

J Mailloux et al

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J Mailloux¹, B. Alper¹, Y Baranov¹, A Becoulet², A Cardinali³, C Castaldo³, R Cesario³, G Conway⁷, C.D Challis¹, F Crisanti³, M de Baar⁴, P de Vries⁴, A Ekedahl², K Erents¹, C Gowers¹, N.C Hawkes¹, G M DHogeweyj⁴, F Imbeaux², E Joffrin², X Litaudon², P Lomas¹, G.F Matthews¹, D Mazon², V Pericoli³, R Prentice¹, F Rimini², Y Sarazin², B.C Stratton⁶, A.A Tuccillo³, T Tala⁵, K-D Zastrow¹ and contributors to the EFDA-JET workprogramme*

¹Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK

²Association Euratom-CEA, CEA Cadarache, 13108, St Paul-lez-Durance, France

³Associazione Euratom-ENEA sulla Fusione, Centro Ricerche Frascati, C.P. 65, 00044-Frascati (Rome), Italy

⁴FOM-Rijnhuizen, Ass. Euratom-FOM, TEC, P.O.Box 1207, 3430 BE Nieuwegein, NL

⁵Association Euratom-Tekes, VTT Chemical Technology, P.O. Box 1404, FIN-02044 VTT, Finland

⁶Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ, 08543, USA

⁷Max-Planck-Institute für Plasmaphysik, EURATOM-Association IPP, Garching D-85748, Germany

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ABSTRACT

In optimised shear plasmas in the Joint European Torus[11], safety factor (q) profiles with negative magnetic shear are produced by applying Lower Hybrid (LH) waves during the plasma current ramp-up phase. These plasmas produce a barrier to the electron energy transport. The radius at which the barrier is located increases with the LH wave power. When heated with high power from ion cyclotron resonance heating and neutral beam injection, they can additionally produce transient Internal Transport Barriers (ITBs) seen on the ion temperature, electron density and toroidal rotation velocity profiles. Due to recent improvements in coupling, q profile control with LH current drive in ITB plasmas with strong combined heating can be explored. These new experiments have led to ITBs sustained for several seconds by the LH wave. Simulations show that the current driven by the LH waves peaks at the ITB location, indicating that it can act in the region of low magnetic shear.

1. INTRODUCTION

Scenarios based on Internal Transport Barriers (ITBs) are highly desirable for a fusion power plant, since plasmas with ITBs exhibit a strong pressure gradient, consistent with high bootstrap current fraction plasmas which are desired for steady-state[1]. Scenarios based on ITBs are likely to be explored in the International Tokamak Experimental Reactor (ITER)[2]. However, presently ITBs are usually transient, and often terminated by detrimental MHD events linked to the strong pressure gradients and to the safety factor (q)[3,4,5]. The integer q surfaces and magnetic shear also play an important role in the triggering and performance of ITBs, as observed in several tokamaks[6,7,8]. The development of reliable steady-state scenarios with ITBs thus requires control of the q profile using some form of external current drive.

The lower hybrid wave is the most efficient method for non-inductive current drive in tokamaks. The radial location of the lower hybrid current density, j_{LH} , can be controlled through tuning the refractive index of the lower hybrid (LH) wave parallel to the magnetic field (n_{\parallel}). This makes the lower hybrid wave a good tool for controlling the current profile, and hence the q profile, as has been demonstrated in several tokamaks, for example ToreSupra[9] and JAERI Tokamak-60 Upgrade (JT-60U)[10,11]. Moreover, the JT-60U experiments[10,11] demonstrate that LH waves can produce and sustain negative magnetic shear over several seconds.

In recent experiments in the Joint European Torus (JET)[12], LH power has been applied during the beginning of the current ramp-up phase to obtain q profiles with negative magnetic shear[8]. Further experiments[13] have shown that q profile reversal (i.e. the amount by which the central q (q_0) exceeds the minimum q (q_{min})), can be varied by increasing the LH power. In some cases, the core plasma current goes roughly to zero, due to the large off-axis current driven by LH [14]. This leads to deeply negative magnetic shear, with extremely large q in the core. When heated with high power from Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH), plasmas with negative magnetic shear have led to ITBs with very high performance, in terms of global confinement and neutron yield, at record values of normalised beta (β_{N})[13,15] above 3.3T for JET.

Until recently, it had not been possible to couple significant LH power during the high additional power phase of JET ITB plasmas, because they have an H-mode edge with Edge Localised Modes (ELMs). Advances in solving the problem of coupling the lower hybrid wave in H-mode plasma¹⁶ have made it possible to investigate its use for the control of the q profile of strongly heated ITBs. Results from these new experiments are described in part IV of the paper, while part II concentrates on ITB plasmas with LH only, and part III summarises the consequences of using negative magnetic shear plasmas on ITB formation and performance in strongly heated plasmas[15].

2. ITBS WITH LH ONLY IN NEGATIVE MAGNETIC SHEAR PLASMAS

In typical JET Optimised Shear (OS) plasmas, the first seconds of a pulse are used to shape the q profile, in order to obtain a magnetic configuration that favours the production of ITBs. To get a low central magnetic shear, a fast current ramp-up is used. Negative magnetic shear is obtained by adding LH power [8]. This period, hereafter referred to as preheat, is followed by the application of high additional power, usually by NBI and ICRH, while the current is still ramping, to generate ITBs capable of delivering high plasma confinement and fusion yield. The q profile at the beginning of the high power phase is called the ‘target q profile’.

