TOWARDS STEADY-STATE TOKAMAK OPERATION WITH DOUBLE TRANSPORT BARRIERS

The JET Team[1]
(presented by F.X. Söldner)

JET Joint Undertaking,
Abingdon, Oxfordshire,
United Kingdom.

Abstract

Internal Transport Barriers characteristic for the Optimised Shear regime and an edge transport barrier of an ELMy H-mode regime have been superposed in the Double Barrier mode. In DT discharges the Double Barrier mode has resulted in 50% higher fusion power output and a factor 2 higher fusion gain Q than in conventional sawtoothing steady-state ELMy H-mode plasmas. Steady-state conditions in temperature and density profiles have been approached in Double Barrier discharges in deuterium. The Double Barrier mode has been routinely established in the new Gas Box divertor configuration on JET. Off-axis LHCD has been used for current profile control during the high performance phase. In preparation of a new DTE2 campaign on JET the potential of the Double Barrier mode for sustained high fusion performance has been explored in modelling studies. Steady-state operation on ITER has been studied in transport code modelling for Advanced Tokamak scenarios in the Double Barrier mode.

1. DT EXPERIMENTS WITH DOUBLE TRANSPORT BARRIERS ON JET

Double Barrier (DB) modes with an Internal Transport Barrier (ITB) and a superposed edge barrier in ELMy H-mode have been readily produced with the Optimised Shear scenario in DT discharges on JET during the DTE1 campaign. The ELMy H-mode edge prevents excessive pressure peaking and improves MHD stability. ITB´s with the largest pressure gradient and high fusion power have been obtained transiently with L-mode or ELM-free H-mode edge [1]. In the Double Barrier mode the rate of rise in neutron rate is smaller and flat-top conditions are attained later. Neutron economies of DTE1 therefore have necessitated a limitation of the discharge duration. Density and temperature profiles, however, still approach stationary conditions. Fig.1 shows a Double Barrier mode in DT attaining 6.8 MW fusion power output and an H-factor $H^{ITER\ 89\text{-}P} = 2.3$ before the heating power from NBI and ICRH is ramped down. The fusion gain with Q = 0.4 is a factor 2 higher and the triple product with $n_i(0)T_i(0)\tau_E = 4.4\text{x}10^{20}\text{m}^{-3}$keVs a factor 2.5 higher than in the best steady-state DT discharge in conventional sawtoothing ELMy H-mode. The ELMs are an order of magnitude smaller in the Optimised Shear Double Barrier mode and give the prospect of a strong reduction of the critical peak heat load on the divertor plates in reactor conditions.

The ion heat conductivity falls to neo-classical levels in the core region of Double Barrier mode plasmas after the confinement bifurcation. The improved confinement region expands gradually outwards. The ELMy H-mode provides an additional reduction in the peripheral heat conductivity by about a factor 3. The improved core is maintained after the edge H-mode transition. The radial profile of the ion heat conductivity in this Double Barrier state is well reproduced in transport code modelling by introducing a dependence on magnetic and poloidal rotational shear into the anomalous term [2]. Experimental and modelled profiles are compared in Fig. 2 for the discharge shown in Fig. 1. The electron heat conductivity is also reduced across the whole plasma cross section but less than the ion heat conductivity. Ion and electron temperature profiles peak strongly inside the Internal Transport Barrier in the Double Barrier mode. The density profiles, however, develop similarly in Double Barrier and conventional ELMy H-mode. This decoupling between strong temperature and moderate density peaking has been consistently observed in Double Barrier modes in deuterium and DT. Detailed particle transport studies have shown that impurity accumulation is avoided in these conditions established in the Double Barrier mode.

[1] See Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L. Watkins)

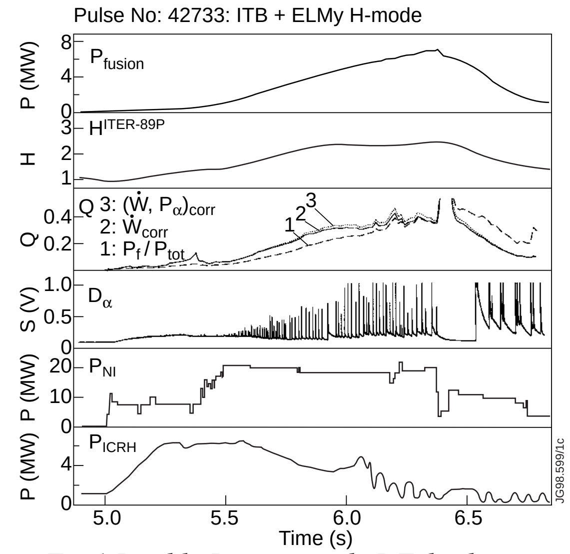

Fig.1 Double Barrier mode DT discharge.

