport of JET High Density H-mode Plasmas in Carbon Wall and ITER-Like Wall
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* See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

A consistent deterioration of global confinement in H-mode experiments has been observed in JET [1] following the replacement of all carbon Plasma Facing Components (PFCs) with an all metal (‘ITER-like’) wall (ILW). This has been correlated to the observed degradation of the pedestal confinement, as lower electron temperature ($T_e$) values are routinely measured at the top of the edge barrier region. A comparative investigation of core heat transport in JET-ILW and JET-CW (Carbon Wall) discharges has been performed, to assess whether core confinement has also been affected by the wall change.

The results presented here have been obtained by analysing a set of discharges consisting of high density JET-ILW H-mode plasmas and comparing them against their counterpart discharges in JET-CW having similar global operational parameters. The set contains 10 baseline ($\beta_n=1.5$~2) discharge-pairs with 2.7 T toroidal magnetic field, 2.5 MA plasma current, and 14 to 17MW of Neutral Beam Injection (NBI) heating.

Based on a $T_e$ profile analysis using High Resolution Thomson Scattering (HRTS) data, the $T_e$ profile peaking (i.e. core $T_e (\rho=0.3) / edge T_e (\rho=0.7)$) is found to be similar, and weakly dependent on edge $T_e$, for both JET-ILW and JET-CW discharges. When ILW discharges are seeded with $N_2$, core and edge $T_e$ both increase to maintain a similar peaking factor.

The change in core confinement is addressed with interpretative TRANSP simulations. It is found that JET-ILW H-mode plasmas have higher NBI power deposition to electrons and lower NBI power deposition to ions as compared to the JET-CW counterparts. This is an effect of the lower electron temperature at the top of the pedestal. As a result, the core electron energy confinement time is reduced in JET-ILW discharges, but the core ion energy confinement time is not decreased. Overall, the core energy confinement is found to be the same in the JET-ILW discharges compared to the JET-CW counterparts.
1 INTRODUCTION

Carbon Plasma Facing Components (PFCs) have been recently replaced in JET with an all metal Beryllium first wall and Tungsten divertor, which comprise the ILW (ITER-Like Wall) [2]. It is well known that the interaction between plasma and the surrounding wall can influence plasma energy confinement significantly as a result of the sputtering of different impurities and modified wall recycling [1]. In addition, the operational techniques required for the ILW (e.g. higher gas fuelling, to avoid W accumulation in the core) differ from those required for CW (Carbon Wall) operation. After the wall change, the global energy confinement in JET-ILW was routinely found to be degraded, when compared to similar plasmas in the CW configuration. A similar confinement loss was also reported in ASDEX-Upgrade after the installation of the full tungsten wall [3]. In both devices, the core temperatures are found to be lower as are the temperatures at the top of the pedestal [3] [4].

These observations have an impact on the extrapolation to ITER plasma performances as a full metal wall (Be first wall and Tungsten divertor) is planned in ITER. One current research topics at JET-ILW is therefore the investigation of the cause for this deterioration [1] [4]. It is well known that the core temperature depends on the temperature at the plasma edge. Since the edge temperature is lower in the ILW configuration, it is not obvious whether the decrease in core temperature is only due to the degradation of the edge confinement or if the core confinement itself has also been degraded.

A heat transport analysis of 10 pairs of counterpart discharges (10 CW discharges and 10 corresponding ILW discharges), has been carried out to address this question. Counterpart discharges have been carefully selected to match the time-averaged value of the controllable global plasma parameters -

