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The Effect of LHCD on the Evolution of Internal Transport Barriers in JET

C.D.Challis[1], Yu.F.Baranov[1], C.Gormezano[2], C.W.Gowers[1], N.C.Hawkes[1], T.C.Hender[1], E.Joffrin[3], J.Mailloux[1], D.Mazon[3], S.Podda[2], S.Sharapov[1], B.C.Stratton[4], D.Testa[5].

JET Joint Undertaking, Abingdon, Oxon., OX14 3EA, UK
[1]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon., OX14 3DB, UK
[2]Centro Ricerche Energia, Associazione Euratom/ENEA/CNR sulla Fusione, CP 65, 00044 Frascati, Rome, Italy
[2]Association Euratom-CEA, CEA-Cadarache, F-13108, St. Paul lez Durance, France
[4]Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543, USA
[5]Plasma Science and Fusion Centre, Massachusetts Institute of Technology, Cambridge, USA

1. Introduction

Tokamak plasma regimes where the heat transport is reduced in the plasma interior by the presence of an internal transport barrier (ITB) have been investigated on many experimental devices. A common method that has been used for the production of ITBs is the application of heating early in the discharge before the plasma current has fully penetrated (e.g. [1-4]). Using this technique the central safety factor (q_0) can be significantly above unity and the magnetic shear ($s=r/q(dq/dr)$) low or negative in the plasma core when the heating is applied.

In JET Optimised Shear experiments this method has been used to produce ITBs, mainly with combined neutral beam and ion cyclotron resonance heating [5]. The formation of these ITBs has been linked to the presence of integer q surfaces in the plasma interior in a region of weak positive magnetic shear [6].

In this paper experiments are reported where the magnetic shear of the plasma was further reduced or reversed in the plasma core by applying lower hybrid heating and current drive (LHCD) prior to the main heating pulse. By this method ITBs were generated that do not appear to be linked to integer q surfaces.

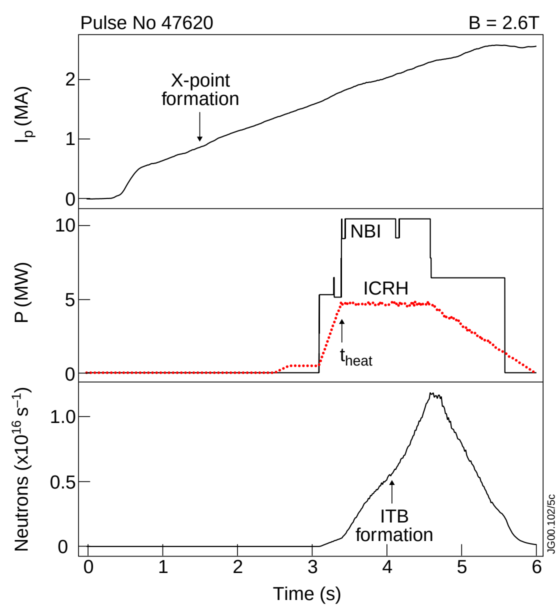

Fig.1. Typical time evolution of the plasma current, heating power and neutron yield in the JET Optimised Shear regime.

2. JET Optimised Shear Regime

The time history of a typical JET Optimised Shear experiment is illustrated in Fig.1. A 'strong' transport barrier, and consequent high fusion performance, can be achieved if the main heating is applied when the central value of q is just below 2 [6]. In this case the position of the q=2 surface within the plasma also correlates with the location where the ITB formation occurs. Figure 2 shows two examples where the radial position of the q=2 surface was altered by varying the start time of the main heating pulse (t_{heat}). The q-profiles shown were determined using the EFIT equilibrium reconstruction code [7,8] constrained by motional Stark effect (MSE) data [9] and the temperature profiles were measured from ECE emission with a heterodyne radiometer. In the case with delayed heating the ITB formed at a wider radius, as shown by the evolution of the electron temperature profile. The location of the ITB correlates well with the q=2 surface in the target q-profile. A mechanism involving the perturbation of plasma profiles by magnetohydrodynamic (MHD) activity associated with integer q surfaces has been proposed to explain this phenomenon [10]. It is believed that the underlying cause of the reduced transport is probably due to localised turbulence suppression, perhaps by sheared plasma flow [11] in a low magnetic shear region, and that the plasma behaviour close to the integer q surfaces acts as a trigger. The wider ITB obtained with delayed heating is typically 'weaker' than is the case with a q=2 surface near the plasma centre, perhaps due to the increased magnetic shear at the larger plasma radius.

