Internal Transport Barriers in JET Plasmas

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High performance optimised shear plasmas with a broad or hollow current density profile have been produced in JET in both DD and DT plasmas showing improved core confinement in an Internal Transport Barrier (ITB) [1]. Two preheating phases were used during the early current ramp-up phase, “freezing-in” a flat or hollow current density profile: a short pulse of 1 MW of Lower Hybrid Current Drive (LHCD) power applied (time t = 0.4 s - 1.2 s), followed by 1-2 MW of Ion Cyclotron Resonance Heating (ICRH) until the start of the main heating (Fig. 1).

With T fuelling, the H-mode power threshold was reduced and the heating timing modified to avoid an early H-mode. At t ~ 5.6 s, an ITB formed with the confinement improvement propagating out from the centre, reaching ρ ~ 0.55 at t = 6.4 s. The peaking of parameters increased during the L-mode. $T_i(0)$ in DT was several keV higher than in DD owing to the lower density. At t = 6.6 s the central plasma pressures were equal:

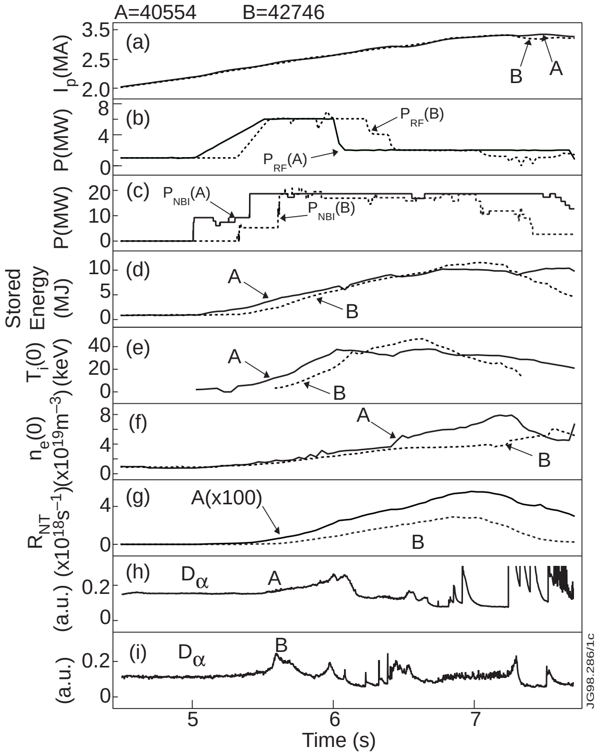

Fig. 1: Plasma parameters: DD Pulse “A” (No. 40554) and DT Pulse “B” (No. 42746). (a) current, I_P; (b,c) NBI and ICRF powers; (d) diamagnetic energy, W_{dia}; (e) ion temperatures, $T_i(0)$; (f) electron densities, $n_e(0)$; (g) neutron emission, R_{NT}; (h, i) D_α emission (A, B). In pulse A, $n_e(0) \leq 7.0 \times 10^{19}$ m^{-3}, was 27% higher than in B; this can be compared with a 36% reduction in the total fuelling when 8 (out of 16) of the NBI sources were converted to tritium (E_b = 150 keV).