- 2.5MA of total plasma current $I_p$,
- 2.7T of toroidal magnetic field $B_t$,
- 14 - 17MW of applied NBI power $P_{NBI}$,
- $7.1-10.2 \times 10^{19} m^{-3}$ volume-averaged electron density $<n_e>$
- safety factor $q_{95}$,
- triangularity $\delta$
- as closely as possible within a reference time window, from \( t_{\text{ref}} - 0.5 \) s to \( t_{\text{ref}} +0.5 \) s. The reference time \( t_{\text{ref}} \) is selected during the stationary flat-top phase of the discharge (see Figure 1(a), (b), (c), (d), and (e)). Core MHD activity in the selected discharges is not significant enough to affect core transport within the analysed interval. Figure 1 (f)(g) shows that the core \( T_e \) and \( n_e \) are in steady state with only small-amplitude fluctuations around the average value. The counterpart discharge selection is designed to remove the influence of the global plasma parameters, and allow an investigation of the effects of the different walls on transport processes. It is observed that \( Z_{\text{eff}} \) in CW shots is much higher than \( Z_{\text{eff}} \) in the ILW counterparts i.e. \( Z_{\text{eff}} = 1.7\sim2.4 \) for CW and \( Z_{\text{eff}} = 1.1\sim1.3 \) for ILW. This indicates that the plasma compositions in CW and ILW are different. For CW discharges, \( Z_{\text{eff}} \) is subject to significant variation even without any impurity seeding. This can be attributed not only to the wall material, but also to the impurity retention from the previous impurity-seeded discharges. On the other hand, the \( Z_{\text{eff}} \) variation in the ILW discharges is much less significant allowing a higher degree of reproducibility, although small variation can still exist when the discharges are following after impurity-seeded discharges on the same day. It should be noted that the highest \( Z_{\text{eff}} \) in unseeded ILW discharges is still smaller than the lowest \( Z_{\text{eff}} \) in CW, but with \( \text{N}_2 \) seeding in ILW discharges the \( Z_{\text{eff}} \) increases up to a comparable value in CW.

The analysis reported in this paper is focused on low beta baseline H-mode plasmas. Figure 1 shows a typical example of the counterpart discharges selected amongst low beta baseline (\( \beta_N \approx 1.5\sim2 \)) H-mode plasmas, which have high plasma density \( (7\times10^{19} m^{-3} < \bar{n}_e \leq n_{GW} \approx 9\times10^{19} m^{-3} ) \). At these level of collisionality, the electron and ion temperature profiles tend to be very similar because of the high equilibration power i.e. \( T_e \approx T_i \). High beta hybrid (\( \beta_N \approx 3 \)) plasmas [5] have been analysed in Challis et al [6], where it is reported that the power degradation of thermal energy confinement with heating power is weaker in JET-ILW discharges. The main parameters of the discharges analysed are given in Table 1. In order to minimise the effect of measurement errors, time averaged values are used in this study.

In section 2 we report the comparison of the High Resolution Thomson Scattering \( T_e \) profiles between JET-ILW and JET-CW discharges. In section 3, the interpretive analysis of
core confinement, using the TRANSP transport analysis code [7] [8] is presented. Discussions and Conclusions are given in sections 4 and 5, respectively.

Figure 1. A typical example of counterpart H-mode plasmas in CW (#77428, Red) and ILW (#83182, Blue). The counterpart discharges having similar controllable global parameters – (a) plasma current $I_p$, (b) Toroidal magnetic field $B_t$, (c) Applied NBI power $P_{\text{NBI}}$, (d) Volume averaged electron density $\langle n_e \rangle$, $q_{93}$, and (e) Upper triangularity $\delta$ - around the reference time $t_{\text{ref}}$ (indicated with 0). The vertical dashed lines show the averaged time interval for selection of counterpart discharges. (f) Core $T_e$ and (g) $n_e$ at $R=3.2m$ are measured by HRTS.
Table 1 Plasma parameters of counterpart discharges in Carbon Wall and in ITER-Like Wall. (N2) shows N₂ seeded discharges. * indicates (unseeded) discharges after seeded discharges on the same day.

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<th>Shot</th>
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<th>Bt [T]</th>
<th>Ip [MA]</th>
<th>Applied P_NBI [MW]</th>
<th>$\left&lt;\frac{E_p}{T_\epsilon}\right&gt;_{\rho&lt;0.5}$</th>
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2 ELECTRON TEMPERATURE PROFILE ANALYSIS

