EUROPEAN FUSION DEVELOPMENT AGREEMENT
EFDA JET

EFDA–JET–CP(01)02-36

G.D. Conway, C.D. Challis, J-M. Chareau, T. Estrada, J. Fessey, N.C. Hawkes, G.M.D. Hogeweij, X. Litaudon, L. Meneses, T. Ribeiro, R. Sabot, Y. Sarazin, J. van Gorkom, K-D. Zastrow and JET EFDA Contributors

Turbulence Behaviour During Electron Heated Reversed Shear Discharges in JET

Turbulence Behaviour During Electron Heated Reversed Shear Discharges in JET

G.D.Conway[1], C.D.Challis[2], J-M.Chareau[3], T.Estrada[4], J.Fessey[2], N.C.Hawkes[2], G.M.D.Hogeweij[5], X.Litaudon[3], L.Meneses[6], T.Ribeiro[6], R.Sabot[3], Y.Sarazin[3], J.van Gorkom[5], K-D.Zastrow[2] and JET EFDA Contributors*

[1]EURATOM-Association IPP, Garching, D-85748, Germany
[2]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK
[3]Association EURATOM-CEA Cadarache, F-13108 St. Paul-lez-Durance, France
[4]EURATOM Association-CIEMAT, Madrid, Spain
[5]FOM-Instituut voor Plasmafysica, Associatie EURATOM-FOM, Netherlands
[6]Associação EURATOM/IST, 1049-001, Lisboa, Portugal
**See appendix of the paper by J.Pamela "Overview of recent JET results", Proceedings of the IAEA conference on Fusion Energy, Sorrento 2000*

Preprint of Paper to be submitted for publication in Proceedings of the EPS Conference,
(Madeira, Portugal 18-22 June 2001)

INTRODUCTION

In previous studies of plasma turbulence behaviour, during dominant ion heated ($T_i > T_e$) internal transport barrier (ITB) discharges in the JET tokamak using reflectometry, low frequency turbulence (f < 20kHz) was observed to be reduced within the volume enclosed by an ion thermal barrier (i-ITB). The reduction was also correlated with reduced ion thermal conductivity χ_i. Higher frequency turbulence (f > 50kHz) was locally reduced around the electron thermal barrier (e-ITB), also coinciding with reduced electron thermal conductivity χ_e [1]. This paper reports observations on core and edge turbulence behavior during dominant electron heated ($T_e \geq T_i$) discharges with a pure e-ITB generated using Lower Hybrid Current Drive (LHCD).

1. ELECTRON ITBS

The formation of an e-ITB in JET typically begins with the application of 2 - 3MW of LHCD during the plasma current ramp up. Fig. 1 shows time traces for a typical 3.4 T/2.6MA Pulse No: 53449. With the LHCD power stepup at t = 1.5s the core electron temperature rises to T_e > 10 keV with n_e ~ 1.5 10^{19} m^{-3}. An e-ITB forms around r / a ~ 0.3 – 0.4 as shown in the radial profiles in Fig. 2, with comparative T_e profiles from ECE radiometer, ECE Michelson interferometer and Lidar diagnostics. n_e is from Lidar and T_i from CXRS during the NBI beam blip at 2.5s. Without significant ion heating note the absence of an ion ITB (T_i gradient). Ing. 3 profiles from an LHCD plus ICRH Pulse No: 53557 (with q profile from EFIT with MSE constraints) illustrates that the e-ITB is correlated with the reversal in magnetic shear s. Discharges without negative central shear display no e-ITB. In ref. [2] it is noted that the e-ITB is located around the position of maximum negative s.

