CORE AND EDGE TRANSPORT OF SCENARIO WITH INTERNAL TRANSPORT BARRIER IN TRITIUM AND DEUTERIUM-TRITIUM PLASMAS IN JET WITH BE/W WALL

[1]CF MAGGI, [1]M FITZGERALD, [2]F ALBERT DEVASAGAYAM, [3]E DELABIE, [1]H DUDDING, [4]B ERIKSSON, [4]J ERIKSSON, [1]A FIELD, [5]E JOFFRIN, [5]X LITAUDON, [1]E LITHERLAND-SMITH, [1]S MENMUIR, [6]M NOCENTE, [1]C OLDE, [7]M PORADZINSKI, [8]I PREDEBON, [6]D RIGAMONTI, [1]S SAARELMA, [1]Z STANCAR, [2]T TALA, [1]I VOITSEKHOVITCH, JET Contributors* and EUROfusion Tokamak Exploitation Team[$]

[1]United Kingdom Atomic Energy Authority, Culham Campus, Abingdon, Oxfordshire OX14 3DB, United Kingdom of Great Britain and Northern Ireland; **[2]**VTT, PO Box 1000, FI-02044 VTT Espoo, Finland; **[3]**Oak Ridge National Laboratory, Oak Ridge, TN 37831-6169, USA; **[4]**Department of Physics and Astronomy, Uppsala Universitet, Uppsala, Sweden; **[5]**CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France; **[6]**Dipartimento di Fisica, Universita' degli Studi Milano-Bicocca, Milan, Italy; **[7]**Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland; **[8]**Istituto per la Scienza e Tecnologia dei Plasmi, CNR, Padova, I-35127, Italy
See the author list of "Overview of T and D-T results in JET with ITER-like wall" by CF Maggi et al. 2024 Nucl. Fusion **64 112012; [$]See the author list of E Joffrin et al 2024 Nucl. Fusion **64** 112019*

Email: Costanza.Maggi@ukaea.uk

In view of ITER and future fusion reactors, where internal transport barriers (ITBs) may form spontaneously, there is a need to fully understand the physics of ITB trigger and sustainment in order to avoid it or control its strength. For the first time on JET with metallic wall, we reveal the importance of the main ion isotope mass on ITB physics (triggering and strength) by comparing a unique dataset of discharges performed in D, T and D-T. First principle calculations of the reduction of anomalous transport with different isotopes are provided to shed light on the underlying physics.

ITB scenario in JET with Be/W wall. The JET-ILW D-T ITB scenario was aimed at providing a suitable, albeit transient, target plasma for the observation of toroidal Alfvén Eigenmodes (TAEs) destabilized by fusion born α-particles [1]. First developed in D plasmas [2], the ITB scenario was subsequently tested in T plasmas for isotopic dependencies and finally executed with D-T mixtures. The main characteristics are $B_T = 3.4$ T, $I_P = 2.7$ MA ($q_{95} \sim 3.8$), low density ($n_e \leq 4 \times 10^{19}$ m^{-3}), high core ion temperatures ($T_{i,core} \geq 10$ keV) and central q-value above unity, with auxiliary heating from NBI only ($P_{NBI} = 22 - 30$ MW). Since the presence of an extended region of low positive magnetic shear in the plasma centre is known to favour triggering of ITBs when q_{min} reaches rational values [3], to obtain a central q-value $q_0 \sim 1.5$ the NBI heating was applied during the plasma current ramp-up phase to slow down the current profile diffusion [4]. While there is no indication of a reversed q-profile during the discharge phase with high NBI power, there is indication of reversed q-profile in the Ohmic phase and up to the NBI-heated L-mode phase, concomitant with hollow T_e profile. The optimised q-profile in the phase prior to full NBI heating likely facilitates the transition to improved core thermal ion and electron confinement. This hypothesis is being tested against the semi-empirical ITB transport model, which combines the effects of magnetic and ExB rotation shear [5]. The ITB appears to be triggered at the location of the plasma $q = 2$ surface, as was observed in JET with C wall (JET-C). After ITB onset, the density profile becomes very peaked, primarily due to a reduction in pedestal density, $n_{e,PED}$. A clear ITB is observed at mid-radius in both ion and electron channels.

Fusion performance. The total neutron rate computed by interpretative TRANSP simulations is in good agreement with that measured by fission chambers. After ITB onset, the thermonuclear (TH) contribution to the total neutron rate increases significantly, reaching up to 50% of the beam-target (BT) component in the D-T shots and ratios of TH /BT ~ 1 in the T shots at peak neutron rate. State of the art neutron spectroscopy analysis – of time-of-flight TOFOR measurements for D and T plasmas and of diamond detectors data for D-T plasmas - confirms the TH /BT neutron ratios calculated by TRANSP and validates the core plasma fuel ratio.