Electron temperature ($T_\epsilon$) profiles measured by the High Resolution Thomson Scattering (HRTS) system are used in the present study [9]. Figure 2 shows that the $T_\epsilon$ profiles are fitted using a constrained optimisation method based on tomographic techniques (this method optimises the smoothness function while the calculated profile is constrained by measurements [10]), and then remapped to the flux coordinate computed by EFIT [11]. Figure 3 shows $T_\epsilon$ profiles at each reference time $t_{\text{ref}}$ (at which each pair of counterpart shots has similar global parameters). The profiles have a constant local temperature gradient in the radial region between $\rho=0.3$--$0.7$, which enables them to be compared using the temperature ratio between the two fixed end points. $\rho$ is the square root of normalized toroidal flux,
In this paper, the temperature ratio (i.e. \( T_e \) peaking) is defined as \( T_e(\rho = 0.3)/T_e(\rho = 0.7) \). Figure 3 shows that for the same controllable global parameters (i.e. applied NBI power, \( I_p \), \( B_t \), \( <n_e> \), \( q \), and \( \delta \)), JET-CW discharges have steeper \( T_e \) profiles than the JET-ILW counterparts without any exception. Figure 4 shows the corresponding pressure profiles. As \( <n_e> \) is one of the matching criteria for the selection of counterpart discharges, the steeper pressure profiles in JET-CW discharges result from steeper \( T_e \) profiles.

Figure 2 Remapped HRTS \( T_e \) profile (#82819, 55 seconds). \( \Delta T_e \) shows the deviation of the fitting lines from measured data points.
Figure 3 Electron temperature profiles of counterpart discharges in CW (red) and ILW (blue) measured by HRTS (High Resolution Thomson Scattering) and mapped on TRANSP radial coordinate (fitting applied). In the analysed region (i.e. $\rho=0.3 \sim 0.7$), $T_e$ profiles show a linear increase, justifying the profile analysis based on $T_e$ peaking (i.e. $T_e(\rho=0.3)/T_e(\rho=0.7)$).

Figure 4 plasma pressure ($=n_e \times T_e$) profiles of counterpart discharges in CW (red) and ILW (blue). $n_e$ and $T_e$ used for calculation are measured by HRTS. The profiles are mapped as in Figure 3.
Figure 5 shows the variation of core temperature with edge temperature. The error bars $\sigma_i$ are calculated considering statistical and systematic errors of the HRTS measurement, i.e. $\sigma_i^2 = \sigma_{SEM}^2 + \sigma_{SYS}^2 = \sigma_{sta}^2 / N + (0.05 \times T_{e,core})^2$. $\sigma_{SEM}$ is the standard error of the mean, which is calculated as $\sigma_{SEM}^2 = \sigma_{sta}^2 / N$ where $\sigma_{sta}$ is the standard deviation. Here, N=10 as $T_e$ data used is an averaged value over 10 data points for the reference time window. The systematic error $\sigma_{SYS}$ is calculated as $\sigma_{SYS}^2 = (0.05 \times T_{e,core})^2$, assuming a 5% uncertainty in HRTS $T_e$ measurement comparisons between the ILW and C walls. The fit error in Figure 2 is not included to calculate the error bar in Figure 5 as they are small enough to be ignored for the analysed radial interval. In addition, a few data points deviated from the fit are removed in the time-averaged data.

![Figure 5 Core $T_e(\rho=0.3)$ vs Edge $T_e(\rho=0.7)$. The blue and red symbols indicate ILW and CW plasmas respectively. Dashed lines indicate the change from CW to the counterpart ILW discharge for $N_2$ seeded plasmas. Blue filled symbols are $N_2$ seeded ILW plasmas, and red filled symbols are their counterparts in CW. Blank symbols are without impurity seeding. The triangles and circles indicate high and low $\delta$, respectively. The black solid line is a linear fit to the unseeded ILW+CW plasmas, and shows that the $N_2$ seeded plasmas are positioned between the unseeded ILW and CW discharges.](image-url)
The dashed lines in Figure 5 indicate the change from each CW to its counterpart ILW discharge. As discussed in the introduction, the core $T_e$ is found to be lower in ILW, and this is accompanied by the decrease in edge $T_e$. An important point to note is that both ILW and CW data are well represented by the same linear fit, showing that the $T_e$ peaking is not significantly modified by the change of PFCs.

Recently it has been observed in JET-ILW that nitrogen seeding can help to recover the edge $T_e$, and the core $T_e$ in turn, although the full recovery of edge $T_e$ to the previous value has not yet been achieved [12]. A similar result was also reported in $N_2$ seeded plasmas in ASDEX-Upgrade [3]. The seeding of $N_2$ in ILW discharges (blue filled symbols) has the effect of moving the profiles towards the CW counterparts, along the same trend line – suggesting that the decrease in core $T_e$ for the ILW discharges is due only to the decrease in edge $T_e$, and not to any degradation in the $T_e$ peaking.

