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INTRODUCTION

The triggering and evolution of internal transport barriers (ITBs) in optimised shear (OS) plasmas in JET is linked to the q profile [1], [2]. Moreover, the duration and performance of ITBs are often limited by MHD activity related to the q profile [2], [3]. Hence it is of primary importance to learn how to control the q profile, both before the high power phase, to prepare the target plasma, and during, to maintain the ITB. The high current drive efficiency of the lower hybrid wave makes it an obvious candidate for this purpose. Lower hybrid current drive and heating (LHCD) is used routinely to get reversed q profiles in OS plasmas in JET. Recent experiments indicate that LHCD can control the q profile also during the high power phase.

1. CONTROL OF THE TARGET Q PROFILE WITH LHCD PREHEAT

The basic OS scenario uses a fast current ramp-up, to slow down current diffusion and obtain monotonic q profiles with low magnetic shear. This is followed by the application of high power, usually neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH), when the current is still ramping, to produce ITBs. In this paper, the period between the plasma initiation and the beginning of the high power heating is referred to as ‘preheat’, and the q profile at the end of preheat is called ‘target q profile’. By applying LHCD power (P_{LHCD}) during preheat, a wide range of target q profiles with negative magnetic shear can be produced [4]. The q profile reversal (i.e. the amount by which q_0 exceeds q_{95}) depends on P_{LHCD}. Also, the q profile evolution is slowed down by the LHCD. Plasmas with reversed q profile have produced some of the best performance OS plasmas, at lower total power than plasmas with monotonic q profile [5]. The LHCD system in JET generates power at 3.7GHz. In all experiments presented here a refractive index parallel to the toroidal magnetic field ($N_{//0}$) of 1.84 is used, and the current is driven in the direction of the plasma current. ITBs are often observed during the preheat with LHCD only, marked by a strong gradient in the electron temperature (T_e) [6], both on Thomson scattering (LIDAR) and electron cyclotron emission (ECE) measurements (Fig. 1). ECE measurements can be polluted by the presence of fast electrons due to LHCD, but the central T_e and the position of the T_e gradient agree with LIDAR T_e profile within measurement errors. Sawtooth-like collapses are observed on T_e when an ITB is present. They are linked to the reversed q profile, and are attributed to magnetic reconnections. For the same P_{LHCD}, the ITB presence and width during preheat depends on the plasma parameters early in the discharge (Fig. 1). In particular, shots with low plasma current at plasma initiation do not exhibit ITBs on T_e collapses. Also, plasmas with lower electron density (n_e) during preheat have a wider ITB. In plasmas with reproducible initial parameters, it is possible to move the T_e ITB location outward by increasing P_{LHCD} (Fig. 2). This means that it is possible to control both the q profile and the ITB position during preheat with LHCD. Note that only target plasmas with wide ITBs led to high performance ITBs with NBI and ICRH.

2. ITB SUSTAINED BY LHCD DURING THE MAIN HEATING PHASE

Transport modelling of OS plasmas ($B_T = 3.4T$, $I_P = 3.9MA$) has predicted that adding 3.5MW of

P_{LHCD} could lead to a q profile with negative magnetic shear, and sustain the ITB [7]. However, until recently, it was not possible to couple enough P_{LHCD} in high power OS plasmas, as they usually exhibit a H-mode during which the density in the scrape-off layer falls near or below the cut-off density ($n_{e, cut-off} = 1.7\times10^{17}m^{-3}$ for waves at 3.7GHz). Following dedicated experiments to improve coupling, more than 3.5 MW can now be coupled to plasmas with H-mode and ITB, by optimising the plasma shape and distance, and puffing CD_4 near the grill to increase the density locally [8], [9].