2. CORE TURBULENCE

4 X-mode (75, 92, 96 & 105GHz) and 10 O-mode (18 - 69GHz) re ectometer channels were routinely used to monitor the core and edge turbulence throughout JET ITB discharges. During the e-ITB phase the core turbulence behaviour can be summarized in one sentence: low frequency (f <100kHz) uctuations are reduced (to below the diagnostic noise floor) from the core to the e-ITB radius. Fig. 4 shows two reflectometer spectra ($Ae^{i\phi}$ signal) from a 96GHz X-mode channel from inside the e-ITB (at t = 3.0s, r = a = 0.2) and outside (at t = 6.0s, r = a = 0.4) during Pulse No: 53449. Note the spike at zero frequency is the reflectometer carrier wave. The radial extent of the suppression is illustrated in Fig. 5 by the root-mean-square (rms) uctuation level vs normalized radius. The two traces were compiled from a single X-mode reflectometer channel during the Ip ramp with an evolving cuto layer position and are from matched Pulse No: 53449 (with LHCD and e-ITB) and Pulse No: 53453 (without LHCD). In the initial ohmic limiter phase of the pulses (t <1.1s) the core turbulence ($|r / a|$ < 0.6) is large, but is transiently suppressed around the time of the X-point formation. In pulses without an e-ITB the core turbulence quickly reappears and rises in amplitude with increasing radius. The peak in the non-LHCD case (g. 5 green) is where the cuto layer coincides with the q = 2 surface. In pulses with an e-ITB (g. 5 red) the core turbulence

remains suppressed out to the e-ITB gradient radius. This is also shown in ref. [2] to be the same region where χ_e is reduced (from TRANSP calculations in a similar pulse). It must be stressed that the turbulence behaviour was highly reproducible in all discharges and in different reflectometer channels as they crossed the e ITB gradient region at dierent times in the pulse.

3. WAVELENGTH ESTIMATION

The core turbulence wavelength range can be estimated using the NBI beam blip in Pulse No: 53453. Although the 2MW / 250ms long beam blip is primarily for diagnostic purposes (CXRS and MSE) it also briefly induce a toroidal rotation of ~25krad/s on axis. In the core reflectometer channels this appears as a Doppler broadening in the spectra, typically from 45kHz to ~215kHz. Assuming that (1) the NBI does not alter the turbulence wavenumber k-spectra, and (2) that $k_{||} << k_{\perp}$ then the toroidal velocity translates via the -3^{o} field inclination at the cuto layer to an additional rotation of $v_{rot\perp} \approx 3.3$km/s in the v_i* direction. From the frequency spread one obtains an intrinsic turbulence phase velocity $v_{ph} = +0.87$ or -0.57km/s depending on whether v_{ph} is with or against v_{rot}. This gives for the 45kHz width in the stationary phase a minimum fluctuation wavelength of $\lambda_{min} \approx 0.02$m. This λ_{min} is of the same order as the resolution limit of the reflectometer, so shorter wavelengths may exist but are not measured.

4. EDGE TURBULENCE

Outside the e-ITB radius the turbulence is unaected by the formation of the barrier - i.e. there is no core - edge linkage. Using the temporal evolution of the reflectometer cut off layers from many pulses with different magnetic fields and densities a picture has been compiled of the edge turbulence behaviour. Moving away from the core on both the high field and low field sides, the turbulence spectra both rises in amplitude (rms) and broadens. Figure 6 shows a series of spectra from a 75GHz X-mode channel at various edge radii during Pulse No: 53453 as the cuto moves out with increasing I_p. The rising rms level follows the trend shown in Fig. 5 for the core region. The spectral broadening is a pure spatial effect since different reflectometer channels give the same spectra as their cuto layers cross the same radii at different times in the discharge. Since the plasma is practically (toroidally) stationary during the LHCD heating these spectra illustrate the increasing wavenumber content or phase velocity as a function of radius. The last trace in Fig. 6(d) however shows the spectrum narrowing again as the cuto approaches the separatrix. This narrowing is a consistent feature in all e-ITB shots, however evidence suggests there is also a temporal effect due to the evolving (steepening) q profile at the edge. Figure. 7 shows the temporal evolution of (a) the 75GHz reflectometer cuto layer location, (b) the half spectral width at -10dB height plus rms amplitude, and (c) the local magnetic shear $s = r = q\ (dq / dr)$ at the cuto layer computed from EFIT (reliable in edge) for Pulse No: 52449. The transition from a broadening to a narrowing spectra appears to coincide with s exceeding unity. This effect is consistent with data from other reflectometer channels further in (where $s < 1$) which show no narrowing.

DISCUSSION

The core turbulence follows two distinct phases - an initial transient suppression triggered by either the transition in the magnetic conguration from limiter to X-point, or perhaps to an improved ohmic connement phase [3]. Secondly, the turbulence remains suppressed by the prompt formation of an e-ITB with a non-monotonic q profile. The coincidence in the radial extent of the turbulence reduction and χ_e is reminiscent of the turbulence behaviour during dominant NBI ion heating where the low frequencies were suppressed by the i-ITB. However this may simply be a case of the low frequencies being the easiest to suppress, by whatever transport barrier forms first. The edge turbulence shows the ubiquitous trend of increasing towards the edge, but the edge magnetic shear also appears to be a factor [4].

