

Conditions for Internal Transport Barrier Formation in JET

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1. Introduction

The goal of an economical tokamak fusion reactor that is fully steady state has given great impetus to the study of plasma regimes where the heat transport is reduced in the plasma interior by the presence of Internal Transport Barriers (ITBs). One method that has been effective for the production of ITBs and high fusion yield is the application of neutral beam heating early in the discharge before the plasma current has fully penetrated [1-3]. 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.

ITBs have been obtained in JET Optimised Shear experiments using this method [4], although typically with combined neutral beam and ion cyclotron resonance heating. Many parameters may influence the ITB formation: plasma density, plasma rotation, magnetic shear, heating scheme, etc., but the individual effects of these are difficult to isolate fully. However, three key parameters have been identified and their effects are described in this paper.

2. Effect of Toroidal Magnetic Field Strength

Optimised Shear experiments have been performed during the JET 1998-9 campaign over a wide range of toroidal magnetic field strengths ($B=1.8-4.0T$). The comparison of the power required to form an ITB with different field strengths is complicated by the need to avoid changes in other key parameter such as the q profile shape. However, a large number of pulses have been obtained at $B=2.55T$ and $3.45T$ allowing the systematic trend to be seen despite the variations in q profile and other parameters on individual pulses.

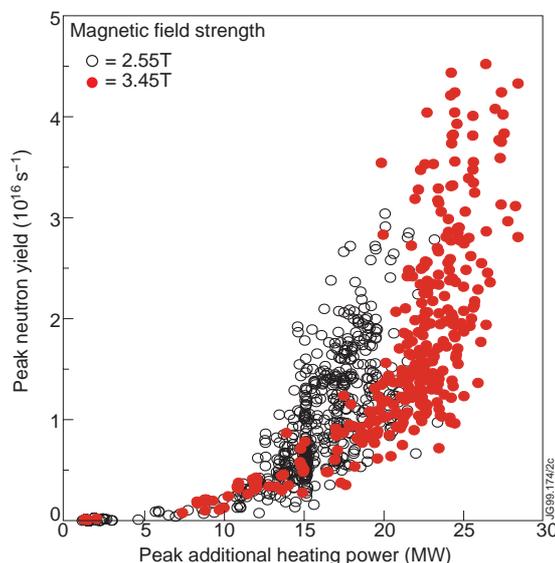


Fig.1. Peak neutron yield plotted against maximum applied heating power for each pulse at $B=2.55T$ and $3.45T$.

Figure 1 shows the fusion yield achieved in plasmas at $B=2.55\text{T}$ and 3.45T plotted against the highest additional heating power applied in each pulse before the time of the peak yield. It is clearly seen that the performance is improved in the power range 12-20MW at $B=2.55\text{T}$ compared with the higher field strength suggesting a power threshold for ITB production that is roughly proportional to B [5]. Note that the magnetic field strength and plasma current are coupled in this comparison as most pulses were performed with similar values of q . However, it is even more impressive that the improved performance at $B=2.55\text{T}$ was typically achieved with lower plasma current. The use of neutral beam heating also results in a coupling of input power with fuelling, current drive and toroidal momentum input.

3. Effect of Heating Start Time

The heating start time was scanned between 2.4s and 7.2s at $B=2.6\text{T}$ to provide pulses with a wide range of target central safety factor as seen in figure 2. The value of q_0 shown here has been calculated using the EFIT equilibrium reconstruction code [6, 7] constrained only by magnetic data. The target density, main heating power level and pulse

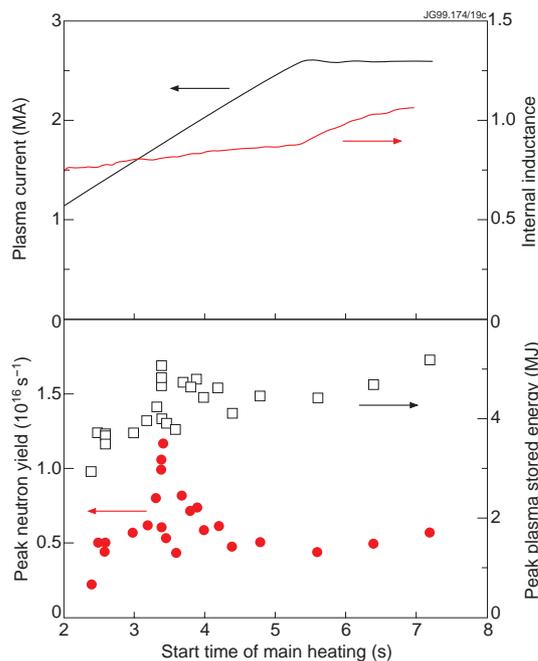


Fig.3. Peak plasma stored energy and neutron yield for each pulse plotted against the heating start time (bottom). Typical target plasma current and internal inductance (top).

