# Development of Internal Transport Barrier scenarios at ITER-relevant high triangularity in JET

F.G. Rimini 1), M. Bécoulet 1), E. Giovannozzi 2), P.J. Lomas 3), O. Tudisco 2), B. Alper 3), F. Crisanti 2), M. de Baar 4), E. de La Luna 5), P. de Vries 4), A. Ekedahl 1), N. Hawkes 3), G. Huysmans 1), E. Joffrin 1), X. Litaudon 1), V. Parail 3), G. Saibene 6), K.D. Zastrow 3) and JET-EFDA Workprogramme Contributors

1) Association Euratom-CEA, CEA/DSM/DRFC, Centre de Cadarache, 13108 Saint Paul lez Durance, France
2) Associazione Euratom/ENEA/CNR sulla Fusione, Frascati, Rome, Italy
3) Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, United Kingdom
4) Associatie EURATOM-FOM, TEC Cluster, 3430 BE Nieuwegein, The Netherlands
5) Association Euatom-CIEMAT, Madrid – Espana
6) EFDA CSU (Garching), 2 Boltzmannstrasse, Garching, Germany

e-mail contact of main author : fernanda.rimini@cea.fr

**Abstract**. The development of ITB scenarios in high triangularity discharges is of particular interest for ITER AT operation. Previous JET experiments have shown that high triangularity favours ELM-free or type I ELMs, which inhibit long lasting ITBs. The recent experiments reported here concentrate on integrated optimisation of edge and core conditions. Edge pedestal was controlled using gas injection, Deuterium or light impurities, and plasma current ramps. Both methods yield more ITB-friendly edge pedestal conditions, varying from small type I to type III ELMs and, in extreme cases, to L-mode edge. In parallel, the conditions for triggering and sustaining a wide ITB were optimised. This plasmas have deeply reversed target current profiles with $q_{min} \sim 3$. A narrow inner ITB, located in the reversed shear region, is routinely observed. Large radius ITBs are only triggered when the input power exceeds 20-22 MW, but they do not usually survive the transition into H-mode. The best results, in terms of sustained high performance, have been obtained with Neon injection: a wide ITB is triggered during the phase with L-mode edge and survives into H-mode for about 2s at $H_{89}\beta_N \sim 3.5$ and ~ 60% of the Greenwald density limit. In summary, a high triangularity scenario has been developed, which combines the desirable characteristics of controlled edge, long lasting wide ITBs and high performance at density higher than the low triangularity JET scenarios.

## 1. Introduction

The issues related to the development of Internal Transport Barriers (ITB) scenarios in high triangularity discharges are of particular interest in view of possible Advanced Tokamak (AT) operation of ITER. Previous JET experiments [1] have shown that high triangularity favours ELM-free or type I ELM edge conditions. In parallel, it has been observed at JET that large ELMs tend to produce a perturbation that propagates inwards up to the ITB and generally destroys it [2]. In this earlier set of experiments, carried out in the MK2GB divertor equipped with septum, the edge effects were dominant and prevented formation of long-lived ITBs : high triangularity in JET was incompatible with the existence of ITBs. New experiments have thus been carried out in the last couple of years, with the septum replaced by a flat plate, acknowledging that the route towards a high triangularity ITB scenario in JET has to go through the integrated optimisation of the edge pedestal and of the ITB behaviour.

## 2. Edge control

For these new discharges a high toroidal field was chosen ( 3.45 T ), as compared to 2.7 T for the previous set of experiments, in order to have a higher power threshold for type I ELMs. An ITER-relevant high triangularity configuration was used, $\delta$ ~0.4-0.5. This choice entailed a significant limitation of the maximum value of plasma current that could be used; the experiments were therefore carried out with flat-top current in the range of 1.5-2 MA, reaching occasionally up to 2.5 MA, corresponding to $q_{95}$ in the range of 4.5-7.5. On the other hand, the configurations selected are characterized by a lower vertical instability growth rate than the equilibria used in earlier experiments, thereby giving a better chance to survive a giant ELM crash without a disruption.

