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ABSTRACT

Optimised Shear (OS) experiments in JET can generate an Internal Transport Barrier (ITB) during a high power heating phase early in the plasma discharge. A strong link is generally observed between the formation of the barrier and the location of an integer q magnetic surface within a low magnetic shear (s=r/q(dq/dr)) region of the plasma. However, if the q-profile for such experiments is modified by applying Lower Hybrid Heating and Current Drive (LHCD) before the main heating pulse, to provide a region of reduced or negative magnetic shear in the plasma core, ITBs can be formed whose location does not exhibit any apparent association with a particular internal magnetic surface. Initial results suggest that q-profile modification using an LHCD prelude can also be used to reduce the heating power level required for ITB generation.

1. INTRODUCTION

Tokamak plasma regimes where the heat transport is reduced locally in the plasma interior by the presence of an ITB have been investigated in many experimental devices. Research in this area has received impetus from the prospect that the design of tokamak fusion reactors might be improved as a result of an increased plasma confinement in the core of the device. In particular, presently envisaged concepts for a steady-state tokamak reactor rely on plasma regimes capable of providing high confinement and stability without the use of a very large plasma current.

A potential route to such a condition involves the combination of an H-mode edge transport barrier with improved internal plasma confinement. The generation of ‘strong’ internal barriers to heat and particle transport in present devices also offers the means to provide high central plasma pressure and allows an extension of the plasma parameter range accessible for experimental study.

A common method that has been used to produce ITBs in most large tokamaks is the application of additional heating early in the discharge before the plasma current has fully penetrated (e.g. [1-7]). Using this technique the central safety factor (q_0) can be significantly above unity and the magnetic shear low or negative in the plasma core when the main heating is applied. Barriers have been observed on either the electron or ion heat transport or simultaneously on both, and there is sometimes evidence of a corresponding improvement in the particle confinement.

A single picture is not yet available to describe the whole range of experimental phenomena and, in particular, the relationship between the q-profile and the transport effects that are observed. Nevertheless, many of the features can be explained by models that describe the reduction of transport in terms of turbulence suppression due to sheared plasma flow [8] and low magnetic shear. Explanations of this type, together with empirical observations that transport characteristics can vary significantly in the interior of plasmas with different q-profiles (e.g. [9]), have motivated investigations into the effect of modifying the magnetic shear on the behaviour of transport barriers.

In JET OS experiments this early heating method has been used to produce ITBs, mainly with combined Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH) [5]. The reduction in transport in JET has been associated with localised turbulence suppression [10] and correlates with both the plasma flow shearing rate and magnetic shear [11]. The formation of these barriers has also been linked to the presence of integer q magnetic surfaces in the plasma interior in a region of weak magnetic shear [12]. Connections between transport barriers and the location of low order rational q surfaces in the plasma have also been reported on other tokamaks [13-16].

Careful tuning of this regime has led to the achievement of the highest fusion yield from a JET deuterium plasma [17]. In this paper experiments are reported where the magnetic shear of the plasma was further reduced or reversed in the plasma core by applying LHCD prior to the main heating pulse. By this method ITBs were generated that have no apparent link to the location of integer q surfaces in the plasma interior. The comparison of the differences between these two regimes gives valuable insight into the mechanisms responsible for the production of ITBs in JET.

2. THE JET OS REGIME

The temporal development of a typical JET OS experiment with a toroidal magnetic field strength of 2.6T is illustrated in Figure 1. The inductive plasma current is typically ramped up at 0.4-0.5MA/s, following an initial fast current rise at the time of plasma initiation. A large volume plasma is quickly established to slow the current penetration and an X-point configuration is achieved about a second after the plasma formation. The behaviour of the plasma confinement depends critically on the time at which the main heating pulse is applied. In the case illustrated in Figure 1 the main heating pulse begins when the central value of q has fallen to a level just below 2. Under these circumstances a ‘strong’ transport barrier (i.e. one producing a very large local pressure gradient within the plasma) can be formed as evidenced by the resultant rise in the fusion yield.

Low level (up to 2MW) ICRH is sometimes applied during the prelude phase before the main heating pulse. In the discharge shown in Figure 1 0.5MW of ICRH was used during the latter part of the prelude phase, but this heating is applied with a resonance location close to the plasma centre and does not strongly affect the q-profile evolution before the start of the main heating pulse. The main heating pulse is composed of NBI and ICRH with the frequency again chosen to match the hydrogen minority fundamental resonance near the plasma centre. The plasma density at the end of the prelude phase is typically low ($n_e<10^{19}m^{-3}$) which only provides a suitable target for half of the JET neutral beams. Consequently, the NBI power is applied with a short (0.3-0.5s) preheat phase, which ensures that the plasma density rises sufficiently to prevent excessive shine-through from the remaining beams. The end of the NBI preheat phase is defined as t_{heat} for the remainder of this paper. The ratio of the NBI and ICRH power levels is roughly equal to or greater than two in the JET OS experiments discussed in this paper, and deuterium is used for NBI and the main plasma species. The major radius of the plasma magnetic axis is in the range 2.95-3.0m during the preheat phase and typically increases by 10-15cm with the application of high power heating due to the Shafranov shift. The outermost edge of the last closed magnetic flux surface is at a radius of about 3.85m in the equatorial plane of the plasma.

