Progress Towards Steady-State Operation and Real Time Control of Internal Transport Barriers in JET

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Abstract. In JET advanced tokamak research mainly focuses on plasmas with internal transport barriers (ITBs), generated by modifications of the current profile. The formerly developed optimised shear regime with low magnetic shear in the plasma center has been extended to deeply reversed magnetic shear configurations. High fusion performance with wide ITBs has been obtained transiently in deeply reversed magnetic shear configuration: $H_{IPB98(y,2)}$~1.9, β_N=2.4 at I_p=2.5MA. At somewhat reduced performance electron and ion ITBs have been sustained in full current drive operation with 1MA of bootstrap current: $H_{IPB98(y,2)}$~1, β_N=1.7 at I_p=2.0MA. The ITBs have been maintained up to 11s. This duration, much larger than the energy confinement time (37 times larger), is already approaching a current resistive time. New real-time measurements and feedback control algorithms have been developed and implemented in JET for successfully controlling the ITB dynamics and the current density profile in the highly non-inductive regime.

1. Introduction

Improvement of the tokamak concept in terms of confinement and stability is a crucial challenge that could lead to operating the device in a continuous mode. In a steady-state tokamak reactor the plasma current is entirely sustained by non-inductive means and the self-generated bootstrap current provides a significant fraction of the plasma current. A major challenge remains to extend the high performance regimes obtained in present days tokamaks towards genuine steady-state conditions where the current density profile is non-inductively driven. The development of steady state operational regimes with improved confinement and stability is known as 'advanced tokamak' research (e.g. [1-4]). This paper reports on the recent (2000-2002) progress achieved on JET towards controlled steady-state regime.

In JET, advanced tokamak research mainly focuses on plasmas with Internal Transport Barriers (ITBs), generated by modifications of the current profile [5-6]. ITBs are qualitatively defined as core plasmas regions with low radial thermal transport, i.e. regions where the anomalous transport of the conventional confinement mode (L-mode) is reduced. Moreover, a quantitative ITBs definition has been proposed and successfully applied to characterise the JET ITBs (emergence, strength and space-time evolution) in a wide range of plasma parameters [7]. It was found that the dimensionless local parameter, $\rho_T*=\rho_s/L_T$ characterises with a low computational cost the ITB features [ρ_s/L_T is the local ion Larmor radius at the sound speed normalised to the (electron or ion) temperature gradient scale length L_T]. An ITB exists when the normalised Larmor radius, ρ_T*, exceeds a critical value. This practical ITB criterion has been used routinely to speed up the identification of the experimental database and ultimately to control in real time the ITB dynamics.

The paper is organised as follows. In section 2, the achievement of (transient) high fusion performance in deeply reversed magnetic shear configuration is reported [8]. The influence of the q-profile in the plasma performance is also stressed. Then in section 3, we will describe the quasi-stationary operation with a high fraction of non-inductive current [9-10]. Finally, the recent and major developments to control in real time with closed feedback loop the local ITB or current profile characteristics are reviewed in section 5 [11].

2. High fusion performance plasmas with reversed magnetic shear

The formerly developed optimised shear regime with low or weakly negative magnetic shear in the plasma center [3], has been extended to noticeably reversed magnetic shear configurations [8, 12-13]. The q-profile has been varied using mainly the LHCD during the initial current ramp-up phase of the plasma discharge, prior to the application of the high power heating. Dedicated set of experiments has been performed to reveal the role played by the q-profile in the ITB formation and performance [8]. The magnetic shear in the plasma interior was varied from small and positive in the ohmic preheat case, through weakly to highly negative ('current hole') by increasing the LHCD power and/or optimising the plasma initiation (Fig. 1 (left)). In addition, the injected torque in the co-current direction has been systematically varied for each q-profile (B_o=2.6T, I_p~2.2MA). Figure 1 (right) shows the peak value of $\rho_{Te}*$ applied to the electron temperature profile in the region of 'wide' transport barrier (r/a>0.5), as a function of additional power for the different q-profile and injected torque. The wide ITBs required for high fusion performance are formed close to the low order rational q=2 surface for both the weak [14] and reversed shear configuration [15]. The plasmas with an LHCD prelude tend to provide a 'stronger' electron ITB (e.g. larger value $\rho_{Te}*$) than the ohmic preheat cases. This observation is attributed to the reduction of the magnetic shear at the location of the q=2 surface which is expected to be favourable for the ITB formation and performances [16].