To investigate the effect of LHCD on high power ITBs, reproducible plasmas with long heating pulses at $B_T = 3.4T$ and $I_P = 2.4MA$ were chosen. Reversed target q-profiles are prepared by LHCD preheat. The starting time of the high power phase is chosen so that the q minimum (q_{min}) is still above 3. A first ITB is triggered when q_{min} goes through 3, provided enough NBI + ICRH is used (>15MW), and lasts for up to 1s typically. A second ITB appears 3 to 4s later, when q_{min} goes through 2. During the high power phase, the separatrix strike-point's positions are controlled in feedback to avoid touching the central part of the divertor, as it leads to an increase in recycling detrimental to ITBs. In addition, the plasma of the experiments described here is optimised for LHCD coupling, and CD4 is injected during the high power phase, even on the shots without LHCD. The additional heating power and neutron rate during the high power phase of Pulse No's: 53432 and 53429 are shown on Fig. 3. Pulse No: 53432 is the reference shot, and exhibits the q = 3 ITB and the q = 2 ITB, seen in T_e, n_e and T_i. The q = 3 ITB last until 6.5s, at which time it is ended by an MHD event Indicating the presence of a q = 3 surface at ~3.6m. Equilibrium calculations constrained by polarimetry data agree with that observation and indicate that the q profile is still reversed at that time, with qmin above 2. The q = 2 ITB appears ~4s later, at 10.5s. On Pulse No: 53429, 2.2MW of PLHCD is added at 5.7s. To make sure that the effects seen are not caused by stronger electron heating, the ICRH power is decreased to 4MW. This delaìs the start of the q = 3 ITB in comparison to 53432, but the delay is not long enough to change significantly the q profile, given the slow current diffusion time. The evolution of the T_e ITB is seen on Fig. 4, where its position is plotted as a function of time. The normalised inverse gradient scale length of T_e ($\rho^*_{Te} = \rho_s/L_{Te} \geq 0.01$) is used as a criterion to determine the existence of the ITB [10]. The inner ITB is typical of plasmas with reversed shear and is at a similar position to the preheat ITB, after taking into account the Shafranov shift. It is also seen, although weakly, on Pulse No: 53432. In contrast to the outer ITB, it does not appear to be associated with a rational q [1]. The outer ITB, related to q = 3, appears at ~5.8s, and lasts for 3.8s, when the H-mode goes into an ELM free phase. Moreover, the ITB moves slowly outwards with time. In comparison, on 53432, the ITB lasts for less than 1s, and moves outward by a similar distance in only 1s. Finally, the q = 2 ITB appears ~2s later on 53429 than on 53432. A likely explanation of these observations is that the q profile evolution is slowed down by LHCD. During similar experiments, but with $I_P = 2.0MA$ and P_{LHCD} n~3.0MW, ITBs lasting ~8s were seen on T_i, n_e and the toroidal rotation velocity, with v_{loop} near 0 [11]. The T_e ITB remains for the duration of the LHCD, 11s. The q profile evolution on such shots is frozen, and the ITB position does not change during the high power phase.

3. MODELLING OF LHCD

Different codes were used to model LHCD, and their results agree well with each other. Figure 5 shows the results of transport modelling of the LHCD preheat for Pulse No: 51897 with JETTO [12], which includes a module for fast ray tracing calculation [13]. P_{LHCD} and current (j_{LHCD}) deposition is mainly determined by T_e, and peaks near the ITB footpoint. The current driven by lower hybrid (600-800 kA) is required to form a negative magnetic shear [14]. Moreover, in plasmas without an ITB on T_e, j_{LHCD} is broader, and the resulting q profile is much less reversed (Fig. 5). P_{LHCD} and j_{LHCD} during the preheat and main heating phase of Pulse No: 53429 were calculated by the 2-D relativistic Fokker-Planck and ray tracing code DELPHINE [15]. Again, the lower hybrid power deposition is determined mainly by T_e, and most of the current is driven off-axis, in the vicinity of the ITB. The total lower hybrid current is ~300kA between 6 and 9.5s. Transport modelling with JETTO + 2D relativistic Fokker-Planck and ray tracing [16], shows that the lower hybrid current is well aligned with the bootstrap current. Calculations where j_{LHCD} is turned off show that it is required to maintain a reversed q profile during the high power phase.

