HIGH FUSION PERFORMANCE IN JET PLASMAS WITH HIGHLY NEGATIVE CENTRAL MAGNETIC SHEAR

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1. Introduction

The aim to realise an economical steady-state tokamak power plant has given much impetus to the development of plasma regimes that can generate a region of high energy confinement in the plasma core, called an 'Internal Transport Barrier' (ITB). In these JET experiments the q-profile shape and heating parameters, thought to be key ingredients in the formation of ITBs, have been varied to investigate the effect on plasma performance.

2. *q*-profile variation

Experiments performed on a wide range of tokamak devices show that low or negative magnetic shear ($s=r/q(dq/dr)$) is favourable for the production of ITBs. In JET the most effective method for varying the q-profile shape is the application of Lower Hybrid Current Drive (LHCD) during the initial current ramp up phase of the plasma discharge [1]. Figure 1 shows the typical q-profile shapes obtained four seconds after plasma initiation in cases with and without an LHCD prelude. The plasma current had reached 2MA at this time and was still increasing. The toroidal magnetic field strength was 2.6T. The LHCD started within one second of plasma initiation and continued at an average power of 1.8MW until the time of the q-profile measurements shown in figure 1. At this point the LHCD was switched off and a main heating pulse was applied using various combinations of Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH).

During the LHCD prelude phase and with low power NBI and ICRH heating ITBs can sometimes be seen in the plasma core [2, 3]. Transport barriers of this type, occurring at small plasma radius, are of interest for the investigation of the physics concerning plasma transport processed, but do not significantly affect the global plasma performance. The presence of a q=2 magnetic surface near the half radius of the plasma throughout the main heating phase in the case with no LHCD allows an ITB to be formed in this region if the additional heating power is high enough [4]. ITBs thus generated can have a significant impact on the global plasma performance due to the substantial enclosed plasma volume. The modified q-profile evolution due to an LHCD prelude leads to the arrival of the

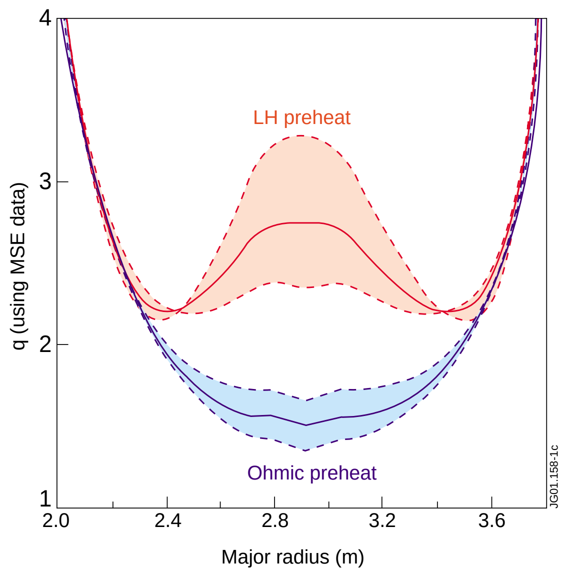

Figure 1. Comparison of q-profiles during the initial current ramp up phase with and without an LHCD prelude. The shaded area indicates the shot to shot reproducibility of these current profiles.

* *see J Paméla et al, Proc. 18th Int. Conf. on Fusion Energy, Sorrento, 2000, IAEA.*

q=2 surface during the main heating pulse, but at a similar plasma radius. In this case an ITB is triggered at roughly the same location as in the Ohmic preheat example, but after a short delay (at t=6s in figure 2). The plasma conditions at the ITB are therefore similar except that the local magnetic shear is much lower in the cases following an LHCD prelude. This technique allows the effect of magnetic shear to be assessed for this class of ITB.

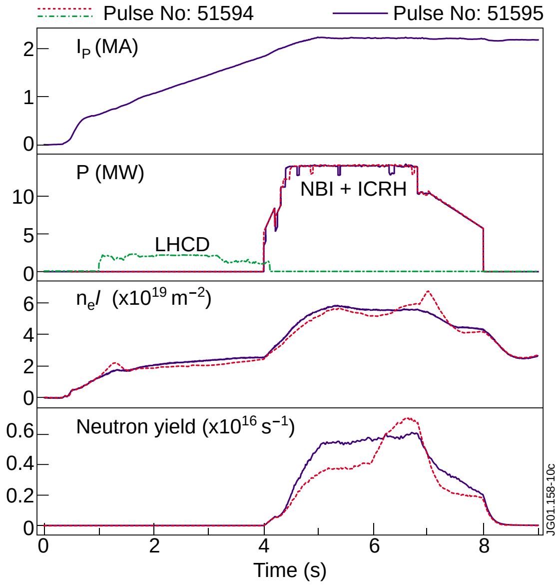

Figure 2. Time evolution of the plasma current, heating power, plasma density and neutron yield for pulses with and without and LHCD prelude.

