EFDA–JET–CP(03)01-45

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**See Annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives",*
*Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference on Controlled Fusion and Plasma Physics,
(St. Petersburg, Russia, 7-11 July 2003)

## INTRODUCTION

Scenarios based on internal transport barriers (ITBs) are highly desirable for a steady state tokamak reactor, because together with good confinement characteristics, strong pressure gradients are built inside. These originate a high bootstrap current, which in turn reduces the demand on the external current drive (CD) source needed to operate without the ohmic transformer. Then, a large effort is being spent in the tokamak community to identify an ITB regime, suitable for ITER, whose properties are preserved for several diffusion times of the plasma current. Indeed, at present, an ITB regime is often terminated by MHD (magneto-hydrodynamic) instabilities linked to the pressure gradients and to the safety factor q. On the other hand, q itself and the associated magnetic shear ($s=r/q\cdot dq/dr$) play also an important role in the triggering and in the performances of ITBs. The working point in this many parameter space must then be chosen carefully and several quantities need to be controlled in order to attain stationarity. The present paper describes the experiments carried out at JET to establish a long lasting ITB by a proper choice of parameters. The final goal is to achieve full control in real time of the ITB strength and radial extension and of the q profile by means of the external power sources. Progress made at JET on this latter topic is described in Ref [1].

## 1. EXPERIMENT

The attainment of long lasting steady ITBs poses several technical and scientific problems. The major technical challenges concern the additional heating systems, whose operation need to be checked for long high power pulses, and the heat removal efficiency from the divertor tiles. The neutral beam injectors (NBI) need to be used for the maximum allowed time and their reliability has to be tested, whereas the ICRH (ion cyclotron resonance heating) and LHCD (lower hybrid current drive) antennas, exposed to a long high energy flux, could suffer from the formation of arcs or hot spots and then release impurities. The thermal load on some tiles could exceed the present safety limits and the behaviour of the radiative cooling of the tiles over long times, when the thermal equilibrium is more closely approached, has to be assessed. From the scientific site we should be able to maintain for longer than the current resistive diffusion time ($t_{R/L} \approx$ 7-8s):

i) a full CD regime (loop voltage, $V_{loop} \approx 0$) and a non-evolving j(r) (current) profile,

ii) a suitable ITB size and strength to avoid dangerous MHD instabilities or interaction with the edge,

iii) the core plasma free from impurity accumulation,

iv) a mild edge activity (edge transport barrier) to avoid ITB erosion or collapse.

The plasma target has been established as the best compromise between many requests. The length of the pulse is limited to 20s, due to both the magnetic field coils and their power supply and the NBI performances. The CD efficiency of the LH waves suggests to work at the highest toroidal field allowed for such a long time, namely $B_T = 3T$, whereas the $q_{95}$ reference value for such scenarios in ITER, $q_{95} \approx 5$, requires a plasma current Ip close to 2MA. However, the need of full CD conditions suggests to lower $I_p$ to 1.8MA, in order to increase the fraction of both ILH and Iboot.

Moreover, this combination of $I_p/B_T$ also makes it easy to have ITBs triggered when qmin crosses the $q = 3$ value, which are more MHD stable than those established when $q_{min} = 2$, and hence more suitable for a steady state regime. The waveforms of the additional power are adjusted in order to start the high power phase just before the $q = 3$ surface appears inside the plasma, when the q profile is still deeply reversed by LHCD at the very early phase during the $I_p$ ramp-up. As a result, a reliable scenario has been established at $B_T = 3T$, $I_p = 1.8MA$, $q_{95} \approx 6$, with $P_{NBI} = 11MW$ $P_{ICRH} = 3MW$ and $P_{LHCD} \approx 3MW$. A medium strength ITB is built, $\rho^*_T \approx \rho_{L,s}/L_T \approx 0.02$ ($\rho_{L,s}$ is the ion sound Larmor radius and $L_T$ is the temperature scale length, with the ITB threshold value for $\rho^*_T = 0.014$ [2]), which survives till the end of the NBI high power phase, longer than 8s. The global confinement is quite good, with the enhancement factor $H_{89}$ close to 1.9 and the normalized $\beta$, $\beta_N \approx 1.6$. The ITB radius stays almost steady around $r_{ITB}/a \approx 0.6$, and the impurity accumulation is negligible. As an example in Fig.1 and 2 are shown the time traces of the main plasma parameters for a discharge where the real time control on $\nabla T_i$ (ion temperature gradient) was also successfully attempted using the NBI power as actuator. A true stationarity, however, is not achieved yet, as the slight increase of $l_i$ with time shows. The current profile j(r) is getting more peaked due to the residual ohmic current ($|V_{loop}| > 50mV$), which is around 15% of the total. The rest of the current is driven 40% by LHCD, 30% by bootstrap and 15% by the NB. The evolving q(r) profile also causes the slow outward drift of the ITB footprint, which is linked to the radius where $q = 3$, and leads to a disruptive ITB end when the surface $q = 2$ enters the plasma. In Fig.2 it is shown how $\nabla T_i$, i.e.the strength of the barrier is feedback controlled by the NBI power. The quasi stationarity of the core plasma is inferred from the traces of $T_{e0}$, $T_{i0}$, and of the neutron rate. The amount of the NBI requested power, ≈ 11MW, gives very good prospects for extending the ITB up to the maximum length of 20s. In this same figure, the divertor Da emission enlightens the stationarity also of the ELMs (type III) activity, giving confidence that the interplay ITB-edge plasma should not create troubles in longer pulses. The impurity behaviour is presented in Fig.3 for a discharge at even higher power than in the previous figure. During the whole ITB phase no significant increase in the emission from the main impurities, in the total radiated power, or in $Z_{eff}$ (effective plasma charge), and no sign of profile variation in either density or radiation loss are detected. This latter is evaluated as the ratio of the line integrated signal along a central chord and a chord external to the ITB. Then, the concern about a radiative collapse due to a central impurity accumulation, often observed in many ITBs [3] appears to be removed from the present scenario. By comparison with other discharges the quantity $\rho^*_T$, seems to discriminate whether impurities accumulate or not in the centre. In barriers stronger than the present ones the particle transport across the barrier is modified to lead both to more peaked density profiles and to larger central impurity content.