CONCLUSIONS

It is possible to control the q profile and the ITB position during preheat with P_{LHCD}. The experiments presented here and in [11] show that P_{LHCD} can sustain high power ITBs during the main heating, by slowing down the q profile. Modelling shows that the P_{LHCD} deposition peaks near the ITB footpoint, indicating that it can act on the magnetic shear at the transport barrier location. The control of ITBs at higher performance with P_{LHCD} will be investigated further, also in experiments at higher I_P. However, this requires more P_{LHCD}, and additional work is needed to increase P_{LHCD} in OS plasmas.

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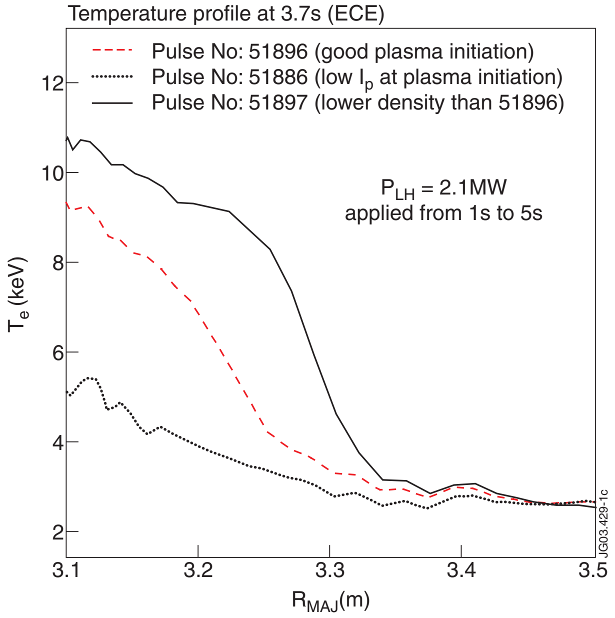

Figure 1: T_e profile during LHCD preheat for shots with different plasma parameters.

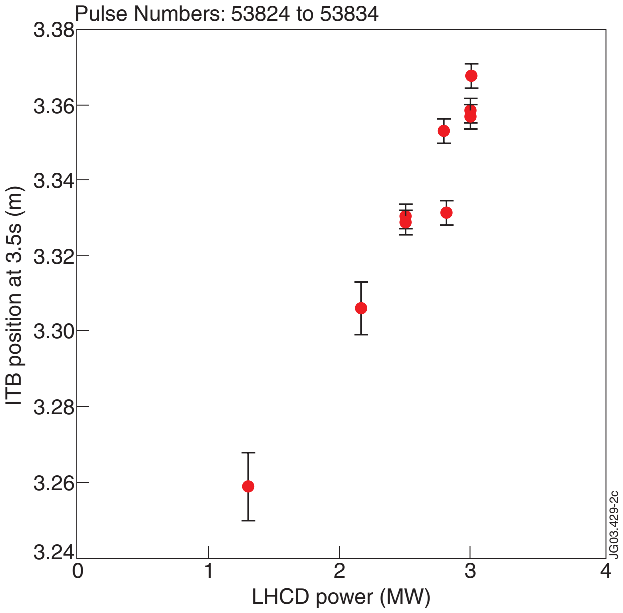

Figure 2: Position of the ITB as a function of P_{LHCD} for shots with reproducible plasma initiation. (Note: variation in Shafranov shift measured by soft X-ray is <3cm for the extreme powers, and therefore is too small to explain the change in the ITB position)