The LH system in JET [17] generates power at 3.7GHz. In all shots presented here, a peak refractive index parallel to the magnetic field ($n_{//0}$) of 1.84, with full width $\Delta n_{//} = 0.46$, is used, driving current in the direction of the plasma current. Typically, in JET, the major radius (R_{MAJ}) is ~ 3 m, and the outboard last closed magnetic surface is at ~ 3.9 m. Figure 1 shows the time evolution of a typical preheat phase that results in a target q profile with deeply negative magnetic shear. After an initial fast current ramp, the total plasma current increases at a rate of ~ 0.4 MA/s (Fig.1(a)). The toroidal central magnetic field (B_T) also increases, from 3.1T to 3.4T at the end of preheat (5 s). The density during preheat is usually low, increasing until ~ 2.5 s and remaining nearly constant until the end of preheat (Fig.1(b)). LH power is applied from 1.0s, at a level of ~ 2 MW (Fig.1(a)). The plasma is formed in limiter mode, and the transition to divertor configuration occurs between ~ 1.2 s and 1.5s. Soon after the application of LH power, a large increase in the electron core temperature, T_e , is seen, both in the Electron Cyclotron Emission (ECE) and Thomson scattering (LIDAR) measurements (Fig.1(c)). The fast electrons produced by LH can pollute the ECE measurements where the plasma is optically thin, while LIDAR only measures the temperature of the thermal electrons. This explains the discrepancy between the two different core measurements early in the shot, which disappears once the plasma density is high enough. The very large rise in the core temperature, up to 10keV, is caused by the presence of an ITB on the electron energy, which is seen as a sharp change in gradient in the T_e radial profile (fig.2), at ~ 3.35 m. The LIDAR and ECE measurements agree well, within error bars, on the radial position of the ITB and on the central temperature. At radii greater than 3.5m (not shown here), the plasma is optically thin and the ECE measurements diverge from the LIDAR T_e . Figure 3 shows results from calculations of the preheat phase of shot 51897 by the transport code JETTO [18], which includes a LH module [19]

for ray tracing and 1-D Fokker-Planck calculations. The simulation uses smoothed experimental temperature (Fig.3(a)) and density profiles. It starts at 1s with a monotonic q profile (Fig.3(d)), taken from the equilibrium code EFIT[20], using magnetic measurements only. The evolution of the q profile is calculated during the rest of the simulation. To avoid the situation where the toroidal current vanishes, where JETTO calculations would stop being valid, $q < 60$ has been enforced in the code. The calculated q profile shows little dependence on the shape of the initial q profile, since, early in the shot, the total current profile (Fig.3(c)) is dominated by the LH current contribution (Fig.3(b)). In fact, so much LH current is driven that, in response, the inductive contribution becomes negative in the centre, leading to a hollow total current profile which is nearly zero in the core [14]. This leads to a highly non-monotonic q profile already 0.5s after the start of P_{LH} . As the total current increases (Fig.1(a)), the LH current contribution becomes comparatively smaller, and the region with small total current, and hence extremely large q , shrinks. Also, the LH power deposition depends mostly on T_e , consequently, j_{LH} rapidly peaks, off-axis, at the ITB location. This has the effect of keeping q_{min} at a wide radius. The high core temperature helps to slow down the q profile evolution significantly, and helps to maintain the central q at high values, because it reduces the current diffusion by decreasing the plasma resistivity. However, additional transport simulations, where the lower hybrid current is switched off, show that its contribution is crucial to obtain a q profile with large negative shear [21].

The electron density profile during LH preheat remains flat. No T_i measurements were available on shot 51897, but short pulses of NBI power have been applied in similar plasmas to measure T_i , with the charge exchange diagnostic, which was found to be much lower than T_e , $\sim 2-3$ keV, and not to exhibit a steep profile gradient [22]. ITBs with electron heating in plasmas with negative magnetic shear have been observed on other machines, for example with electron cyclotron resonance heating in DIII-D [23], in the Rijnhuizen Tokamak Project (RTP) [24] and in the Frascati Tokamak Upgrade (FTU) [25], or with LH waves, in Tore Supra [26] and JT60-U [10].

In addition to the high core temperature, the ECE measurements show sawtooth-like collapses (Fig.1(c)), which are observed also in the soft X-rays measurements (Fig.1(d)) (the measurement frequency of LIDAR is too low to measure these collapses). The soft X-ray measurements exhibit a strong gradient in the radial profile. Since the soft X-rays signal is proportional to $n_{e0}^2 T_{e0}^{2.3} z_{eff}$, where z_{eff} is the effective charge of the plasma, and the n_e profile remains flat, the gradient comes primarily from the large T_e gradient. q is well above 1 during the whole preheat phase, hence the collapses are not the results of conventional $q=1$ sawteeth. Their inversion radius corresponds to the position of the T_e gradient caused by the ITB. The collapses are observed only on shots that exhibit T_e ITBs and a large negative magnetic shear. In general, there is no obvious precursor MagnetoHydroDynamic (MHD) modes to these collapses. T_e collapses are observed also in the electron heated negative magnetic shear plasmas in DIII-D²⁷. However, they are attributed to $m=1$, $n=1$ kink instability and are linked to the presence of a $q=1$ surface in the negative magnetic shear configuration.

There is now a large database of shots with LH during preheat in JET, in which the line integrated density ranges between $0.4 \times 10^{19} \text{ m}^{-3}$ and $1.7 \times 10^{19} \text{ m}^{-3}$, B_T between 2.6T and 3.4T, and P_{LH} between 0 and 3.4MW. The plasma current ramp-up remains the same for all shots, having been optimised to avoid the MHD instabilities that are observed when the plasma current at the edge is too large [8]. T_e ITBs have been observed at a LH power as low as 1.3MW. However, in several cases, no ITB is observed. For example, shots 51886 and 51897 have similar plasma parameters and P_{LH} . However, as shown on figure 2, shot 51886 does not have an ITB, contrary to 51897. Observation of the first few hundreds ms of these shots (fig.4), show that the initial plasma current increase is not reproducible (Fig.4(a)), being lowest for shot 51886. Figure 4 also shows the data from another shot, 51896, that has an intermediate value of the current. It does have an ITB, but it is situated at a smaller R_{MAJ} , 3.28m, in comparison to 3.35m on 51897. This behaviour is systematic throughout the database: plasmas with a low initial current (i.e. $< 0.3\text{MA}$ at 0.6s) will not exhibit an ITB later during LH preheat. The plasma internal inductance, l_i , is calculated with EFIT using magnetic measurements (shown on Fig.4(d) for shots 51886, 51896 and 51897). Only cases with a fast current rise lead to a low l_i , indicative of a broad, possibly hollow, current profile, prior to the start of the LH pulse. This could be explained by the fact that a current ramp which is fast, compared to the current diffusion time, results in an accumulation of current in the plasma periphery. Also, a higher current leads to a higher temperature, and hence a slower current diffusion. These two factors can produce a hollow current profile. However, a very high current rise can lead to MHD instabilities associated with excessive current at the periphery, resulting in a redistribution of the current and preventing the development of a hollow current profile. Optimisation of the initial current rise has made possible the reproducible generation of target q profile with large negative magnetic shear. This allows systematic investigation of the ITB behaviour, and more efficient development and exploitation of high performance transport barriers.

