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Real-Time Plasma Control of Internal Transport Barriers in JET

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ABSTRACT
Development of advanced steady-state operation scenarios in tokamaks requires real time control of the plasma profiles, e.g. temperature, pressure, rotation and current profiles. Recent experiments devoted to the first real time profile control of Internal Transport Barriers (ITB) in JET are described in this paper. The dimensionless ratio of the ion gyro-radius to the local gradient scale length of the electron temperature has been recently shown to characterise satisfactorily and with a low computational cost the main ITB features [1]. In the first section we report briefly the experimental device used to obtain in real time the electron temperature profile as well as the definition of the dimensionless ratio and its implementation in the real time system at JET. Then in the second section, the emphasis is laid on the main experimental conditions and the results obtained in scenarios with different plasma current and toroidal field.

1. REAL-TIME CHARACTERISATION OF THE ITB DYNAMICS

Recently a simple local criterion characterising the emergence and space-time evolution of ITB has been proposed and extensively validated on a large JET database [2]. It was shown that a dimensionless local parameter, $r_{Te}* = r_s/L_{Te}$ related to drift wave turbulence stabilisation and anomalous transport theory, characterises the typical ITB features such as the emergence, location, collapse time and dynamics [r_s is the local Larmor radius at the ion sound speed and L_{Te} is the electron temperature gradient scale length $L_{Te} = -T_e / (\partial T_e/\partial R)$]. The underlying physics is the breaking of the gyro-Bohm turbulence scaling by the diamagnetic velocity shear, which has been observed in various numerical simulations [3]. The presence of the ITB is detected when $r_{Te}*$ exceeds a threshold value which corresponds to the time when the shearing rate exceeds the maximum linear growth rate of the instability. The real time system is based on a VME crate using a 350MHz Motorola PowerPC CPU and two ADC/DAC modules. Its purpose is to acquire at 1kHz sample frequency all the 48 analogue channels of the high space resolution electron temperature ECE diagnostic (heterodyne radiometer). It also calibrates the raw data and calculates in real time the relevant ITB parameters, which are used for the control: the maximum value of $\rho_{Te}*$ and its spatial location characterising respectively the strength and radius of the ITB, the width of the barrier (range around the ITB position where the criterion is still valid), the core and volume averaged electron temperatures. These outputs are sent at a frequency of 100Hz to the real time central controller of JET. Then following the criterion [2], we detect the existence of an ITB at major radius R and at time t if max $(\rho_{Te}*(R,t)) \geq 1.4.10^{-2}$. The latest value has been found after a statistical analysis of a large JET pulse database. We have used that criterion in a large variety of experimental conditions, including various toroidal field, in ITB regimes with strong ELMs activities, with faulty ECE channels in order to optimise our algorithm [4]. The different ITB signals available in real time are presented in Fig.1 (right) for a case of a shot presenting an outer ITB (B_T = 2.6T; I_p = 2.2MA P_{NBI} = 10MW P_{ICRH} = 5MW). Despite the fact that the electron temperature profile is severely perturbed by non-thermal electrons and faulty calibrated channels (see left example at 7.4s) the location of the ITB at 3.55m in that case is well determined by the algorithm. The time evolution of the other real-time signals is in agreement with the off-line analysis.

2. REAL-TIME FEEDBACK CONTROL OF ITB: EXPERIMENTAL RESULTS

The aims of the experiments were to assess different control schemes using Ion Cyclotron Resonance Heating (ICRH) or Neutral Beam Injection (NBI) power to trigger and control the ITB with and without LHCD during the main heating phase. An example of an open loop, in order to apply the ICRH power when an ITB is formed during the LHCD phase, is shown in Fig.2. The ICRH is applied while the LHCD is switched off when ρ_{Te}^* exceeds a pre-set value of 0.03. The application time of the power is therefore optimised in order to avoid time when the LHCD barrier collapses. The ITB located at R = 3.3m is sustained during 2 seconds with ICRH only. Then we also feedback controlled the value of ρ_{Te}^* with NBI or ICRH at a fixed value using a proportional-integral gain:

$$P(t)[MW] = P_0 + G_p\Delta\rho + G_I \int_{t_0} \Delta\rho dt$$

where P_0 is the power at the initial time t_0 of the control and $\Delta\rho$ is the difference between the target value and $\rho_{Te}^*(t)$. Constrained by the limitation of the maximum power available for ICRH and NBI, numerical simulation [1] and the experiments showed that the use of an integral control [Gp around 10 and GI around 1000] is the most appropriate setting. We see in Fig.3 an example of a control with NBI power. The control starts at 4s and the reference value for ρ_{Te}^* is chosen equal to 0.025. The control is well achieved during 1.7s except at the end where ρ_{Te}^* is increasing even when the feedback loop reduces the NBI power. It demonstrates the difficulty linked with the control using NBI: this heating scheme is not directly linked to the electron temperature since it heats mainly the ions and changes the particle fuelling. There are two solutions available: either use mainly the ICRH to keep the density constant or use a double feedback scheme where the electron heating source (ICRH) controls the temperature gradient and the NBI the neutron yield. The results of a control with ICRH only are shown in Fig.4 left. The normalised electron temperature gradient at the ITB location is controlled during 3.4s by the ICRH power in a regime with Ti = Te = 7keV. The value of ρ_{Te}^* is close to the target, and the inner barrier linked with a negative shear located at 3.3m shrinks when the LHCD is stopped in relation with the q profile evolution (see Fig.4 right).When the minimum q-value approaches 2 (around 6.5s), the ITB within the error bars followsthat integer surface.

The effect of the double control on the neutron rate with NBI power and ρ_{Te}^* with ICRH (see Fig.5), shows that it is possible with a high degree of reproducibility to control high performance regime [6] in view of steady state operation. The ITB is controlled during 7.5s with ρ_{Te}^* and the neutron rate maintained constant respectively at 0.025 and $0.9.10^{16}$ neutrons/s while the loop voltage is close to zero volts. The LHCD power is constant during the control phase, to slow down the q-profile evolution. The freezing of the q-profile evolution allows maintaining the ITB position in the weak or negative magnetic shear region. On the same graph is shown a high performance shot not controlled. This shot reaches MHD limits as we can see from the different collapses in the time evolution of $\rho_{Te}*$. These comparison shows the better stability achieved with the control but at reduced performance.

CONCLUSION

The calculation in real time of the local criterion in JET from the ECE radiometer allows for the first time a control of the electron temperature radial profile. The different experiments carried out during the campaign 2001 shows that it is now possible to access steady-state plasma with high performance regime using a double feedback algorithm controlling separately the production of the neutron rate using NBI in order to avoid disruption and the temperature gradient using ICRH. It increases the reproducibility of improved confinement discharges. Other signals characterising the ITB features are now available in real time at JET and the real time assessment of these quantities opens a new field of application in view of controlling and sustaining advanced tokamak discharges. The determination in real time of the q profile evolution is the next step to improve the control of the ITB location.

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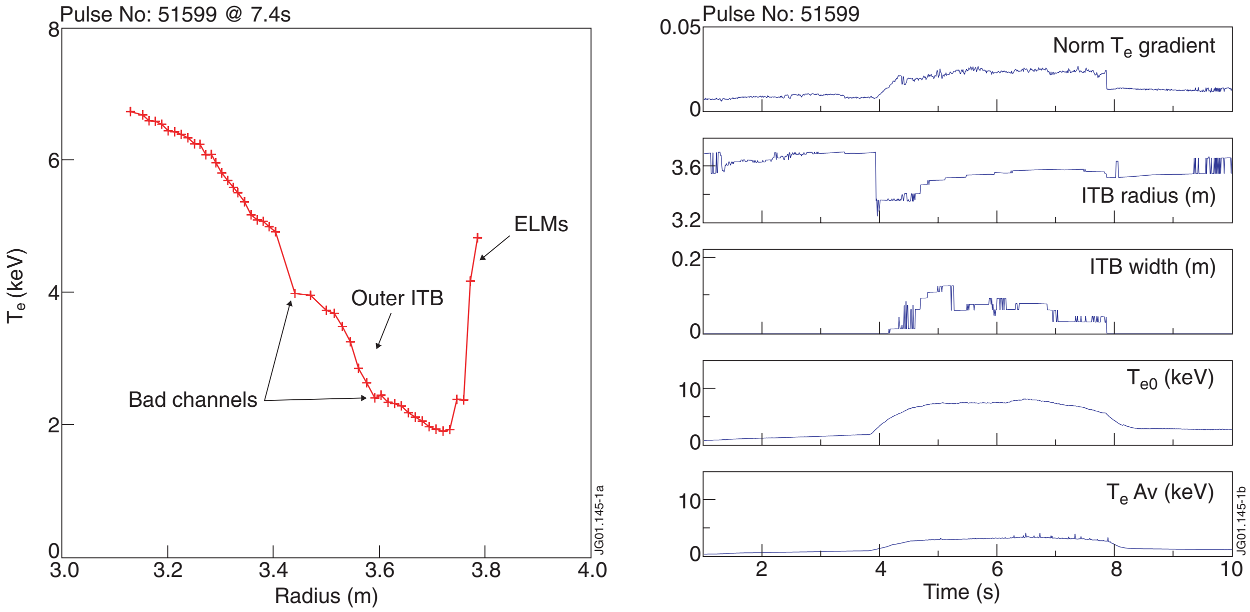