The time evolution of the discharge is typical of the Advance Tokamak scenarios developed at JET. Lower Hybrid Current Drive (LHCD) is applied early during the plasma current rise in order to tailor the safety factor profile aiming, in particular, for a reversed shear profile with $q_{min}$=3 at roughly half the minor radius. A high power phase, with combined Neutral Beam (NBI) and Ion Cyclotron Resonance Heating (ICRH) follows, before the current flat-top is reached. In this paper, electron ITBs are identified according to strength of the normalised local gradient $\rho^*_{Te}$ as compared to the experimentally determined critical value $\rho^*_{Te}$=0.014 [3].

The experiments described in this paper concentrated on edge pedestal control based on the use of neutral gas injection, either Deuterium or light impurities, and of plasma current variations.

It is well known from the standard H-mode scenario, both at low and high triangularity [4], and from earlier AT JET experiments in low triangularity configurations [5] that injection of neutral gas can influence the edge pedestal characteristics. We have, therefore, undertake to find first of all an ELM mitigation scenario based on the use of Deuterium gas injection. It is also worth reminding here that the L-H threshold is typically higher in AT scenarios than for conventional fully relaxed current profiles, which we have experimentally verified to be valid even for these high triangularity cases. This additional feature is helpful in steering the edge away from type I ELMs.

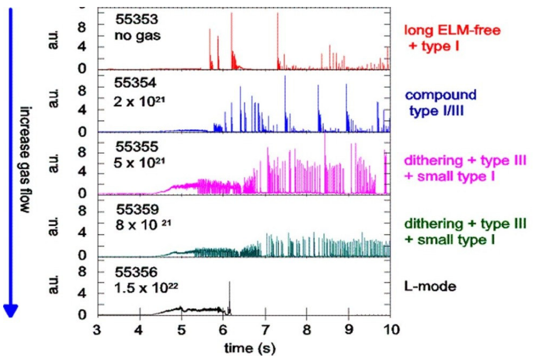
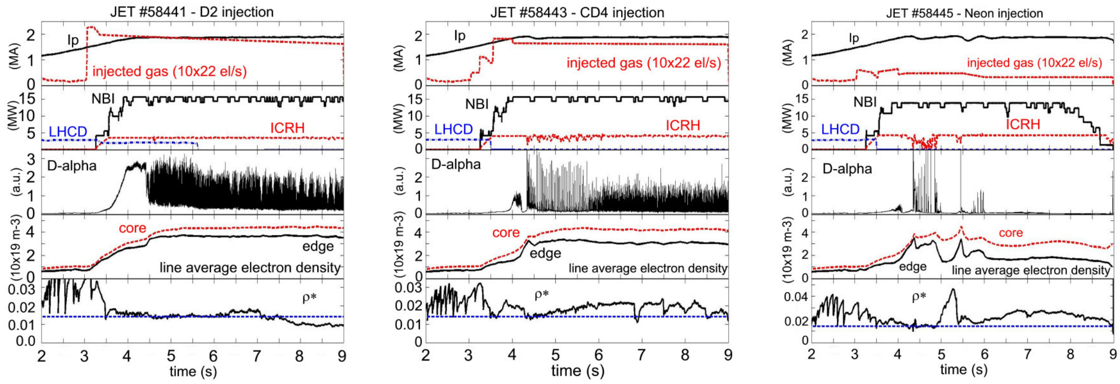



*Figure 1: time evolution of D-alpha signal showing ELM variation with increasing levels of $D_2$ gas injection*

A series of discharges, at 2.0 MA and ~14 MW of total input power where the level of injected Deuterium was progressively increased is shown in fig. 1. With no gas injection long ELM-free phases are observed, terminated by giant ELMs. With increasing levels of injected Deuterium type I ELMs become more frequent until type III ELMs appear. Eventually, at relatively large gas flow values, the edge reverts to L-mode. This is the first time that edge pedestal control with pure $D_2$, as opposed to impurity, injection was demonstrated in high triangularity AT scenarios. Positive tough this result may be, it has to be mentioned that the way the injected gas influences the edge characteristics depends strongly, as one should expect, not only on the amount of injected power but also on the recycling properties of the machine. More specifically, if the machine walls are de-conditioned less gas is needed to achieve type I ELMs suppression. On the other hand, the amount of gas necessary to avoid type I ELMs increases with increasing input power, which again is not unexpected because of the increased power margin with respect to the L-H and type III-I thresholds. This is particularly unfortunate for experiments aiming at high performance AT scenarios which do, indeed, require high power in order to trigger and sustain ITBs located at large radii.