In plasmas with reproducible initial parameters, it is possible to control the radial position of the electron ITB by changing P_{LH} . Figure 5 shows that the normalised radius of the ITB increases from 0.20 to 0.38 when P_{LH} is varied from 1.3 to 3MW. Figure 5 was obtained using the soft X-ray data, taking the difference between the inversion radius of the collapse event on the low field side and that on the high field side, and dividing it by the plasma diameter. This eliminates any effect from the Shafranov shift, which increases when the LH power increases, and pushes the plasma centre outwards. The data from soft X-rays was used instead of ECE since this diagnostic does not cover the whole plasma. The outboard radial location of the inversion radius measured by ECE agrees with the soft X-ray measurement. It corresponds to the radius of highest T_e gradient due to the ITB. There are no MSE measurements available on these shots, but measurements on similar plasmas show that the width of the ITB is proportional to the width of the region with large negative shear. This indicates that LH can control the ITB, through control of the q profile.

In dedicated experiments, the preheat phase has been prolonged to 10s. The electron ITB survives for as long as the LH pulse [22], although the radius of the ITB shrinks with time.

The use of LH power during the preheat phase of JET plasmas has greatly extended the range of target q profiles available in JET. This has brought new elements to the study of the relation between the q profile and the triggering and evolution of the ITBs that are obtained when high additional power (NBI and ICRH) is applied following the preheat phase.

3. ITBS WITH NBI AND ICRH IN NEGATIVE MAGNETIC SHEAR PLASMAS

Unlike the plasmas with LH described above, JET plasmas with NBI and ICRH power can produce internal barriers in the particle and ion energy transport, in addition to the electron energy transport. These ITBs are seen as discontinuities in the gradient of T_e , T_i , n_e and toroidal velocity (v_ϕ) profiles. In JET plasmas with low but positive magnetic shear, ITBs are formed near the location of an integer q surface [8] (typically $q=3$ or 2 , depending on the time of the main heating). The triggering of the ITBs is attributed to coupling between an edge MHD mode, destabilised when q at the edge reaches an integer value, and a mode at a rational q surface [28] inside the plasma. The internal mode is thought to locally enhance the ExB shearing rate, which is one of the key factors for turbulence stabilisation [29], and leads to an ITB inside the integer q surface. In plasmas with negative magnetic shear, two types of ITBs can be seen, often simultaneously [8, 30]. One of them is typically at a small major radius ($<3.5\text{m}$), and does not seem to be related to integer q surfaces. The second one is usually situated at a wider radius (up to 3.7m), and is linked to integer q surfaces. The triggering mechanism has not been identified yet, but in several shots, the ITBs appear when the minimum value of q , q_{\min} , reaches an integer value [30], similarly to observations that have been made in reversed shear plasmas in the Tokamak Fusion Test Reactor (TFTR)[6]. At a moderate level of NBI and ICRH power (additional power (P_{ADD}) $<16\text{MW}$), plasmas with negative magnetic shear form ITBs more easily than plasmas with low but positive magnetic shear [8,15,30]. Moreover, the additional power required to access very high performance is lower in negative magnetic shear plasmas [15]. An ITB scenario with long NBI and ICRH power pulses (up to 8s) has been developed in JET that demonstrates the role of the q profile in the ITB triggering and termination. The time evolution of such a plasma is shown in figure 6. It has a q profile with deeply negative magnetic shear at 4.4s, obtained by applying 3MW of P_{LH} during preheat, which is subsequently heated with high NBI and ICRH power (Fig.6(a)). At the start of the high power phase, I_p is still ramping up. The current flat top begins at 6.0s, with $I_p=2.4\text{MA}$, and $B_T = 3.4\text{T}$. This scenario is characterised by reproducible ITBs emerging at two times during the pulse. The presence of the ITBs is made clear by the increase in T_e , n_e , T_i (Fig.6(b)) and the toroidal velocity, and by a strong increase in neutron yield (Fig.6(c)), attributed mainly to the large core ion temperature. Soon after the start of the main heating phase the plasma forms an edge pedestal with associated ELMs (Fig.6(d)), which remains until the end of the heating pulses. The ICRH and NBI powers do not change during the high additional power phase. The plasma density also remains constant, except during the ITBs where it peaks. However the current profile, and hence the q profile, is evolving, although very slowly. Figure 7 shows q_{\min} for the q profiles calculated by EFIT constrained with Motional Stark Effect

(MSE)[31,32] or polarimetry measurements that were available for that type of shot, as a function of the time of the measurement. At the start of the main heating, q_{\min} is near 3. At the end of the heating pulses, 7s later, the magnetic shear is still weakly negative in most cases, with q_{\min} below 2. The evolution of the q profile illustrates how slow the current diffusion is, with a diffusion time at mid-radius of ~ 18 s. The first ITB is triggered at ~ 5.4 s, and lasts until ~ 6.9 s, at which time the edge pedestal temperature and density increase and the ITB is lost. On similar shots a snake [33], related to a $q=3$ surface, is observed at the same time as the ITB degradation and/or termination. Snakes are MHD modes triggered by the simultaneous presence of a strong pressure gradient, a low magnetic shear and an integer q surface, and are often observed during ITBs, usually leading to their termination [5]. On shot 53432, the snake is observed at 6.5s, and the MHD analysis indicates that there is a $q=3$ surface at 3.66m. This corresponds to the outer ITB location at that time (Figure 8), where the pressure gradient is maximal. The location is also consistent with that of the $q=3$ surface (Figure 9), when taking into account the fact that the q profile evolves between the time of the q profile measurement (4.44s) and the time of the snake (6.5s), due to the current diffusion. According to figure 8, q_{\min} goes down by ~ 0.4 in that time. If the q profile retains a shape similar to what is measured at 4.44s (Figure 9), then at 6.5s the $q=3$ surface is located at $R_{\text{MAJ}} \sim 3.65$ m. These observations confirm the link between the first ITB and the $q=3$ surface. The second ITB is triggered when q_{\min} reaches 2, and persists until the heating pulse ends. The q profile measurements available for these shots show that at the end of the heating, q_{\min} is below 2.