ACKNOWLEDGEMENTS

This work has been performed under the European Fusion Development Agreement.

REFERENCES

[1]. G.D.Conway et al, Phys. Rev. Lett. 84, 1463 (2000)
[2]. G.M.D.Hogeweij et al, This conference. 28th EPS Conf. Madeira (2001)
[3]. V.A.Vershkov et al, Nucl.Fusion39, 1775 (1999)
[4]. F.Romanelli & F.Zonca, 20th EPS Conf. Lisboa, ECA vol.17C, pt.IV, 1387 (1993)

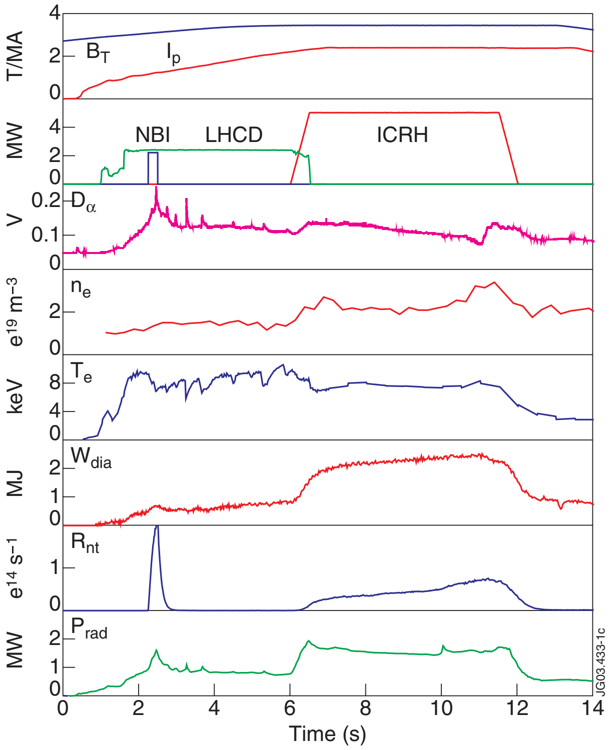

Figure 1: Plasma parameter time traces for 3.4T/2.6MA Pulse No: 53449.

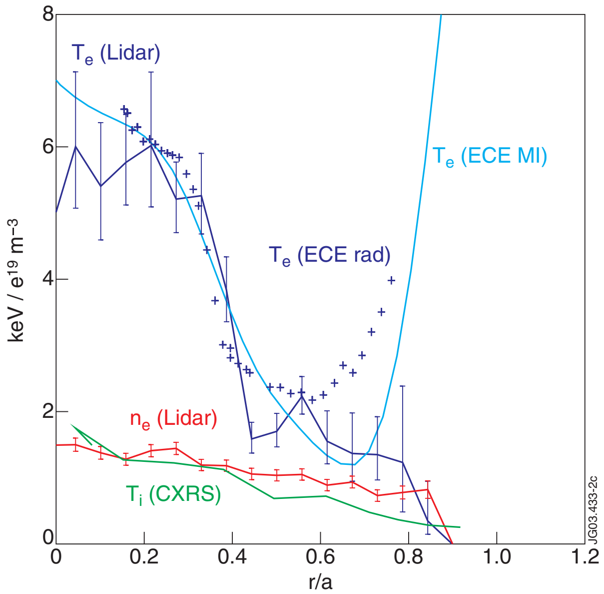

Figure 2: T_e (ECE, Lidar), T_i (CXRS), n_e (Lidar) profiles, Pulse No: 53449.

