Role of MHD in the triggering and destruction of ITBs in JET

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Introduction

Studies of the underlying process to form internal transport barriers (ITB) have remained an important part of the Optimised Shear experiments [1] on JET during 1999. Analyses have shown links between integer q surfaces and ITBs [2]. A power timing scan experiment has revealed that the q=2, and also the q=3 surfaces appear to play a major role in the formation of the barrier. In addition, the sensitivity to the integer q surfaces seems to decrease as the input power is increased above the power threshold for ITB production. Signs of the role of magnetic rational surfaces has also been observed on other devices such as JT60-U [2] or TFTR [3]. This experimental evidence suggest that a trigger mechanism might be responsible for the onset of ITBs.

This paper presents a new candidate mechanism explaining the triggering of ITBs in JET which is consistent with the experimental evidence on the power threshold and on the role of integer q surfaces. In particular, the coupling between edge magneto-hydrodynamic (MHD) activity and internal integer q surfaces is analysed both experimentally and by a computational model. This mode coupling process is a good candidate for the origin of the triggering of ITBs.

Role of rational q surfaces in the ITB formation.

The heating timing scan experiment [2] (2.6T with 10.5MW of neutral beam heating and 5MW of ion resonance heating) has revealed the link between integer rational surfaces and ITB formation. In this experiment, the time of the main heating is scanned during the current rise (0.4MA/s). High performance ITBs are only encountered when the target q_o is close to 2 (fig 1 and 2a). In this case, the foot of the barrier is located at 3.35-3.4m (fig 2b).

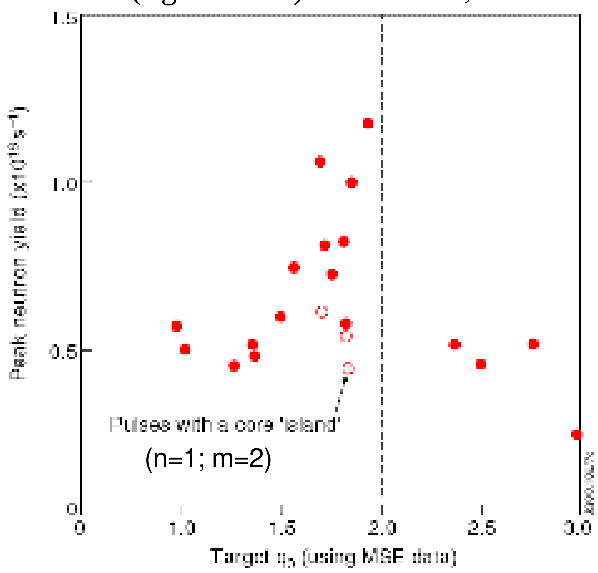

Fig1 : Peak fusion yield obtained against q_o when scanning the heating time.

With later heating and therefore at lower target q_o, weaker ITBs are formed at a wider radius (typically 3.5m) consistent with the location of the q=2 surface. Also, early heating can produce very wide ITB (foot at R=3.65m) indicating a possible link with this time the q=3 surface. This is indeed confirmed statistically when comparing the ITB foot point location determined on temperature profile with the position of the q=3 surface determined by the EFIT equilibrium code. The q=3 surface lies systematically outside the ITB foot point. This is very similar to the observations in JT-60U [3] for weak positive shear plasma.

It is also important to note that with the optimum timing either prompt ITBs or flattening are observed on the electron temperature profile. This flattening is associated with the presence of a core q=2 island growing possibly in a low shear region in the plasma center confirming that q_o is close to 2.

In addition to revealing the role played by integer rational q, the heating timing scan is also a very useful tool to study the ITB triggering itself.

