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High Performance with Modified Shear in JET D–D and D–T Plasmas

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ABSTRACT

The observation of Internal Transport Barriers (ITBs) in which ion thermal diffusivity is reduced to a neo-classical level and the electron thermal diffusivity is substantially reduced has been made in JET with the optimised shear scenario with the MkII divertor both in D-D and in D-T. Central ion temperatures of 40keV and plasma pressure gradient of 10^6 Pa/m were observed in D-T leading to a fusion triple product $n_i T_i \tau_E = 1\times10^{21}$ m-^{3} keVs and 8.2MW of fusion power. ITBs have also been produced in the new Gas Box divertor configuration with a similar behaviour. With the new divertor an L-mode edge has only been produced using edge radiation cooling. For the first time, ITBs have been triggered by radiating about 40% of the power with a krypton puff. A tentative scaling of the power needed to trigger an ITB with magnetic field is indicated.

1. INTRODUCTION

Development of operational regimes with improved confinement allowing operation of a tokamak reactor at relatively low plasma current and high bootstrap current fraction is important in order to improve the present reactor concept based on ELMy H-modes. Transport in the plasma core has been substantially reduced, and therefore confinement improved, in plasmas where the plasma current profile is modified as observed in JET and in other experiments [2,3,4,5]. In particular, by applying additional heating during the current ramp-up phase in order to slow down the diffusion of the current, ion transport can be reduced to neo-classical level values within a region called Internal Transport Barrier (ITB). The understanding of the underlying physics mechanism is progressing [6]. ITBs are likely to be triggered by a combination of ExB shear flow and low or negative magnetic shear which can stabilise toroidal drift instabilities, in particular ion temperature gradient instabilities. Electron ITBs have been produced in JET for several seconds using Lower Hybrid Current Drive (LHCD) where central T_e goes up to 10keV with 2MW of LHCD power. These results have been reported previously [7] and will not be discussed here. Simultaneous Ion and Electron ITBs have been achieved [8] and have produced the highest fusion yield in D-D with a combination of Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH). Results obtained during the recent D-T campaign will be discussed as well as ITBs recently produced with the new Gas Box divertor configuration. Quasi steady-state ITBs in JET are discussed in a companion paper [9].

2. OPTIMISED SHEAR IN D-T PLASMAS

Scenarios developed for D-D plasmas [10] have been modified mainly to take into account the lower power threshold for L to H-mode transitions in D-T plasmas. An early appearance of large ELMs has prevented the formation of ITBs. Also, the formation of an ITB in JET is very sensitive to target current profile. The additional heating power has to be sufficiently large and a q=2 magnetic surface has to be present in the plasma in order that an ITB is triggered [11]. In D-T target q profiles were slightly different to those in D-D. By tuning power waveforms and timing of the high power phase, ITBs have been triggered at the same power level in D-T as in D-D, both at a magnetic field of 3.4T and of 3.85T. A typical optimised shear scenario is shown in fig.1. Ion temperature and density profiles are shown in fig.2. Main results are given in Table 1.

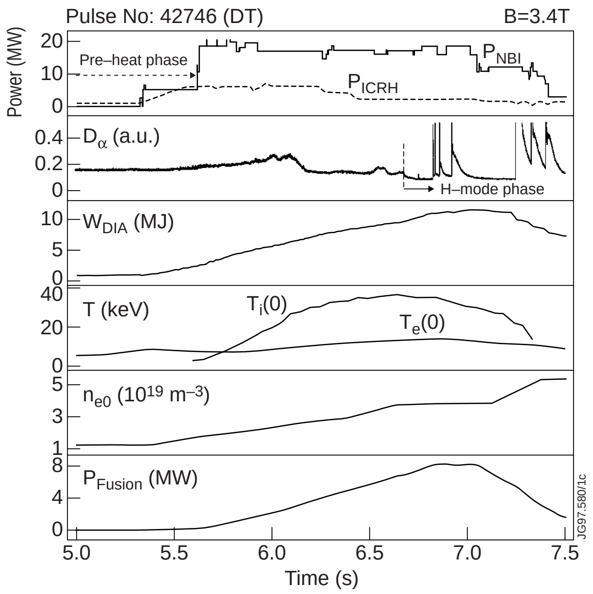

Fig.1: Time evolution of typical signals for pulse 42746 in D-T at B_t=3.4T. I_p is increased at 0.4MA/s up to 3.24MA at 7s, f_{ICRH} = 51.3MHz, Z_{eff} = 1.4.