In a well conditioned machine and with increasing power levels the path to type III ELMs needs ever-increasing amounts of injected gas. Following previous successful AT JET experiments we have, therefore, investigated the use of light impurities for ELM control, concentrating on comparing $D_2$ with $CD_4$ and Ne injection. For this set of discharges the machine was, indeed, well conditioned, the recycling conditions stable and the available total power was about 18 – 20 MW, of which about 15-16 MW of NBI. During the LHCD pre-heating phase electron ITBs are consistently observed at small radii, most likely located within the negative shear region.

Reproducibly, small type I or type III ELMs are obtained with $D_2$ injection (fig. 2a), but only intermittent and short-lived ITBs. On the contrary, with $CD_4$ (fig. 2b) at the same power and injected gas levels an initial phase of frequent type I ELMs is observed, which destroys the inner ITB, until both type III ELMs and the inner ITB reappear.




*(a)* *(b)* *(c)*

*Figure 2 : time evolution of main plasma parameters for discharges at 2 MA and different injected gases : a) $D_2$, b) $CD_4$ and c) Ne*

The behaviour is again different when Ne is injected ( fig. 2c) : as usual, the inner ITB is lost during the initial ELM-free and type I phase. An L-mode phase follows during which an outer ITB develops at R=3.6m: this outer ITB does not, however, survive the return of the H-mode. In the subsequent L-mode phase the outer ITB, however, does not reappear and only an inner ITB can be seen. A more detailed discussion of the core conditions and confinement observed in these discharges will be provided in the next section. A comparison of the edge pedestal parameters for discharges with different gases is given in figure 3 in terms of average temperature $(T_e+T_i)/2$ as function of the edge line average density. The ion and electron temperatures are taken close to the top of the pedestal R~3.75m, while the line average density is measured along a vertical chord passing through the plasma midplane at R~3.75m. In this paper the distinction made between frequent or small type I and large type I ELMs is based on the ELM size and the ELM affected area. The discrimination between frequent type I and type III ELMs will be based on their appearance in the D-alpha signal, strong peaks vs noisy multiple peaks, and on the correlation between the peaks observed in the inner and outer divertor D-alpha signals.

The $T_eT_i$-ne diagram (fig. 4) shows little difference in edge parameters between frequent type I and type III ELMs. The electron temperature perturbation following the crash of these ELMs is also similar, within the uncertainties on the experimental measurement, and much smaller and less extended radially than it is the case for larger type I ELMs. This is consistent with the fact that inner ITBs have been observed to coexists with frequent type I ELMs, in the $CD_4$ injection cases, while they are incompatible with the larger type I ELMs. Figure 3 shows that the edge parameters are essentially the same for $D_2$ and $CD_4$ injection. It is worth noting that the discharges with $CD_4$ have higher levels of Carbon, radiation and $Z_{eff}$ both in the core and in the edge, and hence different edge resistivity which could, in turn, lead to differences in edge current. The case with Ne injection alternates between large type I ELMs and L-mode without ever displaying smaller ELMs.

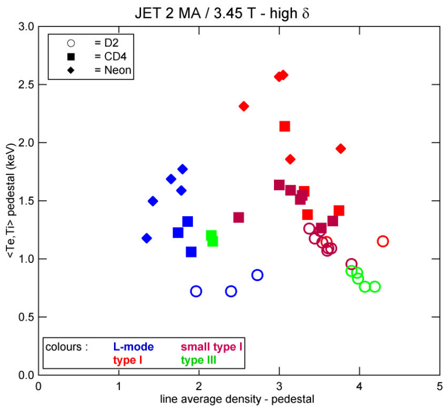



*Figure 3 : edge temperature vs. line average density for a set of 2 MA discharges with different injected gases*

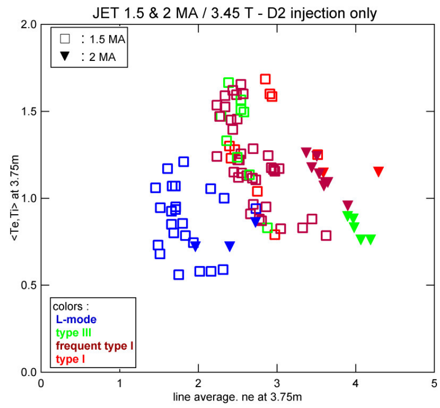



*Figure 4 : edge temperature vs. line average density for a set of 1.5 and 2 MA discharges with D2 injection only*

