Influence of rotational shear on triggering and sustainment of internal transport barriers on JET

K. Crombé, Y. Andrew, T.M. Biewer, E. Blanco, M. Brix, P. de Vries, A. Fonseca, C. Giroud, N.C. Hawkes, E. Joffrin, P. Mantica, A. Meiggs, V. Naulin, S. Pinches, E. Rachlew, T. Tala, A. Whiteford and JET-EFDA contributors*

JET-EFDA Culham Science Centre, Abingdon, OX14 3DB, UK

1 Postdoctoral Fellow of the Research Foundation –Flanders, Department of Applied Physics, Ghent University, Rozier 44, 9000 Gent, Belgium
2 EURATOM/UKAEA Fusion, Culham Science Centre, OX14 3DB, Abingdon, UK
3 Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA
4 Laboratorio Nacional de Fusion, Asociacion EURATOM-CIEMAT, Madrid, Spain
5 Associação EURATOM-IST, Instituto de Plasmas e Fusão Nuclear, Lisbon, Portugal
6 CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
7 Instituto di Fisica del Plasma, Associazione EURATOM-ENEA-CNR, Milano, Italy
8 Association EURATOM-RISØ DTU, PO Box 49, DK-4000 Roskilde, Denmark
9 Association EURATOM-VR, SCI, KTH, SE-10691 Stockholm, Sweden
10 VTT Association EURATOM-TEKES, PO Box 1000, FIN-02044 VTT, Finland
11 Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK

*See the appendix of F. Romanelli et al., Fusion Energy Conferences 2008 (Proc. 22nd Int. FEC Geneva 2008) IAEA, 2008

1. Introduction

Plasmas with improved confinement by an Internal Transport Barrier (ITB) are considered in the Advanced Tokamak scenarios for ITER. Dedicated pulses to study the effect of poloidal ($v_\theta$) and toroidal ($v_\phi$) rotation velocities on the triggering and sustainment of ITBs have been carried out on JET. A new instrument has recently been added to the suite of charge exchange spectrometers allowing $v_\theta$ measurements up to 10 ms in the ITB region [1], which is the same temporal resolution as for the $v_\phi$ and ion temperature ($T_i$). A torque and power scan was performed. Pulses with reversed and monotonic $q$-profiles are compared to investigate the role of magnetic shear on the ITB triggering and growth.

2. Experimental results and discussion

A series of JET plasmas were run at $B_t/I_p=2.2T/1.8-1.9MA$ and central line averaged density of $7-8e^{19}$ m$^{-2}$. The NBI power was varied between 7 MW and 15 MW and the ICRF heating power that was coupled to the plasma varied between 1.0 MW and 3.3 MW. In some of the discharges 2 MW of LHCD was applied during the current ramp-up phase to create a
reversed $q$-profile. Alfvén cascades were observed in these discharges during the entire main heating phase indicating shear reversal.

2.1 Torque and power scans
The total torque was varied between 6 and 17.5 Nm and total power between 10 and 19 MW. It has been found that the largest $T_i$ gradients were created in plasmas with negative magnetic shear, a total torque of 15-16 Nm and 18 MW of additional heating power. The maximum $\rho^*_T$ value, a normalized local gradient scale length that indicates the existence and performance of an ITB on JET [2], reached values up to 0.038, well above 0.014, the empirical threshold for an ITB on JET.