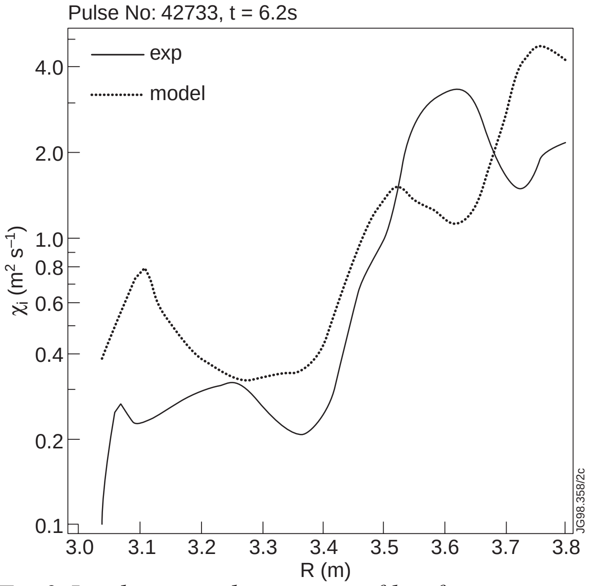

Fig.2 Ion heat conductivity profiles from experiment and model calculations.

2. APPROACH TO STEADY-STATE CONDITIONS

Double Barrier mode discharges have been run for longer durations in deuterium plasmas with restrictions on neutron production being less severe. High performance has been maintained in this case for up to four energy confinement times until the end of the high power heating phase with a neutron rate up to $S_n = 3.3 \times 10^{16} s^{-1}$, a beta $\beta_N \approx 1.8$ and an H-factor $H^{ITER\ 89\text{-}P} \approx 2$. Time derivatives for profile parameters diminish after ~1.5 s and density and temperature profiles approach steady-state conditions.

The Internal Transport Barriers, as determined from electron and ion temperature profiles, follow the q-profile evolution and relaxation and settle close to q=2 in the flat-top phase (Fig. 3). Improved confinement is established in a wide region inside r/a ≈ 0.65. The q-profile evolves only slowly at the end of the high power heating phase. In presence of electron and ion temperature peaking, no accumulation of injected high-Z impurities has been found and the carbon concentration even decreases in the core during the high performance Double Barrier phase.

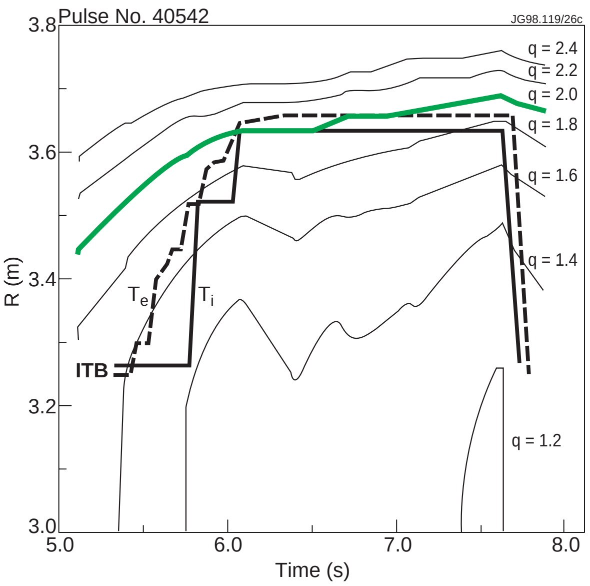

Fig.3 Time evolution of Internal Transport Barrier position and q profile contours.

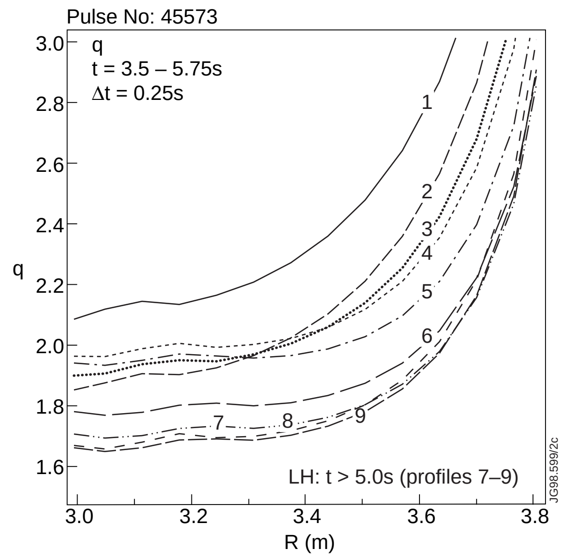

Fig.4 q-profile evolution during ITB formation and expansion and freezing during LHCD.