Following this approach but at higher toroidal field (B_o=3.45T), high fusion performance has been achieved with reversed magnetic shear with a minimum q value, q_{min}, approaching two (Fig. 2 (left)) [8]. The LH power (2-3MW) was applied soon after the plasma initiation until the main heating phase. A narrow ITB is first visible on the electron temperature profile during the LHCD prelude phase, which persists during the early part of the main heating phase. Then, a wide ITB with very steep gradient develop on the thermal pressure profiles, and is thought to be triggered when q_{min} reaches two. ITBs at large plasma radius contribute significantly to the enhancement of fusion performance: total neutron yield,

R_{NT}, R_{NT}=4.1x10^{16}neutrons/s, $H_{ITER-89P}$~3.3, $H_{IPB98(y,2)}$~1.9, β_N=2.4 at I_p=2.5MA (q_{95}=4.5). The transient high performance phase is ended with a large ELM followed by a disruption (global pressure n=1 kink mode instability). A further increase in performance will require the pressure profile to be further broadened by extending the radius of ITB. More recent experiments were carried out in 2002 (campaign C5) to move outwards the q=2 low shear magnetic shear region by ramping-up the plasmas current up to 3.8MA (q_{95}=2.9).

Finally, the performance of the two types of JET ITB regimes are compared on Figure 2 (right) where the peak neutron rate is plotted versus the additional power for weak and reversed shear configuration. Heating power in the range of 16MW is required to generate wide transport barrier and high fusion yield in the reversed magnetic shear configuration, instead of 20MW in the weak shear cases [8].

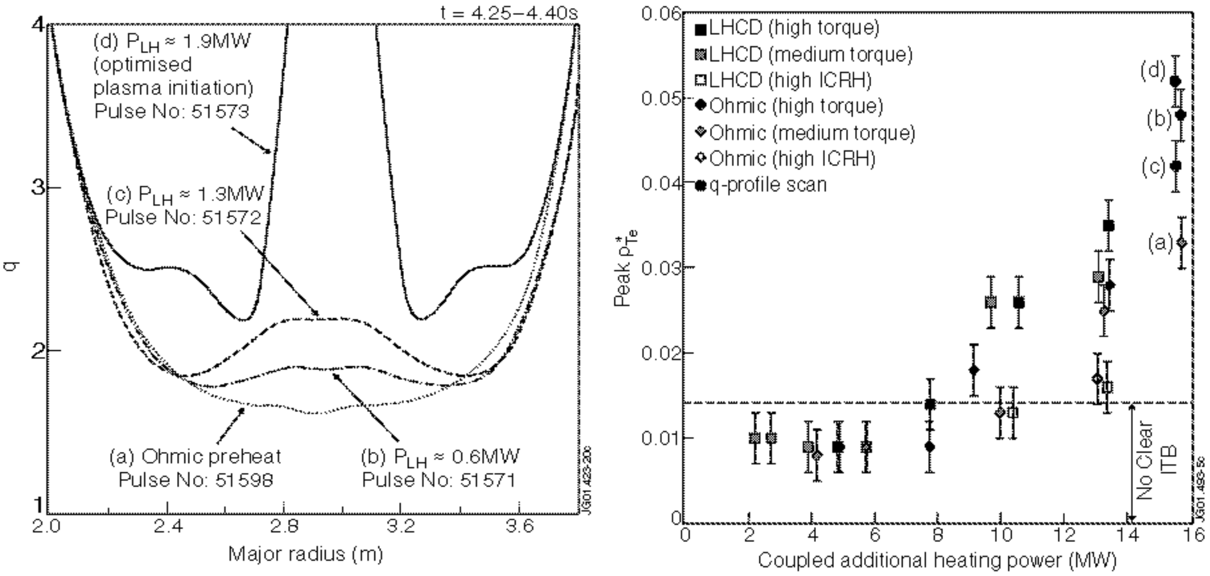

FIG 1: (left) Various target q-profiles prepared with varying LHCD prelude (EFIT equilibrium reconstruction constrained by MSE data). (right) Maximum value of ρ_{Te} versus coupled power for various q-profile and heating scenarios (B=2.6T); Annotations (a) to (d) refer to the q-profile scan shown on Fig. 1 (left) [8].*

