Ion heat channel at the L-H transition in JET-ILW

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Introduction

During the last decades, the transition from low to high plasma confinement (L-H transition) has been analysed in several tokamaks showing that the L-H power threshold depends non-linearly on plasma density. Many devices observed that there is a minimum in density for the L-H power threshold (e.g. [1], [2]). A common finding shown both for AUG and C-mod RF-heated plasmas is that the power coupled to the ions increases monotonically with density [3], [4]. At JET, after the installation of the ITER-like wall (ILW), the L-H power threshold (P_{LH}) again shows a minimum, or in some cases a flattening, in density, and the corresponding minimum density depends on the divertor configuration [5], [6] (see fig. 1). The understanding of convenient conditions for L-H transition and the importance of the ion heat channel has a strong implication for ITER H-mode operation [7] and for DEMO design, where auxiliary heating systems responsible for L-H transition are being currently dimensioned [8].

The aim of the present work is to characterize JET L-H transition in terms of power balance analysis as suggested in [3], in particular regarding the ion heat channel, for a selection of JET-ILW discharges having the same, high, toroidal field (3 T) and plasma current (2.5 MA), but different divertor configuration. The definition of the power crossing the separatrix is:

$$P_{sep} = P_{ion} + P_{electron} = (P_{NBI,i} + P_{ei} - dW_i/dt) + (P_{NBI,e} - P_{ei} + P_{ohm} - dW_e/dt - P_{rad}) \quad \textit{(eq. 1)}$$

with the usual meaning of terms (being P_{ei} the exchange power between electrons and ions, positive for $T_e > T_i$, and P_{rad} the radiation power inside the separatrix). We take into account also the time derivative of the plasma energy content (dW/dt) since auxiliary power is slowly ramped up (1 MW/s) in these experiments to trigger L to H transition.

The discharges considered, with different average plasma density and L-H transition power threshold (see fig. 1), are heated only by Neutral Beam Injection (NBI), and are divided in 2 datasets depending on the location of the outer strike point (HT – Horizontal Target and VT – Vertical Target divertor configuration). HT discharges clearly show a minimum P_{L-H} in density, while VT discharges only exhibit a P_{L-H} flattening in density.

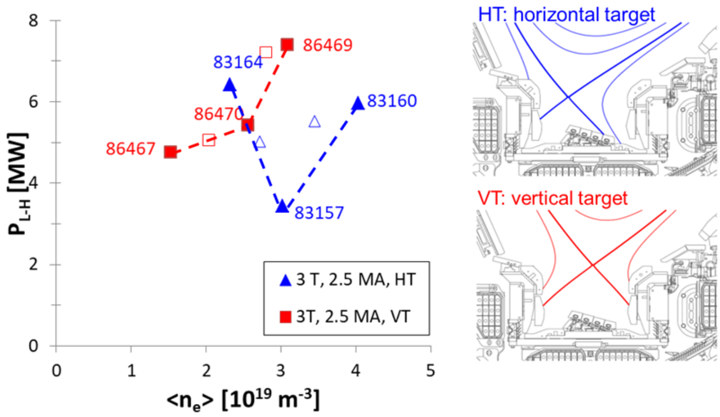

Figure 1: L-H power threshold versus line-averaged density. Full symbols depicts JET shots analysed in this work, color-coded for divertor configurations. Empty symbols represent other, not analysed, pulses of JET L-H database.

Method

In this work, the different terms of eq. 1 are estimated at L-H transition time either directly from measurements or through numerical simulations starting from available experimental measurements. Plasma density is taken from measurements of High Resolution Thomson Scattering (HRTS) system [9] and Li-beam for Scrape-off Layer (SOL) region [10]. P_{rad} inside the separatrix is estimated from tomographic inversion of JET bolometry data [11]. Impurity content (Z_{eff}) is estimated from the Bremsstrahlung diagnostic [12]. Plasma equilibrium is routinely produced with magnetics-only input to the EFIT code [13]. Plasma temperature profiles are necessary to compute the exchange power term P_{ei} in eq. 1. Electron temperature is measured at JET by HRTS and Electron Cyclotron Emission (ECE) [14]. Ion temperature measurements are available for these discharges only for plasma edge by charge exchange spectroscopy (CX) [15], due to core plasma signal contamination by W [16]. To overcome this lack, core ion temperature (i.e. for $\rho_{tor,N} < 0.85$, being $\rho_{tor,N} = \sqrt{\frac{\Psi-\Psi(r=0)}{\Psi(edge)-\Psi(r=0)}}$, with Ψ the toroidal magnetic flux) is predicted by flux driven quasilinear gyrokinetic transport simulations over a confinement time with QuaLiKiz-JETTO [17], [18]. To validate the QuaLiKiz simulations, predicted T_e is compared to measurements, showing good agreement. Fig. 2 shows QuaLiKiz predicted T_i and T_e, and T_e from the measurement fits: T_e discrepancy in the plasma core is due to sawtooth crashes not modelled by QuaLiKiz. Kinetic plasma profiles corresponding to sawtooth drops are indeed not taken into account for transport modelling, in order to avoid affecting L-H power balance analysis. NBI power deposition (for $P_{NBI,e}$, $P_{NBI,i}$ terms in eq. 1) is calculated by JETTO + ASCOT modelling [19], [20].

