# Comparison of Particle Transport and Confinement Properties between the ICRH and NBI Heated Dimensionless Identity Plasmas on JET

T. Tala[1], A. Mariani[2], A. Salmi[1], E.R. Solano[3], I.S. Carvalho[5], A. Chomiczewska[6], E. Delabie[4], F. Eriksson[4], J. Ferreira[5], E. Fransson[7], L. Horvath[4], P. Jacquet[4], D. King[4], A. Kirjasuo[1], S. Leerink[8], E. Lerche[9], C. Maggi[4], P. Mantica[1], M. Marin[10], M. Maslov[4], S. Menmuir[4], R.B. Morales[4], V. Naulin[12], M.F.F. Nave[5], H. Nordman[8], C. Perez von Thun[7], P.A. Schneider[13], M. Sertoli[14], K. Tanaka[15] and JET contributors*

[1]VTT, P.O. Box 1000, FI-02044 VTT, Espoo, Finland
[2]Department of Physics "G. Occhialini", University of Milano-Bicocca, Milano, Italy
[3]CIEMAT, Av Complutense 40, Madrid 28040, Spain.
[4]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
[5]Instituto de Plasmas e Fusão Nuclear, Universidade de Lisboa, Lisboa, Portugal
[6]IPPLM, Warsaw, Poland
[7]Chalmers University of Technology, Göteborg, Sweden
[8]Aalto University, Espoo, Finland
[9]LPP-ERM/KMS, TEC Partner, Brussels, Belgium
[10]DIFFER, Eindhoven, Netherlands
[11]Institute for Plasma Science and Technology, CNR, Milano, Italy
[12]Danish Technical University Physics, Lyngby, Denmark
[13]Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
[14]Tokamak Energy Ltd, 173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD, United Kingdom
[15]National Institute for Fusion Science, Toki, Gifu, Japan
* See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021).

## Introduction

Research on particle transport plays a crucial role in the achievement of practical fusion energy, since fusion power scales with the square of the density ($P_{\text{fus}} \sim n^2$). Reaching very high density is only possible with peaked density profiles. This point is underlined in conceptual studies for a future power plant [1]. There is an on-going activity in the ITPA group on understanding particle transport for ITER, with the emphasis on the three following topics: electron and mixed-ion particle transport, isotope scaling and density peaking. This paper addresses the particular aspect of density peaking. While in JET ITG dominated NBI heated discharges NBI fueling was found to significant (~50%) or even dominant in some cases in a dimensionless collisionality experiment at all $\upsilon^*$ values [2], DIII-D reported the inward pinch to be dominant [3]. And the NBI fueling was found to be only a minor player in affecting density peaking on AUG [4].

In this paper, we aim to quantify the role of NBI fueling in contributing to density peaking in JET by executing identity discharges between the ICRH and NBI heated plasmas. In an ideal situation, the pair would be so identical that any difference in the density peaking could be directly attributed to the influence of the NBI fueling. However, in real experiment, in addition to the obvious desired difference in core particle source, for example the plasma rotation, fast ion content, impurities and edge pedestal properties may not be the same between the NBI-ICRH pair. Both gyrokinetic simulations and integrated transport modelling will be employed to quantify the background transport and thereby support the conclusion on the role of NBI fuelling in contributing to density peaking in these identity discharges.

## Experimental Comparison between the NBI and ICRH Identity Discharges

Up to 15s long H-mode plasmas with 8MW of ICRH power were achieved. This in fact resulted in JET record high injected ICRH energy of 108MJ. The ICRH discharges, using the H minority heating scheme at 3% minority concentration, were stationary without any major MHD activities or impurity accumulation. The time traces of the key parameters for the best matched ICRH-NBI pair are shown in figure 1.