Concerning the heat removal efficiency, a new technique has been developed to alleviate the thermal load on the most loaded tile (No.6, horizontal). Some of the power impinging on this latter is diverted to the neighbouring vertical tile (No.7) by sweeping radially the separatrix X-point at frequency ≈ 4Hz, with peak-to-peak variation for the strike point radius of $\Delta R_{s.p.} \geq 3.5cm$. The insert of Fig.4 gives a sketch of the separatrix shape near the X-point for the two extreme positions of $R_{s.p.}$. Clearly for the outermost one, part of the energy flow along the scrape-off layer should hit the outer vertical tile, giving then relief to the horizontal one. The absence of any effect on the core and on the edge plasma behaviour, on recycling or on the ELMs properties, makes this technique fully compatible with a steady ITB. Figure 4 shows the time traces of the total injected energy, the radius of the strike point and the temperature increment on tiles No.6 and 7, for two very similar discharges one with and one without the X-point sweeping. The more balanced heat load between the tiles for the swept case is inferred from the reduced gap in the final temperatures of the two tiles. It must also be pointed out that the total temperature increment on the most heated tile No. 6 is only $150^{o}$C, lower than the value $\approx 200^{o}$C foreseen on the basis of the old JET data base. It is believed that the more uniform (on average) wetting on the tile, due to sweeping, and the longer energy flows lead the tile closer to the thermal equilibrium and enhance its radiating capability. This technique can be further improved by optimizing the initial strike point position and the other parameters of the sweeping.

## SUMMARY

Almost steady ITBs, lasting longer than 8s till the end of the NBI pulse, have been produced reliably at JET, at $B_T = 3$T, $I_p = 1.8$MA, $q_{95} \approx 6$, with about 11MW of NBI, 3MW of ICRH and ≤3MW of LHCD. Central temperatures and density are $T_{e0} \geq 9$keV, $T_{i0} \geq 13$keV, $n_{e0} \approx 3.5\times10^{19}$ $m^{-3}$, with $H_{89} \approx 1.9$ and $\beta_N \approx 1.6$. The ITB strength given by the quantity $\rho^*_T \equiv \rho_{L,s}/L_T$ is $\approx 0.02$, compared to the ITB threshold value of 0.014, and its radius is fixed to where $q = 3$ ($r/a \approx 0.6$). With a total injected power in excess of 19MW for longer than 9s, no radiation event is detected, no evidence of impurity accumulation is found, a low interaction with the edge plasma is maintained (mild type III ELMs), no detrimental MHD activity is triggered, provided the $q = 2$ surface is kept outside the plasma. The target plasma has however to be still optimized for the very long operation (20 s): full CD conditions should be attained in order to actually freeze the j(r) profile, by decreasing slightly $I_p$, by trying to get more LHCD power and by injecting more ICRH power. A successful real time control on $\nabla T_i$ has been tested. NBI power has been injected for the maximum allowed time (10s), LHCD and ICRH antennas have been kept continuously excited for longer than 12s without troubles. No hot spots have been produced on the ICRH antenna up to 5MW. To withstand the large amount of energy which is dumped onto the divertor tiles (>190MJ have been often injected in the plasma) the technique of sweeping the strike point has proven to be an efficient tool to balance the power load between divertor tiles and not to affect any ITB property.