3 TRANSPORT ANALYSIS

3.1 Input and assumptions for TRANSP analysis

Core transport has been analysed by using the TRANSP code [7] [8]. For these simulations, electron density and temperature profiles are taken from HRTS (High Resolution Thomson Scattering) measurements. Ion temperature ($T_i$) data is not available in most of the analysed discharges. $T_i$ is assumed to be equal to $T_e$ based on the high densities of the selected discharges ($<n_e>$ $> 7 \times 10^{19} \text{m}^{-3}$). Figure 6 shows a sample case in the database, for which the ion temperature measurement by Charge Exchange Radiation was available. The comparison show that $T_i = T_e$ is a reasonable assumption for the analysed discharges. The dominant impurity is determined by the PFC material i.e. Carbon for JET-CW, and Beryllium for JET-ILW. The impurity density profile is calculated to be proportional to the electron density assuming a uniform $Z_{\text{eff}}$ over the whole radius, where $Z_{\text{eff}}$ is determined from visible Bremsstrahlung [13]. The bulk radiation input is given by Bolometry measurement [14]. NBI and RF heating are calculated by NUBEAM [7] and TORIC [15], respectively. The $q$ profile is taken from the equilibrium reconstructed by EFIT [11], constrained by the magnetic probe measurements.
Figure 6 Profiles of $T_i$ measured by Charge Exchange Radiatlon (CXFM/TI) and $T_e$ measured by HRTS (HRTS/TE) at 52 seconds in #77955, which is one of the analysed discharges.

3.2 Comparison of transport properties

Electron and ion heat fluxes $q_e$, $q_i$, and heat conductivities $\chi_e$, $\chi_i$ are key transport properties to quantify core confinement. However, these transport properties are not measurable directly from experiments. In this paper, the transport properties are calculated by interpretative TRANSP simulations, using the measured input data – \{ $T_e$, $n_e$, $P_{\text{rad}}$, $Z_{\text{eff}}$, $I_p$, $V_{\text{loop}}$, $B_t$, applied $P_{\text{NBI}}$, applied $P_{\text{RF}}$, Gas puffing rate, Last Closed Flux Surface (LCFS) \} [16]. It should be noted that heat fluxes and conductivities are calculated by solving the energy balance equation. The energy balance equation of electrons is [17]

$$\frac{3}{2} \frac{\partial (n_e T_e)}{\partial t} + \nabla \cdot (\vec{q}_e + \frac{5}{2} \frac{\vec{v}_e}{T_e}) = P_{\text{source}}$$

(1)

where the electron conductive heat flux is defined as $\vec{q}_e = -\chi_e n_e \nabla T_e$, and ohmic heating, auxiliary heating such as NBI and RF, equilibration power loss, and atomic reaction related power losses are included in the source term ($P_{\text{source}} = P_{\text{oh}} + P_{\text{NBI}} + P_{\text{RF}} - P_{\text{equi}} - P_{\text{rad}} - P_{\text{rec}}$). $n_e(\rho ,t)$ and $T_e(\rho ,t)$ are given by measured input profiles, and the source terms are either functions of $n_e(\rho ,t)$ and $T_e(\rho ,t)$ or directly given by measurements e.g. $P_{\text{rad}}$. The particle flux $\Gamma_e$ appearing in the convective heat flux is calculated by solving the continuity equation, the balance between the particle sources and losses computed in TRANSP using the measured
data. Rearranging equation (1) and integrating over the volume enclosed by the flux coordinate $\rho$ allows one to obtain the radial electron heat flux $\overline{q_e \cdot \hat{r}}$ and in turn $\chi_e = \left( -\frac{\overline{q_e \cdot \hat{r}}}{n_e \nabla T_e \cdot \hat{r}} \right)$, which is consistent with the input profiles of $T_e$ and $n_e$.

Figure 7 (a)(b) Heat conductivity of ion $\chi_i$ and electron $\chi_e$ at $\rho = 0.5$ vs edge $T_e$ (c)(d) Total heat flux of ion $q_i$ and electron $q_e$ at $\rho = 0.5$ (e)(f) NBI power deposition to ion $P_{\text{NBI}}^{i}$ and electron $P_{\text{NBI}}^{e}$ within the volume $\rho < 0.5$. For all figures x axis is edge $T_e$ at $\rho = 0.7$. Each
dashed line indicates the counterpart data to show the change of the data from JET-CW to JET-ILW. The green filled triangles indicate the TRANSP results with \( T_i = 1.05T_e \). Otherwise, the notation of colour and symbols are same as described in Figure 5.