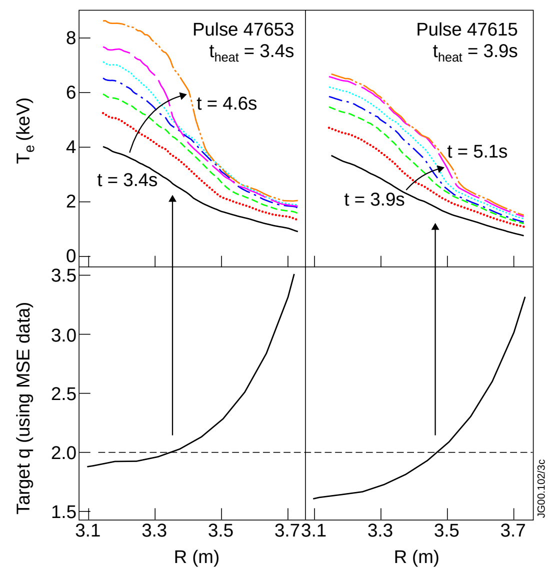

Fig.2. Target q-profile (at t_{heat}) and electron temperature profile evolution during the main heating pulse for two pulses with different main heating start times.

3. Effect of LHCD on the Target q-profile

The application of low power LHCD in the prelude phase before the main heating pulse is very effective for broadening the target current profile. Figure 3 shows the reduction in plasma internal inductance resulting from the application of LHCD early in the current ramp-up phase. It is likely that both the non-inductive current drive and modification of the electron temperature profile contribute to this effect [12].

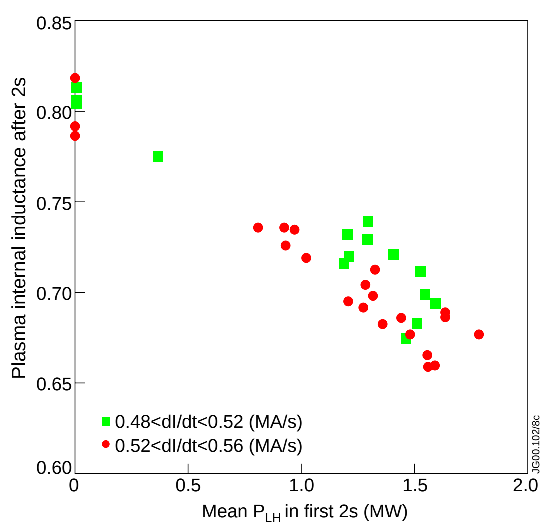

Fig.3. Plasma internal inductance 2 secs. after plasma initiation plotted against the average LH power up to the same time. The current ramp rate in this period is also indicated.

Increasing the plasma current ramp rate also acts to reduce the plasma inductance, as indicated in Fig.3. However, at high ramp rates MHD instabilities were encountered when certain integer q surfaces, most commonly q=6, were present near the plasma edge. These acted to redistribute the plasma current. Increasing the LHCD power level, on the other hand, did not tend to destabilise these modes. This indicates 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.

4. ITBs Produced after LHCD Prelude

Figure 4 shows the target q-profile provided for main heating in a pulse using LHCD throughout the prelude phase at an average power level of 2MW. The profile shown was calculated using EFIT constrained by MSE measurements and is, in this case, consistent with polarimetry [9]. An ITB is typically formed in the plasma core during the main heating pulse after such an LHCD prelude, as illustrated in Fig.4, which does not appear to be linked with the location of an integer q surface. It is more likely that the presence of this ITB in the plasma core is linked to the region of reversed magnetic shear.

The possibility that a q=3 surface was present near the plasma centre in this case cannot be ruled out due to the uncertainties in the q-profile determination. So the heating start time was varied to investigate the sensitivity of this ITB to the presence of integer q surfaces in the plasma interior. The position of the ITBs formed with the various heating start times can be seen in Fig.5. The core ITB occurs in all cases at roughly the same location and does not significantly expand during the pulse (see Fig.4). This is in contrast to the integer q surface linked ITBs shown in Fig.3, which are highly sensitive to the timing of heating pulse, and supports the conclusion that the core ITB formed after an LHCD prelude is not linked to integer q surfaces.

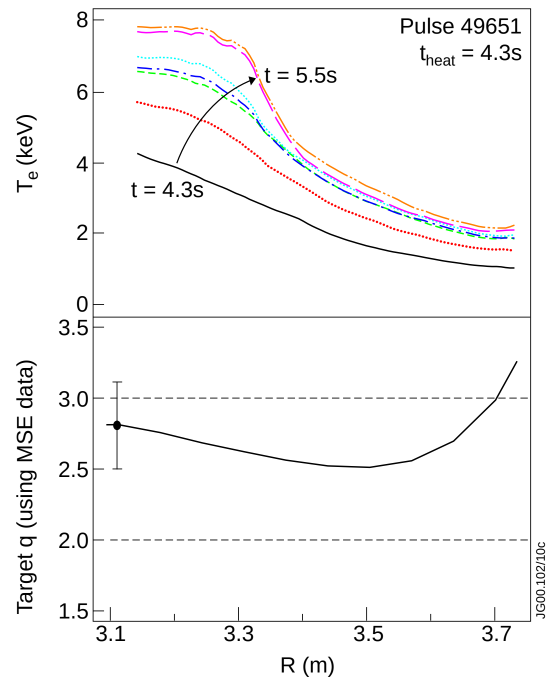

Fig.4. Target q-profile (at t_{heat}) and electron temperature profile evolution during the main heating pulse a pulse with an LHCD prelude.