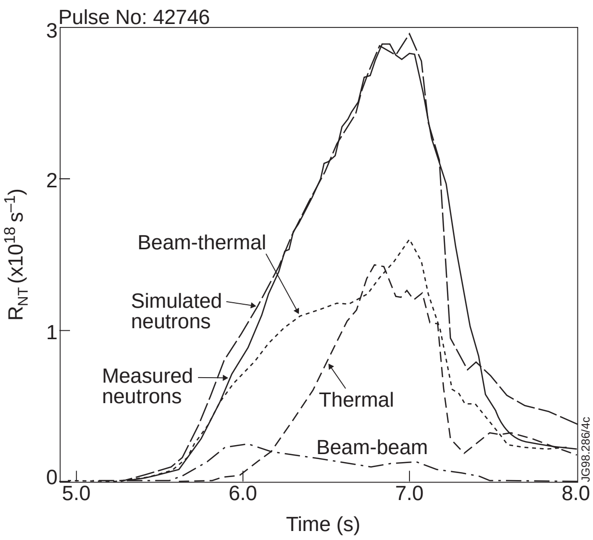

Fig. 2: TRANSP neutron emission modelling for DT pulse B, compared with measurement. The simulated total neutron emission is the sum of the thermal-thermal, beam-thermal and beam-beam rates and is within measurement errors (± 10 %).

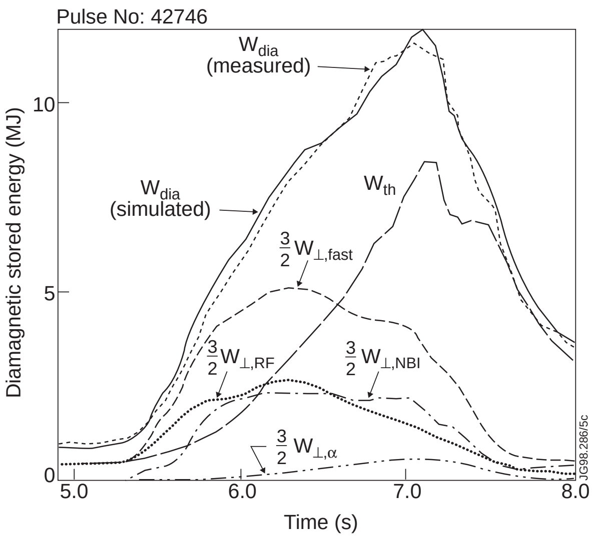

Fig. 3: TRANSP modelling for DT pulse B, compared with measured diamagnetic energy (W_{dia}). Quantities: W_{th}; thermal energy. Perpendicular energies: $W_{\perp,RF}$; from RF fast ions, $W_{\perp, NBI}$; from NBI fast ions and $W_{\perp,\alpha}$; from fusion α-particles.

$p(0) \approx 4.4 \times 10^5$ Pa. In DT pulse B the fusion power generated was 8.2 MW in the H-mode phase (Fig. 2) with ~50% from themonuclear reactions. In the critical time window (5.5 - 6.5 s) when the ITB is born, TRANSP simulation shows the diamagnetic energy (Fig. 3) is dominated by fast ions.

THE INTERNAL TRANSPORT BARRIER

Up to the time of the H-mode, the radii of the ITB footpoints of n_e, T_i (Fig. 4), ion thermal diffusivity, χ_i and angular momentum diffusivity, χ_ϕ correlate with the computed q=2 surface. The ion thermal diffusivity, profiles from TRANSP are compared with the standard neo-classical values in Fig. 5 (no FLR corrections included). With large $T_i(0)$ and low poloidal field, ion banana widths can be comparable with typical length scales making error bars large in the core - the comparison becomes increasingly uncertain as the centre is approached. Nevertheless, χ_i decreases by typically a factor of 10 within the ITB for both DD and DT cases reaching a level close to the standard neo-classical one at $\rho \sim 0.25$.

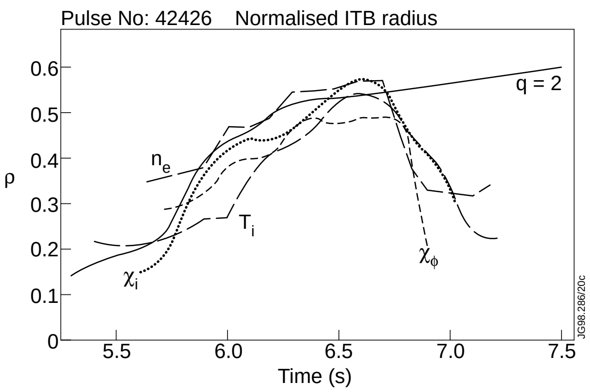

Fig. 4: ITB footpoint radii for a 3.8 T DD pulse, of: T_i; ion temperature; χ_i: ion thermal diffusivity; χ_ϕ : momentum diffusivity, and n_e: electron density compared with the q=2 surface.