All the discharges described so far have a flat-top current of 2 MA. In the same session, experiments were also carried out at 1.5 MA, $q_{95}$~7-7.5. Interestingly, at 1.5 MA it was possible to sustain the inner ITB with pure $D_2$ injection. The comparison of edge parameters for the 1.5 MA and the 2 MA series (fig. 4) indicates that the edge pressure is generally higher in the 2 MA case, as expected if the edge MHD stability is determined mainly by ballooning modes. Within the uncertainties of the EFIT code equilibrium reconstruction, constrained with MSE measurements, the current profiles in the core are substantially the same for 1.5 and 2 MA. In reality, the data suggest that the Deuterium fuelled 2 MA cases are only marginally below the threshold for ITB detection of $\rho^*_{Te}$=0.014. One possible explanation for the different behaviour is that these pulses are so marginal in terms of conditions for ITB sustainment that a small increase in the edge pressure may be enough to tip the balance.

In addition to the above described experiments, variation of the edge plasma current has also been investigated as a mean to affect the edge plasma parameters. Plasma current ramps have been applied to type I ELM discharges to assess the possibility of changing the edge characteristics by moving in the ( $\alpha$ - $j$ ) space for ideal MHD stability. Previous experiments in conventional H-mode and ELM-free scenarios [6,7] had already highlighted the role of the edge current in determining the ELM behaviour and the associated MHD activities.

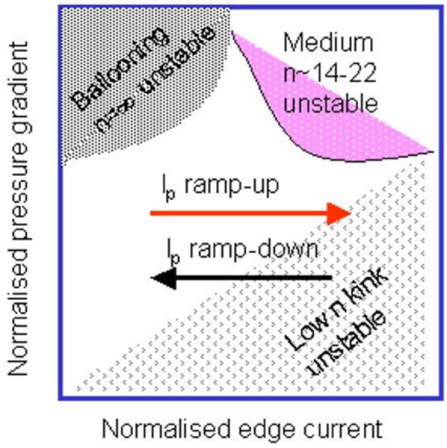



figure 5 : simple picture of possible trajectories in the edge α - *j diagram with current ramps (up and down)*

A simplified picture of how the edge stability could evolve in the case of increasing current is shown in figure 5. The ballooning stability boundary corresponds to the limit for triggering type I ELMs, while type III ELMs are thought to be triggered close to the kink-peeling instability limit. Assuming one starts from a type I situation, the first effect of a ramping-up the plasma current, and therefore directly driving edge current, could be to increase the amplitude of the pressure variation during the ELM cycle and decrease of ELM frequency. Only subsequently, once the edge current has increased enough to approach the kink limit, would type III ELMs appear.

The time evolution of the relevant plasma parameters is shown in figure 6 for a typical discharge with a current ramp-up followed by a short flat-top at 2.3MA and a ramp-down. In this particular case, the ramp-up rate was ~0.4 MA/s, comparable to the average rate during the initial ramp, and lasted 0.5s while the ramp-down is carried out at a reduced rate of ~0.2 MA/s for about 1s. A caveat is necessary here : the control of the plasma current in JET has not, so far, been accurate enough to ensure plasma current variations with a constant ramp-rate and no oscillations. As it can be seen on figure 6, there are hesitations in the ramp-up and down in response to, for example, sudden variation in the input power.

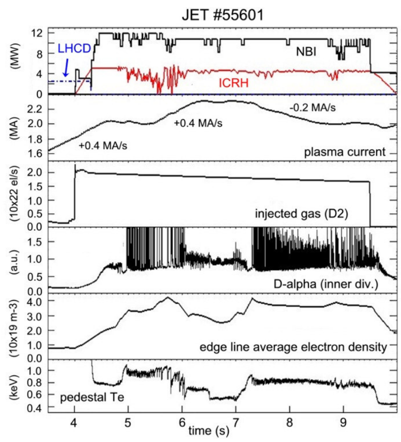



*Figure 6 : time evolution of main plasma parameters for a discharge with current ramp-up and down*