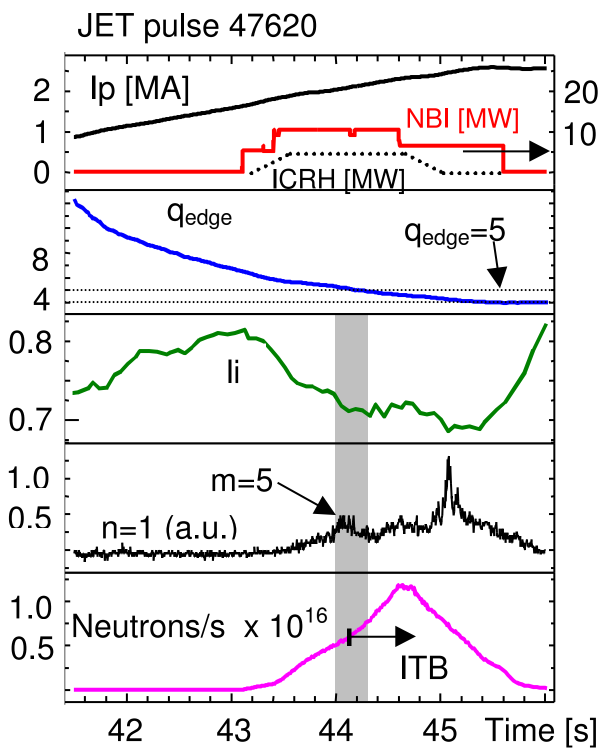

Fig 2a: example of a timing scan pulse at the optimum timing showing the correlation between the barrier onset and the edge MHD.

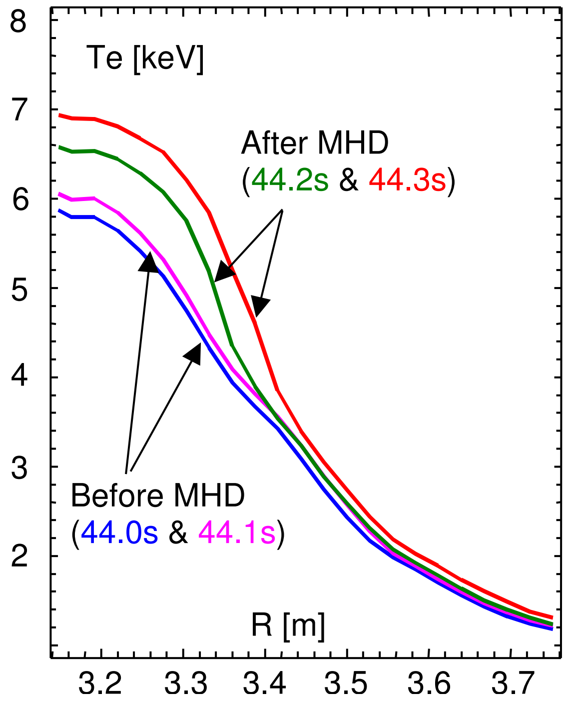

Fig 2b: Te profiles at the ITB formation during the edge external n=1 m=5 mode.

When the additional heating is applied during the current ramp-up, the internal inductance starts to drop (fig 2a), indicating the accumulation of edge current due to the increase of electron temperature and the decrease of plasma resistivity. As q_{edge} (where $q_{edge} \approx 1.23\, q_{95}$) approaches integer values such as 5, the edge current destabilises an external n=1 m=q_{edge} MHD mode. This can been seen on figure 2a showing the n=1 component when q_{edge} crosses q=5 for li close to 0.7. It appears that the ITB is triggered simultaneously (at 44.1s) as illustrated by the increase of the neutron rate and by the temperature profile in figure 2b. Here, ITBs are characterised in location and onset time using the electron temperature measurements from the ECE heterodyne radiometer. The ITB onset time can be determined within –100ms from the ÒbreakÓ of the slope of Te profiles. Thanks to the spatial resolution of this diagnostic, the ITB foot point location can be determined to within 6cm.

Using this procedure for the determination of the ITB onset time, the whole heating timing scan data set has been analysed to verify the role played by the external rational surfaces. It can be seen on figure 3 that the ITB onset time does not follow regularly the heating time. In fact, it appears that there is a clustering of the ITB formation time when rational edge q surfaces penetrates into the plasma (q=6, q=5 or q=4). Therefore, the edge MHD mode, associated with an integer q_{edge}, seems to be the cause of the triggering of the barrier near the q=2 surface.

