EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(07)03/54

J. Mailloux, P. de Vries, V. Pericoli-Ridolfini, B. Alper, Y. Andrew, Yu. Baranov,
M. Beurskens, P. Beaumont, P. Buratti, M. Brix, G. Calabro, R. Castaldo,
R. Cesario, C.D. Challis, V. Cocilovo, K. Crombé, C. Giroud, M. Gryaznevich,
T. Hender, D. Howell, Ph. Jacquet, T. Johnson, P. Lomas, M.-L. Mayoral,
D.C. McDonald, I. Monakhov, S. Nielsen, F. Orsitto, S. Sharapov, C. Sozzi,
I. Voitsekovitch, K.-D. Zastrow, O. Zimmerman, V. Zoita
and JET EFDA contributors

Development of ITB Plasmas at High β_N and High δ in JET

Development of ITB Plasmas at High β_N and High δ in JET

J. Mailloux[1], P. de Vries[1], V. Pericoli-Ridolfini[2], B. Alper[1], Y. Andrew[1], Yu. Baranov[1],
M. Beurskens[1], P. Beaumont[1], P. Buratti[2], M. Brix[1], G. Calabro[2], R. Castaldo[2], R. Cesario[2],
C.D. Challis[1], V. Cocilovo[2], K. Crombé[3], C. Giroud[1], M. Gryaznevich[1], T. Hender[1],
D. Howell[1], Ph. Jacquet[1], T. Johnson[4], P. Lomas[1], M.-L. Mayoral[1], D. C. McDonald[1],
I. Monakhov[1], S. Nielsen[5], F. Orsitto[2], S. Sharapov[1], C. Sozzi[2], I. Voitsekovitch[1],
K.-D. Zastrow[1], O. Zimmerman[6], V. Zoita[7] and JET EFDA contributors*

[2]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[2]Euratom-ENEA association, Centro Ricerche Frascati, C.P. 65, 00044-Frascati, Italy
[3]Association EURATOM-Belgian State, Department of Applied Physics Ghent University, B-9000 Ghent, Belgium
[4]Association EURATOM-VR, Fusion Plasma Physics, SE-10044 Stockholm, Sweden
[5]Association EuratomRiso, Riso National Laboratory, Roskilde, Denmark
[6]Assoziationen Euratom-Forschungszentrum Jülich, D- 52425, Jülich, Germany
[7]Association EURATOM-MEdC, Magurele-Bucharest, Romania
** See annex of M.L. Watkins et al, "Overview of JET Results ",*
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006)).

Preprint of Paper to be submitted for publication in Proceedings of the
34th EPS Conference on Plasma Physics,
(Warsaw, Poland 2nd - 6th July 2007)

1. INTRODUCTION

ITER Non-Inductive (NI) scenario must reach high H factor, $H_{IPB98(y,2)}$ ~ 1.5, and normalised beta, β_N ~ 3, with ~50% of bootstrap current (f_{BS}). It relies on producing and maintaining an Internal Transport Barrier (ITB) at large radius (normalised radius r/a > 0.5). Experiments have been carried out in JET to start developing ITB plasmas at high β_N and triangularity (δ), and study their stability, including the effect of the q profile. Here, the aim was to optimise the core performance with an ITB, rather than rely on a high pedestal pressure as in [1].

2. OPTIMISATION OF CONFIGURATION AND ELM CONTROL

Plasmas with magnetic field B_T = 2.3T and plasma current I_P = 1.5MA were used to get high β_N with the total power currently available in JET. They have q_{95} ~ 5, and upper δ and lower δ ~ 0.4. Previously in JET most ITB plasmas had low δ (~ 0.2), but, recently, priority was given to developing ITB plasmas at high δ [2], which was pre-requisite for this work. Various q profiles at the start of the main heating (from weak negative to strong negative magnetic shear, with qmin above or near 2) were formed using a fast IP ramp-up without or with Lower Hybrid Current Drive (LHCD) in the prelude. High Neutral Beam Injection (NBI) and Ion Cyclotron Resonant Heating (ICRH) (37MHz, H minority heating) power was used to trigger ITBs. LHCD was added during the high power phase in some shots to attempt to slow down the q profile evolution. However, modelling showed that the LH wave can not penetrate the plasma at that BT and electron density, n_e, (the accessible ne scales with B_T). Line averaged ne between 3.4×10^{19} m^{-3} to 4.5×10^{19} m^{-3} were obtained, for Greenwald fractions (f_{GLD}) between 0.56 and 0.74. Large ELMs are not compatible with having an ITB at a large radius, and Ne and D2 puffing was used to maintain small ELMs. The total radiated power between ELMs divided by the total power (f_{RAD}) varied from ~15% (D_2 only) to 60% (higher D_2 + neon). As shown in [3], ELM frequencies large enough to make the edge compatible with ITBs were obtained in two range of f_{RAD}: <30% (small type I ELMs) and 7 50% (type III ELMs). Two configurations were compared, both with $\delta_{up} = \delta_{low}$ ~ 0.4: ITER_AT_1 and ITER_AT_2. The latter had a larger distance between the last closed flux surface and the inner and top walls, and better pumping because the outer strike-point was nearer the pumping throat. As a result, the amount of neutrals in the edge was smaller (seen from lower D_α signal between ELMs) and fuelling control was better. Figs.1 and 2 show example of shots with ITB with similar β_N and H factor, but different f_{RAD} and ELMs. Pulse No: 70069 (Fig.2) had type I ELMs and a higher pedestal pressure than shot 68927 (Fig.1). The ITB in 68927 was perturbed at times by large ELMs that did not occur in later shots with different plasma shape control and gas waveforms.

