# High power baseline H-mode Deuterium plasmas with ion temperature exceeding the electron temperature in JET-ILW

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## 1. Introduction

High $T_i$ in fusion plasmas is one of the key parameters to achieve a high fusion performance. However, in addition to the anomalous ion heat transport, the collisional heat exchange between ions and electrons impedes further increase in $T_i$ beyond $T_e$. $T_i=T_e$ has been commonly observed in high $n_e$ (> 5e19 m-3) baseline discharges where the equilibration power is high, and the gradual departure of $T_i$ from $T_e$ was seen as the plasmas approach hybrid discharge regime and advanced tokamak plasmas where $<n_e>$ is typically lower than 4e19m-3 [1].

High power neutral beams (>25MW) were stably injected in the recent 2016 JET-ILW (ITER-Like Wall) experimental campaign, and this enabled the rapid increase in the measured neutron rates up to 2.8e16 #/sec (highlighted in red in Figure 1), which is much higher than the expected value (~1e16 #/sec) based on the experiments in previous years. While $T_i$ data is essential to understand the unexpected high neutron rates, measured $T_i$ data is not reliable for all discharges in the 2016 experimental campaign due to the Charge Exchange Spectroscopy issue, which has been difficult to analyse since the carbon wall was replaced with the metallic ILW. Alternatively, the 115 Deuterium discharges in 2016 JET experiments have been statistically analysed with interpretive TRANSP simulations [2].

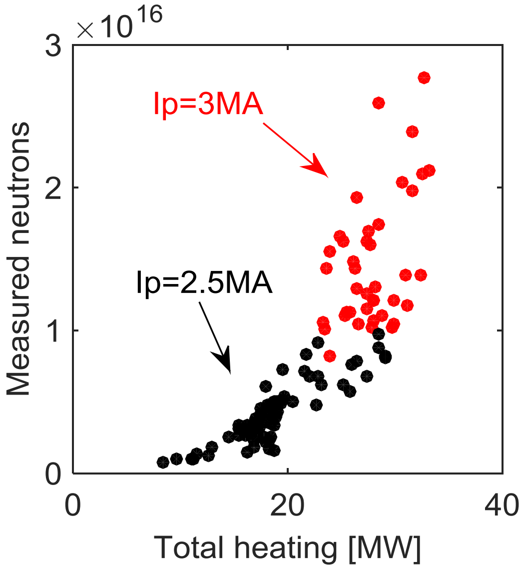

**Figure 1 Total neutron rates measured by the fission chamber against the total heating power (i.e. NBI + ICRF). The black and red points indicate low neutron rates (<1e16#/sec) and high neutron rates (>1e16), respectively, in the recent 2015-2016 JET experimental campaign. The high neutron rates are clearly correlated with the high heating power.**

For the statistical analysis, an identical setting was used in all the TRANSP simulations. One of the most important simulation setting is $T_i=T_e$, which was assumed based on that the selected discharges have high $n_e$ (>7e19 $m^{-3}$) in common. It should also be noted that while Ni signals were detected in the analysed discharges, the precise level of the content is not available. To resolve this issue, for all the discharges two TRANSP simulations were made either with 100% Be assumption or with 100% Ni assumption, and the calculated neutrons of the two TRANSP simulations with different impurity assumptions are used as the error bars of the synthetic neutron rates, which are shown in Figure 2(b). The followings are the summary of the input data and the assumption used identically in all the TRANSP simulations.

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[*] Litaudon et al, Overview of the JET results in support to ITER, accepted for publication in Nuclear Fusion

- $T_e$ and $n_e$ are given by High Resolution Thomson Scattering (HRTS) measurements
- $T_i$=$T_e$, based on high $n_{e0}$ (> 7e19 m-3)
- 100% Be or 100% Ni impurity assumption (used for error bars in synthetic neutron rates).
- Radially uniform $Z_{eff}$ profiles are assumed, and Zeff is given by Bremsstrahlung measurement (i.e. $Z_{eff}$ = 1.1~1.8)
- Radially uniform radiation profiles are assumed, and the total radiation power is given by bolometry measurement
- Neutral beam deposition and the fast ion orbiting are calculated by NUBEAM [3]
- ICRF power deposition are calculated by TORIC [4] (with dipole phasing with toroidal mode number $N_{phi}$=27, and with 3% Hydrogen ICRF minority)

Based on the statistical TRANSP analysis, this paper will report in section 2 that, in the high heating power discharges (>25MW), $T_i$>$T_e$ was observed even in high $n_e$ baseline discharges. Section 3 will discuss how it could be possible, and conclusion will be provided in section 4.