length were unchanged during the scan. The main heating was composed of 10.5MW of neutral beam heating and 4.5MW of ion cyclotron resonance heating deposited close to the plasma centre.

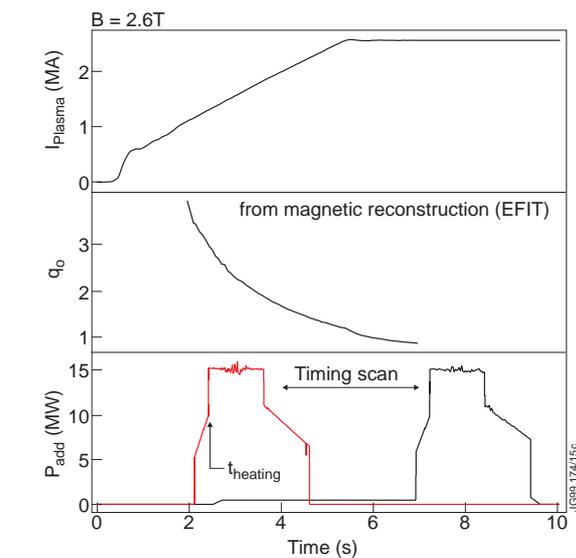


Fig.2. Overview of experiment to vary the heating start time showing the plasma current, target q_0 and typical heating power waveforms.

Figure 3 (top) shows the typical variation of the plasma current and internal inductance before the main heating is applied. Also shown in figure 3 (bottom) is the peak plasma stored energy and neutron yield achieved in each pulse as a function of the heating start time. The underlying trend for the plasma energy content to increase with start time is most likely due to the increasing plasma current and

Figure 3 (top) shows the typical variation of the plasma current and internal inductance before the main heating is applied. Also shown in figure 3 (bottom) is the peak plasma stored energy and neutron yield achieved in each pulse as a function of the heating start time. The underlying trend for the plasma energy content to increase with start time is most likely due to the increasing plasma current and

internal inductance. Superimposed on this trend is a peak for the start time of 3.4s which is due to the production of 'strong' ITBs as evidenced by the substantial improvement in fusion yield.

The peak fusion yield is plotted against the target q_0 from magnetic reconstruction (EFIT) in figure 4 showing that high performance ITBs were only obtained with a target q_0 close to 2. This indicates that the $q=2$ surface plays an important role in the ITB formation. Some pulses taken close to the optimum timing ($t_{\text{heating}} \approx 3.4\text{s}$) exhibit very poor fusion performance. In

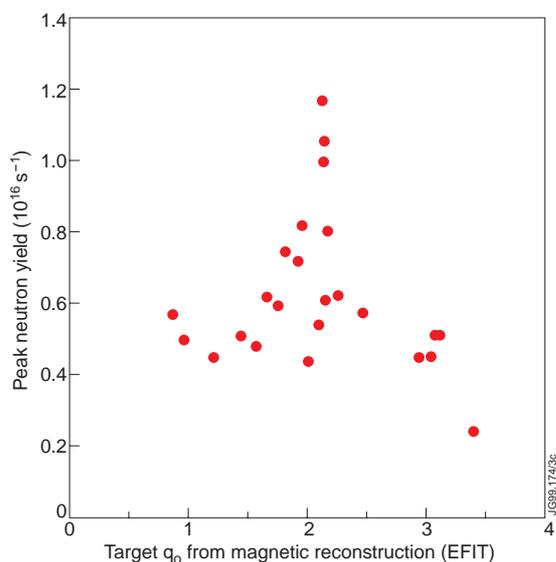


Fig.4. Peak fusion yield for each pulse plotted against target q_0 .