Figure 1: (Left) Electron temperature profile at 7.4s (Pulse No: 51599) with ELM activity at the edge, two faulty channels and outer ITB. (Right) The time evolution of the real time signals for the same shot, respectively ρ_{Te}, ITB radial position, width, central and average electronic temperatures.*

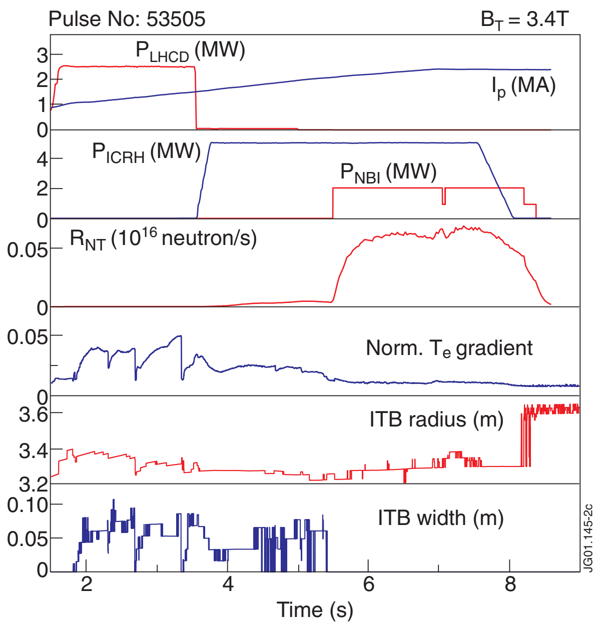

Figure 2: Open feedback loop: Time evolution of LH power, plasma current, NBI and ICRH power, neutron rate, ρ_{Te}, radius and width of the ITB (Pulse No: 53505). Control starts at 3.3s, and ICRH is triggered at 3.5s when ρ_{Te}*>0.03.*

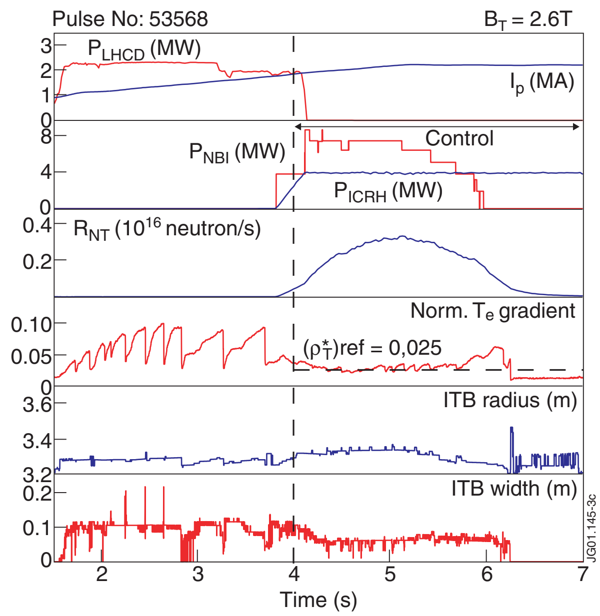

Figure 3: Control with NBI: Time evolution of LH power, plasma current, NBI and ICRH power, neutron rate, ρ_{Te}, radius and width of the ITB (Pulse No: 53568). Control starts at 4s and the reference value for ρ_{Te}* is 0.025.*