## 2. $T_i$ > $T_e$ in high power discharges

Considering the high $n_e$ in the baseline discharges (>7e19m-3), it was actually expected that $T_i$ would be still bound with $T_e$, and for this reason $T_i$=$T_e$ was assumed in all TRANSP analysis in this paper. However, it was observed, in some of the discharges where $T_i$ data is fortunately available, that significant departure of $T_i$ from $T_e$ was made even in the high $n_e$ baseline discharges e.g. #92436 ($T_i$=9keV and $T_e$=6keV at rho=3) and #92432 ($T_i$=6.5keV and $T_e$=5keV at rho=3). Consistently with these observations, the neutrons measured by fission chambers in all the high heating power discharges indeed exceed the neutrons calculated by TRANSP simulations with $T_i$=$T_e$ assumption i.e. neutron surplus in measurement, implying that $T_i$=$T_e$ assumption is not valid anymore after 25MW of the heating power. The discharges with neutron surplus are highlighted in red in Figure 2 (b), which correspond to the discharges with high neutron rates (>1e16 #/sec) in Figure 1. The neutrons are mostly produced by beam-target reactions, rather than thermal reactions. Despite the smaller sensitivity of the beam-target neutrons to $T_i$, the bifurcation of the synthetic neutron rates is clearly observed. In addition, when the measured $T_i$ was used in the TRANSP simulations of #92436 and #92432, the bifurcation was much more reduced (see the blue points in Figure 2). These provide a strong evidence that $T_i$ > $T_e$ was achieved in the high heating power discharges.

As mentioned in the introduction, the error bars in Figure 2 (b) are calculated with two TRANSP runs i.e. with 100% Be or with 100% Ni. For a given Zeff, the ion dilution is reduced with higher z impurity. Hence, the right error bars in Figure 2(b) are the neutron calculations with 100% Ni. The left error bars are calculated with 100% Be assumption, and the middle value between the two calculated values are used as the data points.

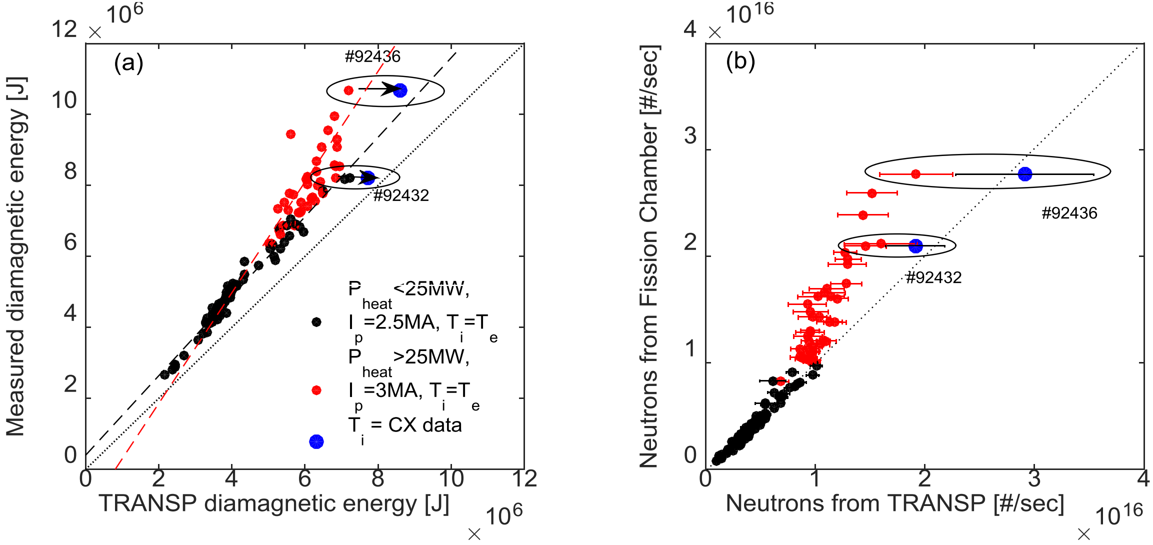

**Figure 2 (a) Comparison of the measurement of diamagnetic energy and the calculation of the synthetic diamagnetic energy in TRANSP, (b) Comparison of the measurement of neutron rates and the calculation of the synthetic neutron rates in TRANSP. The error bars are the calculated neutrons with different impurity assumptions i.e. 100% Be (left error bars) or 100% Ni (right error bars). Red points correspond to the high neutron rates (>1e16 [#/sec]) discharges in Figure 1. Blue points are the TRANSP calculations with measured $T_i$. Blue points shows #92436 and #92432 where measured $T_i$ was used in TRANSP simulations.**

Clearly, the neutron surplus is still observed even with the 100% Ni, which is a very pessimistic assumption (i.e. right error bars). In addition, the synthetic diamagnetic energy calculated with the $T_i$=$T_e$ assumption also consistently much lower than the measured diamagnetic energy for high heating power as shown in Figure 2(a).