4. ITBS SUSTAINED BY LH IN STRONGLY HEATED PLASMAS

4.1. Coupling of LH to ITB plasmas with ELMy H-mode

Once the optimum target q profile for triggering of an ITB providing improved plasma performance is obtained, the problem of maintaining it remains. As described in part III, strongly heated ITBs are usually transient, often disappearing due to MHD events linked to the q profile evolution, or developing very strong pressure gradient that takes them towards the beta limit and cause plasma disruptions. ITBs in other tokamaks exhibit similar behaviour [3,4]. In order to maintain the q profile in a favourable configuration, active control of the current profile during the ITB phase is required. Transport simulations have shown previously that ~ 3.5 MW of LH would be sufficient to maintain a reversed q profile during a high temperature ITB plasma [34], when added to the other non-inductive current contributions from NBI and bootstrap current. However, a major obstacle prevented the use of LH in strongly heated plasmas in JET. In JET, with MK-IIIGB divertor, ITB plasmas with high additional power always exhibit an edge pedestal with ELMs (see Fig.6(d) for example). These plasmas have a smaller decay length of the density than L-mode plasma. As a consequence, the density in the scrape-off layer, and hence in front of the LH launcher, gets below or near the slow wave cut-off density ($1.7 \times 10^{17} \text{ m}^{-3}$ for waves at a frequency of 3.7GHz), making it impossible to couple the LH wave. Previously, in these conditions, it had not been possible to inject a significant amount of P_{LH} during H-mode OS plasmas in JET. By puffing D_2 gas near the launcher,

coupling in difficult conditions can be improved [35]. However, the quantity of D_2 needed to improve coupling in OS plasma with H-mode destroys the ITB. CD_4 was found to increase the SOL density significantly, without affecting the centre of JET H-mode plasmas [36,37]. When puffed near the launcher, CD_4 led to a dramatic improvement of lower hybrid wave coupling, without detrimental effect on the ITB [16,38]. This, in addition to the optimisation of the plasma shape to fit the launcher shape and reduce the distance to the plasma, has made it possible to couple reliably more than 3MW of P_{LH} , and up to 3.8MW peak power, in plasmas with an ITB and edge pedestal. This is illustrated on figure 10, which compares strongly heated plasmas with and without CD_4 puffing. In the latter case, the pressure gradient due to the ITB becomes too high, leading to a plasma disruption.

4.2. Effect of LH on the q profile of ITB plasmas in strongly heated plasmas

To test the effect of LH on the q profile of ITB plasmas with high heating power, the long pulse scenario with reversed q profile and $B_T=3.4T$, $I_p=2.4MA$, described in part III, was used (see Fig.6 for example). Usually in JET ITB plasmas, the ratio B_T/I_p is ~ 1 . However, a lower I_p is used here to get a higher poloidal beta value, which in turn leads to a higher fraction of bootstrap current. A lower I_p also makes the LH contribution more significant. During the high power phase, the position of the X-point and divertor target strike points were controlled simultaneously in feedback to avoid touching the central part of the divertor, as this leads to an increase in recycling detrimental to the ITB performance [39]. At the same time, the plasma shape is adapted to fit the launcher shape. To improve LH wave coupling, CD_4 is injected during the high power phase, at a rate of $\sim 8 \times 10^{21}$ electrons/s. This was done also on the pulses without LH, to provide a good comparison. Shot 53432 (figure 11) is a reference pulse without LH during the high power phase. Its target q profile is deeply reversed, (see Fig. 9), and the T_e profile of the first ITB is on figure 8.

Figure 12 shows the time evolution of shot 53429, where LH is re-applied during the high power phase, after a preheat with LH similar to 53432. As shown on Fig. 9, the target q profile is similar on both shots. To keep the same total P_{ADD} , the ICRH power is decreased to 4MW, instead of 6.5MW. This has the effect of bringing the total P_{ADD} near the threshold for ITB formation, before P_{LH} is re-applied. As a consequence, the formation of the first ITB is delayed when the NBI power steps down momentarily. However, as soon as P_{LH} starts, and the NBI power steps up, the ITB is formed. This first ITB lasts for several seconds, as can be seen by the T_e , T_i and neutron yield evolution with time, Fig.12(b),(c) and (d). In contrast, the first ITB on 53432, without LH power, lasts for only 1s. On both shots, T_e and T_i measurements indicate that the ITB footpoint moves outward with time, from $R_{maj}=3.60m$ to $R_{maj}=3.66m$. However, on the shot with LH, (53429) this evolution occurs in 2.3s, instead of just 1s for 53432 (Fig.8). This indicates that the q profile evolution has been slowed down, or that the magnetic shear at the location of the ITB has been modified. Another difference is that on shot 53429, with LH power, the second ITB, triggered by q_{min} reaching 2 at 11.7, occurs $\sim 1.4s$ later than on 53432. This also points out to a slowing down of the q profile evolution. The q profile at the end of the NBI pulse of another pair of shots, without LH during

main heating (53427), and with LH (53431), was measured using MSE. The same scenario as 53432 and 53429 was used, with 2MW less P_{ADD} . As shown in figure 13, the negative magnetic shear is maintained on the shot with P_{LH} during the main heating (53431), while it is flat on the shot without LH. Moreover, q_{min} is higher on 53431, which is consistent with the late emergence of the second ITB.