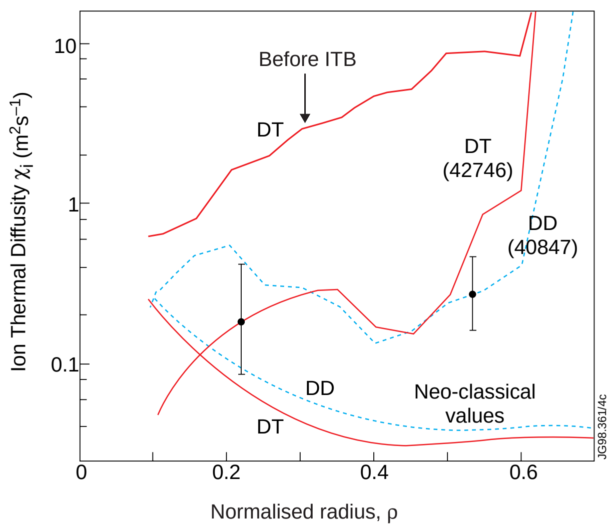

Fig. 5: Comparison of χ_i from TRANSP analysis for the DT pulse A and a similar DD pulse (No. 40847) at time 1 s after applying the main heating. The pre-ITB profile is shown for the DT case

QUASI STEADY-STATE CONDITIONS (DOUBLE BARRIER MODE)

In a conventional H-mode, pressure profile broadening prevents core peaking whilst ELMs limit the pressure gradient and the current at the edge. By combining an ELMy-edge H-mode with an OS core, higher fusion yield, higher H-factors and higher fusion gain Q quasi-steady-state plasmas with confinement significantly above the conventional quasi-steady-state sawtoothing ELMy H-mode have been achieved (Fig. 6). Further optimisation of this double barrier mode has led to improved confinement maintained with $H^{ITER\text{-}89\text{-}P} \approx 2$ for 4 energy replacement times [2].

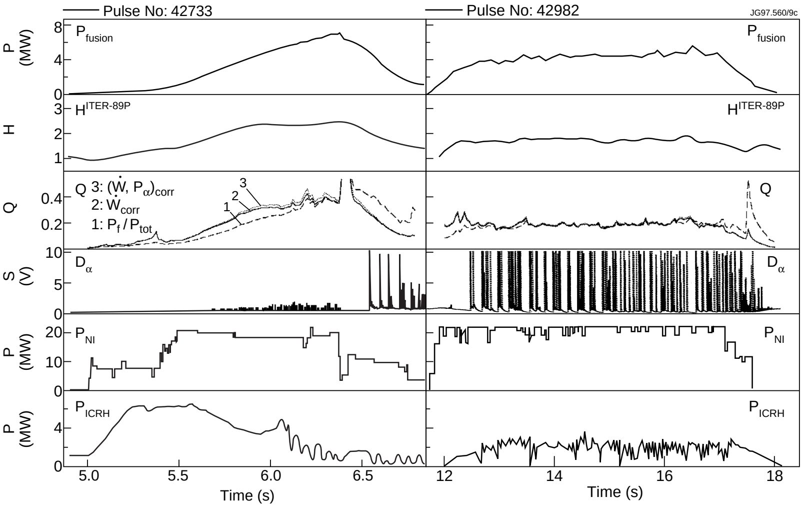

Fig. 6: Comparison of an OS DT plasma with an ELMy H-mode edge (pulse No. 42733) with a standard sawtoothing ELMy H-mode DT plasma (pulse No. 42982).