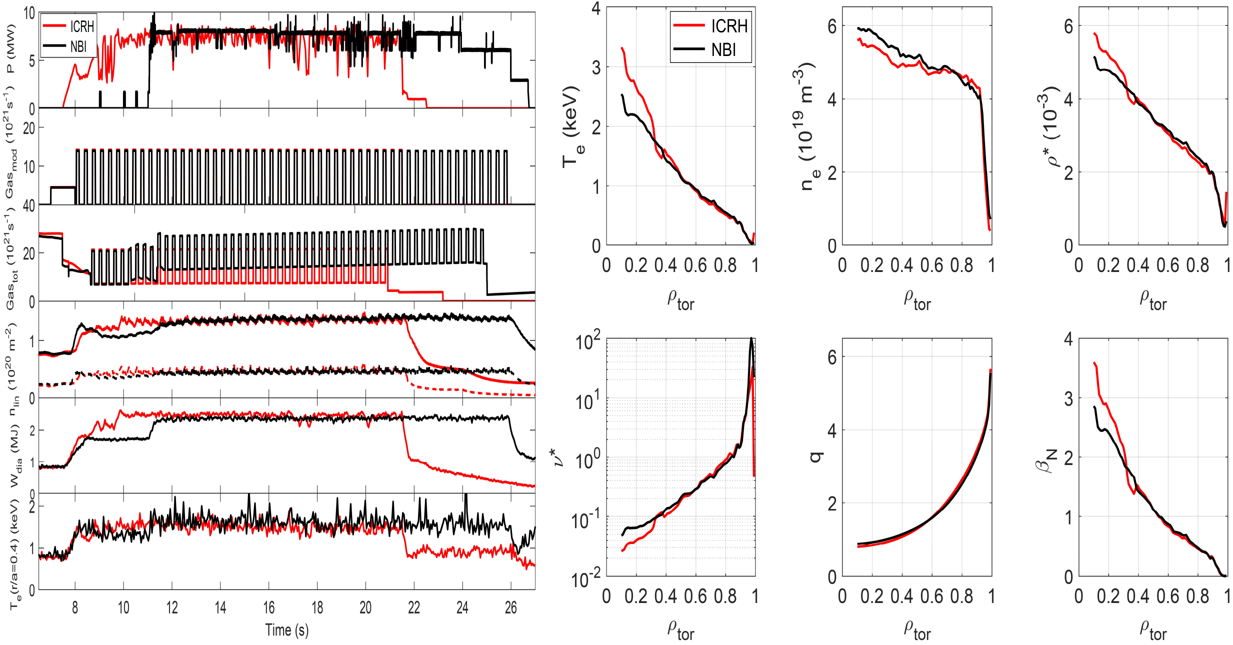

Figure 1. (Left frame) Key time traces of the ICRH (red, #95097) and NBI (black, #95272) discharges and (right frame) a comparison of the main dimensionless and dimensional plasma profiles.

The time traces of the key parameters for the best matched ICRH-NBI pair are shown in figure 1 (left frame). The electron temperature and density traces are similar between the ICRH and NBI discharges at 8MW power. The success in obtaining the identity plasma between the ICRH and NBI pulses is characterised in figure 1 (right frame) where the main dimensionless and dimensional profiles are compared. All the profiles are time averaged over *t*=15-16s. The dimensionless profiles of $q$, $\rho^*$, $\upsilon^*$, $\beta_{\mathrm{n}}$ and $T_{\mathrm{i}}/T_{\mathrm{e}}\approx 1$ were matched within 5% difference except in the central part of the plasma ($\rho_{\mathrm{tor}}<0.3$) where the ICRH discharge has higher electron temperature than the NBI one. For both the ICRH and for the NBI pulse, $T_{\mathrm{i}}$ equals $T_{\mathrm{e}}$ everywhere in the confinement region. This greatly simplifies our analysis as we can assume that $T_{\mathrm{i}}/T_e = 1$ is valid everywhere and similarly $T_{\mathrm{ICRH}} = T_{NBI}$ in the core or confinement region ($0.4<\rho_{\mathrm{tor}}<0.8$).

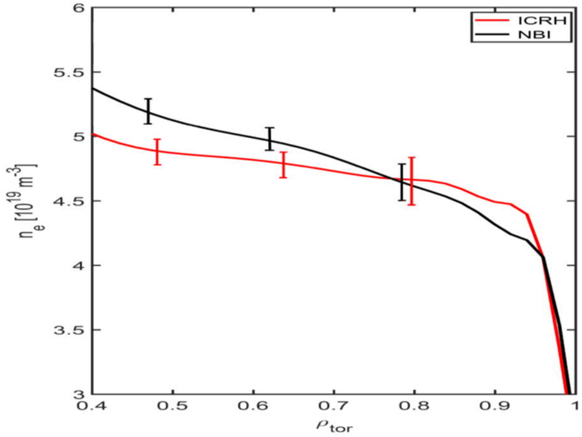

Figure 2. Radially zoomed density profiles (time-averaged, ELM averaging and fitting) of the ICRH heated (#95097) and NBI heated (#95272) discharges.