The LH power deposition and current was calculated using the 2-D relativistic Fokker-Planck and ray tracing code DELPHINE [40]. The results at 6.5s, when the ITB begins, and at 9.5s, just before it ends, are shown of figure 14. The power deposition is mainly determined by T_e , hence the LH current peaks at the position of the ITB. This means that the lower hybrid contribution to the total current affects the magnetic shear at the location of the ITB. In JET, the resistive current diffusion time of strongly heated plasmas at mid radius is of the order of 20s. A very large amount of current would be required to modify significantly the q profile on that time scale. However, local modifications to the magnetic shear are enough to affect the ITB behaviour, and are possible on a smaller time scale. In this case, the fraction of LH current to total current is $\sim 15\%$.

Other experiments were performed at $I_p=2.0$ MA with more than 3 MW of P_{LH} , to maximise the LH current fraction [41,42]. On such shots, the q profile evolution is almost frozen. As a consequence, ITBs can be sustained for times of the order of the current diffusion time, and several times longer than the confinement time. On shot 53521 for example, the ITBs on n_e , T_e and T_i last as long as the high power heating phase, nearly 8s, which represents 27 times the energy confinement time. A strong peaking on the density occurs, which leads to a large accumulation of impurities [42]. Two transient collapses of the ITBs occur, evacuating large amount of impurities, but the ITBs recover each time. The lower hybrid current forms $\sim 30\%$ of the total current, and the total non-inductive current, including the NBI and bootstrap contributions, is more than 80% of the total current [41,42]. The large fraction of bootstrap current plays an important role in maintaining the current profile. However, the LH current is required to sustain the negative magnetic shear.

5. CONCLUSIONS

It has been demonstrated that the use of LH waves can effectively control the q profile, and hence the ITBs, in negative magnetic shear plasmas in JET. The study of the effect of the q profile and magnetic shear on ITB triggering and evolution is enriched by the large range of q profiles now available, in a reproducible way, for experiments in JET. More importantly, the results presented here confirm that ITBs in strongly heated plasma can be maintained for times significant on the scale of the current diffusion. This opens up the possibility to develop scenarios for the study of steady-state ITB plasmas which are desirable for a fusion power plant, including the exploration of feedback control of the ITB, an area of study that is showing promising results in JET^{41,43}.

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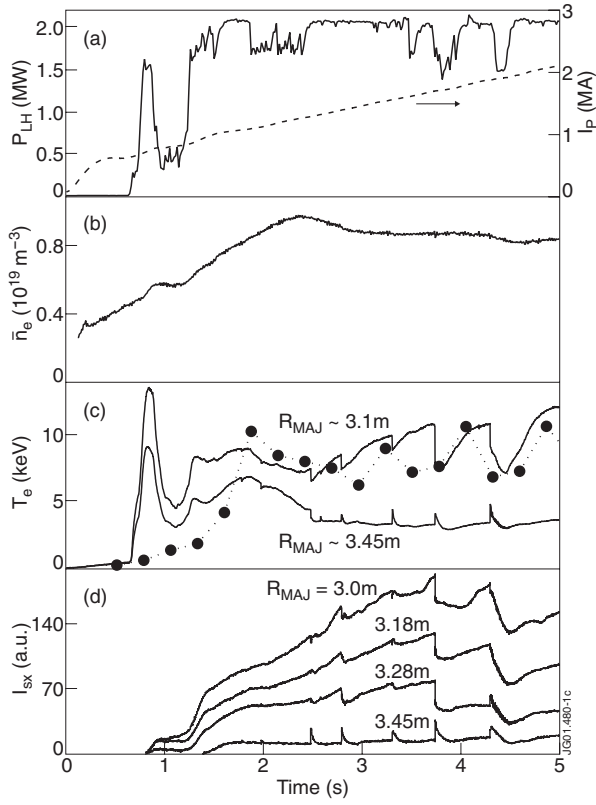


Figure 1. Preheat of shot 51897 with a) plasma current (I_p) and lower hybrid power (P_{LH}), b) line averaged electron density (n_e), c) core electron temperature (T_e) from LIDAR (dot-dash line) and T_e from ECE at major radius (R_{MAJ}) = 3.1m and 3.45m, d) soft X-ray intensity (I_{SX}) at R_{MAJ} =3.0m, 3.18m, 3.28m and 3.45m.

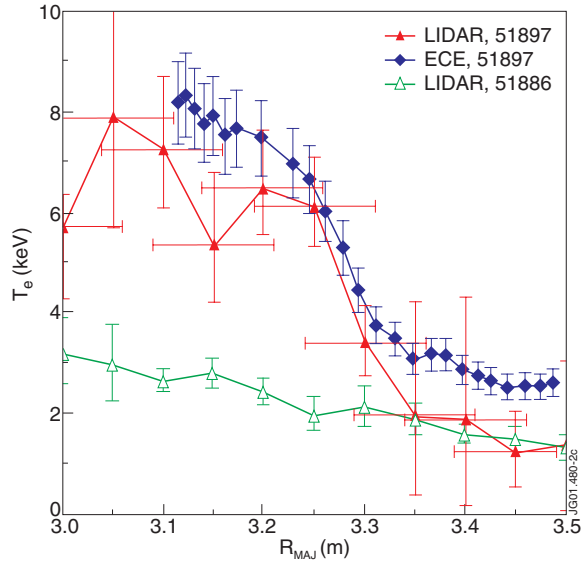


Figure 2. T_e profile measurements at 3.1s from LIDAR (full triangles) and ECE (full diamonds) for shot 51897, and from LIDAR for shot 51886 (open triangles). Both shots have P_{LH} =2MW.