Figures 7(a) and (b) show the TRANSP calculated conductivities \( \chi_e \) and \( \chi_i \) at \( \rho = 0.5 \). As indicated by the dashed lines, there is a consistent change of conductivities from JET-CW to JET-ILW i.e. an increase in \( \chi_e \) and decrease in \( \chi_i \). Figures 7(c) and (d) show that the total radial heat fluxes for electrons (\( q_e \)) and ions (\( q_i \)) at \( \rho = 0.5 \) have similar trends. Although \( n_e \nabla T_e \) is higher in CW data (\( <n_e> \) is one of the matching criteria, but \( \nabla T_e \) is higher in CW), this does not significantly affect the variation of \( \chi_e \) and \( \chi_i \) between CW and ILW. The observed trend of \( q_e \) and \( q_i \) can be correlated to the change in NBI power deposition. TRANSP calculates the deposited power with NUBEAM, a NBI module using a Monte Carlo method, which takes into account effects such as shine-through power, Charge Exchange losses, and orbital drift losses [7].

Figure 8 (a) Core radiation comparison within the volume \( \rho < 0.5 \) between CW (x axis) and ILW (y axis). (b) Convective electron power loss within the volume \( \rho < 0.5 \) between CW (x axis) and ILW (y axis). Triangle and circles are high and low \( \delta \), and the filled and blank symbols indicate \( N_2 \) seeded and unseeded plasmas, respectively.
Figure 7(e) and (f) show the TRANSP calculated NBI power deposition to electrons and ions, integrated over the volume \( \rho \leq 0.5 \). The NBI heating power to the ions \( P_{NBI}^i \) not only shows the qualitative trend of change seen for \( q_i \) but also the same magnitude, indicating that \( P_{NBI}^i \) is in balance with \( q_i \). The electron heating power \( P_{NBI}^e \) also has a variation similar to \( q_e \) but the magnitude of \( q_e \) is slightly smaller compared to \( P_{NBI}^e \) in CW discharges. This can be attributed to other power sink terms such as radiation \( P_{rad} \) and convective power loss terms \( P_{conv} \). Figure 8 shows that the contribution of \( P_{rad} \) and \( P_{conv} \) are higher for CW discharges in most pairs, and therefore relatively less power is transported by \( q_e \) in CW discharges as compared to the ILW counterparts.

The difference in NBI power deposition between CW discharges and the ILW counterparts can be clearly seen in Figure 9, for one pair of discharges from the database. The total deposited \( P_{NBI} = P_{NBI}^e + P_{NBI}^i \) in the ILW discharge is shifted towards the edge (\( \rho \approx 0.8 \)). Since the same total NBI power is applied to the both discharges, this implies that in ILW discharges slightly less NBI power is deposited into the core. This can be seen in Figure 9.
10(a) showing that the total deposited $P_{NBI}$ within the volume $\rho < 0.5$ in ILW discharges is smaller than that in the CW counterparts.

Within the total deposited NBI power $P_{NBI} = P_{NBI}^e + P_{NBI}^i$, the fraction of electron and ion heating is a function of local $\varepsilon_b / T_e$, with higher $\varepsilon_b / T_e$ resulting in lower ion and higher electron heating fractions [18]. The average value of $\varepsilon_b / T_e$ within the volume $\rho < 0.5$ is shown in Figure 10(b). ILW discharges have higher $\varepsilon_b / T_e$ than their counterpart CW discharges due to the lower core $T_e$. Therefore the fraction of total NBI power deposition to electrons is larger for ILW plasmas as compared to the CW counterparts. Hence, as can be seen in Figure 7(f) and 9, the heating efficiency of electrons ($P_{NBI}^e$) within the volume $\rho < 0.5$ is larger in ILW plasmas despite the reduction of total NBI power deposition. On the other hand, both the fraction of core ion heating and the total NBI deposition are higher for CW plasmas, which results in much greater core $P_{NBI}^i$. In summary, the analysis above shows that for the same total NBI power, core electron heating is more efficient in ILW plasmas while ion heating is reduced. It should be noted that the lower fraction of core ion heating in ILW plasmas is attributed to the lower edge $T_e$, which suggests that by recovering the edge electron temperature, the differences in profile of NBI power deposition between ILW and CW plasmas might be removed.