Results and outlook

ASCOT NBI modelling indicates that, at L-H transition, NBI power is mainly absorbed by ions in core plasma and by electrons at the edge, with deposition location depending on injection energy and plasma density. Averaging all over the plasma radius, the ratio of NBI power to ions vs electrons ranges between about 60:40 and 50:50. QuaLiKiz predictive modelling indicates that ion transport dominates and power exchange term is small and generally in favour of the ions. T_e, T_i, $P_{NBI,i}$, $P_{NBI,e}$ and P_{ei} profiles are shown for HT dataset in figure 2. The contribution of the volume-integrated P_{ei} term can be seen in figure 3.

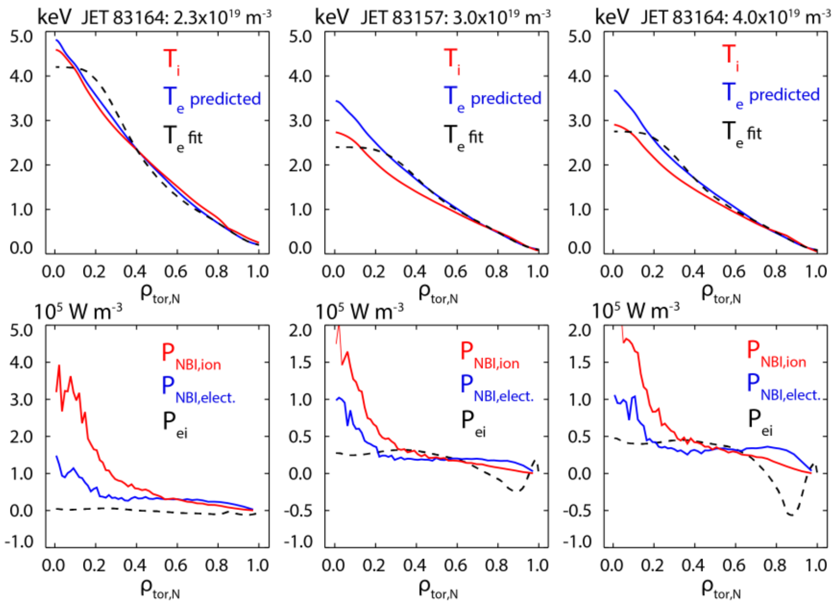

Figure 2: relevant quantities for L-H power balance analysis for HT dataset.

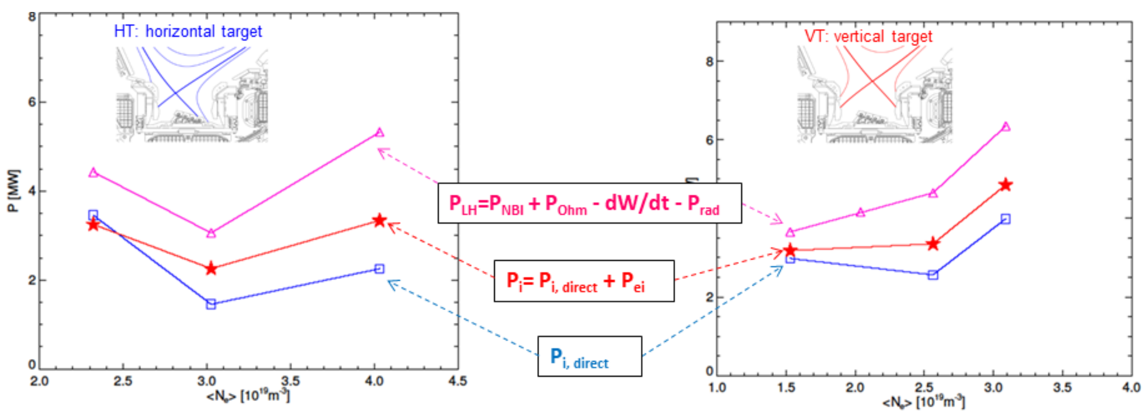

Figure 3: Power balance analysis terms for both datasets as a function of the line-averaged density.

The resulting power balance indicates that, for both datasets, the ion heating is dominated by direct NBI heating, and, at L-H transition time, the total ion heat flux (P_i in figure 3) has not a linear trend as function of the line-averaged density, unlike what was reported for RF heated plasmas in AUG and C-mod [4]. Note that power coupled to ions at L-H transition is not linear in density also for a subset of NBI-heated pulses in AUG [3], not considered in the fit presented in [4]. For these 6 JET pulses, the estimated equipartition term P_{ei} would not only need to be larger than predicted, but it would also require a change of sign to accommodate a linear dependence of the edge ion heat flux (P_i) on density.

This first analysis on JET ion heat channel at L-H transition will be completed with new data from the ongoing experimental campaign, which will have core T_i measurements and data from NBI vs RF-heated discharges for L-H transition studies. In parallel, flux driven first principle models embedding $\vec{E}x\vec{B}$ shear and the complex turbulence drive will help in the understanding of the theory explaining the L-H transition.

Acknowledgments

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. This work has been supported also by an EUROfusion Engineering Grant. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The authors wish to thank F. Ryter, J. Hughes and M. Cavedon for the useful for useful input and discussions.

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