ICRH CORE ION HEATING

A TRANSP Fokker-Planck RF description was used to model DD pulse A, including the RF power absorbed by NBI D ions at second harmonic resonance, $\omega = 2\omega_{cD}$ (Fig. 7). Central ICRF heating with $\pi/2$ phasing and frequency f = 51.2 MHz ($\omega = \omega_{cH} = 2\omega_{cD}$) was applied. With the formation of an ITB and increase of NBI D ion density, the central D ion pressure increased to a level where $2\omega_{cD}$ damping in the hot core became significant [3]. Of the RF power coupled to the D, most went to the NBI ions. The RF interaction increased the average energy of the NBI D ions, $<E_{NBI}>$, from ≈ 80 keV to ≈ 110 keV in the core, an amount insufficiently large to produce a strong D tail. $<E_{NBI}>$ lies significantly below the critical energy, $E_{crit}(0)$ ~ 190 keV; the ratio of NBI ion to electron heating power is not strongly affected by the RF interaction.

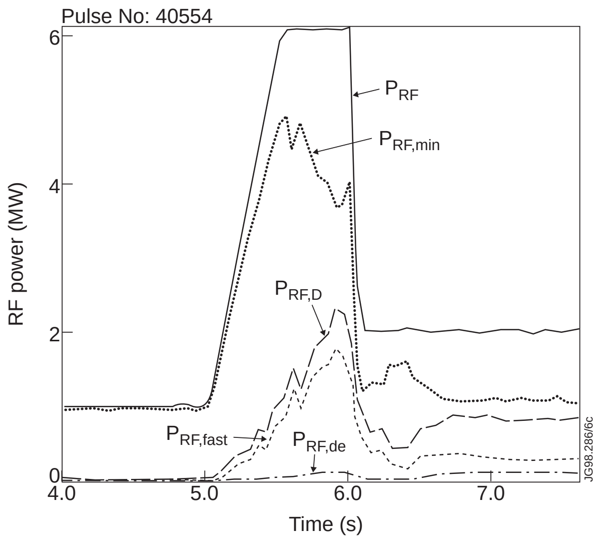

Fig. 7: RF power absorption for DD pulse A. Total coupled RF power (P_{RF}). Power absorbed by: minority H ($P_{RF,min}$), NBI D ($P_{RF, fast}$), NBI and thermal D ions ($P_{RF, D}$) and thermal electrons ($P_{RF, de}$).

CONCLUSIONS

ITBs have been observed for the first time in JET in tokamak plasmas fuelled with DT ions with parameters: $T_i(0) \sim 40$ keV, $\nabla T_i \sim 150$ keV m^{-1} and $\nabla p \sim 10^6$ Pa m^{-1} giving a fusion triple product $n_i T_i \tau_E = 1.10^{21}$ m^{-3} keV s and fusion powers of 7.2 MW with an L-mode edge, and up to 8.2 MW in the H-mode [1]. Although the techniques previously developed with DD plasmas had to be modified to achieve an ITB with DT, the heating power and current density profile required was similar. Although triggering of ITBs with DT has now been optimised, optimisation of the high power phase has not yet been completed owing to limitations on neutron budget. Further DT optimisations include: the use of current profile control and the increase of plasma density. At the time of formation of the ITB, energetic ICRH and NBI ions are the main plasma energy components. The ITB subsequently grows in a region close to the location of the q=2 surface whilst the thermal stored energy increases. By superposing an ITB with an ELMy H-mode, quasi steady-state conditions with high fusion yield have been achieved ($H^{ITER-89-P} \approx 2$ for four energy confinement times). With the birth of the ITB, transport analysis shows that the ion thermal diffusivity is reduced significantly, reacing levels close to the standard neo-classical level in both DD and DT plasmas in the core region, at $\rho \sim 0.25$. ICRH core ion heating plays an important role in maintaining peaked pressure profiles.

REFERENCES

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