## 3. Discussion

### (1) Decrease in equilibration coupling

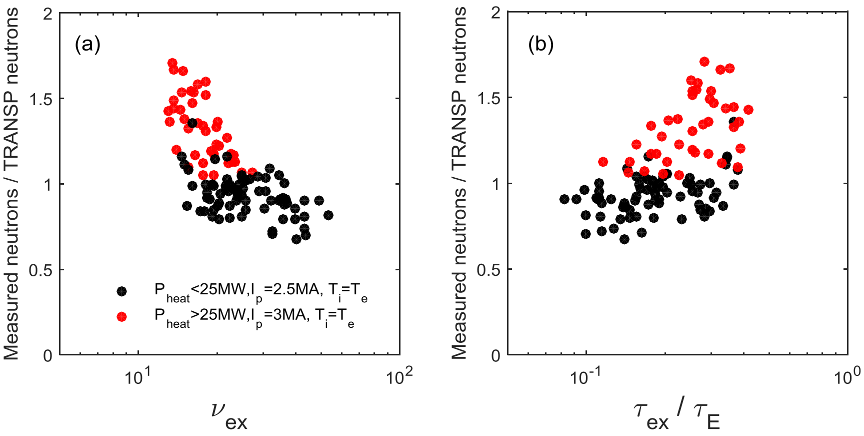

**Figure 3 The measured neutrons over the calculated neutrons against (a) effective collision frequency (b) equilibration time normalized by energy confinement time. Red points correspond to the high neutron rates (>1e16 [#/sec]) discharges in Figure 1.**

As can be seen in Figure 3(a), the neutron surplus is significantly correlated with the decrease in the effective collision frequency between ions and electrons for collisional heat exchange $\nu_{ex}(\equiv 0.16\times10^{-14}\ (2m_e/m_i)(<n_e[m^{-3}]>/<T_e[keV]>^{1.5})$ (where $<>$ is volume averaged) [1]. This implies that the high heating power increased $T_e$, reducing the equilibration coupling power between electrons and ions. Figure 3 (b) shows the equilibration coupling time (i.e. energy exchange time $\tau_{ex}(\equiv \nu_{ex}^{-1})$ [1]) normalized with the global energy confinement time $\tau_E$. It was reported in [1] that for $\tau_{ex} << \tau_E$ the equilibration coupling between electrons and ions is not effective, and $T_i \approx T_e$ is valid regardless of whether electrons or ions are predominantly heated. Although $\tau_{ex}/\tau_E$ is still smaller than unity, but it clearly increases with heating power. This indicates the equilibration coupling is less effective at high beam power, and this enables $T_i$ deviating from $T_e$.

Figure 4 compares the thermal neutrons over the total neutrons calculated by TRANSP against $\nu_{ex}$. While the thermal neutron ratio is not significantly modified with $\nu_{ex}$ in the TRANSP results where $T_i$=$T_e$ assumption is used, the thermal neutron ratio clearly increases for #92436 and #92432 where measured $T_i$ is used. This implies that the thermal neutrons are under-calculated with the $T_i$=$T_e$ assumption, which is not valid anymore for the high heating power discharges.

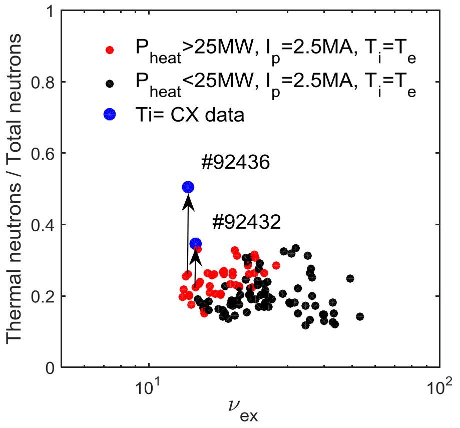

**Figure 4 Thermal neutrons / Total neutrons vs effective collision frequency. Red points correspond to the high neutron rates (>1e16 [#/sec]) discharges in Figure 1. Blue points are #92436 and #92432, where measured $T_i$ are used in TRANSP analysis.**