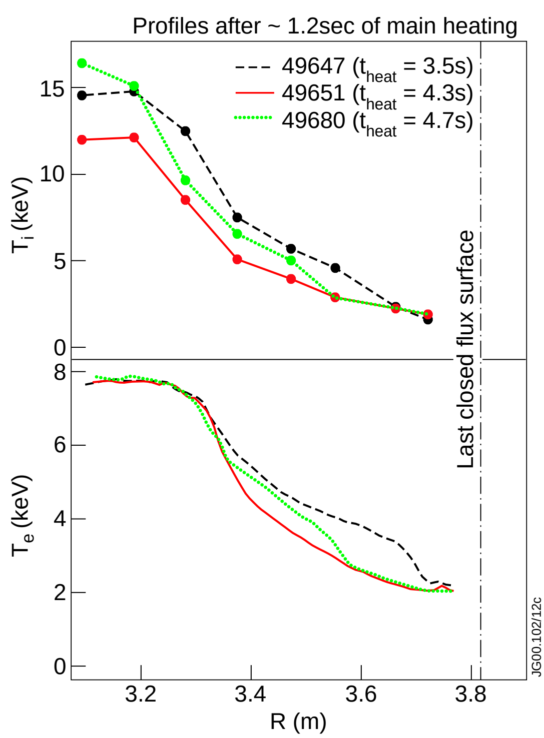

Fig.5. Electron and ion temperature profiles during the main heating phase, after an LHCD prelude, for three pulses with different main heating start times.

A second ITB is also seen in two of the cases shown in Fig.5. The ion temperature profiles shown were determined using charge exchange spectroscopy. The outer ITB varied in location as the heating start time was changed, which is consistent with an integer q surface triggered ITB in a region of weak positive magnetic shear, and demonstrates that both types of ITB can be obtained simultaneously. In general, both ITBs are evident on the radial profiles of the electron and ion temperature, as well as the plasma density. In this sense the experiments do not point to any fundamental difference in the underlying processes controlling the transport reduction in the two cases.

5. Power Threshold for ITB Production

The power required to form an ITB in the JET Optimised Shear regime tends to increase with toroidal magnetic field strength [13]. Figure 6 shows the power at which clear ITBs were achieved at several values of magnetic field in plasmas with q_0 close to 2. A pulse at 2.6T with an LHCD prelude is included for comparison indicating that, in this case, an ITB was obtained at a much lower power level. The number of discharges with an LHCD prelude is, so far, very small, but these preliminary indications suggest that the power threshold for ITB production might be very sensitive to the shape of the q-profile.

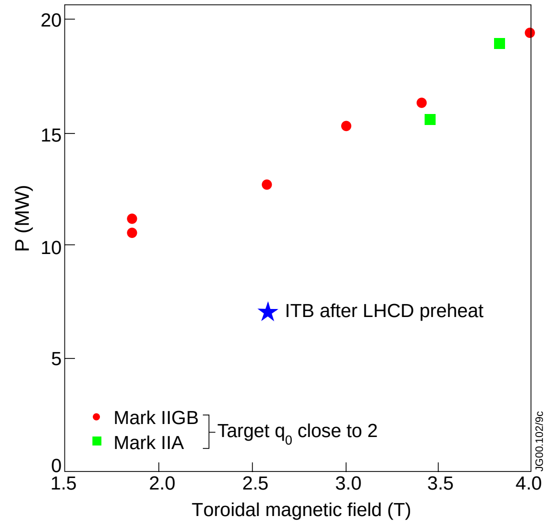

Fig.6. Heating power level required to form a clear ITB plotted against toroidal magnetic field strength (the LHCD preheat case represents the lowest power so far used rather than a threshold level).

6. Summary and Conclusions

Experiments have been performed at JET using LHCD to modify the target q-profile before a high power heating phase. ITBs produced in this way are evident as steep gradients on the ion and electron temperature and plasma density profiles, just as with typical JET Optimised Shear plasmas. However, in contrast to the existing regime, they do not seem to be linked to the presence of integer q surfaces in the plasma interior and appear to be located in a region of negative magnetic shear. A link between the ITB position and critical parameters, such as the radius of the minimum q value, has not yet been established. Both types of ITB can be obtained simultaneously to produce 'double' ITB plasmas and initial results suggest that modifying the target q-profile can substantially alter the power threshold for ITB production.

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