3. CORE AND EDGE PERFORMANCE

So far, values of β_N averaged over the duration of the ITB of up to 2.8 have been reached, with peak β_N up to 2.9, and peak thermal $H_{IPB98(y,2)}$ up to 1.1. Figs. 3 and 4 show that the improvement in β_N comes mainly from the core rather than from the pedestal. (Here the edge is at r/a = 0.9, i.e. near the top of the pedestal typically. The ion data is taken at $r/a = 0.8$ to insure the edge energy is not underestimated due to the limited spatial resolution of the diagnostic.) This is confirmed by the fact that β_N increases as the ITB becomes stronger (Fig.5). The ITB strength is given by the normalised inverse temperature scale length $\rho^*_T = \rho_{L,s}/L_T$, where $\rho_{L,s}$ is the ion Larmor radius at sound velocity and $L_T = T/(dT/dr)$ for either electrons or ions. The threshold value for an ITB is $\rho^*_T = 0.014$, determined empirically [4]. In addition, the best performance is obtained when the ITB is wider ($r/a \sim 0.55$ obtained so far). However the pedestal energy also increases in some of the plasmas with best performance, for example on shot 70069. This shows that significant pedestal performance (with small type I ELMs) is compatible with an ITB, at least for in the experiments shown here.

5. STABILITY

As described in [5], the no-wall limit (determined empirically) was exceeded in several plasmas with ITB in this experiment, up to 25% on 70069 for example (Fig.6). Importantly, no ITB terminations due to strong pressure gradients were observed. The maximum ion pressure peaking measured on the best shots was lower than that resulting in pressure driven kink modes in previous ITB plasma studies [6]. Instead, on most shots a ‘soft’ ITB termination was observed, coinciding with the appearance of a $n = 1$ mode (most probably with $m = 2$), and with the q profile evolving from low negative shear, to flat, then positive magnetic shear. What event came first is not yet clear. No correlation was found between the occurrence of the $n = 1$ mode and the β_N achieved, nor with the ITB strength (in fact, the data suggests that the $n = 1$ mode occurred later in plasmas with better performance). This suggests that the termination is linked to the q profile evolution. Other modes with little effect on the performance were often observed (Figs. 1 and 2). They have been attributed to fishbone activity, probably linked to the $q =$ surface rather than $q = 1$. Similar ITB evolution and termination were observed in plasmas with q profile at the start of the high heating with deeply negative shear (e.g. 68927), suggesting that the strong negative shear was rapidly lost. On shot 70322 (average $\beta_N = 2.5$), the ITB lasted until the end of the high heating, but even in this case, the q profile was evolving. This indicates that more non-inductive current is needed. TRANSP[7] simulations show $f_{BS} \sim 30\%$ in Pulse No’s: 68927, 70069 and 70322 during the ITB. JETTO simulations using steeper edge ne profiles [8] show ~ 40% f_{BS} for 70069. The difference is due at least in part to higher bootstrap current at the pedestal in the JETTO results. TRANSP and JETTO find ~ 30% NB current, for a total NI current fraction between 60% to 70%.

CONCLUSION

This scenario shows encouraging results: with ITBs (plus in some cases a significant pedestal), β_N values near those required for ITER non-inductive scenario are obtained, with no indication that the stability limit for pressure driven kink modes is reached. There is still margin for improving the ITB further (stronger and at a wider radius), which would provide higher HIPB98(y,2) and hence higher β_N. This should also provide higher bootstrap current. The planned JET ICRH and NBI power upgrades will make it possible to reach high β_N at higher BT[2], where the LH wave can access the plasma and provide additional current drive.