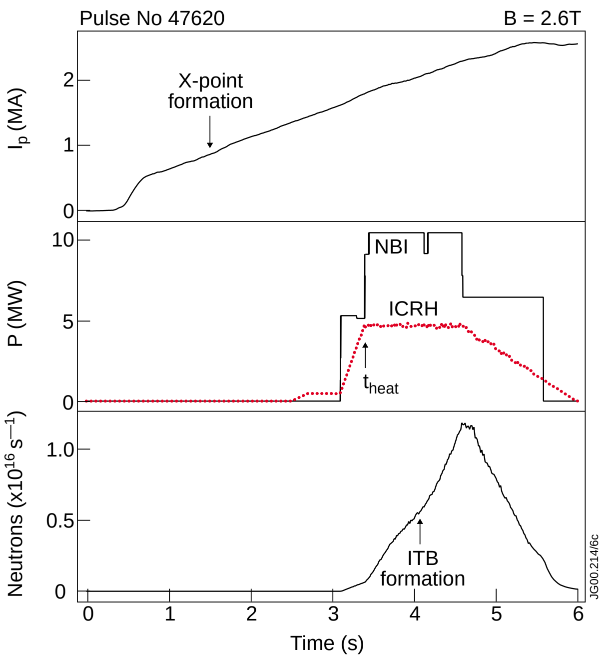

Figure 1: Time evolution of a typical JET OS experiment showing the plasma current, heating power and neutron yield. The early transition from Limiter to X-point configuration is indicated as well as the time of ITB formation during the main heating pulse.

The appearance of the ITB reduces the ion and electron heat transport and the particle transport locally in the plasma interior. This produces a corresponding local increase in the ion and electron temperature and plasma density gradients. The simultaneous increase in the temperature and density of the plasma core results in a corresponding increase in the fusion yield. The evolution of the electron temperature profile during the main heating phase is shown in Figure 2 for two plasmas with a toroidal magnetic field strength of 1.8T. The electron temperature determination was made from Electron Cyclotron Emission (ECE) measured using a heterodyne radiometer. The two pulses are similar except for the additional heating power applied. In the low power case (8.3MW) the electron temperature profile does not vary significantly with time.

At the higher power (10.8MW) the temperature profile is almost identical at first, but then a local increase in the gradient abruptly appears. The discontinuity that develops in the temperature gradient at the outer edge of the steep gradient region indicates a local discontinuity in the heat transport which is reduced in the enhanced gradient region, but largely unaffected at larger radii. The electron density also increases in the plasma core when the ITB is formed, but the JET LIDAR Thomson scattering system has insufficient spatial resolution ≈12cm or temporal frequency (4Hz) to be used for the detailed study presented here. The neutron yield also rises at the time of the ITB formation. In plasmas of this type the fusion yield is dominated by interactions between the beam injected fast ions and the thermal plasma, so is relatively insensitive to the plasma density and rather reflects an increase in the core ion temperature. Direct measurements of the ion temperature profile were not available for these particular experiments, but a local steepening of the gradient is confirmed in other pulses of this type when measurements have been made.

The comparison between two similar plasmas with slightly different additional heating power levels shown in Figure 2 also indicates the existence of a power threshold for the formation of an ITB in this particular regime. The relative resolution of the electron temperature measurement, which is of interest when determining the existence of an ITB, is very high allowing variations in the local temperature to be ascertained to an accuracy of ±2% and providing radial smoothing of only 2cm in radius. This is sufficient to demonstrate that, by comparison with the higher power pulse illustrated in Figure 2, the lower additional heating power level did not lead to the formation of an ITB.

The pulse illustrated in Figure 1 is part of an experiment to investigate the effect of varying the q-profile on the formation of ITBs in the JET OS regime [18, 19]. In a series of otherwise similar pulses the start time, t_{heat}, of the main heating pulse was varied over a wide range. At the start of the earliest heating pulse the value of q was high (3 or above) throughout the plasma because the total current was small and had insufficient time to penetrate to the plasma core. With late heating, on the other hand, q was much lower and, in the case with largest t_{heat}, electron temperature sawteeth were observed during the main heating pulse consistent with the presence of a q=1 surface near the plasma centre.

Figure 3 depicts the range covered by this scan of the timing for the main heating pulse. Also shown are the values of central q, measured for each pulse at the time t_{heat}, which vary in the scan over the range 1 to 3. The q-profiles have been determined using the EFIT equilibrium reconstruction code [20, 21] constrained by Motional Stark Effect (MSE) data [22, 23]. The time, t_{heat}, was chosen for the evaluation of the q-profile because the MSE data is most reliable at the beginning of the neutral beam heating pulse when the measurements are not confused by overlapping signals from different beams. The short duration of the main heating pulse together with the relatively high core electron temperature (typically >4keV) allow only small changes to the q-profile (in the order of a few percent in q) up to the time when an ITB forms. Figure 4 shows the peak fusion yield obtained in each pulse of the scan illustrated in Figure 3 plotted against the q_0 value at t_{heat}.

The high neutron yield obtained in pulses with q_0 just below 2 indicates the production of ‘strong’ ITBs. The three pulses represented by open circles in Figure 4 exhibit a large n=1 magnetohydrodynamic (MHD) tearing mode in the plasma core, under which conditions ITB formation does not occur. The comparison of the electron temperature and density profiles for a plasma with a ‘strong’ ITB and a core tearing mode is shown in Figure 5, together with the q-profile measured at t_{heat}.

