

# Electron heated Internal Transport Barriers in JET

G.M.D. Hogeweij<sup>1</sup>, Y. Baranov<sup>2</sup>, C.D. Challis<sup>2</sup>, G.D. Conway<sup>6</sup>,  
F. Crisanti<sup>3</sup>, M.R. De Baar<sup>1</sup>, N. Hawkes<sup>2</sup>, F. Imbeaux<sup>4</sup>, X. Litaudon<sup>4</sup>,  
J. Mailloux<sup>2</sup>, F.G. Rimini<sup>4</sup>, S.E. Sharapov<sup>2</sup>, B.C. Stratton<sup>5</sup>, R. Wolf<sup>6</sup>,  
K.-D. Zastrow<sup>2</sup> and contributors to the EFDA-JET work programme

<sup>1</sup> *FOM Instituut voor Plasmafysica 'Rijnhuizen', Associatie EURATOM-FOM, Trilateral Euregio Cluster, P.O.Box 1207, 3430 BE Nieuwegein, The Netherlands*

<sup>2</sup> *Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK*

<sup>3</sup> *Associazione EURATOM-ENEA sulla Fusione, C.R.Frascati, Frascati, Italy*

<sup>4</sup> *Association EURATOM-CEA, CEA Cadarache, Saint-Paul-lez-Durance, France*

<sup>5</sup> *Princeton Plasma Physics Laboratory, Princeton, USA*

<sup>6</sup> *Max Planck Institut für Plasmaphysik, EURATOM Association, Garching, Germany*

## 1. Introduction

Tokamak regimes where the heat transport in the plasma interior is reduced due to the presence of an internal transport barrier (ITB) have been investigated on many experimental devices. The usual scenario is based on heating early in the discharge, thus delaying the current penetration, see e.g. [1, 2, 3, 4].

Most of the analysis of Internal Transport Barriers (ITBs) in large tokamaks so far concentrated on regimes with dominant ion heating, i.e. with  $T_i > T_e$ . As reactor conditions are characterized by dominant electron heating, and consequently  $T_e \geq T_i$ , attention has recently shifted to this kind of regimes in JET.

This paper reports on recent experiments in JET, where an electron ITB (eITB) was sustained during many seconds into the current flat-top with electron heating only. Discharges with Ion Cyclotron Resonance Heating (ICRH) will be compared with discharges with Lower Hybrid Current Drive (LHCD) during the current flat-top. Local transport analysis of these discharges will be presented, focusing on the relation between the eITB and magnetic shear.

## 2. Experimental Results

The scenario of the discharges under consideration consists of the switch-on of LHCD very early in the discharge, typically at 1 sec, which is either continued many seconds into the current flat-top phase, or is replaced by ICRH during the current flat-top. Fig.1 gives a typical example of both; it also shows the time evolution of the central electron temperature and density ( $T_e, n_e$ ). ICRH is applied in the H minority heating scheme, which guarantees that most of the heat is transferred to the electrons. It should be noted that the reliable application of long LHCD pulses was only possible after work in improved coupling of the LH waves to the plasmas by Task Force H [8].

Short blips of Neutral Beam Injection (NBI) were applied in order to have measurements of the ion temperature ( $T_i$ ) with charge exchange spectroscopy (CXs) and of the current density with the Motional Stark Effect (MSE) diagnostic. Inclusion of MSE data in the equilibrium reconstruction is essential for the resolution of hollow safety factor ( $q$ ) profiles [12]. In a series of similar discharges the timing of the NBI blips was varied in order to have a full time coverage of  $T_i$  and  $q$ ; without further notice the data on  $T_i$  and  $q$  quoted in this paper has been sampled from this series of discharges.

As seen in Fig.1, high  $T_e$  is established with LHCD and maintained throughout the

discharge (53501), and  $T_e$  recovers quickly from MHD crashes. The discharge with ICRH (53506) seems to perform slightly less well; however,  $n_e$  is slightly higher in this case, so the electron pressure is comparable in both discharges. In Fig.2 profiles of  $T_e$  are plotted, showing that there is a clear electron Internal Transport Barrier (eITB), which slowly moves inward in time. The eITB in the ICRH case (53506, dashed line) appears to be less pronounced. At the position of the eITB a reduction of turbulence has been observed [7]. For comparison, also  $T_i$  profiles are given in Fig.2, showing that the electrons and ions are strongly decoupled ( $T_e/T_i \simeq 5$  during LHCD and  $\simeq 2$  during ICRH); the  $T_i$  profile shows no sign of an ion ITB (iITB).