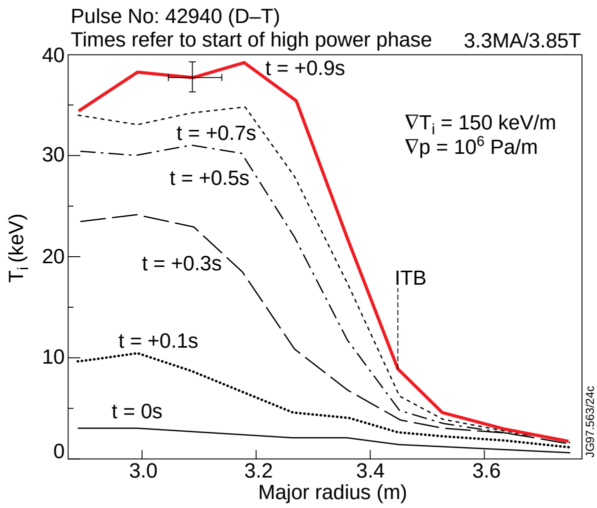

Fig.2: Radial ion temperature profiles from charge exchange spectroscopy for pulse 42940 (B_t = 3.85T, I_p up to 3.4MA). An ITB is triggered 0.3s after the start of the high power phase.

Table 1. Parameters of interest for DT pulses 42746 (at 6.82s) and 42940 (at 6.25s).

	42746	42940			42746	42940	
I_p	3.2	3.3	MA	$n_D(0)+n_T(0)$	3.2	3.4	$10^{19}m^{-3}$
B_T	3.45	3.8	T	$T_i(0)$	33	38	keV
q_{95}	3.9	3.8		$T_e(0)$	13	12.6	keV
P_{NB}	18	20	MW	W_{dia}	11	10	MJ
P_{RF}	2.0	3.0	MW	dW_{dia}/dt	9	8.4	MW
P_{OH}	0.2	0.3	MW	$(n_D(0)+n_T(0)\tau_E T_i(0)$	11±20%	10±20%	$10^{20}m^{-3}s$ keV
P_a	1.6	1.5	MW	$(n_D(0)+n_T(0)/n_e(0)$	0.82	0.8	
P_{SH}	2.6	2.9	MW	$n_T(0)/(n_D(0)+n_T(0))$	0.34	0.34	TRANSP
P_{CX}	0.7	0.5	MW	$n_T/(n_C+n_T)$ at edge	0.14	0.2	from recycling light
τ_E	1.1	0.8	s	Neutron rate	2.9±10%	2.6±10%	$10^{19}s^{-1}$
$n_e(0)$	3.9	4.4	$10^{19}m^{-3}$	Fusion Power	8.2±10%	7.3±10%	MW

It is to be noted that central densities in D-T plasmas are lower than in D-D. This is mainly due to a lower fuelling rate as a consequence of the need to maximise the tritium to deuterium fuelling ratio. Tritium being fuelled by the high energy NB injector (151keV) and deuterium by the low energy NB injector (76keV), it was necessary to maximise the proportion of tritium beams and the average energy of injection was therefore higher in D-T than in D-D plasmas and the fuelling lower for a similar heating power. As a consequence of lower plasma density and high NB energy, the resulting central ion temperature is higher in D-T than in D-D.

The ICRH power has been estimated to be very well coupled to the ions during the high power phase, the frequency used corresponding not only to minority hydrogen and second harmonic deuterium [12] but also to third harmonic tritium. Step down of ICRH was necessary to avoid excessive peaking of the central pressure and a possible disruption.

A TRANSP analysis shows that, within an ITB, the ion heat transport coefficients are substantially reduced and are close to neo-classical levels in the plasma centre, just as they are in D-D [11]. They are also lower at 3.8T than at 3.4T as shown by the higher temperature. Electron transport coefficients are also reduced by a factor 5-10 in a similar way to D-D plasmas. It has been shown [8] that electron temperature, ion temperature and electron density barriers are formed at the same time and radial location. Their time dependence is also closely related.

MHD stability analysis has indicated that the domain of stability is limited by global n=1 ideal pressure driven kink modes. In D-D, real time power control has allowed an operational path close to MHD boundary limits to be followed and thus the optimisation of the neutron yield. The limited amount of available 14MeV neutrons has prevented the performance of a similar optimisation in the last JET D-T campaign.

3. INTERNAL TRANSPORT BARRIERS IN THE GAS BOX DIVERTOR CONFIGURATION

The new Gas Box (GB) divertor is described in [1] and initial experiments have started using a scenario similar to the one used during the preceding campaign: same current ramp-up, similar target q profile, similar target density. So far, in contrast to the MkII divertor, small ELMs cannot be avoided and double barrier plasmas have been produced (see also [7]).