The two pulses are virtually identical up to the main heating pulse and the target q-profiles are essentially indistinguishable within the precision of the measurement. The evolution of the plasma core, however, is quite different in the two cases with a local increase in both the electron temperature and density gradient in the ITB case. The neutron yield is roughly doubled in the

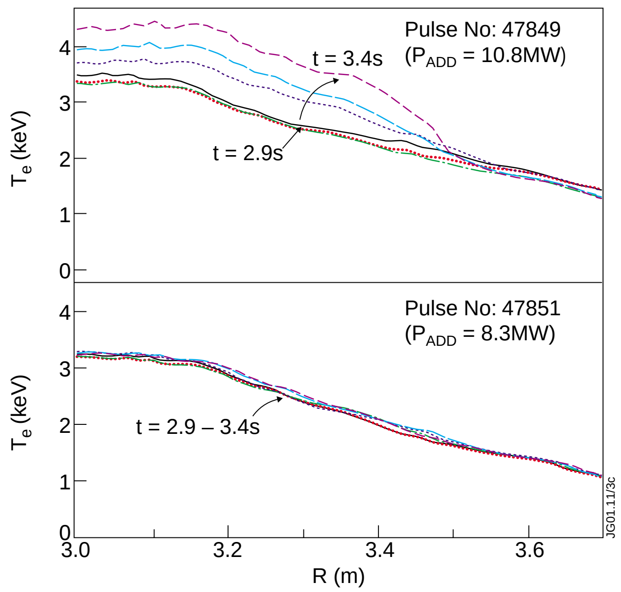

Figure 2: Electron temperature profile evolution for two pulses with magnetic field strength of 1.8T, but different amounts of additional heating power. The electron temperature profiles are shown at 100ms intervals.

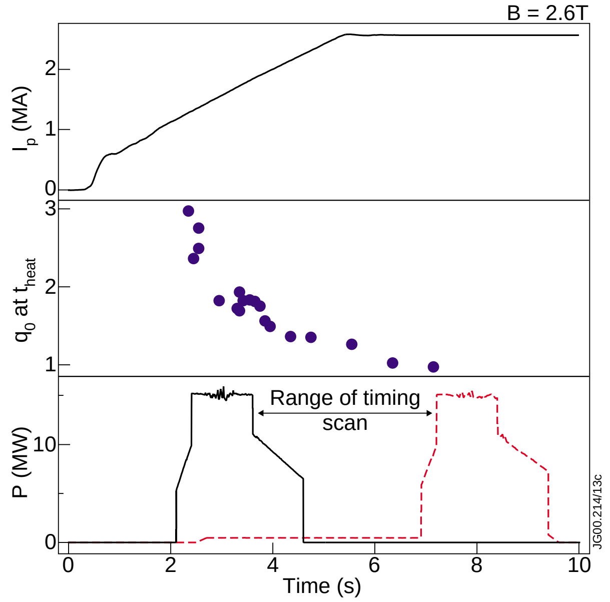

Figure 3: Overview of experiment to vary the heating start time showing the time evolution of the plasma current, the heating power waveforms for the extreme early and late timing cases and the value of q_0 at t_{heat} for each pulse in the scan.

case where a ‘strong’ ITB forms, as shown in Figure 4, due to the coincidental increase in core ion temperature.

The bifurcation between these two states is most likely to be a consequence of very subtle differences in the q-profile in the plasma core. The very low magnetic shear in this region means that a relatively small variation in the value of q can significantly alter the radial position of the q=2 surface and the value of the local magnetic shear at the q=2 location. The poloidal mode number of the tearing mode is even, consistent with the presence of a q=2 surface near the plasma centre in these cases. This mode identification, together with the observation of q=1 electron temperature sawteeth in pulses with late heating, was used to benchmark the current profile analysis and provides a high degree of confidence in the q-profile determination for this experiment.

Figure 6 shows the q-profile at t_{heat} for two pulses, again from the scan illustrated in Figure 3, but this time with significantly different main heating start times. The first pulse has t_{heat}=3.4 s corresponding to the time at which q_0 has just fallen below 2.

The second was similar except that the main heating pulse was delayed by 0.5s. Both q-profiles are monotonic and have a similar shape except that the absolute value of q had fallen to a lower level everywhere in the plasma for the case with delayed heating, and consequently the radius of the q=2 surface was increased.

The time evolution of the plasma electron temperature profile during the main heating pulse is also illustrated in Figure 6 for both pulses from ECE data. In the first case with q_0 close to 2 a

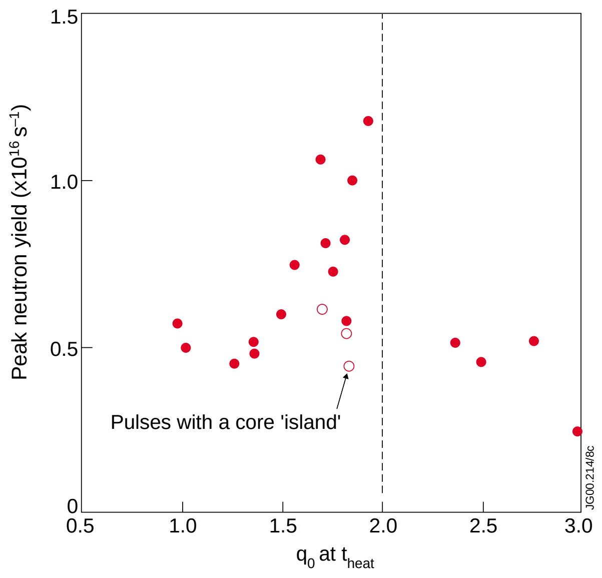

Figure 4: Peak neutron yield plotted against q_0 at time t_{heat}, determined using MSE data, for pulses from the main heating timing scan illustrated in Figure 2. The pulses represented by open circles exhibit an n=1 MHD tearing mode in the plasma core.

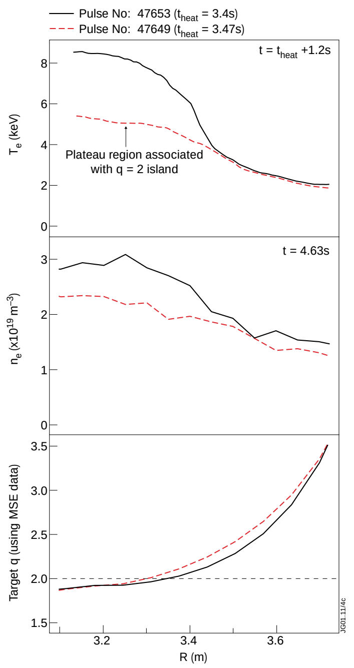

Figure 5: Target q-profile (at t_{heat}) and electron temperature and density profiles during the main heating pulse for a pulse with a 'strong' ITB and a case with a core MHD tearing mode.