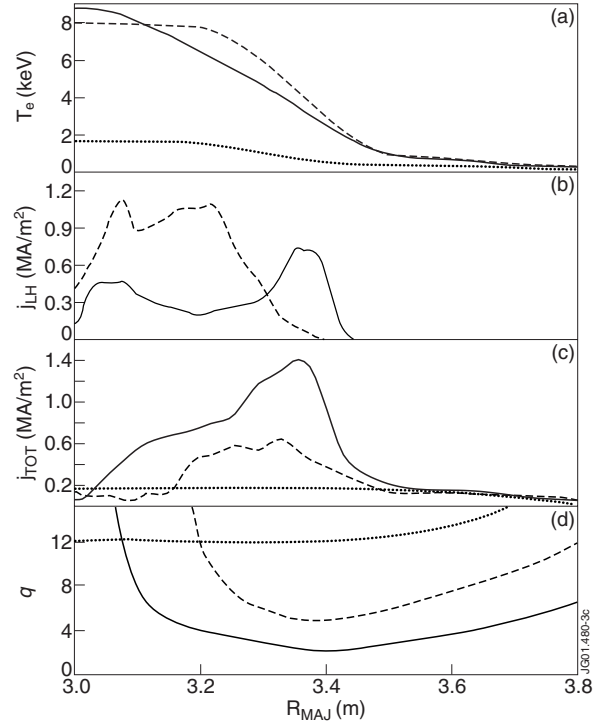


Figure 3. a) Smoothed experimental T_e profiles used in JETTO, b) j_{LH} , c) total current density (j_{TOT}) and d) q profiles calculated by JETTO, at t =1.0s (dotted line), 2.0s (dashed line) and 4.0s (solid line).

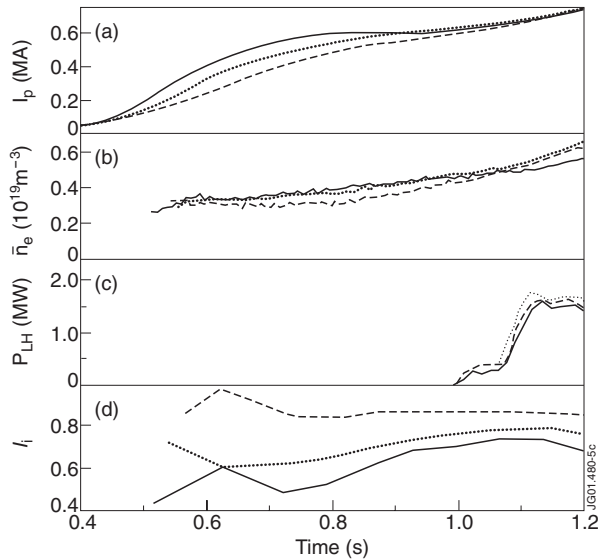


Figure 4. Plasma initiation for shots 51886 (dashed line), 51896 (dotted line) and 51897 (full line), showing a) I_p , b) n_e c) P_{LH} and d) I_r .

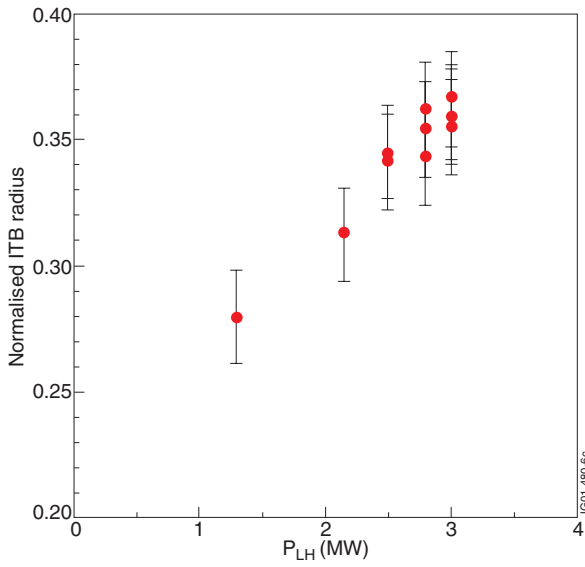


Figure 5. ITB normalised radius as a function of P_{LH}

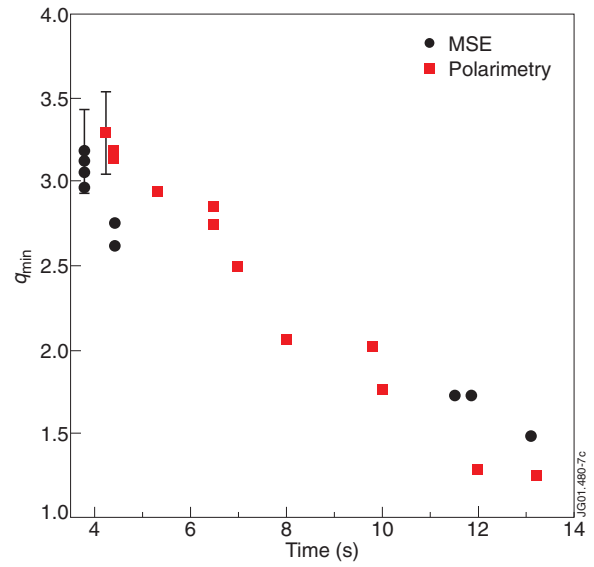


Figure 7. Time evolution of q_{min} from EFIT constrained by Motional Stark Effect or polarimetry measurements, the data comes from 7 similar shots.