At least from the theoretical point of view, we have succeeded to minimize the difference in the curvature pinch (same *q*-profile) and thermo-pinch ($T_{\mathrm{i}}/T_e = 1$ and $T_{\mathrm{ICRH}} = T_{NBI}$) between the ICRH and NBI shots.

The most significant difference is the density profile which is a factor of 2 more peaked for the NBI discharge than for the ICRH discharge as is shown in figure 2. The density gradient length $R/L_n$, has been calculated averaging radially over $\rho_{tor}$=0.4–0.8 resulting in $R/L_n$=0.93 for the NBI shot and $R/L_n$=0.45 for the ICRH shot.

The main engineering and global dimensionless parameters are compared in table 1. Out of the 8MW of total heating power roughly 4MW goes to ions and the other half 4MW to electrons for both the NBI and the ICRH discharges, the ICRH power deposition being more peaked. The main differences in table 1 between the discharges are the toroidal rotation (10km/s counter-$I_p$ for the ICRH pulse and 110km/s co-$I_p$ for the NBI pulse), confinement, fast ion content and profiles (shown also in $\beta_n$), ELM characteristics, radiation and heavy impurity concentration. The most important differences and their possible impact on particle transport are described in more detail later.

| Pulse | 95097 (ICRH) | 95272 (NBI) |
|---|---|---|
| $P_{NBI}$ (MW) | 0 | 8.0 |
| $P_{ICRH}$ (MW) | 7.9 | 0 |
| $B_t$ (T) | 2.15 | 2.15 |
| $I_p$ (MA) | 1.8 | 1.8 |
| $\tau_E$ (s) | 0.23 | 0.21 |
| $H_{98}$ | 0.8 | 0.7 |
| $P_{rad}$ (MW) | 4 | 2 |
| $Z_{eff}$ | 1.25 | 1.3 |
| $\rho^*$ ($10^{-3}$) | 2.8 | 2.8 |
| $\upsilon^*$ | 0.36 | 0.36 |
| $\beta_n$ | 1.3 | 1.1 |
| $\beta_{th}$ | 1.1 | 1.05 |
| $W_{fast}/W_{th}$ | 0.11 | 0.08 |
| $f_{ELM}$ (Hz) | 75 | 40 |
| $f_{savteeth}$ (Hz) | 2.9 | 6.0 |
| $v_{tor}$ (km/s) | -10 | 110 |

Table 1. The main engineering and plasma parameters between the ICRH and NBI pulses. $B_t$ and $v_{tor}$ are local values at magnetic axis, the others are global values.

The comparison of the ICRH versus NBI discharge with respect to impurities shows that the Beryllium density is 20% higher in the plasma center for the NBI discharge, but it is similar in the confinement region at 0.4<$\rho_{tor}$<0.8. On the other hand, there is a large difference in W density between the pulses, the ICRH pulse having a factor of 6 higher $n_W$. The Nickel density is a factor of 1.5 higher for the NBI pulses than for the ICRH one resulting in pretty much the same $Z_{eff}$ profile. The effects of MHD activities on plasma kinetic profiles is limited to the central region ($\rho_{tor}$<0.3), and they do not affect the core (0.4<$\rho_{tor}$<0.8) transport analysis. We also believe that the difference in the ELM characteristics does not play a significant role for the core transport analysis at 0.4<$\rho_{tor}$<0.8 as the influence of the ELMs is localised at the edge.

## Gyrokinetic and Transport Modelling of the ICRH and NBI Heated Discharges

Linear and nonlinear ion-scale gyrokinetic simulations have been performed using the flux-tube (radially local) version of the GENE code [5] at fixed radius $\rho_{tor}$=0.6. The conclusion from the gyrokinetic GENE simulations is that the dependence of the normalized turbulent electron particle flux on the logarithmic density gradient is similar for the ICRH and NBI discharges at $\rho_{tor}$=0.6, except for a tiny effect coming from the $E \times B$ shearing for the NBI case. Furthermore and more importantly, the background transport is almost identical between the ICRH and NBI discharges,

