Towards full current drive operation in JET

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**See appendix of J. Paméla, Proc. 18th IAEA Conf. on Fusion Energy, Sorrento 2000*

Introduction

In a steady-state tokamak reactor where the plasma current is entirely sustained by non-inductive means, it is now well recognised that the self-generated bootstrap current should provide a significant fraction of the plasma current to minimise the external current drive requirement. To investigate the physics of full current drive operation, experiments with Internal Transport Barriers (ITB) have been carried out in JET during the 2000-2001 campaign at reduced plasma current with a poloidal beta, β_p, reaching 1.65 (I_p=1.5-2MA, q_{95}=5.5-8, Gas-Box divertor). Two series of experiments are reported in this paper. Discharges with a zero-loop voltage phase have been produced with 0.7-0.8MA of self-generated bootstrap current combined with either Neutral Beam Current Drive, NBCD, (section 1) or the sum of NBCD and off-axis Lower Hybrid Current Drive, LHCD (section 2). We have found that the off-axis LH current is essential to control the q-profile evolution when approaching steady-state conditions.

1) Sustainement of ITB with bootstrap and neutral beam current drive

An important and open issue is the optimisation of the route towards a genuine steady-state regime where the required current profile for improved confinement and stability is the sum of the different non-inductive currents. The chosen strategy consists in forming a non-monotonic q-profile in the low β_p phase of the discharge by coupling 2-3MW of LH power soon after the plasma breakdown [1] while the current is ramped at a rate of 0.4MA/s up to its flat top value, 1.5MA at B_t=3.4T (Fig. 1, left). Then the full heating power (up to 20MW) consisting of Ion Cyclotron Resonance Heating (ICRH, 5MW) and NB Injection is applied at t=4.1s during 5.5s to form an internal transport barrier while the LH power is switched-off. The target q-profile at the time of the application of the full power is weakly reversed with a minimum q-value, q_{min}, close to three at mid-plasma radius as inferred from the equilibrium reconstruction code EFIT constrained by the MSE or infrared polarimetry data (Fig. 1, right) [2]. The various power waveforms have been varied to tune the target q-profile. The aim is to avoid the development of (double) tearing MHD modes (n=1) [3]. These may persist during the whole heating phase and consequently inhibit the formation of the ITBs. In the successful discharges as shown on Fig. 1, the loop voltage at the plasma surface, V_s, drops down to zero during the high power phase thanks to the build-up of the plasma pressure and the rise of the poloidal beta up to 1.65. The zero loop voltage is maintained during one second from t=7.4s to 8.4s in the 1.5MA current plateau with a core density of $3.310^{19}m^{-3}$, an improved confinement factor of respectively 2.5 according to ITER-89P non-thermal L-mode scaling law [4] and 1 for the thermal H-mode scaling (ITER97-H) at a normalised toroidal beta, $\beta_N \approx 2$. The phase with Vs=0V is terminated by a MHD roll-over of the core performances (inside 0.4 in normalised radius) when q_{min} approaches two and reduces the amount of bootstrap current (β_p drops down to 1.4). Nevertheless, the flux consumption at the plasma boundary is less than 0.02Wb during the high power phase. The improved confinement is due to a combination of an edge and a core transport barrier located at two third of the plasma radius. Although the total applied power is at least a factor two above the power threshold to trigger large amplitudes type I ELMs, the mild ELM activity keeps a type-III behaviour without injecting radiative gases for edge cooling [5]. The electron pedestal pressure stays below 6kPa and the ELM activity does not affect the ITB performance. During the five seconds of the high power phase the internal inductance, l_i, remains low indicating that the initial off-axis currents are partly replaced by the bootstrap and NB current. The q-profile identified by EFIT from the time evolution of the Faraday rotation angles evolves slowly towards a monotonic profile with q-on axis, q_o, approaching two. During the high performance phase the ITB, shown on the toroidal rotation profiles on Fig. 1 (right), is located in the positive shear region around the rational q=3 surface. The density fluctuation measurement indicates a drop of fluctuation at this location. The slow redistribution of the total current from an hollow current profile to a monotonic one is invoked to explain the collapse of the ITB at t≈5.5s (without MHD activity) and the core performance roll-over when q_o is crossing two at t≈7.5s. Resistive current diffusion simulations (TRANSP or CRONOS) indicate that the sum of non-inductive currents reaches up to 80% of the total current with 0.65MA of bootstrap current and 0.6MA of NBCD.