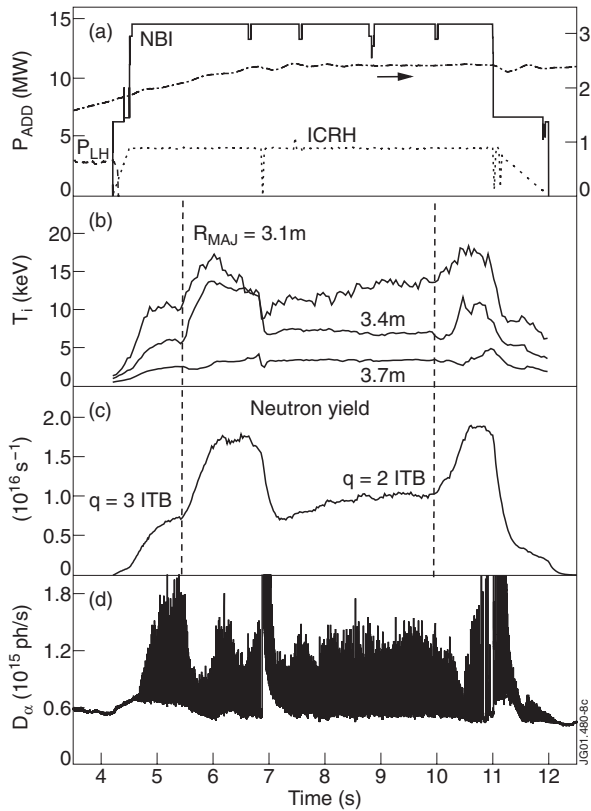


Figure 6. Time evolution of the high heating phase of shot 52874, showing, a) additional power (P_{ADD}): P_{LH} (dashed line), P_{ICRH} (dotted) and P_{NBI} (full) and I_p (dashed and dotted line), b) T_i at $R_{MAJ}=3.1m$, $3.4m$ and $3.7m$, c) neutron yield and d) D_{α}

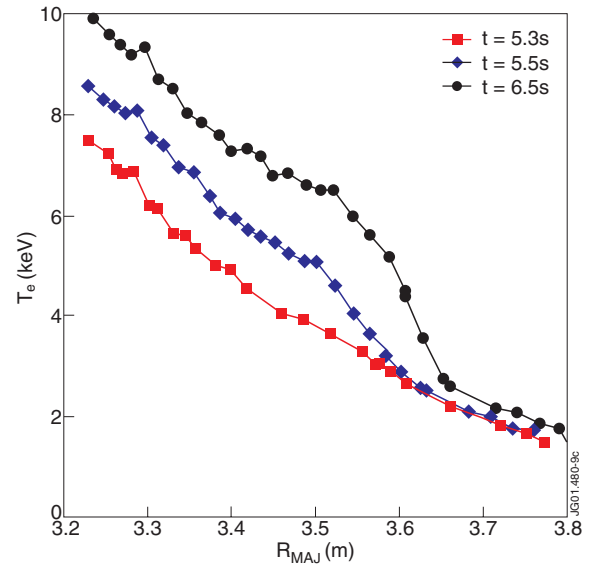


Figure 8. Temperature profile of the first ITB on pulse 53432 at 5.3s, 5.5s and 6.5s.

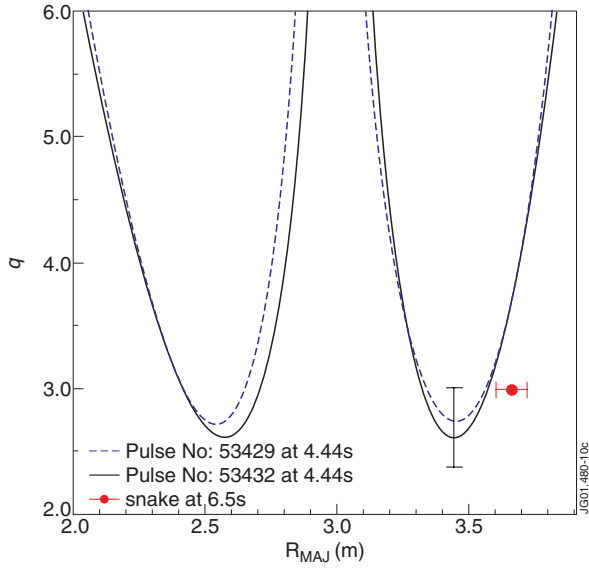


Figure 9. Target q profiles (4.44s) of 53429 and 53432 from EFIT with MSE measurements, and position of snake at 6.5s on 53432.

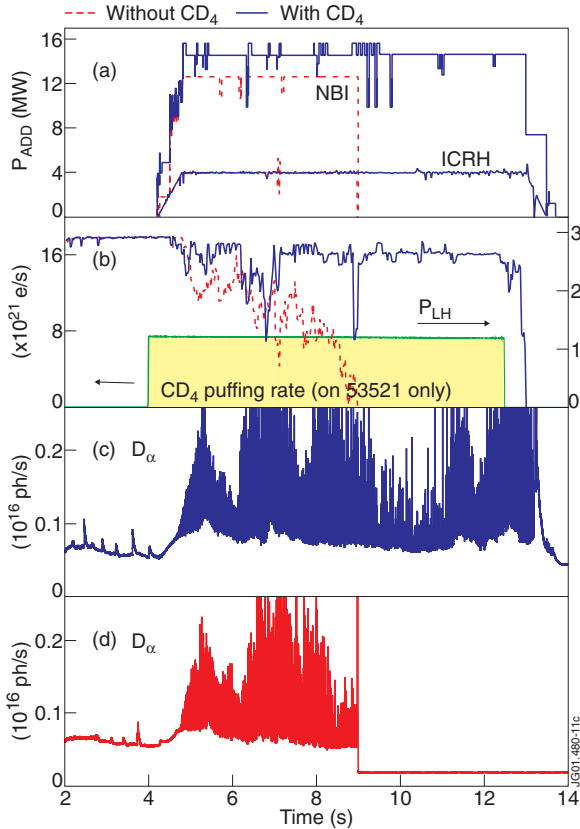


Figure 10. Evolution of shot 53514 (without CD_4 , dashed line) and shot 53521 (with CD_4 , full line), showing: a) P_{NBI} and P_{ICRH} , b) P_{LH} and CD_4 (curve with shaded area), and D_α light for c) shot 53521, and d) shot 53514.