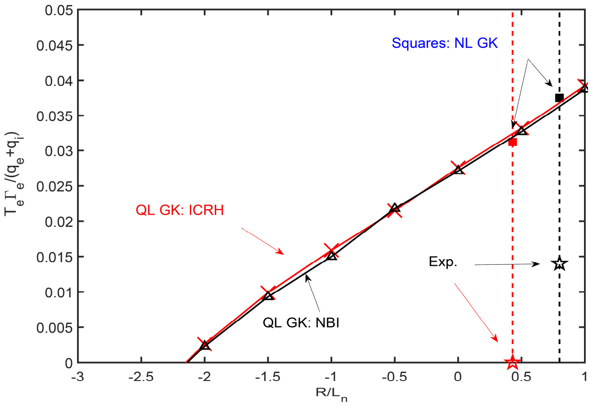

Figure 3. $T_e\Gamma_e(q_e + q_i)$ vs $R/L_n$, comparing QL (solid lines with crosses (ICRH) and with triangles (NBI)), NL (squares), and experimental (stars) results, for the ICRH (red) and NBI (black) discharges.

as the impurities, fast ions and toroidal rotation, which are the only significant experimental differences, do not cause any observable changes in the background transport. This conclusion is illustrated in figure 3.

To further study any possible difference in the background transport between the ICRH and NBI discharges, transport simulations with the JINTRAC transport code TGLF transport model [6] have been performed. The conclusion from TGLF simulations is the same as from GENE, i.e. there is virtually no difference in the background transport between the NBI and ICRH pulses.

## Conclusions and Future Work

The ICRH versus NBI identity plasmas in JET show that the NBI fuelled discharge has a factor of 2 higher density peaking ($R/L_n$=0.93 for the NBI shot and $R/L_n$=0.45 for the ICRH shot). The dimensionless profiles of $q$, $\rho^*$, $\nu^*$, $\beta_n$ and $T_i/T_e \approx 1$ were matched within 5% accuracy except in the central part of the plasma ($\rho_{tor}$<0.3), yielding similar plasma parameters and performance in the confinement region (0.3<$\rho_{tor}$<0.8).

In addition to different density peaking, the three other main experimental differences between the ICRH and NBI plasmas were the toroidal rotation, plasma fast ion density and energy and heavy impurity densities of Tungsten and Nickel. The conclusion from both the gyrokinetic GENE simulations performed with mean experimental parameters and the JINTRAC transport modelling with TGLF were the following ones: (1) the dependence of the normalized turbulent electron particle flux on the logarithmic density gradient is similar for the ICRH and NBI discharges at $\rho_{tor}$=0.6, except for a tiny effect coming from the $E \times B$ shearing for the NBI case, (2) the background transport is almost identical between the ICRH and NBI discharges, as the impurities, fast ions and toroidal rotation do not cause any observable changes in the background transport, and (3) the ion scales are found to be dominated by the Ion Temperature Gradient (ITG) mode.

Based on the almost identical background between the ICRH and NBI discharges, we can conclude that the contribution of the NBI fuelling is exactly to double the density peaking of the ICRH pulse, i.e. to reach $R/L_n$=0.93 from the moderately peaked the ICRH discharge without a central source at $R/L_n$=0.45. This result of $R/L_n$ increasing by 0.5 per 8MW of NBI power is valid for the ITG dominated low power H-mode plasmas. However, some of the physics processes influencing particle transport, like rotation, turbulence, fast ion content scale with power, and therefore, the conclusions on the role of the NBI fueling can be different in full power (30MW) JET conditions. On the other hand, ITG is the dominant turbulence type in either low power or high NBI power JET experiments, supporting the significant role of NBI fueling in contributing to density peaking also at high power experiment. This was already reported in dimensionless collisionality scan in reference [2]. When the ITG turbulence becomes less dominant or TEM dominates, the role of NBI fuelling tends to decrease as reported in [3,4]. An experiment will be performed in JET to study particle transport and density peaking, but this time at 8 MW of NBI heating in full 100% tritium experiment. We are planning to study isotope scaling of density peaking in dimensionless identity conditions in JET L-mode plasma.

Acknowledgement: “This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.”

[1] D. Maisonnier et al., Fusion Eng. Design 75–79, 1173 (2005).
[2] T. Tala et al., Nucl. Fusion 59, 126030 (2019).
[3] S. Mordijck et al., Nucl. Fusion 60, 066019 (2020).
[4] E. Fable et al., Nucl. Fusion 59, 076042 (2019).
[5] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Physics of Plasmas 7, 1904 (2000).
[6] G. Staebler et al., Phys. Plasmas 12, 102508 (2005).