### (2) Increase in the fraction of beam heating to ions

TRANSP analysis also shows that the fraction of beam heating to ions in the core ($\rho$ < 0.5) i.e. $P_{i,beam}/(P_{i,beam}+P_{e,beam})$ increases as $T_e$ increases, providing an additional contribution in the core region, where most neutrons are produced, for obtaining $T_i$ > $T_e$. It is well known that the fraction of the beam heating to ions and electrons are determined by the beam energy normalized with $T_e$ i.e. $\varepsilon_b/T_e$ [5]; the fraction of beam heating to ions increases as $\varepsilon_b/T_e$ decreases, and vice versa. As shown by Figure 5 (a), $\varepsilon_b/T_e$ decreases with the beam power in the analysed discharges. This is because $T_e$ significantly increases with the beam power, although $\varepsilon_b$ increases as well. Figure 5 (b) shows that TRANSP calculations of $P_{i,beam}/(P_{i,beam}+P_{e,beam})$ also consistently increases with the beam power, and the discharges with high neutron rates (highlighted in red) are located at high $P_{i,beam}/(P_{i,beam}+P_{e,beam})$.

## 4. Conclusion

The high heating power operation (>25MW) in 2016 JET-ILW experimental campaign enabled a high fusion performance in baseline plasmas (q95=3). The highest neutron yield achieved is about 3e16#/sec, which is higher than the expected value (~1e16#/sec) based on the results in previous years. The 115 high $n_e$ baseline discharges from the recent JET experiments were statistically analysed using TRANSP simulations with $T_i=T_e$ assumption. One of the important observations in this analysis is that the synthetic neutron rates clearly departed from the measured value in the high heating power discharges, which indicates that, even in high $n_e$ baseline H-mode discharges, $T_i > T_e$ can be produced by the high heating power beyond 25MW. Previously, $T_i > T_e$ was seen in hybrid discharges and advanced tokamak plasmas, but typically C-wall baseline plasmas exhibited $T_i \sim T_e$ at high electron density ($<n_e> > 5e19\ m^{-3}$) [1]. However, the recent success of high beam power injection shows that baseline discharges also achieve partial electron-ion decoupling when the central heating is strong enough.

The statistical TRANSP analysis shows that there is a strong correlation between the neutron surplus and the decrease in the equipartition between $T_e$ and $T_i$. In addition, it was also observed that the fraction of beam heating to ions in the core ( $\rho < 0.5$) consistently increases as $T_e$ increases. The results suggest that the increased core electron temperature achieved in the high power baseline discharges is the key element to enable $T_i>T_e$ and high D-D fusion yield. Whether the lower plasma collisionality (i.e. electron/ion decoupling) or the modified beam slowing-down dynamics (i.e. larger ion heating fraction) is the dominant mechanism enabling the performance enhancement observed needs further investigation.

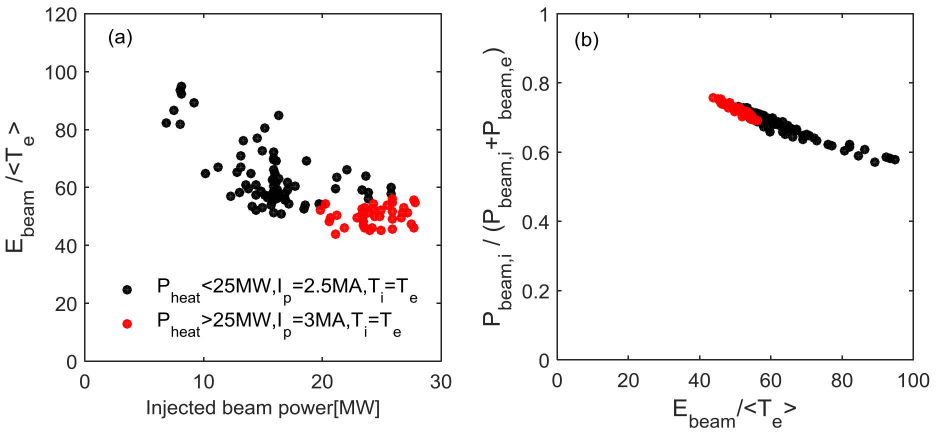

**Figure 5 a) beam energy over $<T_e>$ and beam power (b) fraction of beam heating to ions in the core ( $\rho$ <0.5) and beam energy over $<T_e>$ . Red points correspond to the high neutron rates (>1e16 [#/sec]) discharges in Figure 1.**

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