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Optimised Shear Scenario Development on JET towards Steady-State

F.X. Söldner, B. Alper, Yu.F. Baranov, A. Bickley, D. Borba[a], C.D. Challis, G.Conway, G.A.Cottrell, M. de Benedetti, N. Deliyanakis, C. Gormezano, C.Gowers, C.M. Greenfield[b], N.C. Hawkes[c], T.C. Hender[c], G.T.A. Huysmans[d], E.Joffrin[d], T.T.C. Jones, P.T. Lang[e], X. Litaudon[d], P.J.Lomas, A. Maas, J. Mailloux, M.J. Mantsinen[f], F. Nave[a], V.V.Parail, F. Rimini, B. Schunke[d], A.C.C. Sips, P. Smeulders, M.F. Stamp, E.J.Strait[b], T.J.J. Tala[f], M. von Hellermann, D.J. Ward[c], K.-D. Zastrow

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK

[a] *Assoçiao EURATOM/IST, Lisboa, Portugal*
[b] *General Atomics, San Diego, USA*
[c] *EURATOM Association/UKAEA Culham, United Kingdom*
[d] *EURATOM Association/CEA Cadarache, France*
[e] *EURATOM Association/IPP Garching, Germany*
[f] *EURATOM Association/TEKES, Finland*

Introduction

Optimised Shear plasmas with an Internal Transport Barrier (ITB) and an extended L-mode edge phase have achieved the highest transient performance in deuterium operation on JET [1, 2]. Strong ITBs have also been established in high fusion power DT experiments [3]. Stationary conditions at moderate beta values could be approached by combining an ITB with an ELMy H-mode edge transport barrier (ETB) in the Double Barrier mode, providing improved core confinement and stability with sustainable edge conditions of low pressure and small ELMs [4]. Limitations to further performance enhancements and extensions of the duration of high performance operation have been imposed by MHD modes and the maximum core density attainable with Neutral Beam Injection (NBI) fuelling alone [5, 6]. The recent campaign in the JET gas box divertor configuration has focused on the development of the Double Barrier mode towards high performance steady-state operation with the control of pressure and current profiles, plasma edge conditions and fuelling.

Pressure Profile Control

Excessive pressure peaking in plasmas with an ITB and L-mode edge can trigger kink modes leading to disruptions already at moderate beta values $ß_N \approx 1.5$ [5]. Broadening of the pressure profile by combining an ITB with an ELMy H-mode edge has allowed to steer discharges along the marginal stability boundary, with $ß_N$ approaching 2 [2]. The pressure profile has been controlled by varying the composition of heating power input from Ion Cyclotron Resonance Heating (ICRH) with a narrow deposition profile and NBI with a broader deposition. The ITB is preferentially formed with a combination of maximum available ICRH power and moderate NBI power. With increasing ß, the ICRH power is gradually reduced and NBI is stepped up to full power. Extended duration at high performance up to $ß_N = 2.5$ could then be achieved in discharges with $I_p \approx 2.5$ MA, $B_t \approx 2.5$ T. This scheme of pressure profile control, however, limits the maximum heating power available. It also provides only a transient stabilisation of MHD. Complementary current profile control is required on the way to full steady-state operation.

Plasma Edge Control

Saturation and roll-over of performance are often linked to the growth of local MHD modes in the ITB region. A typical sequence of events is shown in Fig. 1. After 1.5 s Double Barrier mode phase, an MHD mode with a multiple of narrow frequency bands in the range 10-80 kHz develops (Fig. 1/lower part). The mode has a very localised helical m=2/n=1 structure [7]. The electron temperature starts falling first at the outer foot of the steepest gradient region within the ITB (Fig. 1/upper part, R=3.56 m). The drop in T_e propagates inwards while the edge temperatures outside the ITB rise. This leads to a gradual rise of the ELM amplitude and then a transition to ELM-free. The further rise of the edge temperatures is interrupted by a large ELM which transgresses far inside and starts a gradual degradation of the entire ITB. Re-heating of the edge is terminated by another ELM which leads to the irrecoverable destruction of the ITB and an ensuing transition to conventional ELMy H-mode.