Isotope dependence of ITB access and strength. A significant impact of main ion isotope mass on ITB access and strength is observed: the ITB is more easily triggered (namely, at lower NBI power) and, once fully developed, has its foot at a larger radius in T than in D (FIG.1). Indeed, with fully developed ITB the core ion heat diffusivity χ_i (TRANSP) is lower for T than D and over a wider plasma volume, reaching neo-classical values (FIG 2). Furthermore, the ratio of ExB shearing rate to $v_{th,i}/L_{Ti}$ ($v_{th,i}$ = thermal ion velocity, $L_{Ti} = T_i/\nabla T_i$ the ion temperature scale length), an approximate criterion for suppression of ion-scale turbulence, exceeds unity at mid radius in the T plasma at ITB onset, due to the stronger toroidal rotation (and rotation shear) in T than in D. In the context of this work, the ITB is interpreted as extreme case of reduction of core ion (/electron) temperature profile stiffness. A recent experimental study and comparison with gyrokinetic (GENE) simulations of the isotope dependence of core heat transport in JET-ILW D vs T plasmas shows a clear reduction of T_i stiffness with increasing hydrogenic isotope mass A ($A = m_i/m_p$), which is attributed to increased thermal electromagnetic stabilization of ITG turbulence with increasing A [6]. GENE and CGYRO simulations of the core plasma of the JET-ILW ITB scenario are ongoing to understand the impact of A on ITB trigger and strength, as well as the roles of magnetic and toroidal rotation shear, fast ion density (n_{FI}) and thermal ion density (n_i) and their interplay with respect to ITB formation. In the ITB shots analysed, the core fast ion dilution n_{FI}/n_i varies between ~ 15-25 % at ITB onset and ~ 10-20% in the phase with fully developed ITB.

Pedestal and isotope dependence. The discharge phase with ITB is correlated with a transition to a pedestal with 'small/high frequency ELMs' (possibly type III ELMs) and strong decrease in $n_{e,PED}$. The pedestal density of plasmas with ITB decreases with A_{eff} from D to T, opposite to what observed in type I ELMy H-modes, where $n_{e,PED}$ increases with A_{eff} [7], [8]. Gyrokinetic simulations (GENE) of the low-density pedestal of the ITB scenario are on-going to identify the dominant micro-instabilities at play and assess the isotope dependence of pedestal heat and particle transport in these conditions. As expected, linear MHD stability (ELITE) of these pedestals finds the operating point deeply stable to ideal peeling-ballooning modes. A key question addressed is that of core – pedestal interplay: whether low edge density and absence of type I ELMs are necessary to trigger the ITB or if the formation of an ITB leads to degradation of the pedestal pressure gradient.

Core high-Z impurity transport. Intrinsic impurities are Be, W and Ni. The method developed by [9] is used to derive the impurity density and radiation radial profiles and their temporal evolution. The W and Ni density profiles initially peak at the low-field-side of the tokamak and are flat or even hollow at the plasma centre. As the plasma discharge progresses in time, the W and Ni profiles maxima move radially inwards, but central impurity accumulation is not observed during the high-power phase before NBI switched off at peak neutron rate. Core W and Ni impurity transport is explained comparing the neoclassical convection and diffusion computed by FACIT [10] with standalone NEO predictions for the ITB plasma conditions. The complex interplay of high Mach number (M_ϕ ~0.6) enhancing impurity screening at low plasma collisionality, but enhancing inward convection with increasing Z_{eff} (/ increasing collisionality), regulates the high and mid-Z impurity dynamics. Sensitivity scans on the gradients of the driving parameters, ∇T_i and ∇n_e, within experimental uncertainties, are carried out to enhance confidence in the model predictions.

Comparison of the JET D-T ITB scenario with Be/W wall and with C-wall [11] is not straightforward, as the two scenarios were not performed "like for like". However, a consistent difference is the substantially higher core T_i and neutron rate achieved in the JET-C ITB shots. The root cause of this difference is investigated.

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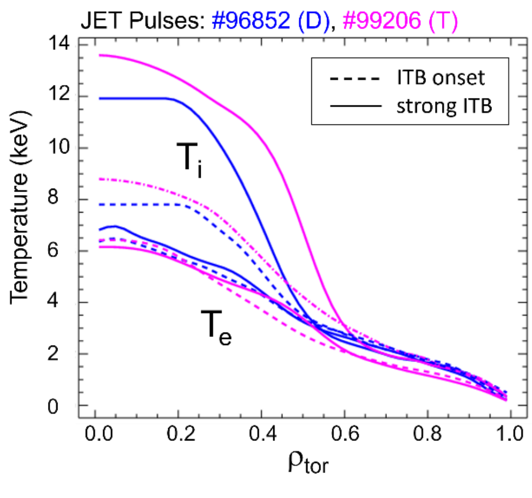

FIGURE 1. Ion and electron temperature profiles for JET-ILW ITB shots #96852 (D - blue) and #99206 (T - magenta). Dashed line: time of ITB onset; solid line: fully developed ITB (50 ms (D shot), 90 ms (T shot) before NBI switch-off).

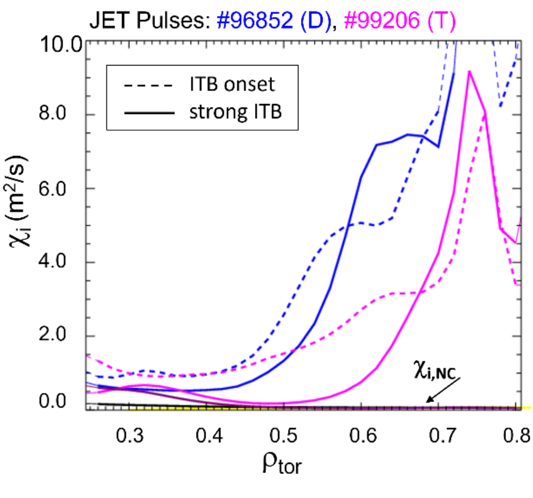

FIGURE 2. Comparison of power-balance core ion heat diffusivity (TRANSP) for JET-ILW ITB shots #96852 (D - blue) and #99206 (T - magenta) and neoclassical value $\chi_{i,NC}$ (same time slices as for FIG.1).