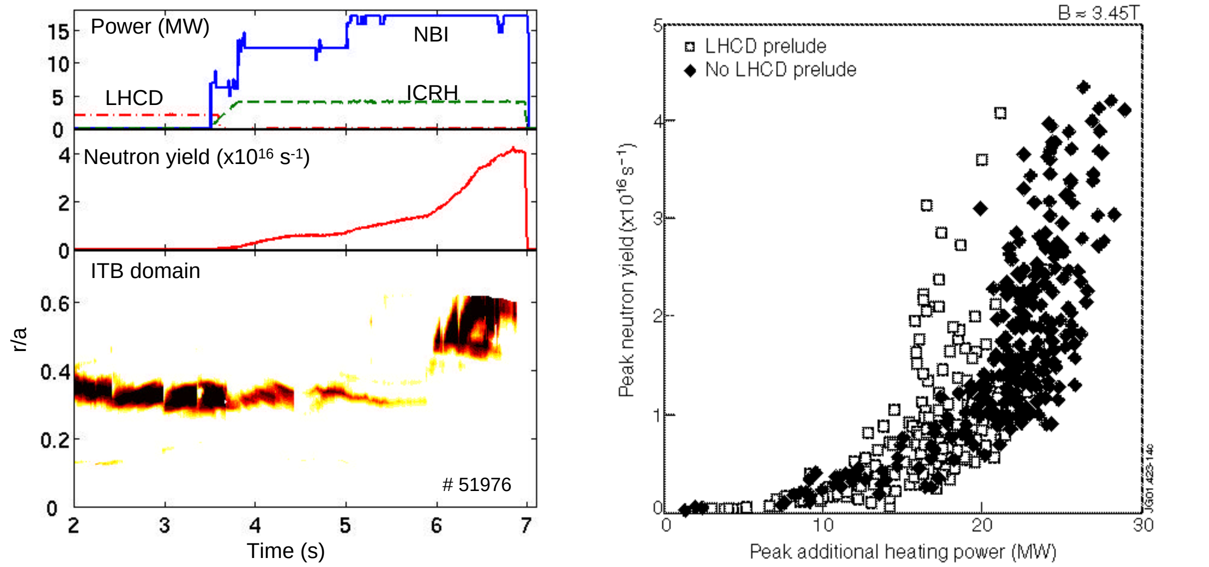

FIG 2: (left) Time evolution of applied powers, neutron yield and ITB radius, as defined in [7], of a high fusion performance reversed shear discharge (#51976). (right) Peak neutron yield versus additional heating power for the weak and reversed magnetic shear magnetic configuration [8].

3. Development of ITB plasmas with steady-state potential

An approach towards stationary operation has been investigated by maintaining the LH power during the high power ELMy H-mode phase in order to slow down the current profile evolution [9-11, 17]. Figure 3 shows one of the longest pulse with LH power combining an ELMy H-mode edge and core transport barrier sustained with a loop voltage, V_s, approaching zero (Ip=2MA, q_{95}=5.5, $H_{ITER-89P}$~2, $H_{IPB98(y,2)}$~1, β_p=1.1, β_N=1.7 at B_o=3.45T). Successful coupling of the LH waves during the H-mode phase has been obtained by controlling the density at the antenna mouth by locally injecting CD_4 gas [18]. In this discharge, the electron ITB is maintained during 11s from the LH preheat phase up to the pre-programmed end of the power waveforms. This is the longest discharge during which an ITB has been sustained on JET and this duration corresponds approximately to 37 energy confinement times, τ_E. Those ITB durations become comparable to the volume averaged resistive current diffusion time evaluated with the local neo-classical conductivity profile. The ITB also observed on the ion temperature, electron density and toroidal rotation profiles is sustained during the high power phase (~8s, ~27τ_E) starting at t=4.2s. The core electron density is rising up to n_{eo}=6.0$10^{19}m^{-3}$, and the line-averaged density normalised to the Greenwald density is 0.55. The duration of this type of discharge is close to the JET technical operational limits fixed by the maximum duration of application of the full NBI power and the high toroidal field operation.