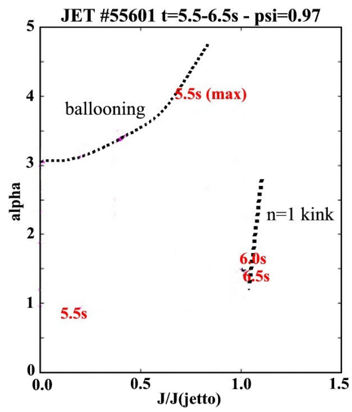



*Figure 7 : ballooning mode and extrenal n=1 kink stability diagram calculated by the Mishka code for the ψ=0.97 surface of the discharge in fig. 6*

As predicted, the immediate response to the ramp-up is a decrease of ELM frequency and an increase of pedestal temperature and density. Eventually, a transition into a dithering H-mode phase is observed, followed by an L-mode. Once the current starts decreasing the dithering H-mode reappears, succeeded by a phase of more frequent type I ELMs. Experiments with faster ( up to 0.6 MA/s ) and longer ( up to 1s) ramps have shown that the ELM stabilisation effect can be quite long-lasting, with an L-mode observed to last up to 3.5s. The effects of the current ramp on the ELM behaviour have been found to vary considerably, depending both on the initial conditions and on details of the current ramp, of the time evolution of the additional heating power and on the injected gas and density. The details of the edge stability have been modelled numerically using the coupled JETTO-MISHKA codes [8,9]. The stability diagram is shown in figure 7 for ψ=0.97 and timeslices just before the current ramp, t=5.5s, and on the second flat-top, t=6.0,6.5s. This analysis confirms that the edge parameters move from being close to the ballooning boundary, at the time of large infrequent type I ELMs, towards a kink-peeling limit at higher edge current and lower edge pressure when a dithering H-mode is observed.

Both gas injection and current ramps were successful in steering the edge pedestal away from large type I ELMs and towards more ITB-friendly type I or III ELMs. Given its sensitivity to initial conditions and unsuitability for steady-state control, it was decided not to apply the current-ramp method for the suite of the experiments. These results, however, highlight once more the role of edge current in controlling the ELMs.

We concentrated henceforth on the control based on gas injection. As expected, the path to ITB-friendly ELMs becomes progressively narrower with increasing power. As will be detailed later, at the highest power levels used in the experiments, ~ 22-24 MW of combined NBI+ICRH, only injection of light impurities (Neon) produced edge conditions compatible with a wide ITB.

## 3. ITB optimisation and core confinement

In parallel to the work on edge control, the optimisation of the conditions for triggering and sustainment of a wide ITB was carried out. The experiments presented here aim to explore the so-called "steady-state" scenario, characterised by deeply reversed current profiles with $q_{min}$ ~ 3 at the start of the main heating phase.

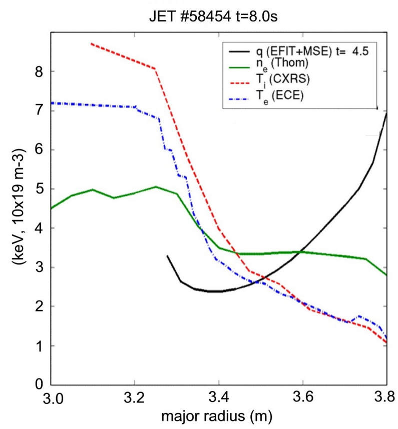



*Figure 8: Ion and electron temperature, electron density and q profiles – 1.5 MA/3.4 T $D_2$ injection*

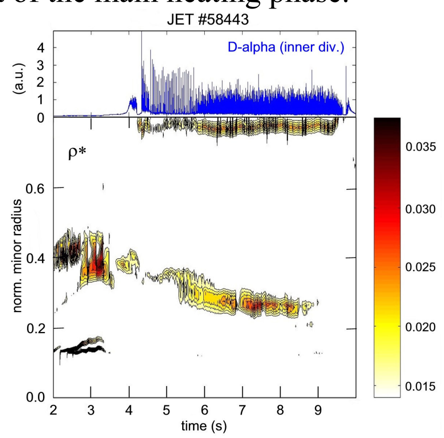



*figure 9 :contours of $\rho^*_{Te}$ and D-alpha for the 2 MA discharge with $CD_4$ injection shown in fig. 2b*