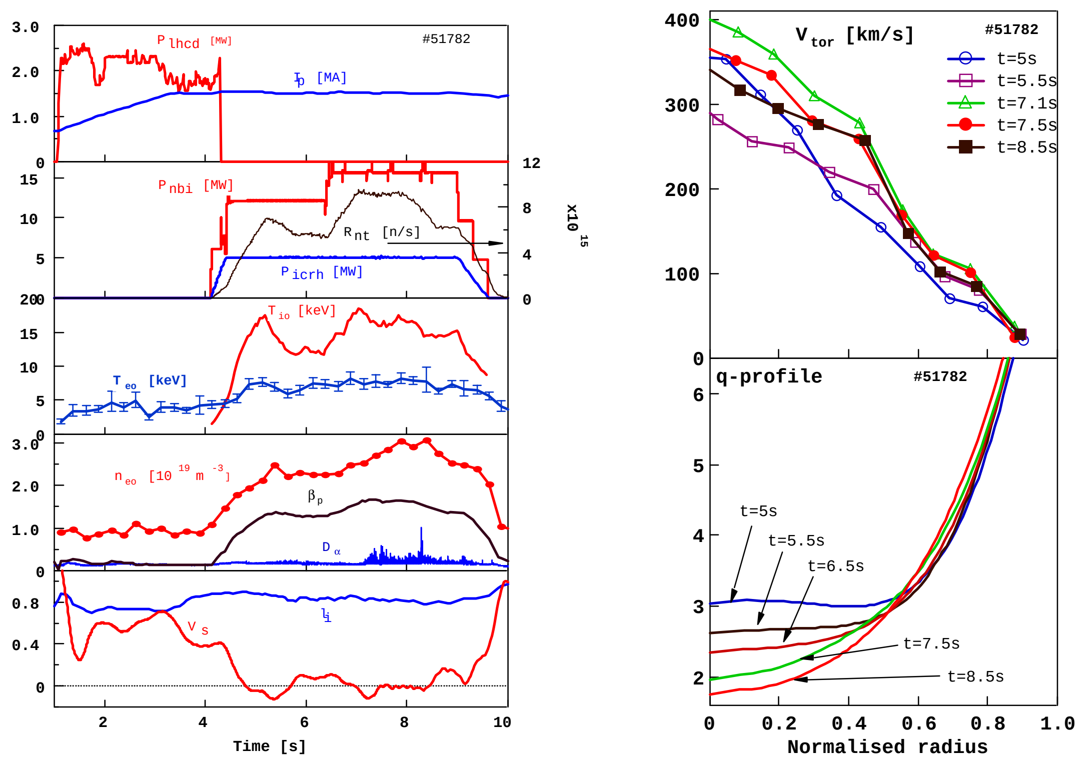

Fig. 1 : (left) Time evolution of the main parameters: full current drive discharge sustained with NB and bootstrap currents; (right-top) Toroidal rotation profile from CXS measurements; (right-bottom) q-profile evolution from polarimetry data (target q-profile at t=5s in agreement with MSE data) (#51782).