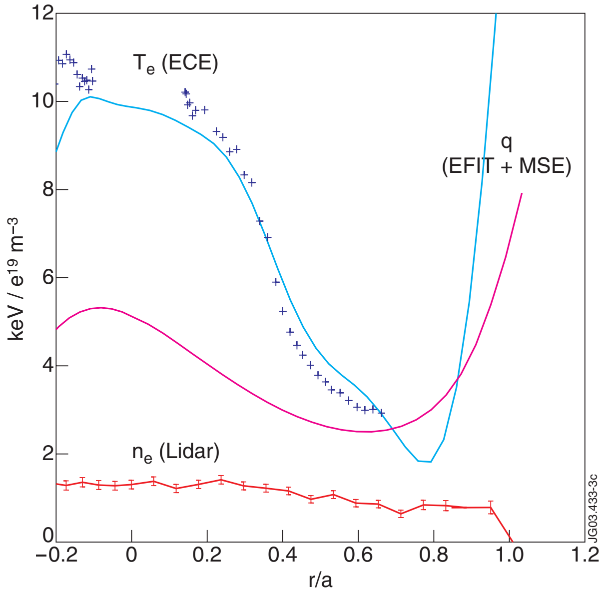

Figure 3: q, T_e, n_e profiles at t = 4.5s in LHCD + ICRH Pulse No: 53557 at t = 2.8s.

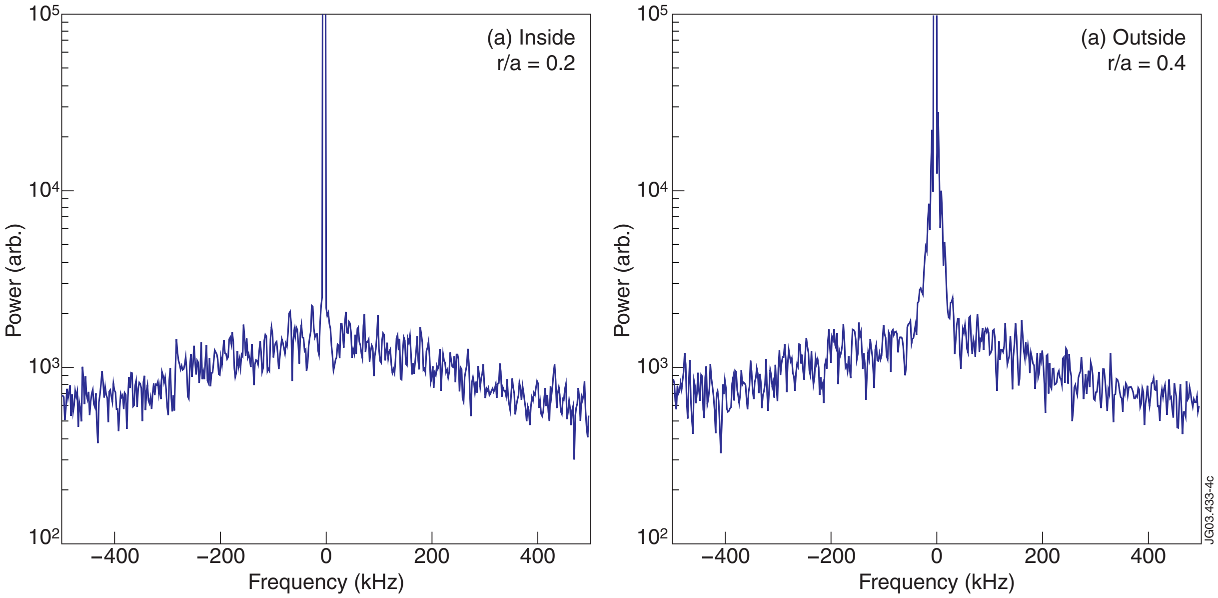

Figure 4: Reflectometer spectra: (a) inside e- ITB at t = 3.0s, (b) outside e-ITB at t = 6.0s; 96GHz X-mode, Pulse No: 53449.