'strong' ITB forms in the plasma core which can be seen as a sudden local steepening of the electron temperature gradient. The position at which the ITB forms corresponds roughly to the location of the q=2 surface. The ITB then rapidly expands, and this leads to the substantial enhancement in fusion yield indicated for pulses of this type in Figure 4.

The second pulse in Figure 6 exhibits an ITB which is formed at a wider radius reflecting the different location of the q=2 surface. The wider ITB obtained with delayed heating is typically 'weaker' than is the case with a q=2 surface near the plasma centre.

The radial heat flux does not vary strongly with plasma radius in the region where these ITBs are produced due to the relatively broad additional heating power deposition profile.

Consequently, the poorer performance of the 'weak' ITB obtained with a wider q=2 surface can be interpreted in terms of less strongly reduced transport and/or an ITB of smaller radial extent.

One explanation for this could be the increased magnetic shear at the larger plasma radius. Pulses with very early heating can also exhibit wide transport barriers, but at a location corresponding to the position of the q=3 surface.

During this timing scan these barriers were evident, but did not give rise to a high core plasma pressure or neutron yield. However, similar experiments with very early heating at higher magnetic field and heating power levels have been used to produce 'strong' ITBs associated with q=3 and high fusion performance. Similar phenomena have been observed elsewhere [13].

3. THE EFFECT OF LHCD ON THE PLASMA DURING THE PRELUDE PHASE

The plasma electron temperature is relatively low (typically <2keV) during the phase prior to the main heating pulse if only Ohmic preheating is used. In these conditions the plasma current penetration can be rapid enough to provide the monotonic q-profile shapes shown in Figure 6. The use of low power ICRH preheat, as illustrated in Figure 1, with the resonance near the plasma centre does not strongly alter the q-profile evolution. This is because the electron temperature and conductivity profiles become more peaked which tends to compensate for the increased current penetration time. The application of low power LHCD during the prelude phase before the main heating pulse is, on the other hand, very effective for broadening the target current profile.

The JET LHCD launcher is located in the tokamak equatorial plane and comprises 12 rows of 32 waveguides. The waves are launched at a frequency of 3.7GHz and, in these experiments, were phased to drive current in the same direction as the plasma current. The launched power spectrum was peaked at a refractive index parallel to the magnetic field of 1.8. Figure 7 shows the time evolution of an Optimised Shear pulse where an LHCD prelude has been added to the scenario described above. In these experiments LHCD was applied continuously from the time of plasma initiation to the start time of the NBI and ICRH pulses.

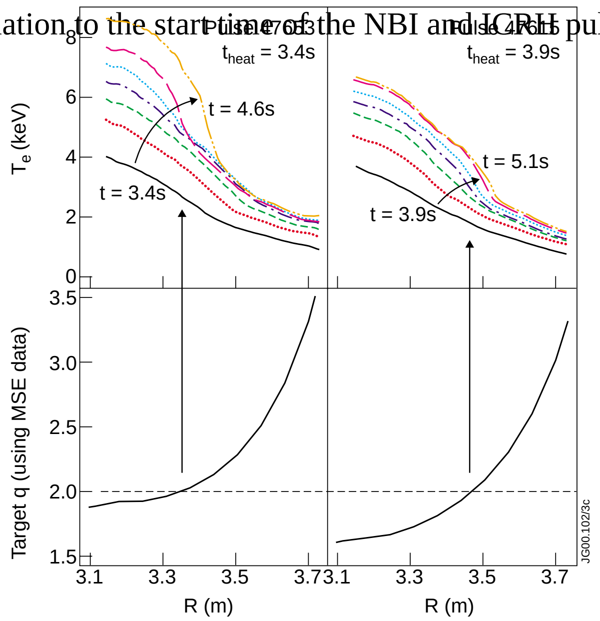

Figure 6: Target q-profile (at t_{heat}) and electron temperature profile evolution during the main heating pulse for two pulses with different main heating start times. The electron temperature profiles are shown at 200ms intervals.

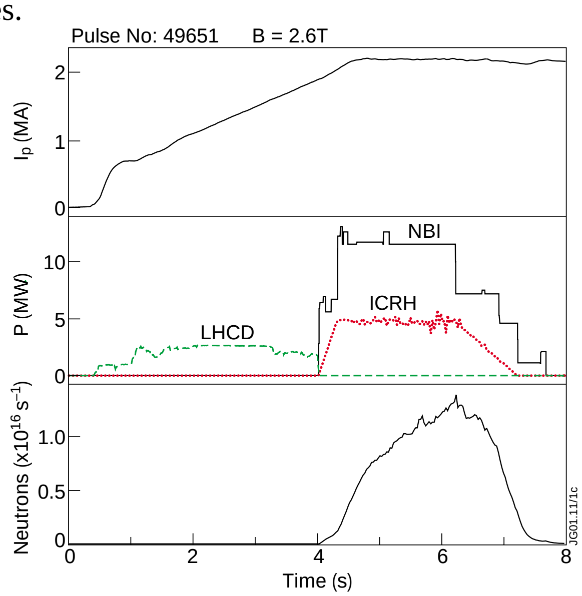

Figure 7: Time evolution of a typical OS experiment with an LHCD prelude showing the plasma current, heating power and neutron yield.