### 3. Q profile evolution and MHD analysis

The evolution of  $q(0)$  and  $q_{min}$  is given in Fig.3. The preheat phase up to 4 s is characterised by a very hollow  $q$  profile. After 4 s,  $q_{min}$  rapidly approaches  $q(0)$  in the discharge with ICRH, leading to a nearly flat  $q$  profile after 6 s. In the case with prolonged LHCD, on the other hand, the  $q$  profile remains clearly hollow at least up to 8 s. During LHCD there are many sawtooth-like MHD events [9]; the postcursors of those crashes, when present, have been analysed. The radial position of the MHD events corresponds well with the position of  $q_{min}$  from MSE, and the  $m/n$  number from MHD agrees with the value of  $q_{min}$  within error bars, although  $q_{min}$  from MSE tends to be slightly higher. During ICRH Toroidal Alfvén Eigenmodes (TAEs) and cascades, excited by the ICRH-accelerated ions, are observed [10]; analysis of their mode numbers is under way.

### 4. Transport Analysis

TRANSP runs have been performed for discharges 53501 and 53506. Fig.4 shows profiles of the electron and ion thermal diffusivity ( $\chi_e, \chi_i$ ) at different time slices for discharge 53501. The eITB is recognised as a local minimum in  $\chi_e$ , which is seen to move steadily inward from  $\simeq 3.30$  m at 43.5 s to  $\simeq 3.15$  m at 48 s.  $\chi_i$  shows no sign of an iITB.

The eITB was further scrutinized with a simple dimensionless criterion based on the ratio of the ion gyro-radius to the local gradient scale length,  $\rho_T^* = \rho_s/L_T$  [13], see Fig.5. The inward movement of the eITB is seen for both discharges; moreover, the eITB becomes poorly established in the ICRH case after  $\sim 5.5$  s.

### 5. Discussion and Conclusions

The relation between the position of the eITB and the  $q$  profile has been a point of discussion for a long time [5]. In Fig.5 the position of  $q_{min}$  ( $r_{qmin}$ ) and of the strongest negative magnetic shear ( $s$ ) are indicated. The footpoint of the eITB ( $f_{eITB}$ ) moves inward at the same rate as  $r_{qmin}$ ; however  $f_{eITB}$  is at a 10-15 cm smaller radius, which is outside the error bars. There seems to be no link between  $f_{eITB}$  and the  $q$  value, as  $q$  is strongly evolving in time (see Fig.3). Apart from the first 2 seconds, the position of the barrier appears to coincide with the region of most negative  $s$ .

It appears to be significant that the eITB weakens during ICRH whereas it remains strong during the long LHCD pulse: as the  $q$  profile loses its clear hollowness during ICRH (and not during the long LHCD pulse), one might conjecture that negative  $s$  is required (or at least helps) for the sustainment of the eITB. A further indication of this is that the timing of the heating turned out to be essential: in discharges where the switching from LHCD to ICRH was slightly earlier, the eITB was lost altogether. This role of  $s$  was also found in Tore Supra [6].

These findings are in qualitative agreement with the predictions of the empirical JET

model for iITBs [11]. It should be noted, however, that the iITB relies on a combination of two parameters:  $s$  and flow shearing rate ( $\omega_{ExB}$ ). The latter, which in engineering terms translates into a threshold power, appears to be insignificant for the eITB.

**Acknowledgements.** This work has been performed under the European Fusion Development Agreement and under the Euratom-FOM association agreement, with financial support from NWO and Euratom.