The target q-profile is reversed with q_{min}~3 at r/a~0.5 as inferred from the EFIT code constrained by MSE measurements or FIR polarimetry data. In the high power phase, the q-profiles keep a non-monotonic shape with q_{min} maintained above 2 at mid-radius. The freezing of the q-profile evolution, in particular the location and value of q_{min}, allows to maintain the ITBs inside mid-plasma radius, i.e. in the weak or negative magnetic shear region, without reaching the disruptive ideal n=1 kink limit. The q-profile evolution is slowed down thanks to the high fraction of non-inductive current reaching up to 90% of the total current as calculated by TRANSP or CRONOS [19]. The non-inductive current fraction is fairly constant with time: when the electron density is increased the LH and NB non-inductive currents are both reduced but this effect is partly compensated by the rise of the bootstrap current. The self-consistent CRONOS simulations of the various non-inductive currents with the 2-D equilibria indicate that the off-axis bootstrap current rises up to 1.0MA, the NBCD varies between 0.2-0.6MA, while the LHCD deduced from ray-tracing coupled to 2-D Fokker-Planck modelling is in the range of 0.4-0.8MA (Fig. 3 (right)) [10]. The LH ray-tracing simulations during the high power phase show that the LH power is absorbed in a broad off-axis region thanks to the strong electron Landau damping with high electron temperature.

The possibility to sustain the ITB characteristics offers the opportunity of quantitatively studying the particle and impurity transport. Such studies require that the regime is maintained on time duration at least of the order of the particle confinement time (several τ_E). These studies have shown that the core impurity transport follows the trends predicted by the neo-classical theory : high Z-impurity accumulation with strong peaking of the density profile competing with the screening effect expected from high ion temperature gradient [20]. In the experiment shown on Fig. 3, the screening effect is either too localised and/or not strong enough to prevent the central accumulation of the metallic impurity. The high-Z impurity accumulation leads to a core radiative collapse (t≈11.1s) in which energy and density are expelled. Control of the impurity content will be investigated either by triggering core MHD activity or by controlling the density and temperature profiles (c.f. section 4).

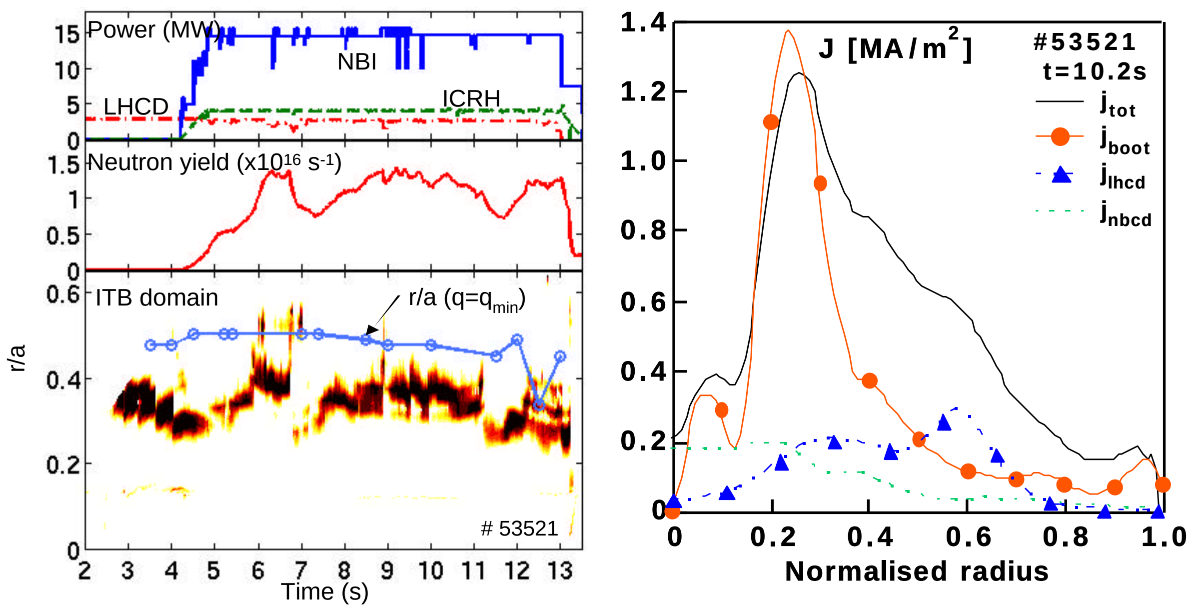

FIG. 3 : (left) Time evolution of applied powers, neutron yield, ITB radius (defined in [7]) and q_{min} normalised radius of a highly non-inductive discharge (#53521). (right) Current density profiles of bootstrap, LH, neutral beam and total deduced from current diffusion simulation [10].