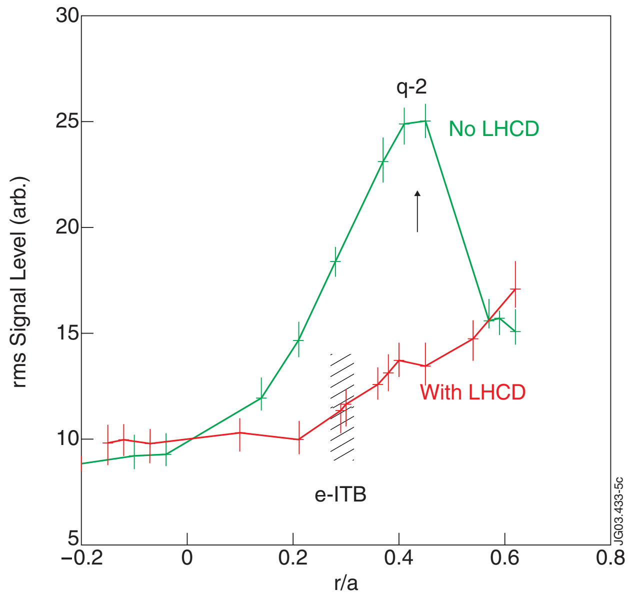

Figure 5: rms fluctuation level vs radius with (Pulse No: 53449) and without (Pulse No: 53453) LHCD.

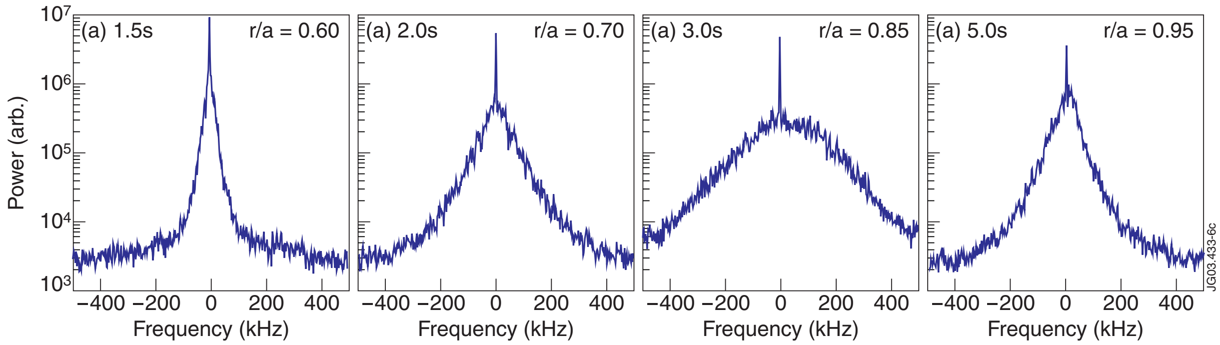

Figure 6: Complex amplitude spectra from 75GHz X-mode edge channel Pulse No: 53453.

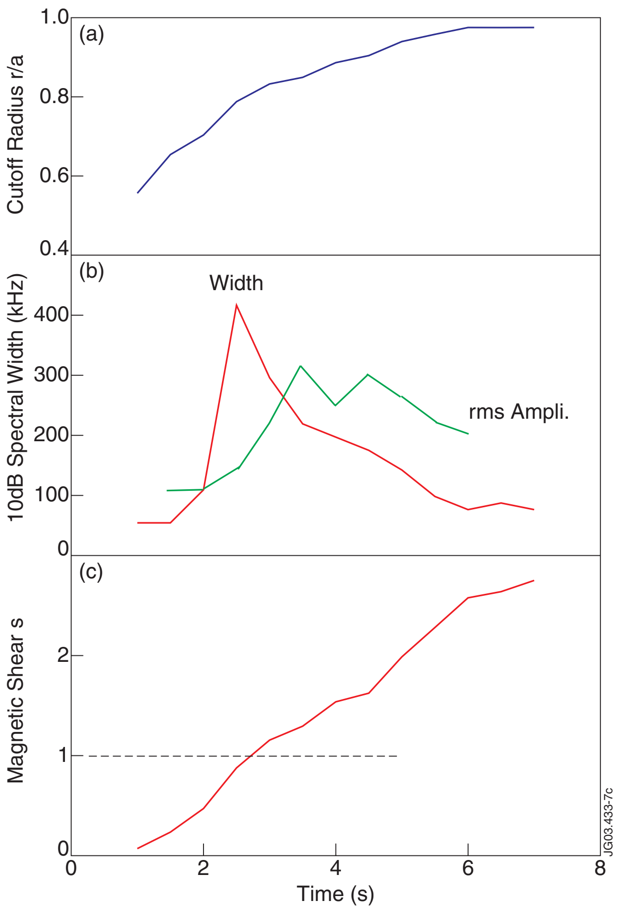

Figure 7: (a) 75GHz X-mode cut off, (b) 10dB width & rms ampl., (c) magnetic shear at cut off, Pulse No: 53449.