Optimised shear scenarios producing ITBs have been developed at a magnetic field of 2.5T and 3.4T. The sensitivity of ITBs triggering with the existence of a q=2 magnetic surface has been confirmed. The minimum power (NBI + ICRH) which is required to trigger an ITB as a function of magnetic field is shown in Fig.3. For similar conditions: target density, q profile (target q_o close to 2) and small ELMs at the edge, the power increases about linearly with the magnetic field. It is to be noted that with a good tuning of the q profile and the power waveforms, ITBs have been produced at slightly lower power at 3.4T with an L-mode edge.

One way to restore the L-mode edge is to radiate the power going through the separatrix by injecting a puff of krypton gas as shown in fig.4. When the radiated power reaches 8 to

10MW for a total injected power of up to 22MW, the grassy ELMs disappear and an ITB is formed leading to significant neutron yield and confinement. Note that the power was stepped-down in this pulse and was not sufficient to maintain an ITB when the ELMs reappear. Accumulation of krypton has not yet been assessed, but ion dilution seems to be limited (~10%).

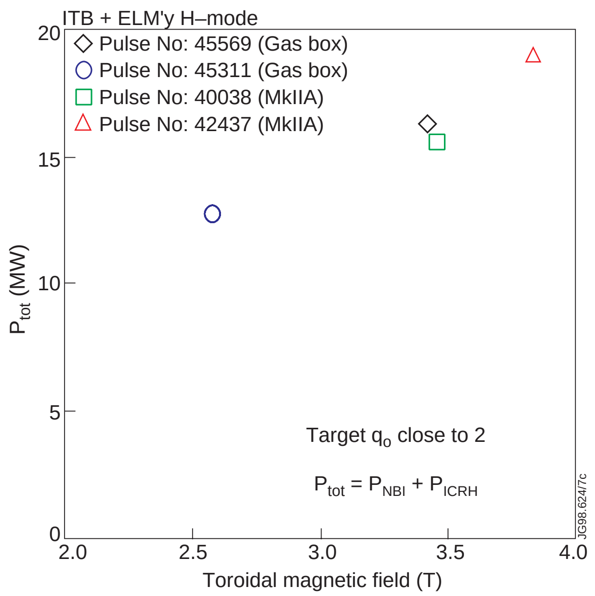

Fig.3: Minimum total power (NBI + ICRH) required to trigger an ITB versus magnetic field. Pulses indicated are representative of pulses where an ITB is produced at low power

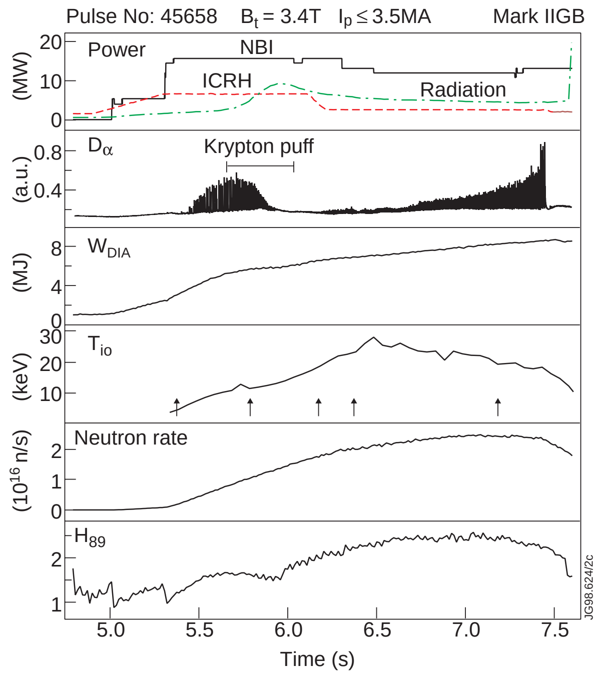

Fig.4: Time evolution of typical signals for pulse 45658 in D-D at B_t= 3.4T. I_p reaches 3.5MA at t = 7s. Krypton is puffed at t = 5.8s for 0.2s.

4. SUMMARY

ITBs have been produced in D-D and in D-T with the MkII and in D-D with the Gas Box divertor configurations. In D-T, ITBs have been produced with similar q profiles and power levels to those in D-D. Reduction in both ion and electron core transport is similar in D-D and in D-T plasmas. Up to 8.2MW of fusion power and $n_i T_i t_E$ of $1.10^{21} m^{-3}$ keVs have been achieved but optimisation has not been done. ITBs have also been produced with the GB divertor with grassy ELMy H-mode edge with a comparable behaviour to that of the MkII divertor. The minimum power required to trigger an ITB seems proportional to the magnetic field. For the first time, ITBs have been produced by radiating about 40% of the power with krypton. Development of these optimised shear scenarios is proceeding.

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