One of the surprising results of this experiment is that the ITB is reformed just after the core MHD (t≈6.7s) or radiative (t≈11.1s) collapses. These collapses affect on a fast time scale the pressure, toroidal rotation and radial electric field profiles but the q-profile, evolving on a longer time scale, keeps a non-monotonic shape. Simulations performed with the electrostatic linear gyrokinetic code, KINEZERO [21], indicate that the ion instabilities driven by the ITG and the trapped electron modes are suppressed in the region of negative magnetic shear [10, 22]. Therefore, the direct reduction or stabilisation of the turbulence through the q-profile is invoked to explain the rapid recovery of the ITB to various collapses as long as these perturbations affect only weakly the low or negative magnetic shear region.

One of the challenges for the viability of steady-state plasmas consists in successfully combining the H-mode confinement with the ITB characteristics. High performance ITB discharges occur typically at power levels well above the L to H mode transition and even above the type-III to type-I ELM transition. When a transition to large amplitude ELMs occurs, the ITB is either lost with a back transition to a lower confinement state or the whole plasma becomes unstable leading to a major disruption. Although the total applied power is at least a factor two above the power threshold to trigger large amplitudes ELMs, the ELM's activity keeps a mild type-III behaviour in these highly non-inductive discharges even without injecting radiative gases for edge cooling. The mitigation of the ELM's activity has been interpreted by analysing the role played by the broad q-profile with low l_i values (l_i~0.7-0.8) on the threshold conditions from type III to type I ELM [23-24]. A larger current fraction at the plasma 'edge' in the ITB discharges compared to the similar standard H-mode ones could prevent a transition to type-I ELM by changing the edge MHD stability conditions. The large edge current fraction is self-sustained throughout the high power phase since a large fraction of off-axis non-inductive current is continuously driven in these ITB discharges.

This edge issue has been further investigated in the 2002 experimental campaign in similar operating conditions but at high triangularity, δ~0.45, where the ELM activity is expected to be even stronger. So far JET ITB experiments were mainly performed at reduced values of triangularity (δ~0.2). The recent modification of the divertor geometry (the septum part of the MKII Gas Box has been removed) has allowed ITB operation with plasma equilibria at triangularity closer to the values envisaged for ITER advanced mode of operation. The ELM behaviour has been changed (at fixed deuterium gas injection rate) by varying the plasma current once the reversed shear configuration was established. In the experiment shown on Figure 4, the full power is applied on a 2MA current plateau where type I ELM activity is triggered. Then, the current is raised by 0.3MA, inducing an increase of the edge current ('skin effect') that destabilises the n=1 peeling modes. The type I ELM activity is then suppressed: confirming the role played by the edge current density on the ELM properties.