At medium power levels, i.e. around 15 MW NBI + 3-5 MW ICRH, electron and ion ITBs are regularly triggered both at 1.5 and at 2 MA in the negative shear region or close to the minimum q (fig. 2 and 8). At 2 MA, however, these inner ITBs are only sustained with $CD_4$ injection (fig. 2b and 9). These narrow ITBs do not generally bring a significant improvement in global performance, but is worth noting that the density is relatively high, ~ 60-70 % of the Greenwald limit as compared to ~ 30-50 % for the usual JET low triangularity scenarios at comparable plasma current (figure 10).

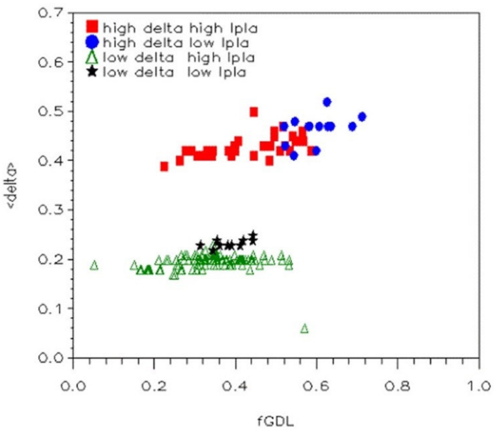



*Figure 10 : existence diagram in the δ vs. $f_{GDL}$ space for typical JET AT discharges*

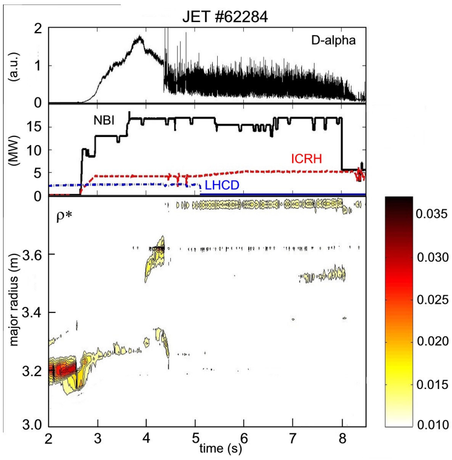



*figure 11 :contours of $\rho^*_{Te}$ , D-alpha and input powers for a 1.5MA discharge with $D_2$ injection*

High performance ITBs located at a large radius are only triggered when the input power exceeds the 20-22 MW level (fig. 11). In the cases when Deuterium is used for edge control, these outer ITBs do not survive the transition into H-mode. Sometimes a weaker ITB appears later in the discharge, ~7s as in fig 11, once the current profile has evolved to reach $q_{min}$=2.

Based on the promising earlier experiments on injection of light impurities, a scenario was developed at high power with edge control via Ne injection. The best results, in terms of sustained high performance, have been obtained when an ITB is triggered at a large radius during the L-mode phase. With Neon edge control, this ITB survives at constant strength into the H-mode phase for a total duration of about 2s, corresponding to ~10 global confinement times $\tau_{E,}$ and it is terminated only by the end of the high heating pulse (fig. 12). The confinement reaches values $H_{89}\beta_N$ ~ 3.5, corresponding to $H_{89}\beta_N/q^2$ ~0.1, at density ~ 60-70% of the Greenwald limit. This is comparable with the performance observed for low triangularity, δ ~0.2, JET plasmas with ITBs in similar current and toroidal field conditions but lower density of ~ 0.3-0.4 of $n_{GDL}$. In these impurity seeded discharges there appear to be no significant impurity accumulation in the core. The level of radiated power is constant during the high performance phase : radiation accounts for 50-55 % of the input power, with divertor and X-point contribution being ~ 30-35%.