3. Heating and torque variation

The shear of the plasma flow is also believed to play an important role in the stabilisation of plasma turbulence, leading to the formation of ITBs [5]. The heating power level has been scanned for plasmas with both q-profile shapes illustrated in figure 1 in order to vary the poloidal flow shear. The relative importance of toroidal flow shear has been investigated by varying the applied torque independently of the power. This was done by comparing ICRH dominated heating with cases using mainly NBI. Such a method allows experiments to be performed with a large range of applied torque, but coincidentally changes the power deposition profile, core fuelling and ratio of electron to ion heating. However, the torque applied by NBI can also be varied with very little effect on the heating characteristics by choosing either mainly 'Normal' or 'Tangential' beams for which the ratio of the tangency radius to machine axis is 0.44 and 0.63 respectively.

Figure 3 shows the effect of varying the q-profile and plasma heating on the ITB production associated with the q=2 surface. The steep plasma pressure gradient produced by an ITB can be most clearly resolved on the electron temperature profile due to the use of a heterodyne radiometer measuring electron cyclotron emission from the plasma. ITBs triggered close to the q=2 magnetic surface tended to be 'stronger', as characterised by the normalised inverse gradient scale length ($\rho^*_{Te}=\rho_s/L_{Te}$) [6], after an LHCD prelude. This is reflected in the higher peak fusion yield shown in figure 2. The use of dominant ICRH produced poorer ITBs than mainly NBI heating, regardless of the q-profile shape, and pulses with high applied torque produced the 'strongest' ITBs, although ITBs can still be obtained with LHCD or ICRH alone [2]. These are important observations since the heating in a reactor will be mainly provided by α-particles that dominantly heat electrons without providing core fuelling or torque.

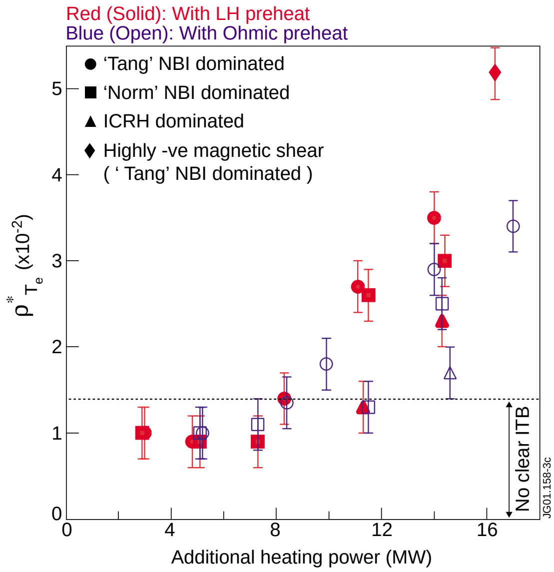

Figure 3. Maximum value of ITB criterion ($\rho^*_{Te}=\rho_s/L_{Te}$) versus power for various heating scenarios. An ITB is deemed clear if $\rho^*_{Te}>1.4\times10^{-2}$.

4. High fusion performance

In previous high fusion performance ITB experiments in JET without an LHCD prelude the power level required to produce a barrier capable of delivering high fusion yield increased with the magnetic field strength. Figure 4 shows the peak neutron yield achieved in deuterium plasmas at B>3.3T during ITB investigations with the MkIIGB divertor configuration. The additional heating power required to obtain the 'strong' ITB responsible for generating the fusion yield above about $2\times10^{16}s^{-1}$ was significantly reduced in experiments performed during 2000 due to the use of an LHCD prelude to provide negative central magnetic shear. This improved ITB accessibility led to the achievement of high transient Q ($\equiv P_{fusion}/P_{in}$) in a regime reminiscent of that previous exploited in JT-60U [7].

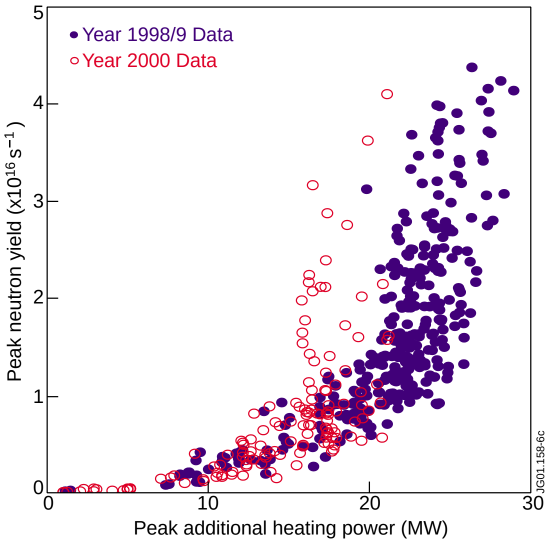

Figure 4. Neutron yield versus additional heating power for plasmas with B≥3.3T. High yield cases were with LH prelude in 2000 and without LH in 1998/9.