A simulation of the current density profile driven by the LH system at various times during this prelude phase is illustrated in Figure 8. The LHCD simulation has been made using a combined ray tracing and Fokker-Planck code [24]. The effect of fast electron diffusion within the plasma, which has been neglected in the calculations presented in Figure 8, could in practice result in some radial smoothing of the current density profile. The differences in the magnitude of the current density shown is due partly to changes in the applied LHCD power and partly to variations in the thermal electron temperature near the plasma centre. Figure 9 shows the reduction in the plasma internal inductance resulting from the application of LHCD early in the current ramp-up phase. This figure shows that the current profile becomes broader with increasing LHCD power. The modification of the q-profile evolution can be attributed in part to the addition of substantial non-inductive current drive. But the effect of the applied LH power is also to substantially raise the thermal electron temperature, especially in the plasma core, which reduces the rate of current penetration during the current ramp phase and consequently contributes to the broadening of the current profile [25]. Increasing the plasma current ramp rate also acts to reduce the plasma internal inductance, as indicated in Figure 9. However, at high ramp rates MHD instabilities were encountered when particular integer q surfaces, most commonly q=6, were present near the plasma edge. These instabilities acted to redistribute the plasma current and resulted in a prompt increase in the internal inductance of the plasma. Increasing the LHCD power level, on the other hand, did not tend to destabilise these modes indicating that the use of LHCD in this way allows the current profile to be substantially modified in the plasma interior without generating an excessive current density in the plasma periphery.

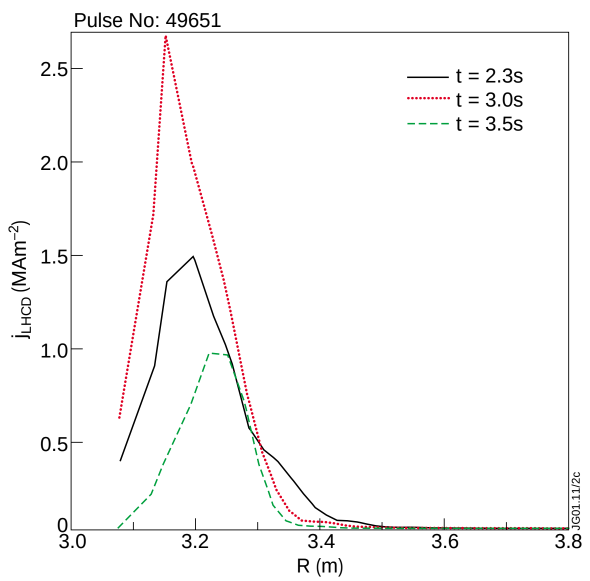

Figure 8: Profiles showing the LH driven current density calculated for various times during the prelude phase of the pulse illustrated in Figure 7.

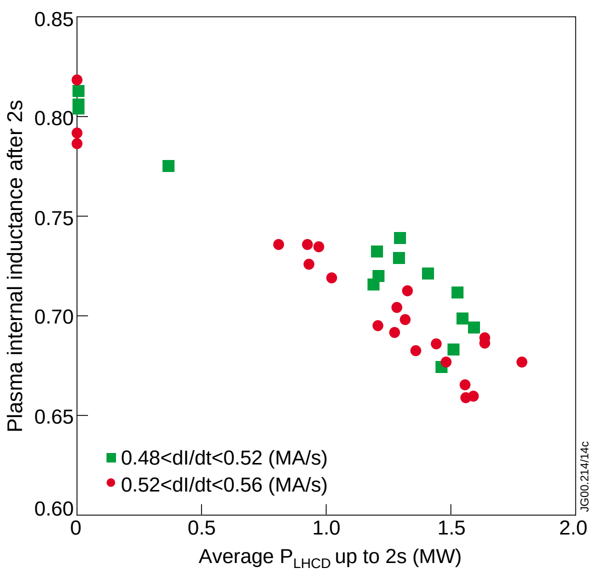

Figure 9: Plasma internal inductance 2s after plasma initiation plotted against the average LH power up to the same time. The average current ramp rate in this period is also indicated.

An MHD characteristic of pulses with significant LHCD early in the prelude phase is the presence of small sawtooth-like collapses in the central plasma electron temperature. Figure 10 shows the temperature measured from ECE data, which illustrates these features. The value of the temperature determined in this way can be subject to significant uncertainties in the presence of suprathermal electrons such as those generated in the plasma by the application of LHCD. However, the magnitude of the electron temperature is confirmed by LIDAR Thomson scattering measurements in the plasma core and is therefore representative of the temperature of the thermal electrons.

These plasmas exhibit a threshold in the applied LHCD power required for the generation of repetitive core collapses. This is illustrated in Figure 11, which shows the number of identifiable collapses during the first 3s of the discharge increasing abruptly when the average LHCD power applied in the first 1.5s exceeds about 1.7MW. Although the LHCD continues to be applied after this initial 1.5s, the occurrence of these sawteeth-like events seems particularly sensitive to plasma conditions during this early phase, suggesting the conclusion that the shape of the q-profile achieved early in the discharge persists and continues to affect the plasma dynamics at later times.

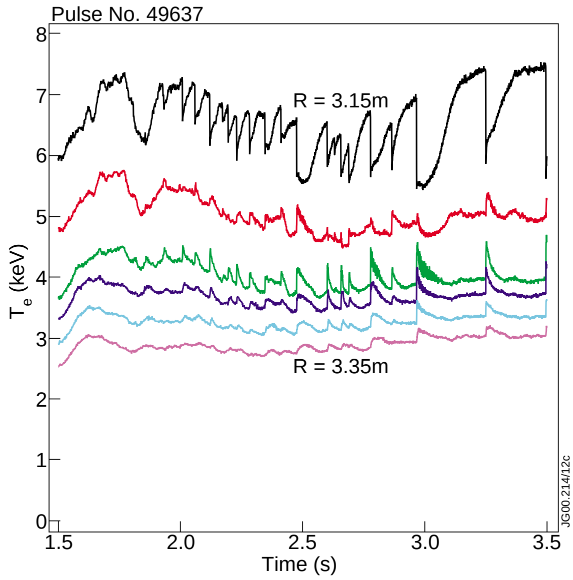

Figure 10: Time evolution of the electron temperature at various radial locations in the plasma core during an LHCD prelude phase.