2) Sustainment of ITB with lower hybrid current drive in high power discharges

A similar approach towards steady-state operation has been investigated but by maintaining the LH power during the high power ELMy H-mode phase in order to further slow down the current profile evolution and avoid q_{min} crossing two. Successful coupling of the LH waves up to 3MW during the H-mode phase with reflected power in the range of 5% has been obtained by controlling the local density at the grill aperture by injecting CD_4 gas from a valve magnetically connected to the LH antenna [6]. One of the longest pulse with LH power combining an ELMy H-mode edge (type III) and core transport barrier sustained with a loop voltage approaching zero at a plasma current plateau of 2MA is shown on Fig. 2 (#53521, q_{95}=5.5, $H_{ITER-89P}$=2, $H_{ITER97-H}$=0.95, β_p=1.1, β_N=1.7 at B_t=3.4T). In this discharge, the electron ITB is maintained from the LH preheat phase up to the pre-programmed end of the power waveforms (11s, $\approx 36\tau_E$). The ITB on the ion temperature, electron density and toroidal rotation is sustained during the whole high power phase (8s, $\approx 27\tau_E$) consisting of 15MW of NBI, 4MW of ICRH and 2.7MW of LHCD powers. Those durations are comparable to the resistive current diffusion time evaluated at mid plasma radius, i.e. at the footprint of the ITBs. During the LH preheat phase, the ITB on the electron temperature profile is located at a normalised radius of ρ/ρ_{max}=0.2-3 and then expands radially up to 0.5 in the high beta phase. Similar location of the ITB is observed on the electron density profile rising up to n_{eo}=6.0$10^{19}m^{-3}$ (line averaged density normalised to the Greenwald density of 0.5), ion temperature, electron temperature and toroidal rotation (core rotation of 500km/s). The target q-profile at t=4.3s is reversed with $q_{min}\approx 3$ at $\rho/\rho_{max}\approx 0.5$. During the high power phase, q_o slowly decreases down to 2.7 together with the slow evolution of l_i. Nevertheless, the q-profiles keep a non-monotonic shape with q_{min} maintained above 2 at mid-radius thanks to the high fraction of off-axis non-inductive current from the bootstrap and LH currents (Fig.3, left). The freezing of the q-profile evolution, in particular the location and value of q_{min}, allows to maintain the ITBs at mid-plasma radius, i.e. in the weak or negative magnetic shear region. A more detailed analysis of the time evolution of the various profiles indicates that two core collapses occur at t=6.7s and t=11.1s from which the ITB spontaneously recovers. The first one is attributed to a n=1 MHD event possibly associated with the hollow q-profile. No MHD event is observed for the second event. A possible explanation arises from a careful analysis of the core impurity behaviour in these long sustained ITB discharges [7]. Indeed, these analyses indicate that the high-Z impurities such as Nickel accumulate in the plasma core following the neo-classical expectation and therefore steadily rise the radiative power density in the plasma center up to 140kW/m^3 : a value approaching the conducted power density. Thus the loss of confinement at 11.1s is probably a radiative collapse. It is worth pointing out that the two ITB collapses at 6.7s and 11.1s transiently evacuate the impurity from the core.

Self-consistent calculation of the various non-inductive current with the actual equilibrium and measured temperature profiles indicates that (i) the bootstrap current rises up to 0.8MA, the NBCD varies between 0.2-0.4MA, while the LHCD deduced from Ray-Tracing Fokker-Planck modelling is the range 0.4-0.9MA (depending on density) corresponding to a normalised LHCD efficiency of 1.5-2$10^{19}m^{-2}$ A/W. The LH simulations during the high power phase show that the LH power is absorbed off-axis thanks to the strong electron Landau damping and the steep gradients of the electron temperature (Fig.3, right). Indeed, simulations at different time slices indicate that the LH current follows the position of the electron ITB, this one preventing central absorption. These are encouraging results in view of controlling discharges with ITB and broad current density profiles.

Finally, the same type of discharge has been successfully repeated in the aim of demonstrating the feasibility of real time control of the electron temperature gradient at the ITB location in full current drive operation [8].