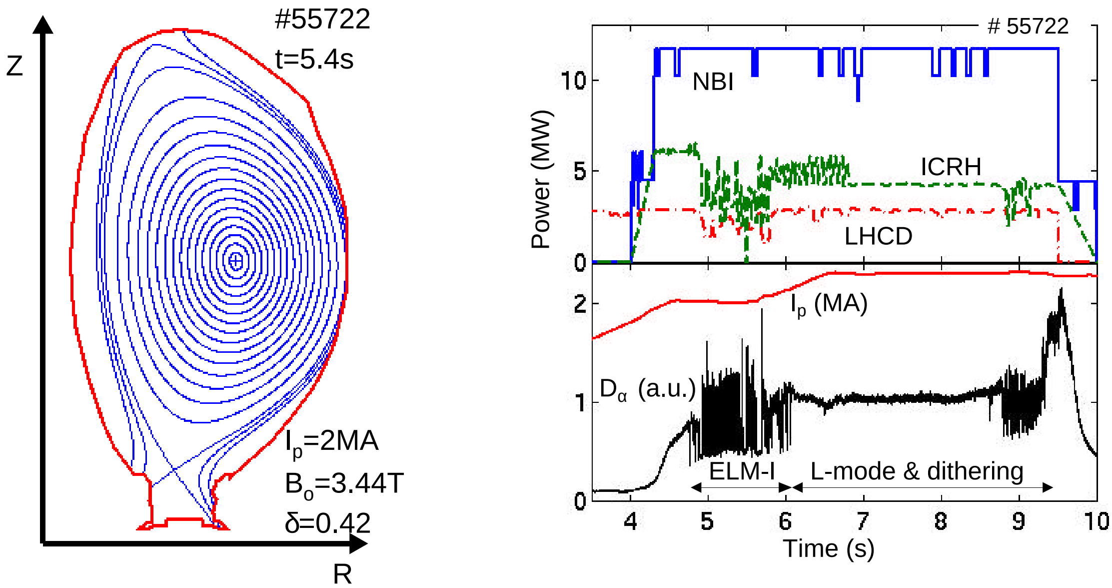

FIG 4 : Magnetic equilibria (t=5.4s) and time evolution of coupled powers, I_p and D_α-emission in ELM control experiment at high δ (#55722). MK II Gas Box divertor without the septum.

4. Real-time feedback control of the ITB plasmas for steady-state operation

New real-time measurements and control algorithms have been developed and implemented for controlling the ITB dynamics and the current density profile: confinement parameters, temperatures, particle and q-profiles are now available in real-time.

A double-loop feedback control with combined ICRH and NBI has been first applied in the non-inductive operational regime described in section 3 [11]. The NBI power controls the total neutron yield, R_{NT}, at a given reference and consequently the total bootstrap current fraction through the control of the core plasma pressure. In addition, the ICRH is simultaneously used as an actuator to control the normalised electron temperature gradient in the barrier region, i.e. the maximum value of $\rho_{Te}^*=\rho_s/L_{Te}$ (Fig. 5 (left)). For this purpose, the local ITB criterion [7] characterising the space-time evolution of the ITBs has been calculated in the real time system from the ECE radiometer data. The LHCD power is maintained in a pre-programmed way to provide the correct q-profile ensuring the core confinement and MHD stability. In the example shown on Figure 5 (left), the values of the maximum ρ_{Te}^*, and of the neutron rate are maintained constant respectively at 0.025 and 0.9×10^{16} neutrons/s. The active control of the temperature gradient provides an indirect way of acting on the current density profile through the bootstrap current (I_{Boot}~0.9MA, I_p=1.8MA). The control of the ITB is applied during 7.5s until the end of the pre-programmed power waveform envelope within which the NBI and ICRH powers are allowed to vary. During the control phase, the plasma parameters of the discharge are fairly stationary with mild and continuous ELM activity. Thanks to the real time control of the ITB characteristics, the improved confinement state is maintained in a more reproducible and stationary manner, e.g. avoiding the occurrence of the core collapses.

Recent efforts have been made in order to develop an algorithm which provides a measurement of the q-profile in real-time and allows feedback control [25-26]. The algorithm uses as inputs the signals of the magnetic and interfero-polarimeter diagnostics. The approach described in the previous paragraph is based on decoupled loops controlling the core pressure and temperature gradient at two radii with devoted actuators. A 'model-based' profile control scheme is now followed, in which more information on the spatial structure of the system is taken into account by retaining its distributed nature, and considering the non-local interaction between various quantities through a diffusion-like operator [27]. To validate this 'model based' technique a direct control of the safety factor profile has been tried using LHCD as the only actuator. The experiment was performed during an extended LHCD prelude phase at low density and beta. The plasma current was fixed at 1.5MA, in order to be close to a purely non-inductive regime with the available LH power and thus have a larger flexibility for obtaining weak shear q-profiles. The feedback control was performed on five points of the q-profile located at fixed normalised radii (r/a=0.2, 0.4, 0.5, 0.6, 0.8) and the reference q-profile is reached within 4s (Fig. 5 (right)). To reach the pre-set reference q-profile the controller minimises in the least square sense the difference between the five target q-values and the real-time measurements. The successful experiment reported here should be considered as a 'proof of principle'. In the near future, this general 'model-based' approach will be implemented in view of controlling high-β, high-bootstrap fraction, ITB discharges where pressure and current density profiles are strongly non-linearly coupled.