Stabilisation of the plasma edge against excursions in power loss from the core due to MHD induced oscillations of the ITB could be achieved with radiation cooling by impurity seeding. The best results have been obtained with argon dosing. The ELMs could then be stabilised at constant amplitude for several energy confinement times. The discharge with the best overall performance of the Optimised Shear scenario in the JET gas box divertor configuration obtained with this scheme is shown in Fig. 2. The neutron yield corresponds in an equivalent DT discharge to a fusion power of 10 MW with a gain of Q = 0.4. Wide ITBs, with the ion heat conductivity in the core region reduced to the neo-classical level have been maintained for a time scale on which temperature and density profiles become stationary. Low reactor compatible ratios of particle to energy confinement times of $\tau_p/\tau_E \approx 3$ have been obtained in the high confinement core region.

The high performance phase is terminated by large ELMs after short ELM-free periods, without signs of preceding MHD activity. A gradual collapse of the ITB leading to an increase of the edge pressure pedestal prior to the giant ELM suggests that in this case the turbulence stabilisation breaks down due to a lack of heating power which would maintain a sufficiently large pressure gradient. This soft termination of the ITB phase without obvious MHD activity has been observed mostly in the high current / high field discharges which also require higher heating power to triger the formation of an ITB. The extent of radiative edge control is also limited by a slow argon penetration into the core. The central dilution parameter $c_d(0) = n_d(0)/n_e(0)$ is falling from 90% at the beginning of the ITB phase to 70% at termination, as seen from Fig. 2.

Current Profile Control

Current profile control with LHCD has been demonstrated during the low ß current ramp-up phase. Short LHCD pulses in the plasma start-up phase render the later ITB formation more reliable and slow down the current diffusion into the core plasma by strong early electron heating [2]. Extended LHCD pulses during the current ramp-up phase broaden the current profile, first still due to continued central heating and in a later stage at higher density and plasma current due to off-axis current drive [8]. Early start of NBI during LHCD enhances strongly the current profile broadening (Fig. 3). The wide variety of current profiles available helps to clarify the mechanisms responsible for forming and maintaining an ITB. The loss of coupling due to reduced density in the scrape-off layer of a Double Barrier mode plasma has prevented routine LHCD current profile control in the high performance phase [8].

Fuelling Control

Higher fuelling rates than available from NBI alone are required to raise the core density and consequently the global performance. Gas puffing has been found to be deleterious both for the formation and sustainment of an ITB [9]. Pellet injection has allowed to build up strongly peaked density profiles prior to the application of high power heating. But no ITB could be formed in these conditions. Pellet injection during high power heating prevents an ITB formation or destroys an already established ITB. An ITB re-formation after pellet injection into plasmas with an L-mode edge, however, leads to higher core densities and stronger density peaking than in NBI fuelled only discharges (Fig. 4). Development of this technique might allow to increase gradually the density by interleaving pellet injection into L-mode plasmas with Double Barrier mode phases.

Sustained Performance

High performance operation has been extended simultaneously to high H-factors and high beta values (Fig. 5). It could be sustained into phases of stationary temperature and density profiles with $ß_N$ x $H^{ITER\text{-}89P} \approx 4.5$ for 12 energy confinement times and $ß_N \approx 2.5$ and $H^{ITER\text{-}89P} \approx 3$ for three energy confinement times at $I_p = 2.5$ MA. At $I_p = 3.4$ MA, $B_t = 3.4$ T, equivalent values of $P_{fusion} = 10$ MW and $Q_{DT} = 0.4$ have been sustained for $t_{flat}/\tau_E \approx 3$. Level and duration of high performance, however, are still limited by the growth of MHD instabilities in the ITB zone. The further development of Advanced Tokamak scenarios towards viable steady-state reactor schemes requires in particular the demonstration of fuelling techniques capable to attain the density limit whilst preserving an ITB and off-axis current profile control to overcome the MHD limitations in conditions of sustained high performance.

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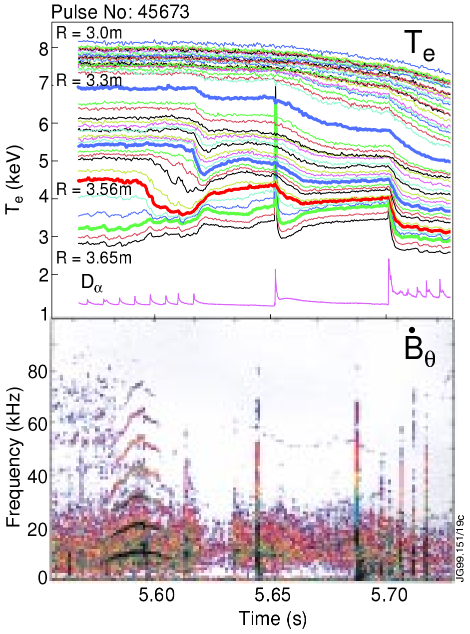

FIG.1: Electron temperature, D_α emission and spectrum of magnetic signals during the growth of an ITB localised MHD mode.