## References

- [1] Sips, A.C.C., et al, *Plasma Phys. Contr. Fusion* **40** (1998) 647.
- [2] Fujita, T., et al, *Nucl. Fusion* **39** (1999) 1627.
- [3] Strait, E.J., et al, *Phys. Rev. Lett.* **75** (1995) 4421.
- [4] Levinton, F.M., et al, *Phys. Rev. Lett.* **75** (1995) 4417.
- [5] Challis, C.D., et al, 'Effect of  $q$ -profile modification by LHCD on internal transport barriers in JET', submitted to *Plasma Phys. Contr. Fusion*.
- [6] Litaudon, X., et al, *Plasma Phys. Contr. Fusion* **43** (2001) 677.
- [7] Conway, G.D., et al, *this conference*.
- [8] Mailloux, J., et al, *this conference*.
- [9] Hennequin, P., et al, *this conference*.
- [10] Sharapov, S.E., et al, *this conference*.
- [11] Tala, T., et al, 'ITB formation in terms of  $\omega_{ExB}$  flow shear and Magnetic shear  $s$  on JET', accepted for publication in *Plasma Phys. Contr. Fusion*.
- [12] Hawkes, N., et al, *this conference*.
- [13] Tresset, G., et al, *this conference*.

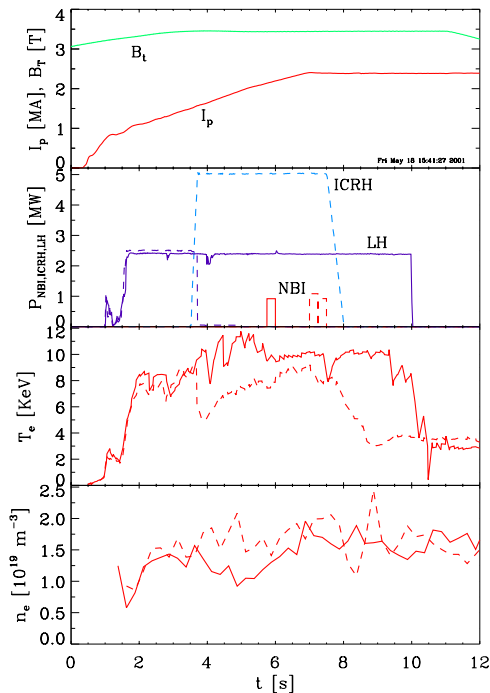


Figure 1: Scenario of discharges 53501 (full lines) and 53506 (dashed lines). Shown are the time traces of plasma current ( $I_p$ ), magnetic field ( $B_t$ ), input powers ( $P_{NBI}$ ,  $P_{LH}$  and  $P_{ICRH}$ ), and central electron temperature ( $T_e(0)$ , from ECE) and density ( $n_e(0)$ ).

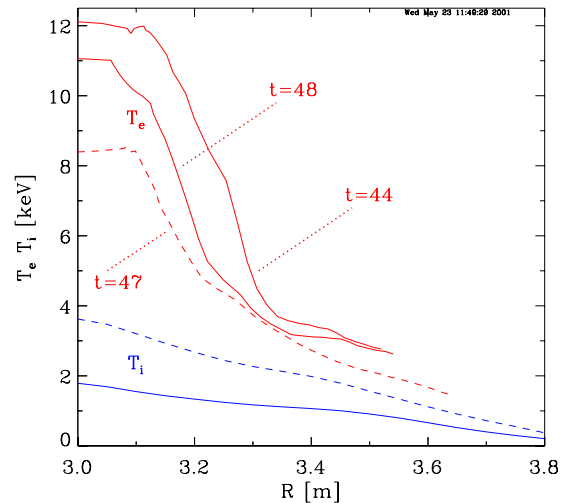


Figure 2: Profiles of  $T_e$  (red) and  $T_i$  (blue) for shots 53501 and 53506 (full/dashed lines) at different time slices. The shrinking of the electron ITB in time is clearly seen. The  $T_i$  profiles (taken at  $t=47$  s) do not show any sign of an ITB, and the large ratio  $T_e/T_i$  shows that electrons and ions are strongly decoupled.

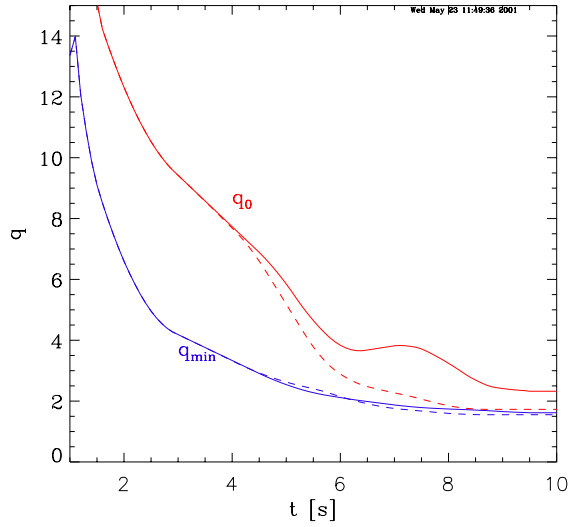


Figure 3: Time evolution of  $q_0$  and  $q_{min}$  from MSE measurements for discharges 53501 and 53506 (full/dashed).