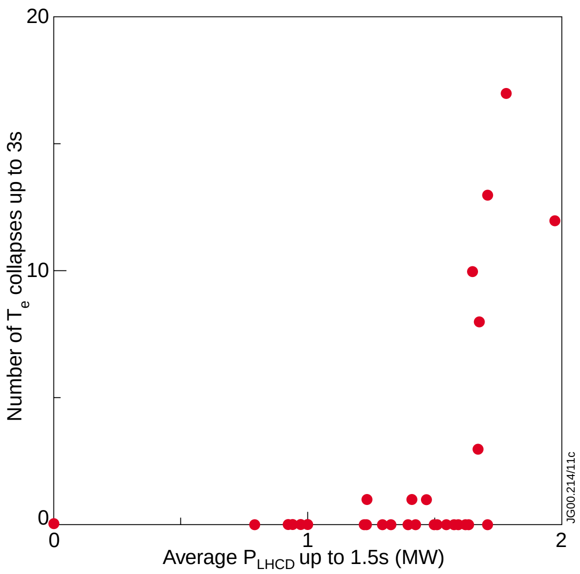

Figure 11: Number of clear electron temperature collapses in the plasma core during the first 3s of the plasma pulse plotted against the average LHCD power during the first 1.5s of the same discharge.

In some cases the central electron temperature rises spontaneously during the preheat phase. Similar phenomena have been observed previously on JET [26] and elsewhere with either LHCD or electron cyclotron resonance heating [3, 27, 7] when a negative magnetic shear region is present in the plasma core. The core temperature peaking tends to correlate with occurrence of the sawtooth-like collapses, and the radius of the steep gradient region is roughly consistent to that estimated for the peak in the LH driven current density. These results indicate that an improvement in the core electron heat confinement can be generated at relatively low heating power with a favourable q-profile shape.

4. ITBS PRODUCED AFTER AN LHCD PRELUDE

Figure 12 shows the target q-profile provided for main heating in the pulse illustrated in Figure 7 where LHCD was applied throughout the prelude phase at an average power level of about 2MW. The toroidal magnetic field strength and current ramp rate are roughly similar to the timing scan cases discussed in Section 2, as is the plasma density at the start of the main heating pulse. The q-profile shown was calculated using EFIT constrained by MSE measurements and is consistent with Faraday rotation data obtained using a polarimeter. In contrast to the q-profiles illustrated in Figure 6, where only low power centrally deposited ICRH preheat was applied late in the prelude phase, the magnetic shear is negative in the plasma core in the LHCD case shown in Figure 12.

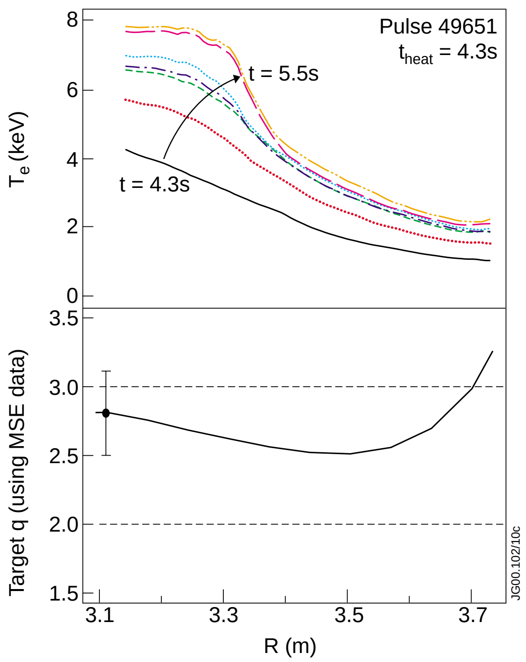

Figure 12: Target q-profile (at t_{heat}) and electron temperature profile evolution during the main heating pulse for a pulse with an LHCD prelude. The electron temperature profiles are shown at 200ms intervals.

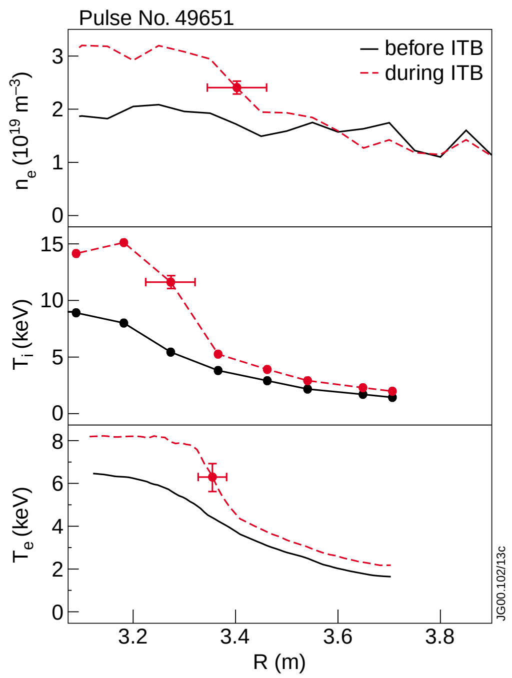

Figure 13: Profiles of electron density, ion and electron temperature during the main heating phase of a pulse with an LHCD prelude. In each case the profiles are shown before and after the formation of an ITB. The error bar indicated for the magnitude and radial location of the electron temperature represents the estimated absolute uncertainty. The relative uncertainties of this measurement are ± 2% and 2cm respectively.