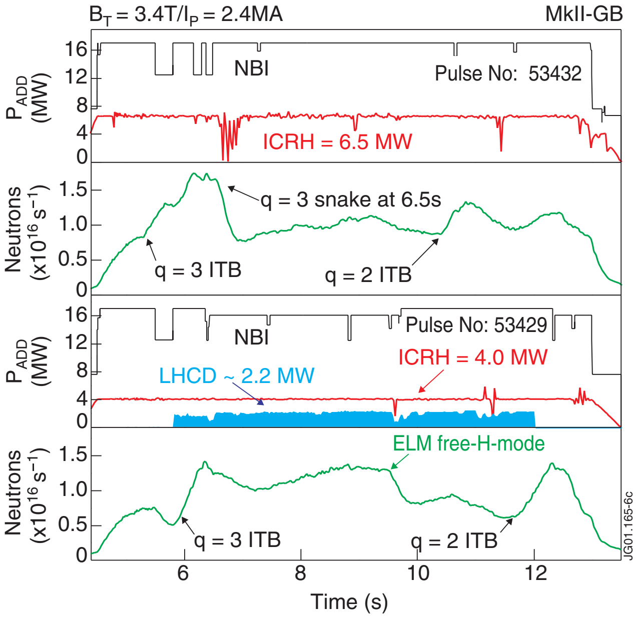

Figure 3: Additional heating power and neutrons for Pulse No's: 53432 and 53429 (with LHCD during main heating). Both shots have LHCD preheat.

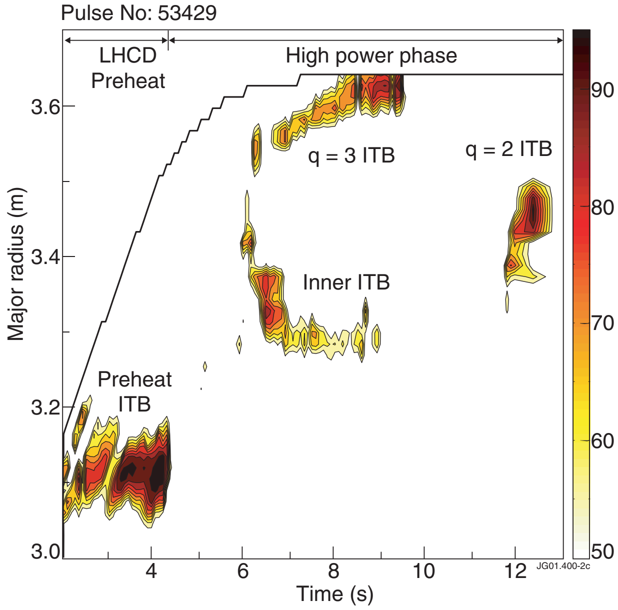

Figure 4: The contours of constant $\rho^*_{Te} = \rho_s/L_{Te} \geq 0.01$ [10] show the evolution of T_e ITB on Pulse No: 53429. LHCD preheat is from 1 to 4.4s, main heating starts at 4.4s, LHCD is reapplied at 5.7s.

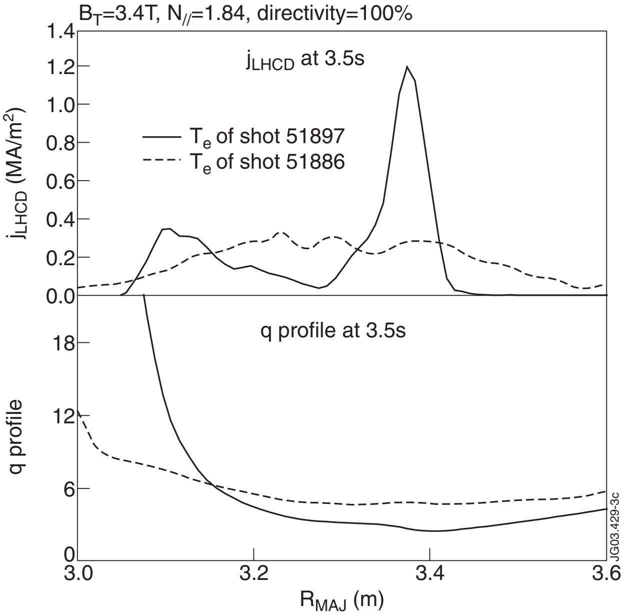

Figure 5: a) j_{LHCD}, and b) q profiles, during preheat for shots with and without electron transport ITB.