ACKNOWLEDGEMENTS

This work was partly funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was carried out within the framework of the European Fusion Development Agreement

REFERENCES

[1]. C. D. Challis, *et al*, this conference P5.124,
[2]. X. Litaudon, *et al*., this conference I5-001,
[3]. M. Beurskens, *et al*, this conference P1.163,
[4]. G. Tresset, *et al*, Nucl. Fusion **42** No 5 (2002)
[5]. M. Gryaznevitch, *et al*., this conference, P5.145
[6]. C. D. Challis, *et al*, Plasma Phys. Control. Fusion **44** (2002)
[7]. R.J. Goldston, *et al*, J. Comput. Phys. **43** (1981) 61
[8]. R. Cesario, *et al*, Proc. of 17th Top. Conf. on RF Power in Plasmas, Clearwater, USA (2007)

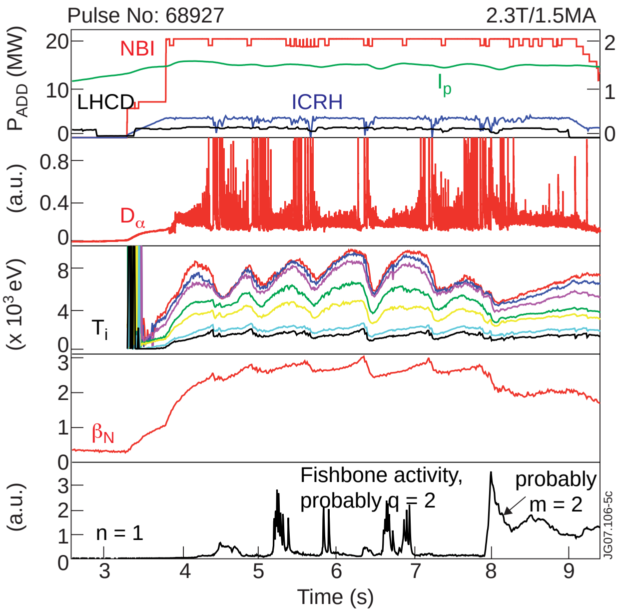

Figure 1: Time evolution of Pulse No: 68927.

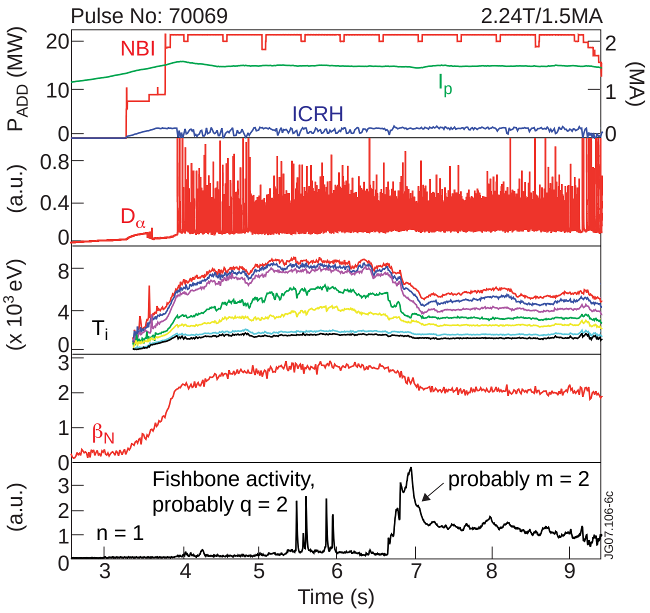

Figure 2: Time evolution of Pulse No: 70069.

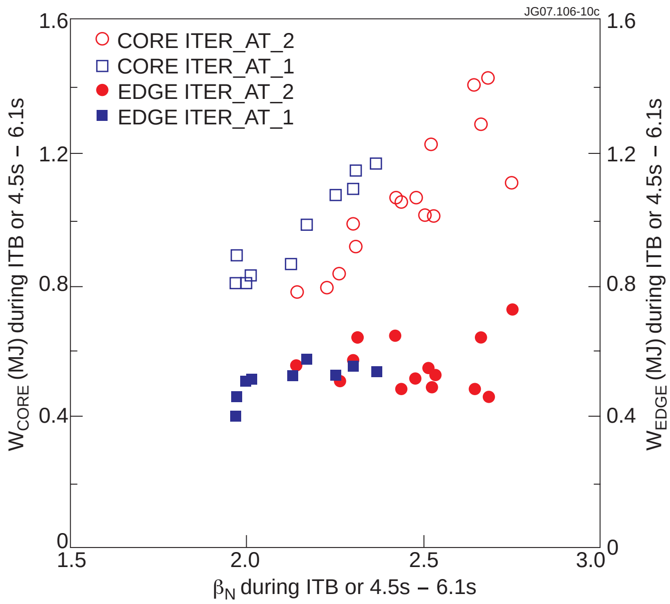

Figure 3: Electron thermal energy in core and edge (r/a = 0.9) as a function of β_N.

