INFLUENCE OF ELECTRON HEATING ON CONFINEMENT IN JET AND ASDEX UPGRADE INTERNAL TRANSPORT BARRIER PLASMAS

R. C. Wolf[1], Y. Baranov[2], C. Giroud[3], M. Mantsinen[4], D. Mazon[3], K.-D. Zastrow[2], N. Hawkes[2], T. Hellsten[5], J. Hobirk[1], M. Laxåback[6], J.-M. Noterdaeme[1], F. Rimini[3], A. Stäbler[1], F. Ryter[1], J. Stober[1], H. Zohm[1], the ASDEX Upgrade Team, and the Contributors to the EFDA-JET Workprogramme

[1]*Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, D-85748 Garching, GERMANY*

[2]*UKAEA/EURATOM Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*

[3]*Association EURATOM-CEA sur la fusion, CEA Cadarache, F-13108 St Paul les Durance, FRANCE*

[4]*Helsinki University of Technology, Association-EURATOM-Tekes, P.O.Box 2200, FIN-02015 HUT, FINLAND*

[5]*EFDA-JET Close Support Unit, Culham Science Centre, Abingdon, OX14 3DB, UK*

[6]*Association EURATOM-VR, Alfvén Laboratory, KTH, S-10044 Stockholm, SWEDEN*

1. Introduction

In plasmas with internal transport barriers (ITBs) different observations have been made regarding the effect of electron heating on confinement. Central counter-current drive, provided by either electron cyclotron resonance heating (ECH) and current drive in ASDEX Upgrade [1] or by fast wave heating (FWH) and current drive in DIII-D [2], to support the negative magnetic shear in neutral beam injection (NBI) heated ITB discharges, does not have any detrimental influence on the plasma confinement. In the case of DIII-D this is partially attributed to the turbulence stabilizing effect of an increase of the $E \times B$ shearing rate due to a reduction of the poloidal magnetic field in the plasma center, caused by the additional bootstrap current of the electron pressure. Although such an explanation is also conceivable for the ASDEX Upgrade case, the stabilizing effect of the additional Shafranov shift seems to be sufficient to compensate the destabilization of the ion temperature gradient (ITG) modes due to the increase of the electron to ion temperature ratio T_e/T_i [3]. In contrast, in DIII-D ITB discharges with low or slightly negative central shear the addition of pure ECH or FWH leads to a confinement degradation in both the ion and electron channel [4,5].

In JET a corresponding experiment has been devised to investigate the influence of electron heating in ITB discharges, using ion cyclotron resonance heating (ICRH) at a low minority concentration to maximize the power fraction going into the electrons. Starting from a negative central shear configuration, produced with off-axis lower hybrid current drive (LHCD) in co-current direction during the current ramp-up phase, plasmas with neutral beam injection (NBI) heating only are compared with combined NBI and ICRH.

2. Characterization of Internal Transport Barriers

In the presence of stiff temperature profiles a reduction of the heat conductivity is not a good indicator for the formation of ITBs. Stiff temperature profiles are distinguished by a constant gradient length $L_T/R = T/R\nabla T$, limited at a critical value due to turbulent micro-instabilities such as ITG modes. As a consequence the heat conductivity is determined by the boundary condition at the plasma edge and the heat flux in the plasma. The exceeding of $R\nabla T/T|_{crit}$, indicating the reduction or suppression of plasma turbulence, separates ITB plasmas well from conventional confinement regimes such as L- or H-mode. This is shown in figure 1 for the ion temperature of JET discharges. A constant ratio of $T_i(r_1/a)/T_i(r_2/a)$ is equivalent to a constant gradient length. In the presentation of figure 1 only ITBs with a radius smaller than $r/a = 0.6$ are included. The corresponding line of ASDEX Upgrade is also shown [3], which suggests a slightly higher $R/L_T|_{crit}$ for L- and H-mode plasmas. For the comparison, the ASDEX Upgrade $R/L_T = const.$ curve has been corrected for the slightly different aspect ratio of the two tokamaks.

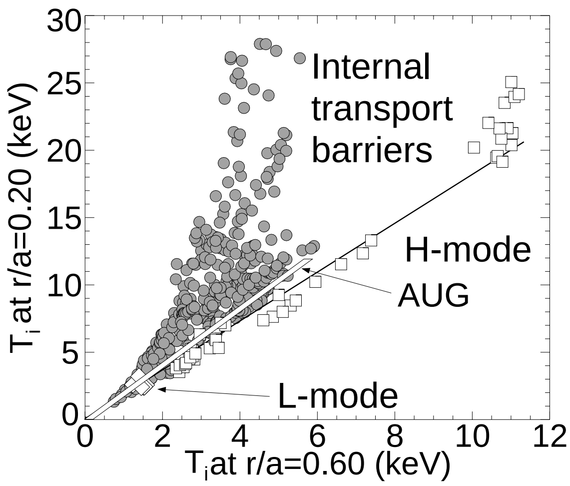

Figure 1: JET ion ITBs (with monotonic and reversed magnetic shear) are clearly separated from L- and H-mode plasmas using the $R\nabla T/T|_{crit}$ criterion [6]. The corresponding ASDEX Upgrade line (AUG) for L- and H-modes is also shown.