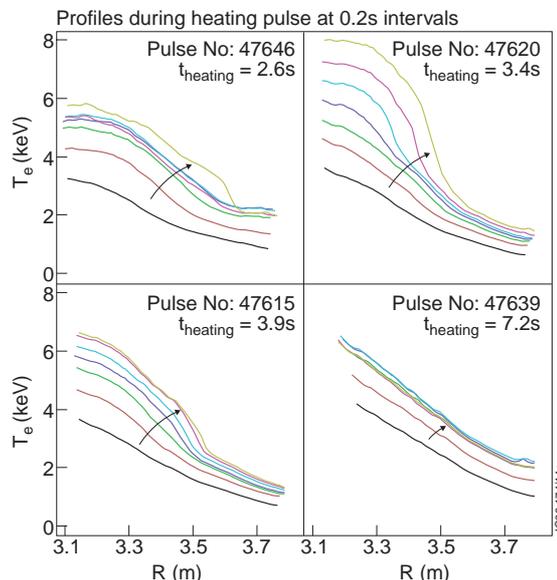


Fig.5. Electron temperature profile evolution (in direction of arrows) during the main heating phase for a variety of heating start times.

these cases a plateau region, apparently associated with a $q=2$ island, is seen on the electron temperature profile in the plasma core. This seems to inhibit the formation of an ITB, but also confirms that q_0 is close to 2 at this point in the timing scan. At the latest timing in the scan electron temperature sawteeth were observed confirming q_0 close to unity.

Figure 5 shows the evolution of the electron temperature profiles for pulses at various points in the timing scan. Although ‘strong’ ITBs only formed in the plasma core at the optimum timing, ‘weaker’ ITBs were observed over a much wider range of start times. With later heating ‘weaker’ ITBs form at a wider radius, consistent with the wider location of the $q=2$ surface. Earlier heating can produce a much wider ITB, perhaps indicating a link with the $q=3$ surface.

4. Effect of Heating Power Level

From figure 1 it can be seen that ‘strong’ ITBs can be formed at $B=3.45\text{T}$ with an additional heating power level of 20MW. Figure 6 shows that the effect of increasing

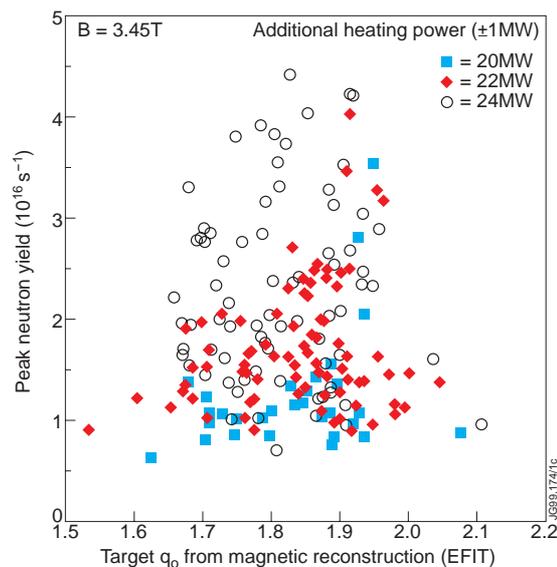


Fig.6. Peak neutron yield plotted against target q_0 of various additional heating power level.

the heating power above this level is to increase the range of target q_0 values at which ‘strong’ ITBs can be obtained. With 20MW of heating power high fusion yield plasmas were only obtained with the target q_0 close to 2. At increased power levels high performance ITBs were also produced at progressively lower q_0 . This suggests that the sensitivity of ‘strong’ ITB formation to integer q surfaces may be a consequence of working close to the power threshold for ITB production.

5. Summary and Conclusions

Three key parameters have been identified for ITB formation in JET:

- Toroidal magnetic field strength.
→ The power required to form a ‘strong’ ITB is approximately proportional to B .
- Main heating time (through the q profile).
→ ITB formation appears to be linked to the location of integer q surfaces. Experiments indicating possible links between rational q surfaces and ITBs have previously been reported on JET and other tokamaks, for example [8-11].
- Heating power level.
→ The range of q profiles where ‘strong’ ITBs can be formed increases with heating power.

The link between integer q surfaces and ITB formation in JET is still unclear. Candidate mechanisms include local pressure gradient perturbation by:

- Magneto-hydrodynamic (MHD) instabilities associated with particular q surfaces.
- Good confinement regions at or close to rational q surfaces.

It is hoped that further analysis of the q profile evolution using motional Stark effect data [12] will help to clarify this issue.

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