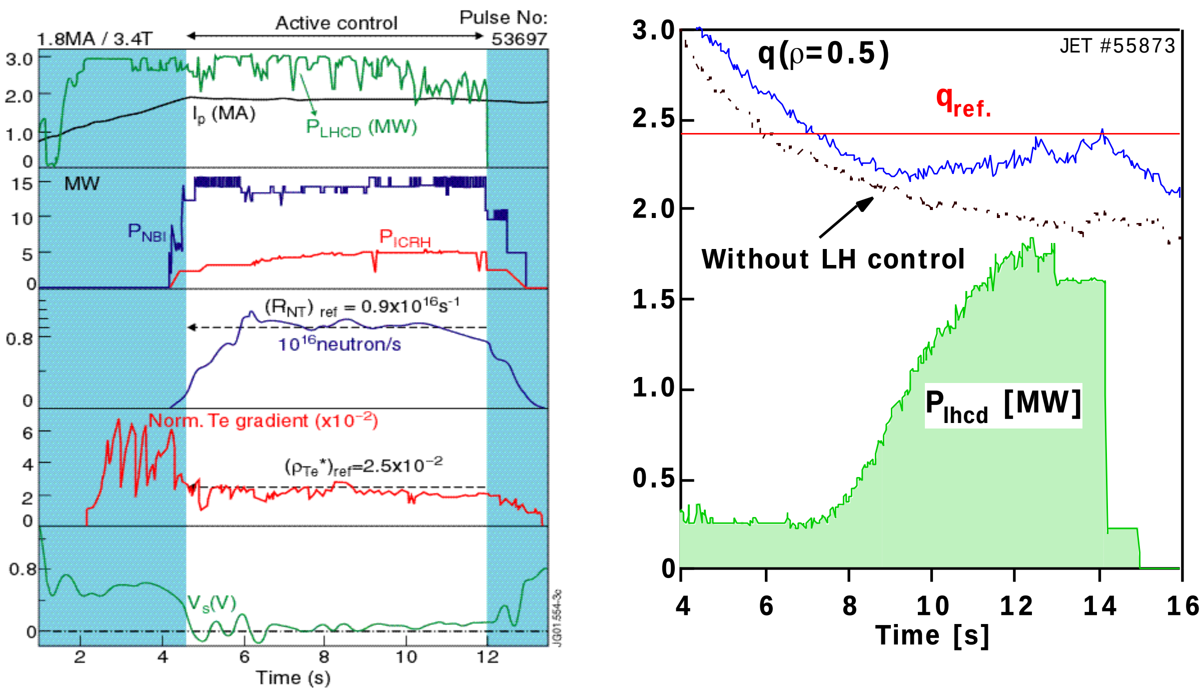

FIG. 5: (left) Time evolution of the main parameters of a discharge with combined ρ_{Te} and R_{NT} feedback control using ICRH and NBI powers (#53697) [11]. (right) Real time q-profile control: time evolution of LHCD power, measured and reference q-values at mid-radius (#55873). A discharge (#55872) without LHCD feedback control is presented for comparison (---) [25].*

5. Conclusion

The sustainement and the real time control of the ITBs in full current drive operation with a significant fraction of bootstrap current represent a major milestone towards the definition and viability of the steady-state tokamak operation. Nevertheless, despite these favourable results for the advanced mode of operation, performance in terms of normalised pressure (β_N) and confinement of this JET non-inductive regime should be further increased: e.g. by extending the radius of the ITB for embracing a larger plasma volume with reduced transport. We have shown that wide ITB with steep gradient, could be formed when the low magnetic shear region is extended close to low order rational q-surface (e.g. q=2). A major challenge remains to sustain and control towards stable steady-state conditions the characteristics of the wide ITBs. The real time measurements of the kinetics and magnetics profiles together with the 'model-based' feedback control algorithms will be extensively used in future experimental campaigns in view of further increasing the plasmas fusion performance in a quasi-steady state manner. In addition, effort will be pursued to develop a non-inductive mode of operation in highly shape plasmas at high triangularity (δ~0.5) as requested in the present ITER design.

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