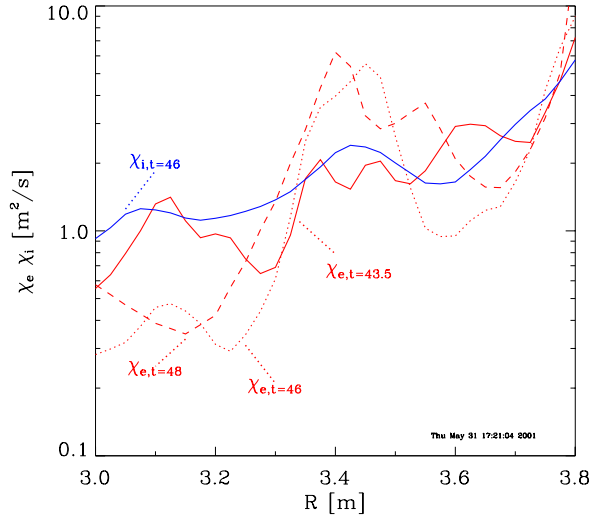


Figure 4: Electron and ion thermal diffusion ( $\chi_e$  in red,  $\chi_i$  in blue) profiles from TRANSP. The eITB, seen as a local minimum in  $\chi_e$ , moves inward and intensifies. There is no sign of an ion ITB.

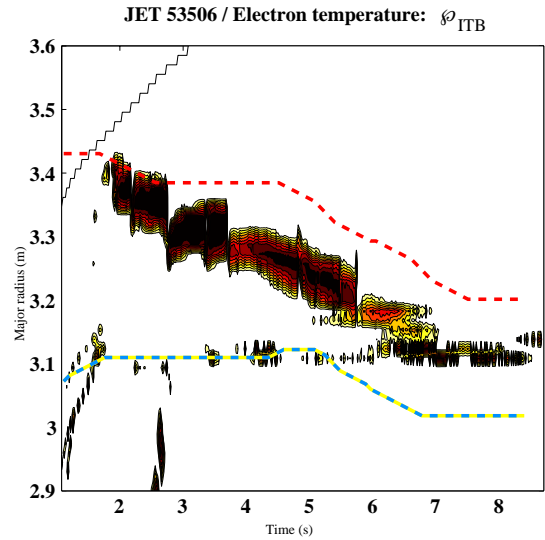
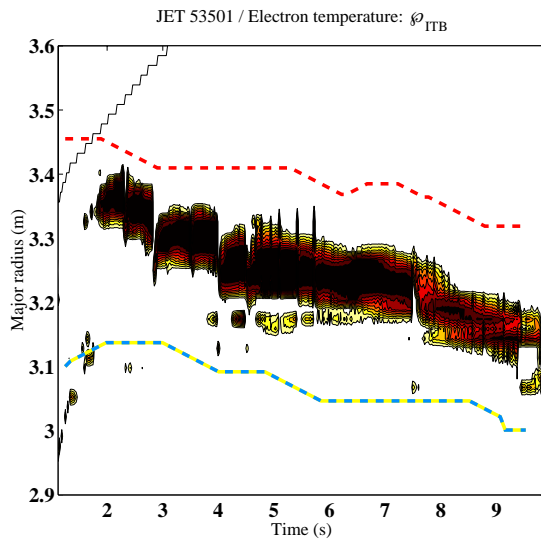


Figure 5:  $\rho_T^*$  ITB analysis of JET discharges 53501 and 53506. The colours indicate the probability that an eITB is present at a given time and radius, see [13]. Only probabilities  $> 50\%$  are shown. The small black features near 3.1 m in the right hand figure are artefacts due to small calibration errors. The slow inward movement of the barrier is clearly seen; moreover the barrier in shot 53506 becomes poorly established after  $t \sim 5.5$  sec. For comparison also the radius of minimum  $q$  and of most negative shear are plotted (dashed red and blue lines, respectively).