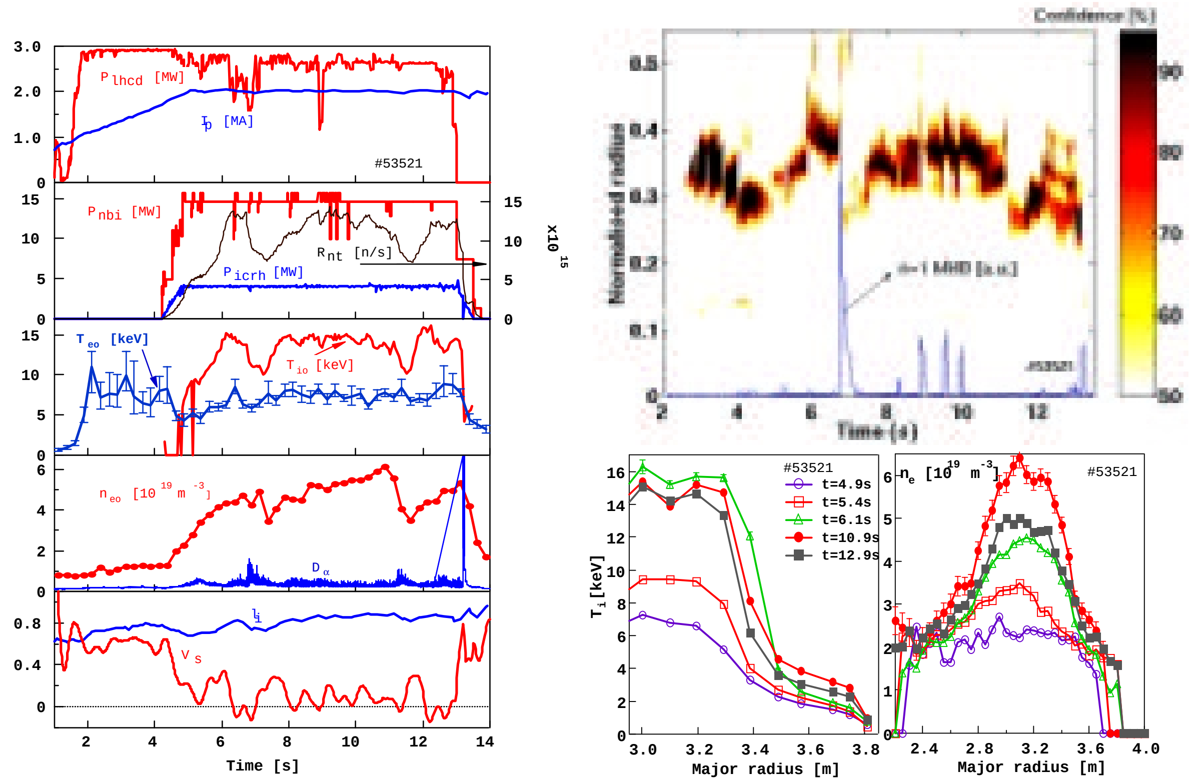

Fig. 2 : (left) Time evolution of the main parameters of a long sustained ITB discharge. (right–top) Time evolution of the position of the electron temperature barrier as calculated in [9] (right-bottom) Ion temperature and electron density profiles (#53521).

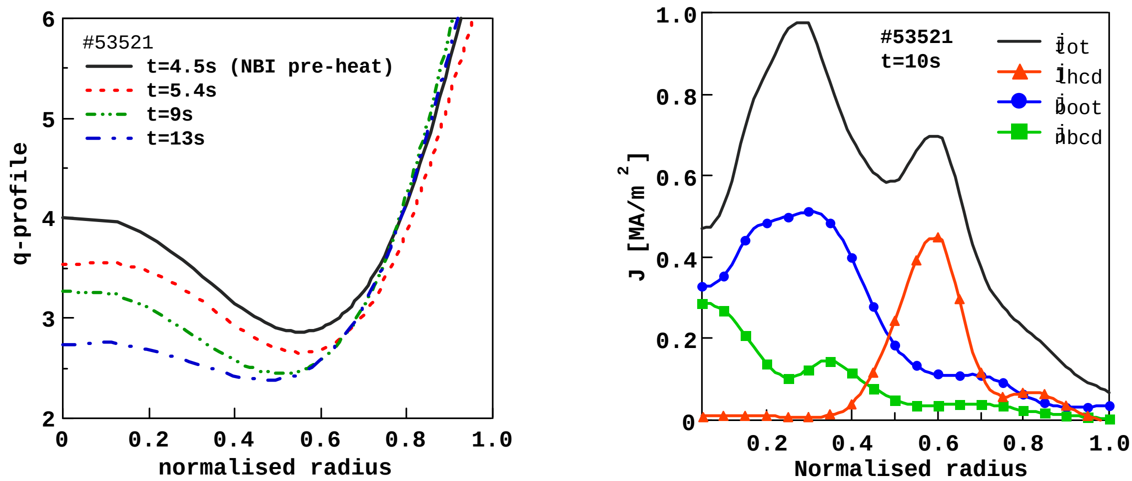

Fig. 3 : (left) q-profile evolution from polarimetry data (target q-profile at t=4.5s in agreement with MSE data). (right) Non-inductive current profiles from TRANSP (#53521).

References

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