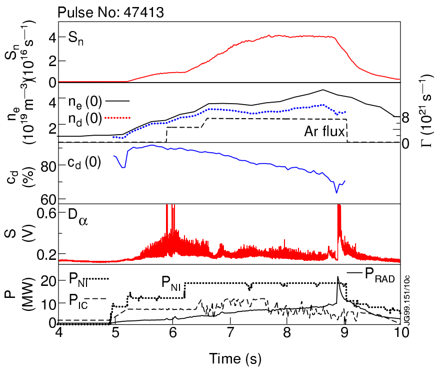

FIG.2: Sustained high performance ITB discharge with Argon seeding. $I_p = 3.4$ MA, $B_t = 3.4$ T.

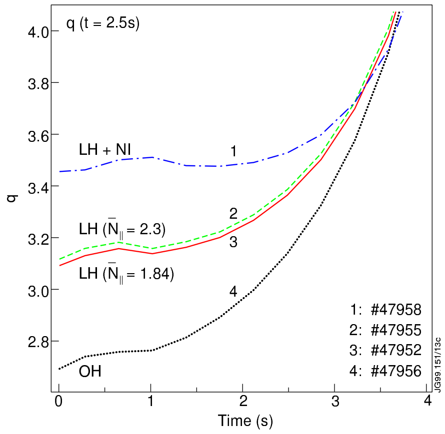

FIG.3: q-profiles with LHCD and NBI. $B_t = 2.6$ T.

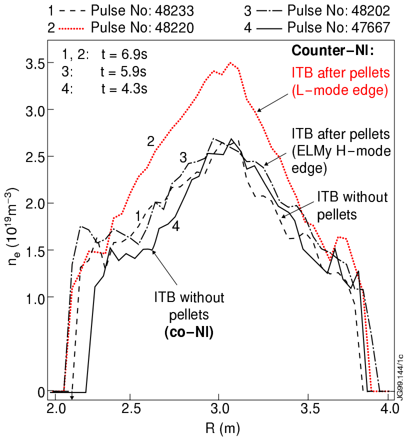

FIG.4: Density profiles in gas and pellet fuelled ITB discharges with co and counter-NB. $P_{NI} = 10.3$ MW, $P_{ICRH} = 4.7$ MW.

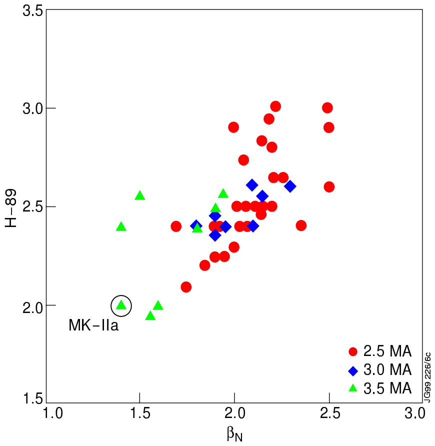

FIG.5: H-factor and normalised beta values in sustained high performance ITB discharges. I_p = 2.5-3.5 MA, B_t = 2.5-3.4 T.

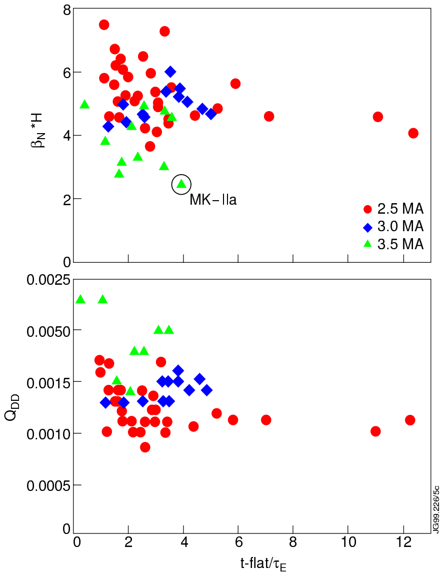

FIG.6: Performance product β_N x H and fusion gain Q in sustained high performance Optimised Shear discharges on JET. I_p = 2.5-3.5 MA, B_t = 2.5-3.4 T.