An ITB typically forms in the plasma core during the main heating pulse after such an LHCD prelude as illustrated in Figure 12 by the appearance of a steep gradient on the electron temperature profile, which does not expand significantly. In this case the main heating pulse was composed of 12MW of NBI and 5MW of ICRH. The high plasma electron temperature generated by this level of heating power, together with the large size of the JET plasma, results in a relatively slow evolution of the q-profile during the main heating phase. In this pulse the value of q in the plasma core is estimated to fall by less than 0.5 in the period over which the electron temperature profile evolution is illustrated. The location of the ITB formed in this case does not appear correspond to the position of an integer q surface. It is rather correlated approximately with the location estimated for the peak of the LH driven current density and the electron temperature peaking during the prelude, once the large Shafranov shift during the main heating phase is taken into account.

The transport barrier can be seen more clearly in Figure 13, which shows the profiles of the electron density, ion and electron temperature before and after the formation of the ITB. The electron density was again measured using the LIDAR Thomson scattering system.

The ion temperature profiles, which have limited spatial resolution compared with that of the ECE heterodyne radiometer due to the sparse radial coverage, were determined using charge-exchange recombination spectroscopy. The evolution of these plasma profiles shows evidence of enhanced confinement on both the electron and ion heat loss channels as well as the particle transport. This characteristic is also typical of ITBs produced in JET OS experiments without an LHCD prelude as described in Section 2.

From Figure 12 the possibility that an integer q surface is present near the plasma centre cannot be totally eliminated within the uncertainties of the q-profile determination and evolution during the main heating phase. Indeed, it is impossible from this example alone to rule out the possibility that other low-order rational q surfaces with $n>1$ may be present in this region and could play a role in the ITB formation process. In order to investigate the sensitivity of this ITB to particular q surfaces the main heating start time was altered, thus varying the location of any critical magnetic surfaces within the plasma.

Figure 14 shows the ion and electron temperature profiles after about 1.25s of main heating for three pulses, all with an LHCD prelude, but with different main heating start times. The edge of the plasma is roughly indicated by the last closed magnetic flux surface. All three pulses exhibit the same core ITB at a plasma radius of about 3.35m. The target q profiles are shown in Figure 15 for the pulses described in Figure 14.

The effect of the change in timing in this scan is amplified by variations in the LHCD power and conditions at the plasma initiation to give a wide range of q_0 values (approximately 2, 2.8 and 6 respectively). This, together with the relatively small q-profile changes during the short main heating phase, exclude the possibility that a particular rational q surface could be responsible for the inner ITB in all cases.

In principle, of course, one might argue that a different low order rational q surface could be present at the same location in each case. But the systematic recurrence of the ITB at the same location (±3cm) in a dozen or so pulses produced in the course of this experiment argues irresistibly that the location is determined by some other parameter.

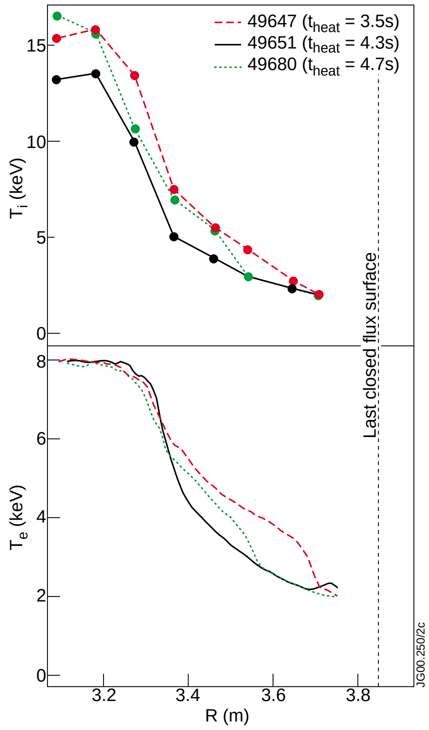

Figure 14: Ion and electron temperature profiles for three pulses with an LHCD prelude, but with different main heating start times. The profiles are shown ≈1.25s after t_{heat}.

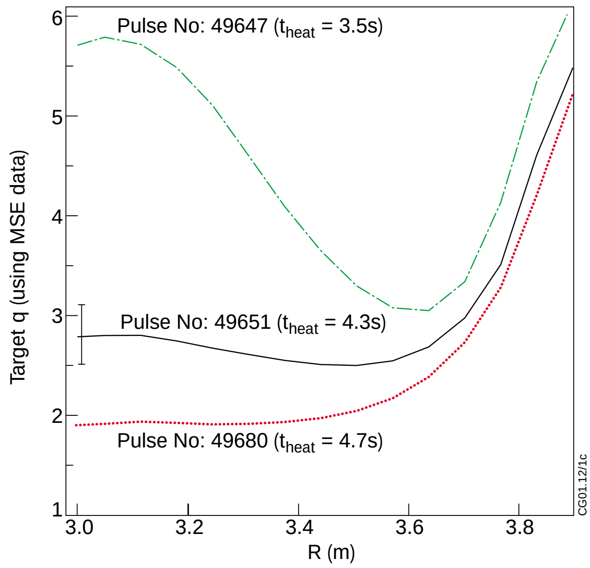

Figure 15. Target q-profile (at t_{heat}) for the pulses with an LHCD prelude and different t_{heat} described in Figure 14.

In two of the cases shown in Figure 14 an additional ITB is also observed at a larger plasma radius. The locations of these two outer ITBs are roughly consistent with the location of the q=2 and q=3 surfaces, respectively, in the positive magnetic shear region of the plasma. Thus both the inner ITBs obtained following an LHCD prelude and the outer ITBs associated with rational q magnetic surfaces discussed in section 2 can be obtained simultaneously.