To confirm the correlation between the edge MHD mode and the onset time of the ITB, a database of more than 40 discharges has been built up with different current ramp-up rate (from 0.37MA/s to 0.45MA/s) and different fields (2.6T and 3.4T). The edge MHD onset time has been taken at its start (44s in the case shown on figure 2a). The ITB onset time is seen to be well correlated, and generally slightly after with the edge MHD start time (Fig 4) indicating the causal role played by the external MHD mode in the ITB triggering.

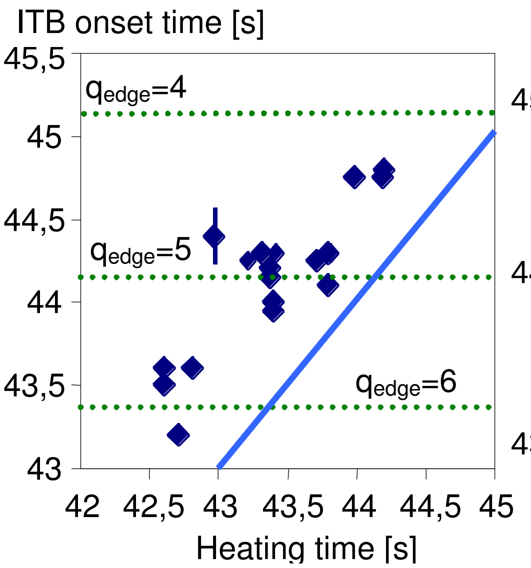

Fig 3: relation between the ITB onset time and the time of the main heating.

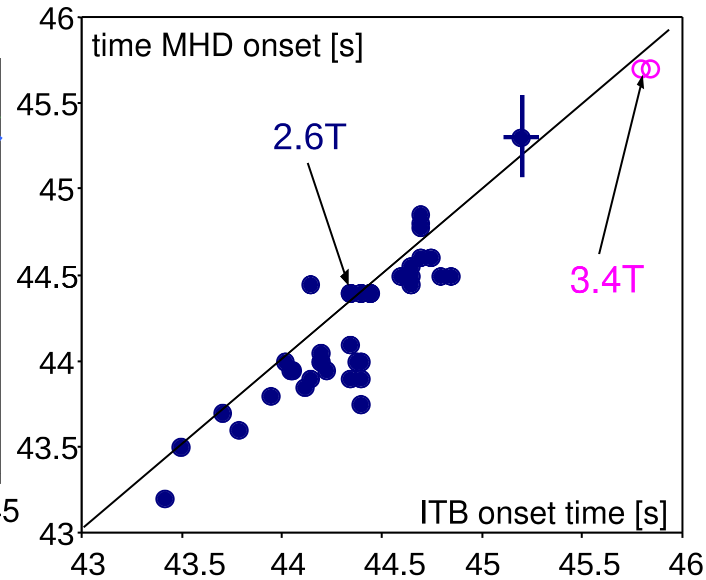

Fig 4: Correlation between the n=1 edge MHD onset time and the ITB onset for various current ramp-up rate (0.37 to 0.45 MA/s) and toroidal field.

The above experimental analysis strongly suggest the presence of a link between the triggering of the ITB and the MHD on the outermost integer q surface driven by the accumulation of edge current in the current ramp-up. Since the ITB is also believed to be linked with integer internal rational q surfaces, toroidal coupling to a q=2 tearing mode is the prime candidate to explain the possible linkage between these surfaces.

Coupling between edge (q=5) and internal (q=2) surfaces and their effect on rotation

Stability of coupled tearing modes depends essentially on the plasma shape (aspect ratio, elongation, triangularity), pressure peaking inside the considered surface (i.e. q=2 here), and magnetic shear through the island size [5]. Coupling between n=1 rational surfaces has been computed with the CASTOR code using typical equilibrium from the JET discharge 47667 with the optimum heating time (i.e. target q_o is close to 2). The edge current has been modified to reproduce the edge current accumulation in the current ramp-up and to stimulate the destabilisation of edge mode on q=5. The central shear has also been varied to check its effect on the q=2 island and on its coupling with the q=5 perturbation.