![Figure 10](image_url)

**Figure 10** (a) Total deposited beam power $P_{NBI} = P_{NBI}^e + P_{NBI}^i$ within the volume $\rho < 0.5$ (b) averaged value of $\varepsilon_b / T_e$ over the volume $\rho < 0.5$. Each dashed line indicates the counterpart data to show the change of the data from the CW to the ILW. The notation of colour and symbols are same as described in Figure 5.
During the steady state, the electrons ($\tau_{\text{core}}^e$), ions ($\tau_{\text{core}}^i$), and plasma ($\tau_{\text{core}}^{ei}$) energy confinement time in the volume within $\rho < 0.5$ are calculated as

$$\tau_{\text{core}}^e (\rho < 0.5) = \frac{\int_0^{V(\rho=0.5)} W_{th}^e (\rho) \, dV}{\int_0^{V(\rho=0.5)} P_{\text{Total}}^e (\rho) \, dV}$$

where $W_{th}^e (\rho) = \frac{3}{2} (n_e (\rho) T_e (\rho) - n_e (\rho = 0.5) T_e (\rho = 0.5))$,

$$\tau_{\text{core}}^i (\rho < 0.5) = \frac{\int_0^{V(\rho=0.5)} W_{th}^i (\rho) \, dV}{\int_0^{V(\rho=0.5)} P_{\text{Total}}^i (\rho) \, dV}$$

where $W_{th}^i (\rho) = \frac{3}{2} (n_i (\rho) T_i (\rho) - n_i (\rho = 0.5) T_i (\rho = 0.5))$,

$$\tau_{\text{core}}^{ei} (\rho < 0.5) = \frac{\int_0^{V(\rho=0.5)} W_{th}^{ei} (\rho) \, dV}{\int_0^{V(\rho=0.5)} P_{\text{Total}}^{ei} (\rho) \, dV}$$

where $W_{th}^{ei} (\rho) = W_{th}^e (\rho) + W_{th}^i (\rho)$, and $P_{\text{Total}}^{ei} (\rho) = P_{\text{Total}}^e (\rho) + P_{\text{Total}}^i (\rho)$.

$W_{th}^e$ and $W_{th}^i$ are the stored core thermal energy in electrons and ions, and $P_{\text{Total}}^e$ and $P_{\text{Total}}^i$ are the total heating power to electrons and ions, respectively. Figure 11 shows that $W_{th}^e$ and $W_{th}^i$ in ILW plasmas are clearly decreased compared to the CW counterparts, as observed by the lower core $T_e$ in ILW. However, $\tau_{\text{core}}^i$ in ILW plasmas is not reduced compared to the CW counterparts since $P_{\text{Total}}^i$ is also lower in ILW plasmas. In other words, this implies that the smaller $W_{th}^i$ in ILW plasmas is just due to the smaller ion heating in the core, rather than degradation of the core ion confinement. $P_{\text{Total}}^e$ is slightly higher in ILW plasmas, and this leads to smaller $\tau_{\text{core}}^{ei}$. As a result, the plasma energy confinement time $\tau_{\text{core}}^{ei}$ is slightly smaller in ILW plasmas.

As observed in Figure 5, by recovering edge temperature the core temperature in JET-ILW approaches the values in the CW counterparts, and this would lead to comparable core energy in JET-ILW. The difference in the core beam heating fraction would be also removed by recovering edge $T_e$, as it is determined by the core $T_e$. Therefore, it is expected
that the core energy confinement time with a fully recovered edge $T_e$ in JET-ILW will be similar with JET-CW.

**Figure 11** Comparison of energy confinement time in the volume within $\rho < 0.5$: (a) electrons $\tau_{\text{core}}^e$, (b) ions $\tau_{\text{core}}^i$, (c) plasma $\tau_{\text{core}}^{\text{pl}}$ between ILW and the counterpart in CW.

Comparison of the stored thermal energy in the volume within $\rho < 0.5$: (d) electrons $W_{\text{th}}^e$, (e) ions $W_{\text{th}}^i$, (f) plasma $W_{\text{th}}^{\text{pl}}$. Comparison of the total heating power in the volume within $\rho < 0.5$: (g) electrons $P_{\text{total}}^e$, (h) ions $P_{\text{total}}^i$, (i) plasma $P_{\text{total}}^{\text{pl}}$.