3. DOUBLE BARRIER MODE PLASMAS IN THE NEW GAS BOX DIVERTOR

Double Barrier mode plasmas have been reproducibly established as routine scenario in the new Gas Box configuration on JET described in [3]. Parameter sets with I_p=2.5 MA/B_t=2.5 T and I_p=3.5 MA/ B_t=3.4 T have been studied. High performance with beta values up to $ß_N \approx 2.2$ and an H-factor $H^{ITER\ 89\text{-}P} \leq 2.5$ has been achieved with a wide core region of low magnetic shear and q_{min} slightly below 2. The formation of the Internal Transport Barrier depends critically on the q-profile at the start of high power heating as found previously [4]. Tight control of the q-profile during the whole Double Barrier phase is required to avoid degradation related to the location of rational q surfaces with q=1.5, 2, 3. Shrinking of the region of low magnetic shear after the plasma current ramp-up phase may limit the expansion of the ITB. A subsequent contraction of the ITB can lead to a roll-over of neutron rate and beta. ELM amplitude and period are slowly growing in this phase. Ensuing large ELMs may finally destroy the Internal Transport Barrier. With off-axis LHCD the q-profile evolution during the high performance phase can be slowed down as seen from Fig. 4. Flat-top phases for durations of order an energy confinement time have been maintained so far. Stationary phases could also be obtained with a radiative mantle by high-Z impurity seeding [5]. Further optimisation of the scenario will be undertaken to secure the transition to sustainable steady-state conditions.

4. TRANSPORT CODE MODELLING OF DOUBLE BARRIER SCENARIOS ON JET

The potential of the Double Barrier mode scenario for high performance DT experiments on JET has been explored with JETTO transport code calculations combined with MHD stability analysis. The mixed Bohm/gyro-Bohm model with a shear dependent multiplier for the Bohm term used in these calculations has been validated on JET Optimised Shear data [2]. Off-axis Lower Hybrid current drive has been found most efficient to establish and maintain a wide core region of slightly negative shear over 70% of the plasma radius, as shown in Fig. 5. This decreases the sensitivity of the barrier location to variations in q- and pressure profile. Without LHCD the q-profile remains monotonic. In these conditions the beta limit is determined by ballooning modes in regions of high pressure in a positive magnetic shear region. The beta limit is increased from $ß_N$=2.4 to 3.0 with P_{LH}=3.5 MW by suppressing ballooning modes completely.

Fusion power in the range 20-30 MW is predicted for I_p = 3.9 MA, B_t = 3.4 T discharges as seen in Fig. 6. Flat-top conditions are obtained in this case after ~5 s into high power heating. Uncertainties in the particle transport model due to limited experimental data sets for validation leave a wide margin in the predictions. With the lowest diffusion coefficients compatible with existing experiments a fusion gain in excess of Q=1 is obtained. The fusion power density in this case exceeds the external input power density over more than half the plasma cross section.

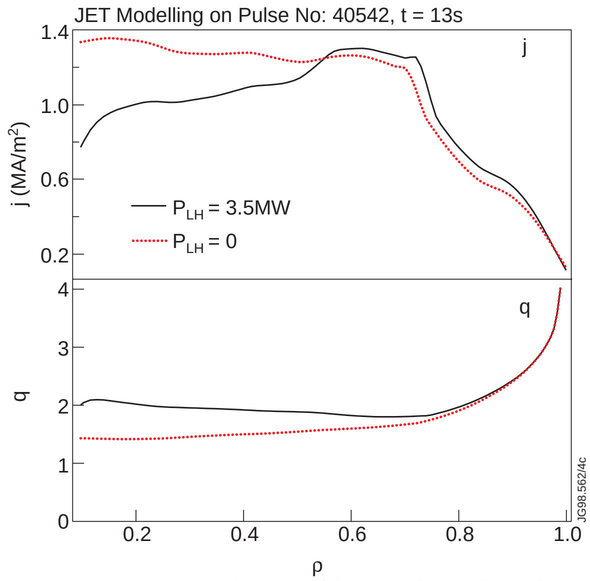

Fig. 5 Current and q-profiles with and without profile control by off-axis LHCD.