The code calculations demonstrate that coupling can occur between the external mode on q=5 and the q=2 suface. Figure 5 shows the increase of the growth rate of the n=1 mode when q_{edge} approaches 5. The width of the resulting island on q=2 is comparable to the edge q kink mode distortion. The ratio of the island width to edge kink distortion depends on the local shear on the q=2 surface, becoming larger when the q=2 surface is in a low shear region. This is consistent with the experimental observation that the optimum heating timing can produce either an m=2 n=1 mode or a strong internal barrier as observed experimentally on figure 1.

Both resistive and ideal calculations are also confirming the strong effect of the pressure peaking on coupling. This pressure dependence is consistent with the observation that a minimum heating power is required (power threshold) [1]. Furthermore, ICRH phasing experiments [6] have shown that central peaked power deposition profiles are more likely to produce an ITB than broad ones. Similar conclusions have also been drawn from experiments balancing off- and on-axis neutral beam injection [7].

Experimentally, signs of mode coupling have been noticed on the fast acquisition data of magnetics. In some cases the toroidal and poloidal structure of the external n=1 m=q_{edge} mode is strongly altered just when the barrier forms suggesting that coupling takes place at this time. Simultaneously, an m=2 n=1 perturbation has also been detected close to the foot of the barrier with the electron temperature fluctuations from an ECE heterodyne radiometer indicating the possible presence of an m=2 island at the foot of the barrier.

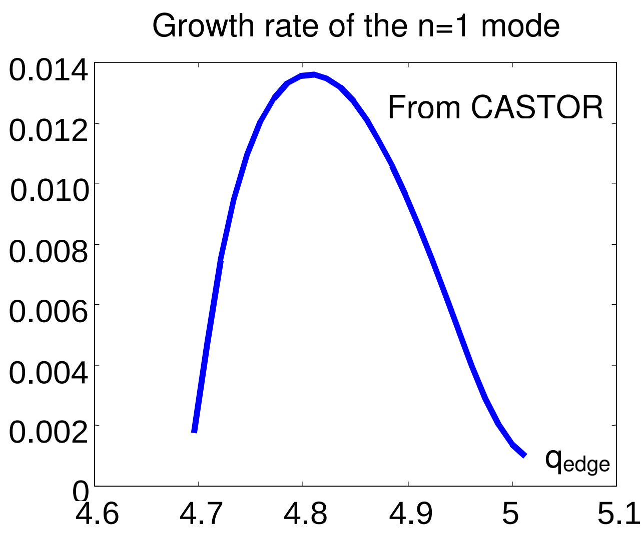

Fig 5: Evolution of the growth rate of the m=2 n=1 mode when q_{edge} approaches 5 as computed with the CASTOR code for typical optimised shear discharge.

When this coupling takes place and once the amplitude of the external mode is sufficiently high, one or more coupled surfaces inside the plasma can suddenly ’lock’ with this external mode (i.e. their natural frequencies are brought into coincidence with the outermost surface). Once locked, it is predicted [5] that the modes could locally modify the gradients of the bulk toroidal rotation. Such modification are opposed by the action of perpendicular plasma viscosity and the profile relaxes to steady state on a viscous diffusion time-scale which is of the order of a few tens of milliseconds in the case of the discharges analysed in this paper. The resulting modification of the bulk rotation can increase locally the ExB shearing rate which, in his turn, stabilises the turbulence and triggers the ITB.

Summary and future prospects for experiments

The Optimised Shear experiments conducted on JET during 1999 have identified the link between internal integer q surfaces (q=2 or q=3) and ITB formation. From the present analysis, it also appears that the MHD taking place on edge q surfaces during the current ramp-up is playing a key role in the ITB triggering. Code computations with CASTOR show that coupling between internal and edge surfaces is possible and consistent with the experimental observations. Once locked, the coupled modes could lead to local change of the toroidal rotation gradient and to the stabilisation of the turbulence by the increase of rotational shear. Ultimately, this mechanism opens the prospect to control ITBs by exciting an m=2 n=1 perturbation with saddle coils or by modifying the plasma shaping parameters or heating deposition profile conditions.

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