A typical example of the q-profile at the start of the main heating pulse in these experiments is shown in figure 5. The current density in the core is small leading to highly negative magnetic shear [8]. With the application of the intense NBI and ICRH a core ITB was promptly observed that did not evolve rapidly or substantially improve the global plasma performance. After a delay of several seconds a 'strong' ITB developed near the half-radius of the plasma in the same way to the LHCD prelude pulse in figure 2.

The 'strong' ITB responsible for this high performance appeared simultaneously on the particle, toroidal momentum, ion and electron heat transport channels. This is illustrated in figure 6, which also shows the location of sharp rises in the measurements of n_e, v_ϕ, T_i and T_e as a function of the onset time. The density measurements were provided by a far infrared interferometer and the rotation and ion temperature data were determined from charge-exchange recombination spectroscopy. The simultaneous rise in all these plasma parameters up to a plasma major radius of 3.48m at t=5.9s indicates the sudden improvement in the plasma confinement within that region. The subsequent rise in the various parameters at increasing plasma radii illustrates the coincidental radial expansion of 'foot-point' of the barrier on the different transport channels. The increase in the plasma volume enclosed within the ITB region is a key component in the achievement of high fusion yield in these plasmas.

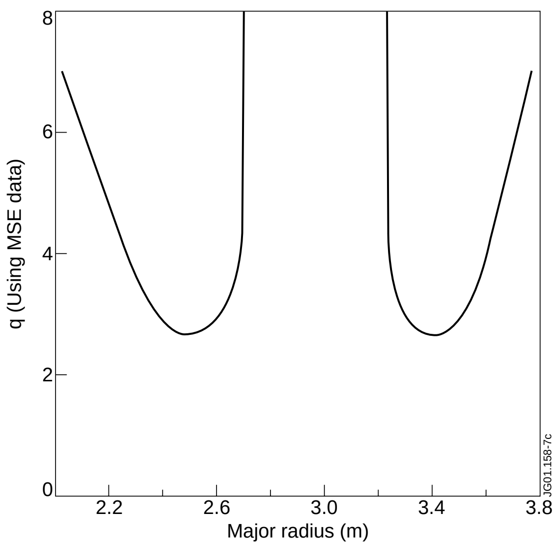

Figure 5. Target q-profile provided for main heating in high fusion yield experiments using an LH prelude phase.

The highest fusion yield following an LHCD prelude was obtained at high toroidal magnetic field strength (3.45T) and moderate plasma current (2.5MA). This led to the transient achievement of high confinement compared with the ITER Physics Basis ELMy H-mode scaling [9] ($H_{IPB98(y,2)}$≈1.9) and high β_N (up to 2.4). A large Edge Localised Mode (ELM), followed by a disruption, ended the high performance phase.

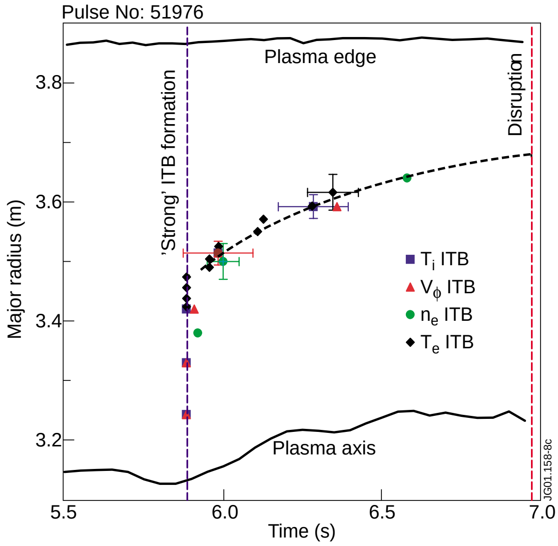

Figure 6. Formation of ITB and subsequent time evolution of the ITB 'foot-point' in a high fusion performance plasma.

5. Conclusions

Experiments to vary the magnetic shear and the shear in the plasma flow suggest that low or negative magnetic shear and high applied torque are favoured for high performance ITB production associated with the q=2 magnetic surface. Further analysis and investigation is required in this area to establish a firm basis for extrapolation to the heating conditions of a tokamak reactor.

Plasmas with highly negative magnetic shear produced by LHCD have improved access to wide ITBs that can enhance the global plasma performance, and this has allowed high confinement H-factor and β_N to be achieved at high magnetic field. In the highest fusion yield case the transient high performance phase was terminated by a disruption following a large ELM. Techniques to minimise the impact of ELMs in this scenario have not yet been fully explored, but the potential for ITB sustainment with LHCD during the main heating pulse has been investigated [10]. Another critical issue is that of impurity transport. Analysis of JET ITB plasmas with negative magnetic shear shows that the increase in core density due to the particle transport ITB can be accompanied by an increase in high Z impurities in the plasma core [11]. Further work is required to optimise the magnetic configuration and plasma pressure and density profiles as well as develop specific impurity control techniques if such regimes are to be fully exploited in current and future devices.

6. Acknowledgements

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