In ASDEX Upgrade discharges which are critical gradient limited, i.e. they follow the curve in figure 1, the addition of electron heating in form of ECH in low density NBI heated plasmas results in a reduction of R/L_T for the ion temperature, while that for the electrons stays constant. This is accompanied by a substantial drop in particular of the central electron density. A conceivable interpretation is that the increase of T_e/T_i causes the rise of the critical gradient length of T_i, as predicted by ITG mode theories. In the low density cases where the ion to electron energy transfer is rather low, the coupling between energy and particle transport still needs to be investigated. At high density the flattening of the density profile can be explained by a rise of the effective heat conductivity χ_{eff} due to an increase of the centrally deposited power at given R/L_T and a constant ratio of χ_{eff} to particle diffusivity including the Ware pinch [7].

The absence of such a degradation of energy and particle confinement in the ASDEX Upgrade ITBs with ECH and central counter-current drive supports the reasoning that the gradient limiting turbulence is and remains suppressed.

3. Electron Heating in JET Neutral Beam Heated ITB Discharges

In JET the effect of a variation of the electron heating on the confinement properties of reversed shear ITBs has been studied. A comparison of two discharges with 12MW NBI only and a combination of 10MW NBI and 6MW central ICRH are presented in figure 2. At first a weak ITB forms, which is followed by a transition into a strong ITB phase at 6s, clearly visible on the neutron signal and the larger R/L_{T_i} (figure 4). In both discharges the ITB phase is terminated by the appearance of strong ELM activity, which at the high power level can be avoided only transiently.

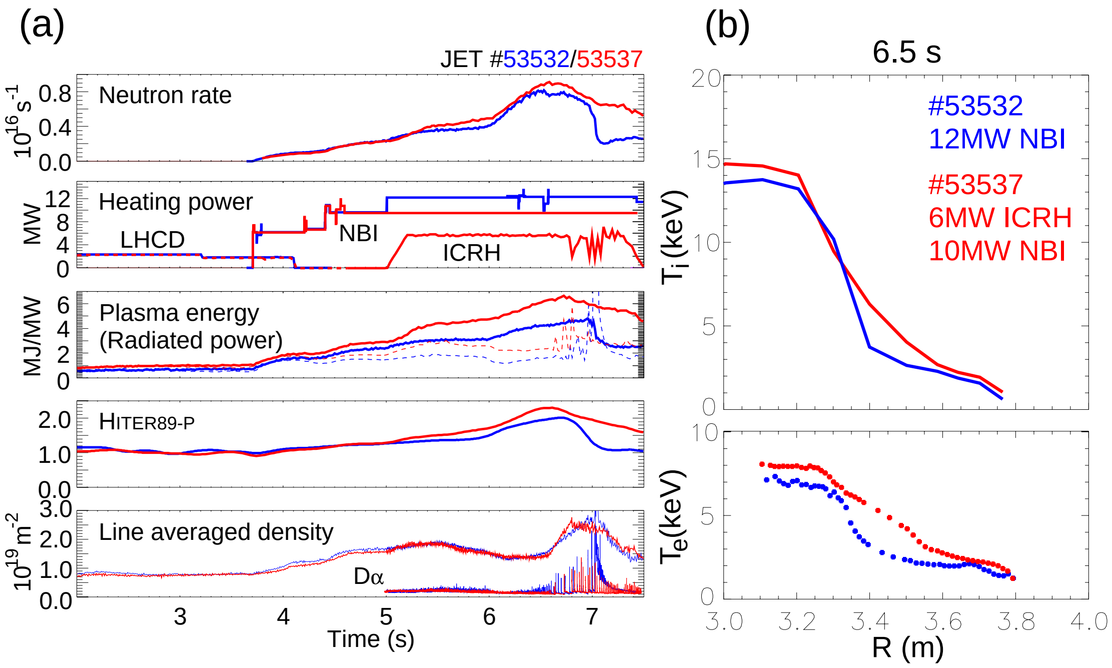

Figure 2: ITB plasmas with reversed magnetic shear (2.2MA and 2.6T), generated by LHCD during the current ramp, which ends at 4.7s. (a) shows the time evolution of neutron rate, heating power, plasma energy, radiated power, H-factor ($H_{ITER89-P}$), line averaged density, and D_α-signal. (b) shows the temperature profiles at 6.5s after the transition into a strong internal barrier.