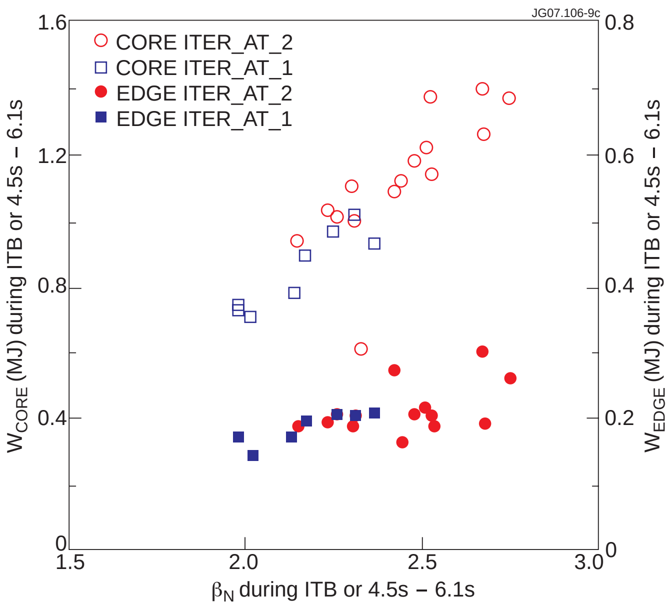

Figure 4: Ion thermal energy in core and edge (r/a = 0.8) as a function of β_N.

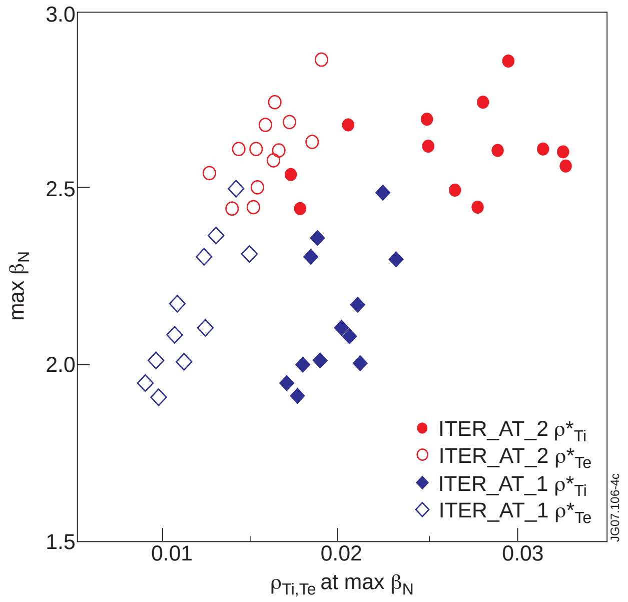

Figure 5: Max β_N as a function of ITB gradient (electron and ion temperature).

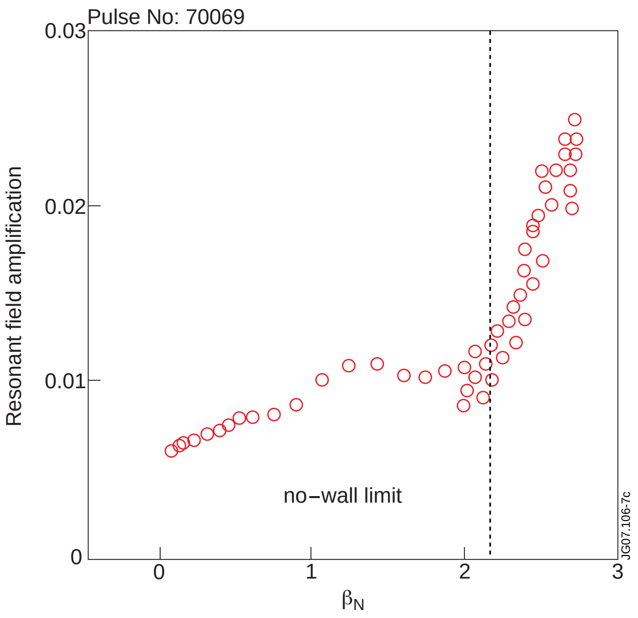

Figure 6: Measured resonant field amplification versus β_N for Pulse No: 70069. No-wall limit exceeded by 25%.