2.2 Role of poloidal rotation velocity on triggering of the ITB
With the improved time and spatial resolution of the diagnostic a detailed study was performed to investigate the causality question between an increase in poloidal rotation velocity and the triggering of the transport barrier. In the majority of the pulses the start of the $T_i$ increase and the excursions in $v_\theta$ are simultaneous (within the 10ms time resolution). As soon as an ITB is triggered $v_\theta$ increases in the region with the strongest $T_i$ gradient, which helps to sustain the barrier, as discussed in [3]. However the discharge for which $T_i$, $v_\theta$ and $v_\phi$ time traces are shown in figure 1, does show an increase in $v_\theta$ 200ms earlier than the temperature rise, which indicates the onset of the ITB. The time $t=5.05$ s when $v_\theta$ starts to increase, coincides with a large Type-I ELM and a dip in the central part of the $T_i$ profile. No strong mode activity has been detected between $t=5.05$s and $t=5.25$s. At the start of the ITB ($t=5.25$ s) an n=1 mode is present in the plasma, which persists for over 500 ms. During the ITB phase the ELMs are Type-III. Alfvén cascades are seen throughout the shots. The EFIT reconstruction, including MSE, Faraday rotation, pressure and electric field effects, indicates that $q_{\text{min}}=2$ at $t=5.15$s. In figure 2 profiles of $T_i$, $\omega_\psi$ and $v_\theta$ are shown before and during the ITB phase. The increase in poloidal rotation is localized to $R_{\text{mid}} = 3.35 - 3.60$m (corresponding to $\rho=0.40 - 0.70$), and a maximum value of 65 km/s is reached at the peak of the barrier, with central a $T_i$ of 14 keV. In figure 3 and 4 the radial electric field ($E_r$) has been calculated at the start of the rise in poloidal rotation. The largest $E_r$ shear is located in the region $\rho=[0.40 -0.50]$, where later on the transport barrier develops. The localized spin-up in $v_\theta$ is larger than the neoclassical prediction by NCLASS for carbon impurity ions. The high poloidal rotation velocity is the reason for the large $E_r$ gradient. It might help to push the shearing rate ($\omega_{E\times B}$) above the linear growth rate of the unstable modes and trigger the ITB. This could explain the existence of a very strong ITB ($\rho^*_T=0.038$) in the plasma despite a moderate value of total torque (9 Nm) and input power (14 MW).
2.3 Role of the $q$-profile
In figure 5 profiles of two discharges (shot no. 72737 and 72747) with similar heating power (i.e. 15 – 16 MW of NBI and 1 – 2 MW of ICRH) and total torque (15 – 15.5 Nm) are compared. On the left hand side $T_i$, $v_\phi$, $v_\theta$ and $q$-profiles are shown at a time before a sustained ITB is present in the plasma. It can be seen that the rotation and temperature profiles are very similar. For shot no. 72737 the $q$-profile is reversed and $q_{\min}$ is still above 2. In shot no. 72747 the $q$-profile is monotonic and the rational surface $q=2$ is already present in the plasma before the start of the main heating phase. On the right hand side are profiles at a later time ($t=6.0s$) when the ITB is fully developed. A strong barrier ($\rho^{*}_{T_i} = 0.025$) is triggered in shot no. 72737 just after $q_{\min}$ hits the rational surface $q=2$. For the same amount of rotational shear the monotonic $q$ case does not develop a sustained barrier, the maximum value of $\rho^{*}_{T_i}$ is 0.019. Some trigger events are observed in the $T_i$ time traces, which coincide with excursions in $v_\theta$ of up to 10 km/s. The values of $v_\theta$ are well above the neoclassical predictions, but they do not appear to be sufficient for the growth of a strong barrier.

3. Conclusions
It has been found on JET that a localized spin-up in $v_\theta$ can precede the onset of a transport barrier. Consequently, the radial electric field shear is enhanced, which then helps to suppress turbulence locally and to trigger an ITB. This increase in $v_\theta$ prior to the triggering of the barrier, is not a common observation in the present database and perhaps not essential. However, when present, it may reinforce other factors that play a role in the triggering such as a rational $q$-surface, MHD activity and a large toroidal rotational shear.

The strongest barriers (corresponding to a $\rho^{*}_{T_i}$ value $> 0.030$) were found in plasmas with a reversed $q$-profile and $q_{\min}=2$ for an input power of 17-18MW and a total torque of 15-17 Nm. In plasmas with monotonic $q$-profile ITBs have been triggered, but they were weaker and did not develop large $T_i$ gradients, the maximum value of $\rho^{*}_{T_i}$ was 0.019.

Acknowledgement This work, supported by the European Communities and the Royal Military Academy (RMA), Belgium, has been carried out within the framework of the European Fusion Development Agreement under the Contract of Association between EURATOM and the Belgian State. Financial support was also received from Ghent University (UG), Belgium, and the Research Foundation - Flanders (FWO). The views and opinions expressed herein do not necessarily reflect those of the European Commission, RMA, UG or FWO.

References
Figure 1: Temporal evolution of $T_i$, $\omega_\phi$, and $v_\theta$ at different radial positions. The $v_\theta$ increases precedes the $T_i$ increase by 200 ms.

Figure 2: Profiles of $T_i$, $\omega_\phi$, and $v_\theta$ at different times before ($t=5.05s$, $t=5.15s$) and during the ITB phase ($t=5.35s$, $t=5.55s$).

Figure 3: Contributions to $E_r$ profile at a time before the start of the ITB. The localized spin-up in $v_\theta$ creates a large gradient in $E_r$ at $r=0.40-0.50$.

Figure 4: Profile of $E_r$ calculated with the experimental and the neoclassical $v_\theta$.

Figure 5: Comparison of $T_i$, $\omega_\phi$, and $v_\theta$ and $q$-profiles for shot no. 72737 and 72747 before (left hand side at $t=4.8s$) and during the ITB phase (right hand side at $t=6.0s$). The $T_i$ gradient for shot no. 72737 with reversed $q$-profile and $q_{min}=2$ is steeper than for the monotonic $q$ case. The $v_\theta$ profile before the ITB is similar in both plasmas, and spins up with the $T_i$ gradient increase for shot no. 72737 [3].