The main effect of the replacement of 2MW NBI by 6MW ICRH is an energy increase, which corresponds to a rise of the H-factor by 15%. The neutron rate increases only marginally, which is reflected in the very small rise of T_i at constant density, while the T_e-profile mainly broadens. This behavior is confirmed by the calculation of the heat flux from TRANSP using the PION code for the ICRH power deposition (figure 3) . The ion heat flux hardly changes, as the reduction of the NBI contribution is compensated by the ICRH. In contrast, the electron heat flux increases by more than 40%.

In both cases at 5.5s the profiles of the ion and electron heat conductivity are very similar, which is in qualitative agreement with the comparable H-factors. After the transition to the strong ITB phase the increase of $H_{ITER89-P}$ is reflected in shift of the low electron and ion heat conductivity values in the plasma core to larger radii, concluding that the additional electron heat flux causes a broadening of the high confinement region. Currently we can only speculate, whether this is a consequence of the relatively strong shear reversal produced with LHCD in JET or whether other turbulence stabilizing effects such as the increase of the Shafranov shift contribute.

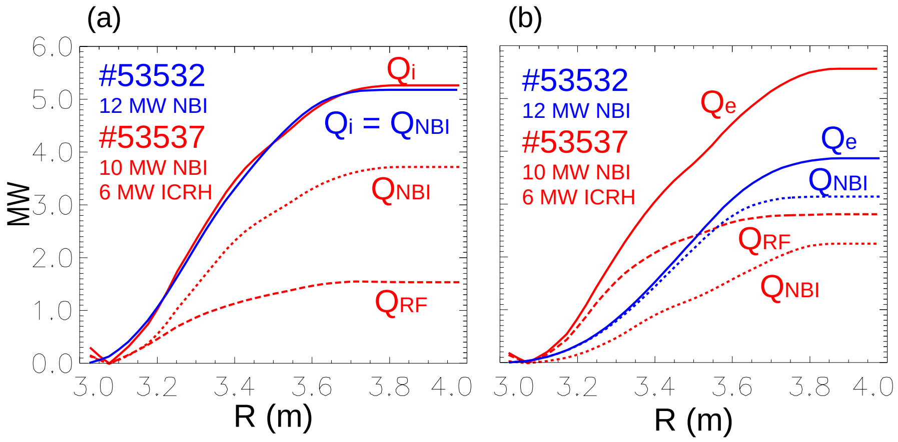

Figure 3: Composition of (a) ion and (b) electron heat flux at 6s of the two discharges shown in figure 2, just prior to the transition to the strong ITB phase.

A power scan from 10MW NBI only to 18MW of combined NBI and ICRH shows, that both the time of the transition to the strong ITB (t_{ITB}) and the gradient lengths before and after the transition are independent of the power level and the partition between electron and ion heat flux (figure 4). Only the temperature at which the transition takes place increases with power. This endorses the conclusion that at least the level of electron heating produced with 6MW ICRH does not lead to a degradation of the ion confinement.

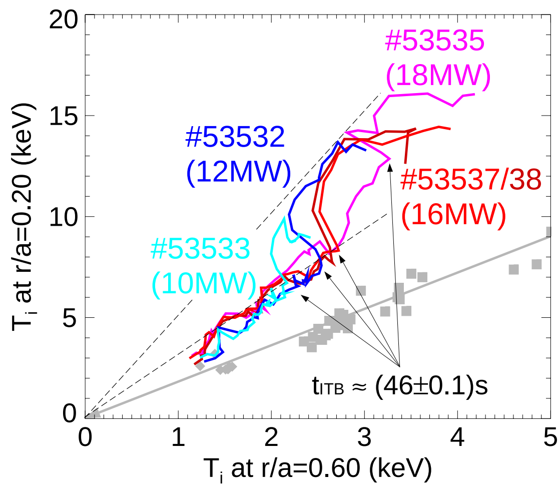

Figure 4: Time trajectories of R/L_T for different power levels. The strong ITB exhibits a larger R/L_T, indicated by the dashed lines.

4. References

[1] R. C. Wolf et al., Phys. Plasmas **7** (2000) 1839

[2] C. B. Forest et al., Phys. Rev. Lett. **77** (1996) 3141

[3] A. G. Peeters et al., 18th IAEA Fusion Energy Conf. (2000) IAEA-CN-77/EXP5/06

[4] C. M. Greenfield et al., Nucl. Fusion **39** (1999) 1723

[5] G. M. Staebler et al., 25th EPS Conf. on Control. Fusion and Plasma Phys. **22C**(1998) 2006

[6] E. Joffrin et al., this conference (P2.015)

[7] J. Stober et al., submitted for publication in Nucl. Fusion and this conference