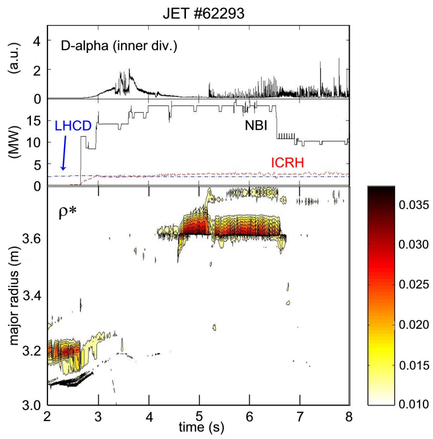



*figure 12 :contours of $\rho^*_{Te}$ , D-alpha and input powers for a 1.5MA discharge with D2 injection*

A summary of the confinement for the whole set of discharges at 1.5 MA is shown in figures 13 and 14 as function of a parameter $r^2_{ITB}$ x $\rho^*_{Te}$ representing a combination of volume and strength of ITB. It is clear that in JET high triangularity configurations only the scenarios with outer ITBs can provide the high performance required for viable Advanced Tokamak operation. In addition, figure 13 confirms that, in our set of discharges, outer ITBs are only compatible with L-mode or small frequent ELMs, either type I or III. The fraction of core, as opposed to pedestal, energy is shown in figure 14.

It is evident that in the discharges with outer ITBs the enhanced confinement originates from the core rather than from an edge pedestal.

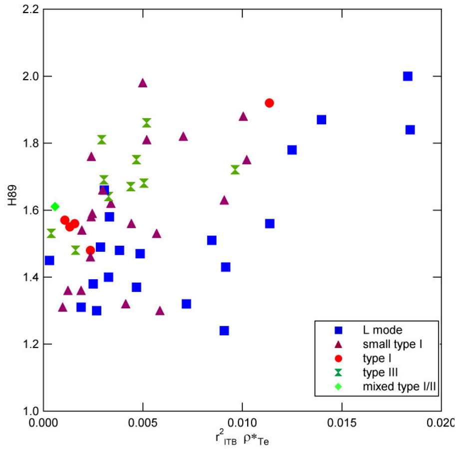



*Figure 13: global confinement, in terms of H89 factor, as function of $r^2_{ITB}$ x $\rho^*_{Te}$ for high $\delta$ 1.5 MA / 3.45 T discharges*

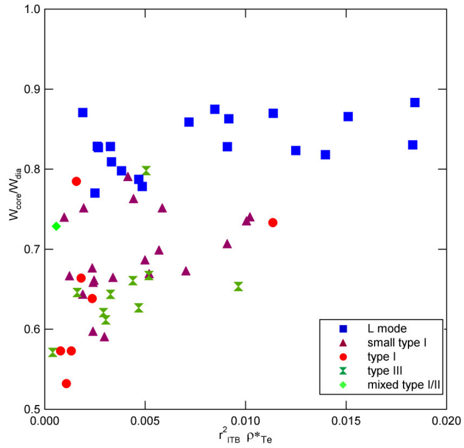



*Figure 14: core stored energy, normalised to total energy, function of $r^2_{ITB}$ x $\rho^*_{Te}$ for high $\delta$ 1.5 MA / 3.45 T discharges*

## 4. Conclusions

The recent experimental effort on integrated optimisation of edge and core conditions in ITB scenarios at ITER-relevant high triangularity has resulted in a significant progress with respect to previous experiment, where type I ELM and ELM-free phases were dominant and, at best, only marginal ITBs had been observed. A high triangularity scenario has been developed, which combines the desirable characteristics of controlled edge, long lasting wide ITBs and high performance at higher density than the standard low triangularity JET scenarios [10]. Although lasting only for ~2s, the high confinement ITB phase is MHD quiescent and is terminated only by the end of the high power pulse. View in the light of the rather negative results reported in [1], the experiments discussed here have given a more positive outlook on the prospects of high performance ITB scenarios at ITER-like high triangularity in JET.

## References

[1] F. Crisanti et al., PPCF 45 (2003) 379
[2] Y. Sarazin et al., PPCF 44 (2002) 2445
[3] G. Tresset et al., Nuclear Fusion **42** (2002 ) 520
[4] G. Saibene et al., PPCF 44 (2002) 1769
[5] A. Bécoulet et al., NF 40 (2000) 1123
[6] M. Bécoulet et al., PPCF 45 (2003) A93
[7] M.F. Nave et al., NF 39 (1999) 1567
[8] A. Cherubini et al., PPCF 38 (1996) 1421
[9] G. Huysmans et al., NF 38 (1998) 179
[10] A. Tuccillo et al., this conference