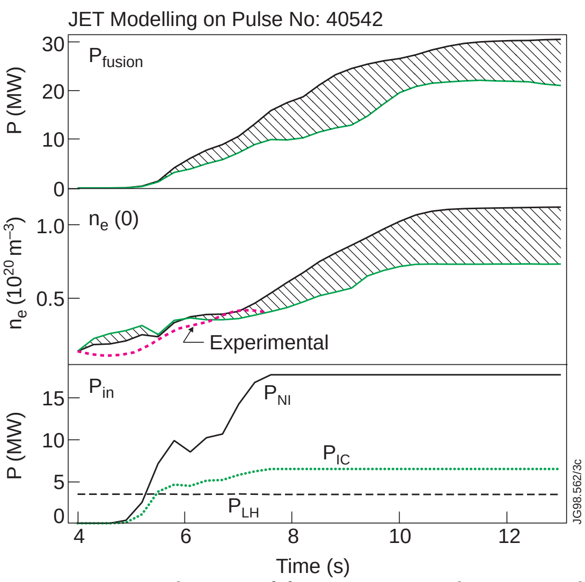

Fig.6 Time evolution of fusion power, density and input powers in model calculations for JET

5. ADVANCED TOKAMAK SCENARIOS IN DOUBLE BARRIER MODE ON ITER

Steady-state operation of ITER with profile control in Double Barrier mode has been studied with JETTO transport code calculations using the transport model developed on JET Optimised Shear discharges. Off-axis Lower Hybrid current drive provides negative shear in a wide core region. This results in turbulence stabilisation and a wide Internal Transport Barrier.

The wide pressure gradient zone with peaked profiles leads to very large bootstrap currents exceeding even slightly the plasma current. This allows full non-inductive current drive with additional RF current drive. The external RF current drive is also required to correct for misalignments in the bootstrap current profile.

A fusion power of 1.3 GW is produced in steady state in a Double Barrier scenario on ITER with 13 MA plasma current applying an LH driven current of I_{LH}=3.9 MA for current profile control.

6. SUMMARY

Improved core confinement and sustainable plasma edge conditions could be combined on JET in the Double Barrier mode by the superposition of an Internal Transport Barrier of the Optimised Shear regime and an edge transport barrier of an ELMy H-mode regime.

In DT discharges the Double Barrier mode has achieved a fusion gain of Q=0.4 and a triple product of $n_i(0)T_i(0)\tau_E = 4.4\text{x}10^{20}\text{m}^{-3}$ keVs, compared with Q=0.2 and $n_i(0)T_i(0)\tau_E = 1.9\ \text{x}10^{20}\text{m}^{-3}$ keVs in the conventional sawtoothing ELMy H-mode. The ELM amplitude is an order of magnitude smaller in the Double Barrier mode. Steady-state with improved confinement at $H^{ITER\text{-}89} \approx 2$ for four energy confinement times has been approached in the Double Barrier mode in deuterium.

Transport analysis of Double Barrier mode discharges shows a sustained reduction of the heat conductivity across the whole plasma cross section, with the ions in the core at neo-classical level. Ion and electron temperature profiles are peaked in the Double Barrier mode while the density profile is broad and similar in shape to the conventional ELMy H-mode profile. This indicates a favourable combination of improved energy confinement and moderate particle confinement improvement, thereby reducing the risk of impurity accumulation.

Recent experiments in the new Gas Box divertor configuration have reliably reproduced the Double Barrier mode. Off-axis LHCD helps to freeze in the current profile during the high performance phase.

Self-consistent scenario studies with transport and MHD stability codes validated on JET experimental data predict further performance improvement by expanding the internal transport barrier with off-axis Lower Hybrid current profile control. Fusion power output in the range 20-30 MW is predicted for DT operation in the Double Barrier mode.

Steady-state conditions in Advanced Tokamak operation in the Double Barrier mode are predicted in transport code calculations for ITER. In a 13 MA discharge, a fusion power output of 1.3 GW can be obtained, using off-axis current profile control with LHCD to expand and control the location of the internal transport barrier.

REFERENCES

[1] GORMEZANO, C. , et al., Phys. Rev. Lett. 80, 5544 (1998).
[2] THE JET TEAM (presented by V.V. Parail), this conference.
[3] THE JET TEAM (presented by M.L. Watkins), this conference.
[4] SÖLDNER F.X., JET TEAM, Plasma Physics and Contr. Fusion 39, B353 (1997).
[5] THE JET TEAM (presented by C. Gormezano), this conference.