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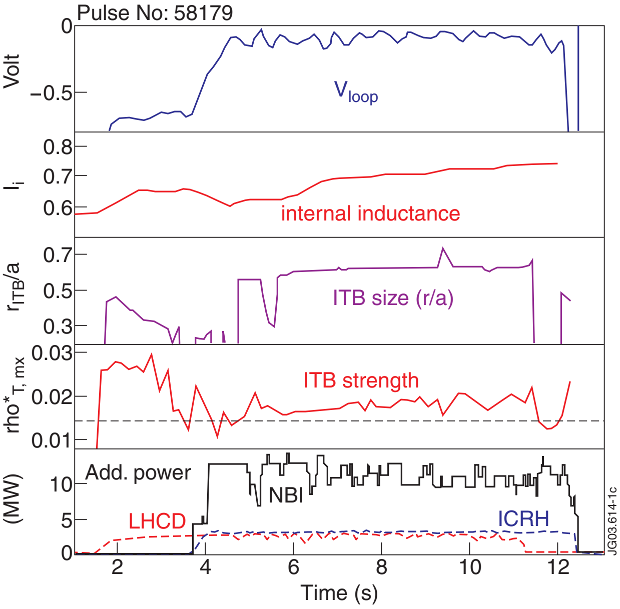

*Figure 1: Long lasting ITB: time evolution of the main quantities. For this particular pulse $E_{inj}$ = 150MJ during a real time controlled, long lasting ITB.*

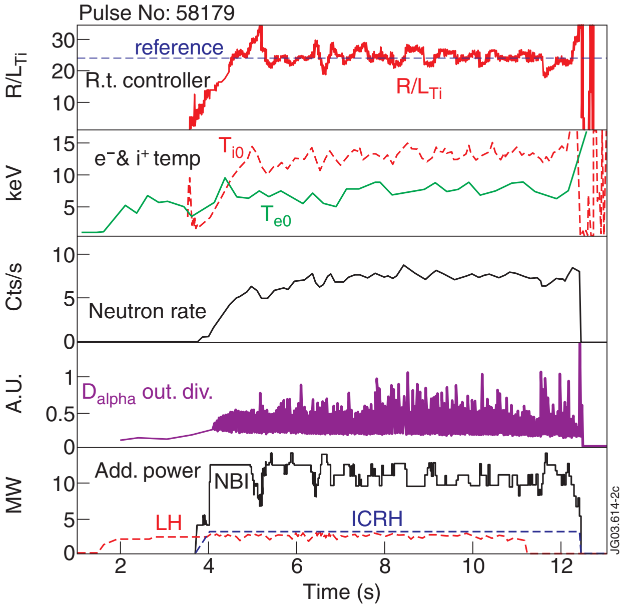

*Figure 2: Time evolution of the main quantities.*

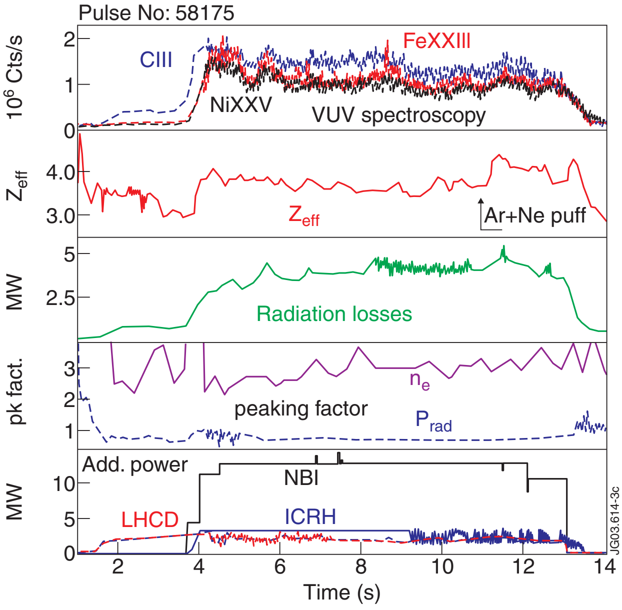

*Figure 3. Time behaviour of the most relevant plasma parameters referring to impurities.*

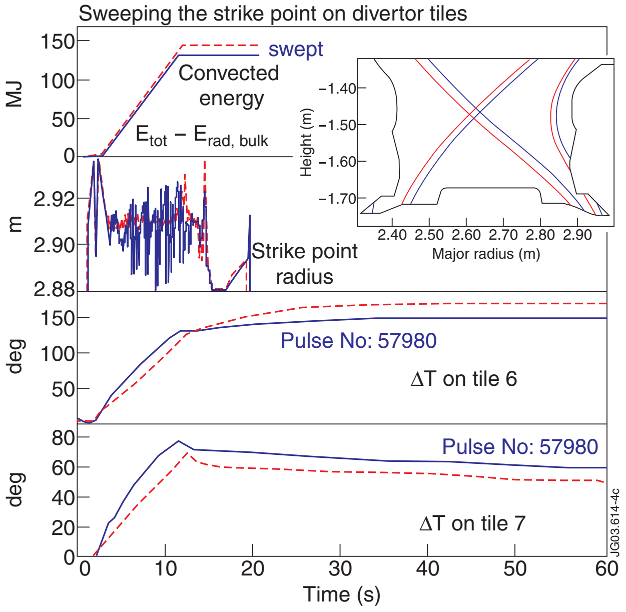

*Figure 4. Comparison of the divertor tiles behaviour with/ without the strike point sweeping. In the insert: the divertor legs with the two extreme positions of the separatrix during the sweeping.*