5. THE POWER THRESHOLD FOR ITB FORMATION

The power required to form an ITB in the JET OS regime tends to increase with toroidal magnetic field strength (or plasma current, which is varied in proportion) [28]. Figure 16 shows the power at which clear ITBs were achieved at several values of magnetic field in plasmas without an LHCD prelude and with q_0 close to 2.

These data points represent the marginal values for transport barrier production from a large number of pulses and show little difference between experiments performed with the JET MkIIA and MkIIGB divertor configurations, despite the significant change in plasma edge conditions [29].

A pulse at 2.6T with an LHCD prelude that produced a clear ITB is included for comparison. The pulse in question represents the lowest main heating power level applied in the series of experiments described in this paper and is therefore not necessarily the threshold value for the generation of an ITB after an LHCD prelude. Nevertheless, it is clear that ITBs can be obtained at a much lower power level with an LHCD prelude than has so far been achievable in the JET OS regime using a mainly Ohmic ramp-up phase. These indications suggest that the power threshold for ITB production is very sensitive to the shape of the q-profile.

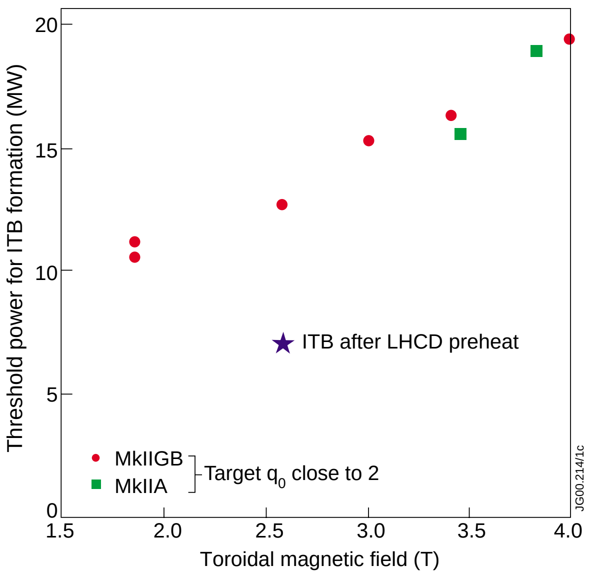

Figure 16: Heating power level required to form a clear ITB plotted against the plasma toroidal magnetic field strength. The squares and circles represent plasmas with q_0 close to 2 and no LHCD prelude obtained with the JET MkIIA and MkIIGB divertor configurations respectively. The star indicates the power level at which a clear ITB was obtained following an LHCD prelude. However, the minimum power level to produce an ITB in this regime has not yet been established.

6. CONCLUSIONS

Previous experiments in the JET Optimised Shear regime have mainly been performed with little or no additional preheating power during the current ramp-up phase prior to the main heating pulse. In this scenario ‘strong’ internal transport barriers can be produced by timing the start of the main heating pulse so that q_0 is just below 2 or 3. ITBs typically form in a region of low positive magnetic shear close to the integer magnetic surface. Mechanisms involving the perturbation of the plasma profiles by MHD activity at integer q surfaces provide a plausible explanation for the JET phenomenon. MHD at an integer q surface could provide a locally enhanced shear in the plasma flow that would then act to trigger the ITB formation [30]. However, mechanisms that rely on a local reduction in transport associated with the low order rational q surfaces themselves [14] cannot be ruled out.

Efforts are also being made to understand this connection from a theoretical point of view [31]. The production of clear transport barriers with q_0 close to 2 in this regime has, so far, required at least 10MW of main heating power and this threshold power rises with the plasma toroidal magnetic field strength.LHCD has been found to be very effective for modifying the target q-profile for high power heating when applied throughout the preceding current ramp-up phase. In this way a q-profile can be produced with a reversed magnetic shear region in the plasma interior. ITBs produced during a main heating pulse following such an LHCD prelude are evident as steep gradients on the ion and electron temperature and plasma density profiles, just as with ‘q=2’ cases. However, their position has no apparent link to the presence of integer q surfaces in the plasma interior and they are instead located in a region of very low or negative magnetic shear. These observations contrast with experiments reported on some other tokamaks where a dramatic reduction in the electron thermal conductivity was only seen in strong negative shear discharges [9, 16].

A link between the ITB position and critical parameters, such as the radius of the minimum q value, has not yet been established for cases with an LHCD prelude. Previous experiments using pellet injection to produce improved core confinement of both heat and particles, designated the Pellet Enhanced Performance (PEP) mode [32], suggested a correspondence between the regions of reduced transport and reversed shear. A similar relationship has been reported in plasmas with negative central magnetic shear on a variety of tokamaks (e.g. [1, 2, 33, 34, 4]).

The simple characterisation of q-profiles with and without an LHCD prelude as being monotonic and non-monotonic respectively is not necessarily universal for the JET OS regime. Many factors can affect the current profile evolution before the main heating is applied in either case, including plasma temperature and composition, current ramp rate and MHD phenomena, and there are probably some weak shear reversal cases within the large database of Ohmic and ICRH preheat pulses. Nevertheless, the observation that integer q surfaces play a key role in ITB formation in regions of positive magnetic shear appears quite general.

Both types of ITB can be obtained simultaneously to produce a 'double' ITB plasma. An inner barrier is located in the plasma core with an outer ITB in the positive magnetic shear region at larger plasma radius.

Initial results suggest that the addition of an LHCD prelude can substantially reduce the power required to produce an ITB. This initial indication suggests that the threshold power is very sensitive to the shape of the q-profile. This leads to the conclusion that any comparison of regimes of this type, obtained in different tokamaks, would necessarily require the achievement of a close match in the q-profiles used in each device. Such studies will become necessary if a sound basis is to be established for the purpose of extrapolating scenarios with improved core confinement to reactor sized devices.

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