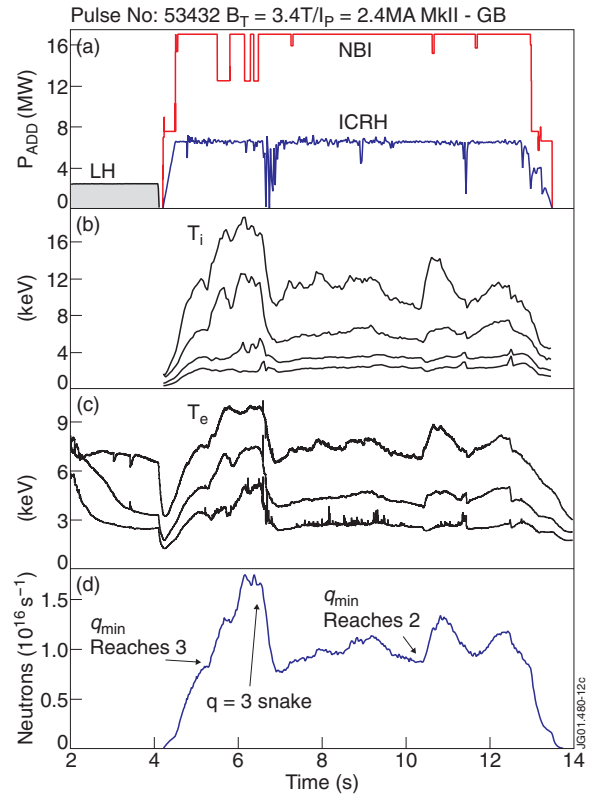


Figure 11. Time evolution of reference pulse 53432 with a) P_{LH} , P_{ICRH} and P_{NBI} , b) T_i for (from highest to lowest T_i) $R_{maj} = 3.2m, 3.4m, 3.6m, 3.8m$, c) T_e for (from highest to lowest T_e) $R_{maj} = 3.22m, 3.41m$ and $3.59m$ and d) neutron yield.

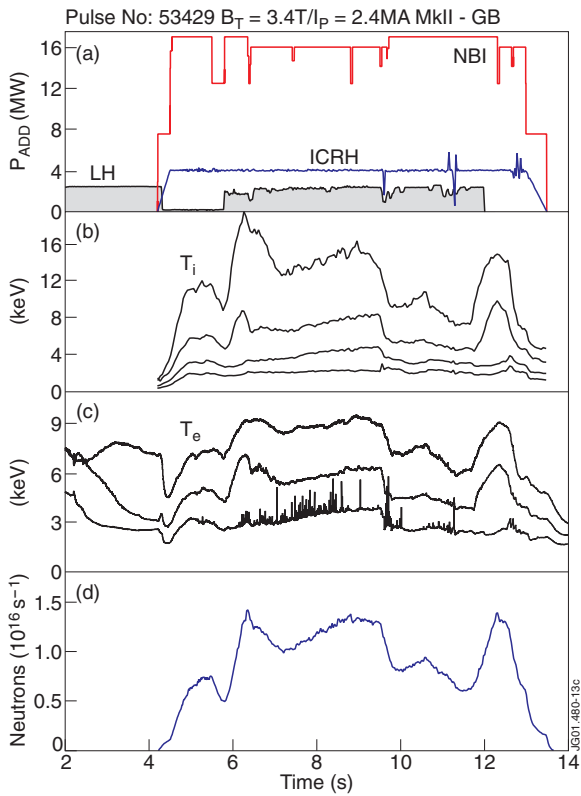


Figure 12. Time evolution of pulse 53429 with LH re-applied during main heating with a) P_{LH} , P_{ICRH} and P_{NBI} b) T_i for (from highest to lowest T_i) $R_{maj}=3.2m, 3.4m, 3.6m, 3.8$, c) T_e for (from highest to lowest T_e) $R_{maj}=3.20, 3.38m, 3.60m$ and d) neutron yield.

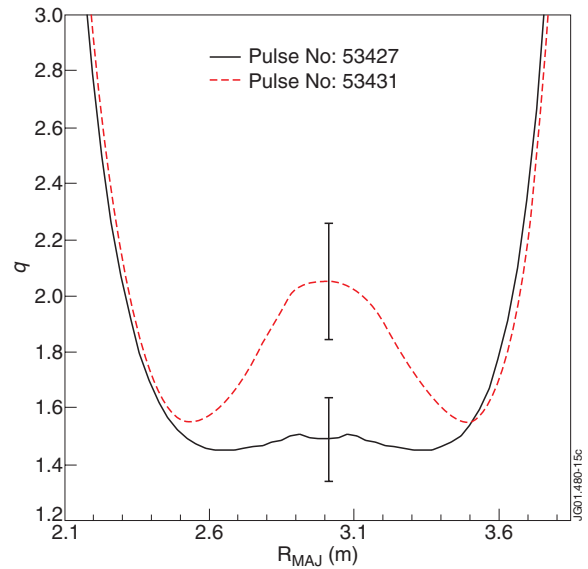


Figure 13. q profiles, from EFIT with MSE measurements, at the end of a shot without LH during the high power phase, 53427 (full line), and with LH during the high power phase, 53431 (dashed line).

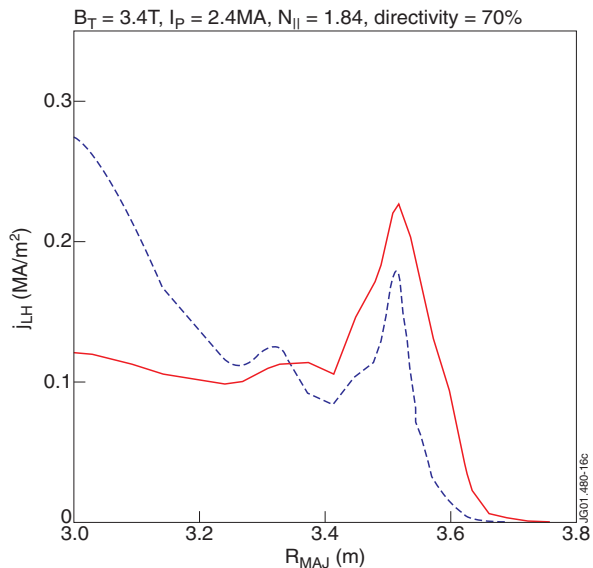


Figure 14. Calculated LH driven current profile for shot 53429 at 6.5s (dashed line) and 9.5s (full line).