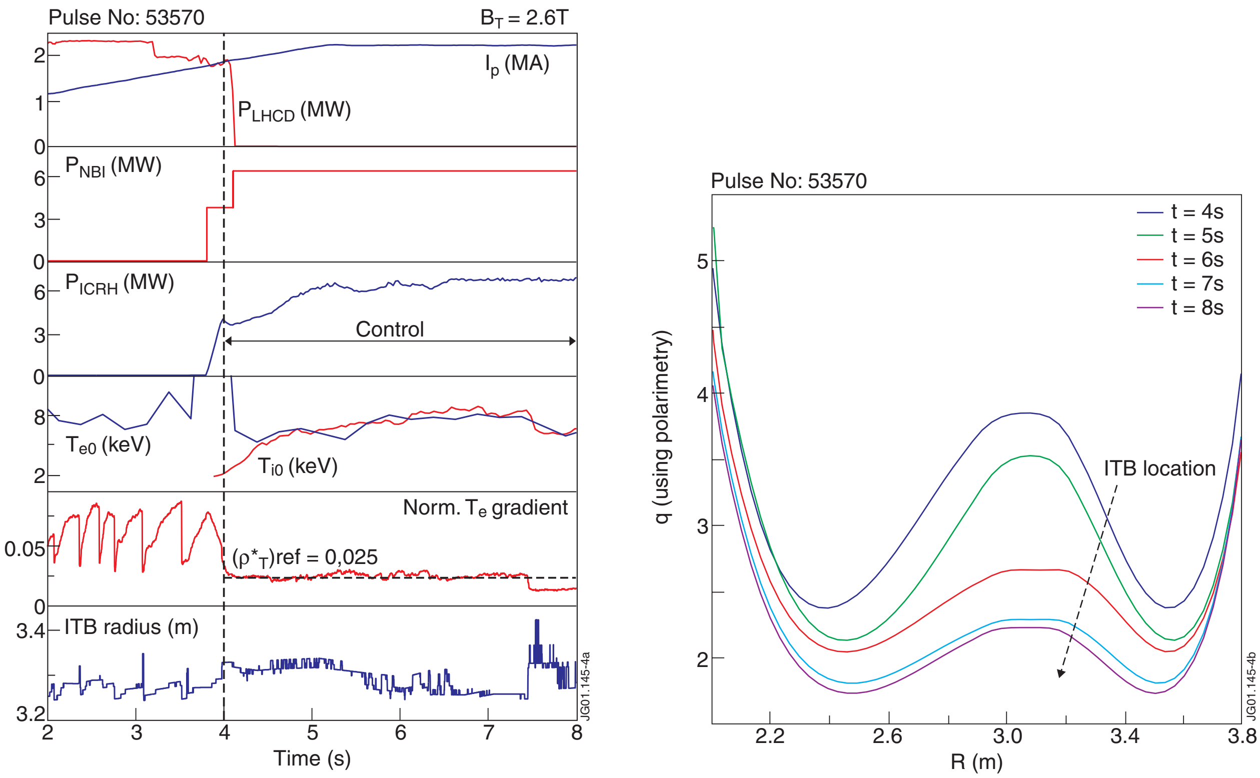

Figure 4: Control with ICRH: (Left) Time evolution of LH power, plasma current, NBI, ICRH power, Te0 Ti0, ρ_{Te}, radius and width of the ITB (Pulse No: 53570). Control starts at 4s and the reference value for ρ_{Te}* is 0.025. (Right) q-profile evolution) using EFIT [5] with polarimetry during the main heating phase (Pulse No: 53570).*

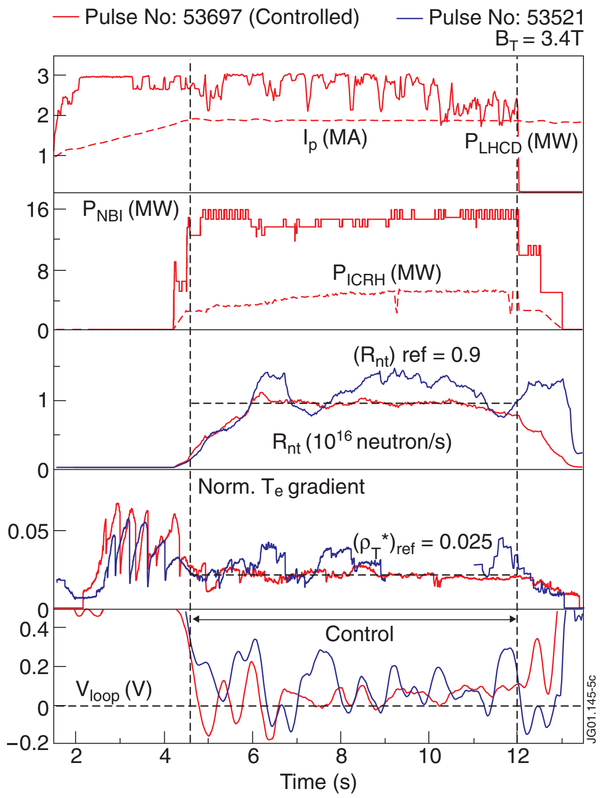

Figure 5: Control with ICRH and NBI: Time evolution of LH power, plasma current, NBI, ICRH power, neutron rate, ρ_{Te}, loop voltage (comparison Pulse No: 53521 without control with the controlled Pulse No: 53697). Control starts at 4.5s and the reference values are 0.025 for ρ_{Te}* and $0.9.10^{16}$ neutron/s for the neutron rate.*