### 4 DISCUSSION

Although equal electron and ion temperature profiles is assumed for all TRANSP simulations in this analysis, there is a possibility that the core ion temperature is higher than the electron temperature in CW discharges due to higher NBI ion heating as compared to ILW discharges. The green filled triangles in Figure 7 indicate the TRANSP results for a CW discharge assuming slightly higher $T_i$ profile i.e. $T_i=1.05xT_e$. Due to the high equilibration power, heat fluxes and conductivities can be changed by even a small discrepancy in $T_i$ and $T_e$, while the NBI heat deposition is not sensitive to the change in $T_i$. Thus, with a slightly higher $T_i$, the CW plasma has higher $q_i$ and $\chi_i$ and lower $q_e$ and $\chi_e$, making it more similar to its ILW counterpart. This implies that the value of the calculated heat transport coefficients
can be affected by a large uncertainty. However, the above uncertainty does not affect the energy confinement calculation as the sum of heat-flux-power-loss and equilibration-power-loss does not depend on the assumption on $T_i$ (i.e. same total power loss). Hence, the conclusion made by comparing the core energy confinement time remains valid despite the uncertainty in the $T_i$ profiles.

The lack of agreement between the measured and the calculated beam-target neutron rates is an issue in many tokamaks including JET. It was reported that in order to reproduce JET neutron rate measurements for high density baseline JET plasmas, which is the same case analysed in the paper, an anomalous radial transport diffusivity of the fast ions of the order of $5-10 \text{ m}^2\text{s}^{-1}$ needs to be included in TRANSP simulations [19] [20]. This issue was also observed in other devices such as ASDEX Upgrade [21], DIII-D [22] [23], and MAST [24]. Figure 12 compares the neutron rate measured by Fission chamber [25] which was calibrated in 2013 [26], and the neutron rate calculated by TRANSP (without anomalous fast ion diffusivity). As dominant neutrons are generated by the fusion reaction between beam fast ions and thermal ions, without a model for fast ion anomalous transport in TRANSP, the calculated neutron rates are always higher than the measured value i.e. there is a neutron deficit in the measurement. However, the fraction of neutron deficit is around 30% for all the discharges, as can be seen by the linear alignment in Figure 12. This indicates that the neutron deficit with respect to the fast ion model in TRANSP is the same for all the discharges, and therefore does not have an impact on the comparative analysis between CW and ILW plasmas. In addition, the consistent neutron deficit fraction implies that uncertainty in neutral density or $Z_{\text{eff}}$, which can affect neutron production through fast ion losses or ion dilution, respectively, should be small in the database.
In this paper we have investigated the core transport of high density JET H-mode discharges to assess whether core confinement has been affected by the change of PFCs. To address the above question, a comparative analysis of the core transport of similar H-mode plasmas with Carbon and ITER-like wall has been presented. The discharges analysed have been carefully selected to have the same main global parameters so that any difference in core transport and confinement can be ascribed to effects linked to the different wall composition or different scenario operation.

Similar temperature peaking is observed in both ILW and C-wall plasmas. When ILW discharges are seeded with N$_2$, both core and edge $T_e$ increase to maintain a similar peaking factor. The analysis carried out with interpretative TRANSP simulations shows that in ILW discharges higher NBI power is deposited towards the plasma edge ($\rho$>0.6), reducing by 1~2 MW the power deposited in the central region ($\rho$<0.5). Lower electron temperature is consistently observed at the top of the pedestal of ILW discharges; as a result, the fraction of NBI power deposited to the ions is reduced while the fraction of NBI power to the electrons is increased. This implies that the core electron energy confinement time is somewhat smaller in ILW discharges, but the core ion energy confinement time is not changed.

5 CONCLUSION

Figure 12 Comparison between the measured neutron rate and the TRANSP calculated neutron rate
The analysis reported in this paper indicates that the overall core energy confinement is not degraded in the ILW discharges as compared to the CW counterparts. Since the NBI power deposition and core ion transport depend strongly on the electron temperature profile, it is likely that high core electron temperatures (comparable to that in CW) and improved plasma performance would be achieved if the edge $T_e$ were recovered.

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6 BIBLIOGRAPHY


