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**See Annex of J. Pamela et al., "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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INTRODUCTION

The extension of advanced tokamak scenarios towards densities close to the Greenwald value is important to demonstrate its reactor relevance. At JET a scenario for high-density internal transport barriers (ITB) has been developed (see Fig.1). Plasmas with a reversed magnetic shear were fuelled by pellets, creating a peaked density profile. Additional heating by NBI and ICRH caused a strong internal transport barrier to form in these plasmas. The density and temperature gradients due to the transport barrier cause a large bootstrap current fraction that helps to sustain the shear reversal [1,2].

Discharges in JET with a negative central magnetic shear often feature temporal collapses of the internal transport barrier that are attributed to double tearing modes [3]. It is known that rotational shear has a stabilising effect on these modes. The high density and consequential low plasma rotation may have a destabilising effect on these modes. The paper addresses the stability of high-density discharges and gives a detailed description of the MHD characteristics and its influence on the plasma rotation.

1. MHD CHARACTERISTICS OF HIGH-DENSITY ITB DISCHARGES

In spite of the pellet injection and a high density, the applied heating and current-drive during the current-ramp maintained a q-profile beneficial to ITB formation. MSE measurements show a q-profile with a negative magnetic shear in the centre and an approximate minimum $q\approx3$ at the start of the main heating phase. Coincidently, cascades of Alfvén waves, triggered when the minimum q value decreases below a rational value, were observed [4].

Simultaneous with the formation of a high-density ITB, low frequency MHD activity appeared. The mode number, identified by cross correlation of toroidally and poloidally separated magnetic probes, is $m/n=3/1$. Hence, the modes are related to the $q=3$ surface. However, similar discharges with a similar q-profile but without pellet fuelling did not trigger these modes. This indicates that the high density and low plasma rotation also played a role in the mode destabilisation. The modes are identified as magnetic islands by their characteristic signature on the ECE temperature profile measurements. This also enables the localisation of the modes.

In Fig.2 the frequency behaviour of the modes is shown for two similar high-density ITB discharges. Both feature an $m/n=3/1$ mode that initially increases in frequency at the start of main heating phase. The modes feature characteristics of double tearing modes with islands observed on both sides of the ITB (at $R=3.25$ and 3.45m, respectively). In Fig.2(a) these modes de-couple at $t=4.43$s, yielding a stabilisation of the inner magnetic island. At the same time a $m/n=6/2$ or $5/2$ mode appears that spins up, while the frequency of the outer $3/1$ magnetic island decreases until it stabilises at $t=4.7$s. A similar observation is presented in Ref. [6]. The mode de-coupling process appeared to be more difficult at higher density, as seen in Fig. 2(b).

The modes remain coupled over a longer period, and even lock between 4.7s and 5.1s, when the size of the outer island reaches a maximum width of $w=9$cm. This, however, did not deteriorate the ITB. De-coupling and stabilisation finally take place after $t=5.5$s. The mode amplitude was found to be greatly reduced at higher NBI input power ($P=13$MW). In Fig.3 it is shown that large coupled MHD activity was only observed in those high-density ITB discharges in which the NBI power was limited.

2. EFFECT OF DOUBLE TEARING MODES ON ROTATION

The low frequency modes were found to modify the plasma rotation profile. Carbon rotation velocities have been measured by Charge Exchange Spectroscopy (CXS). However, especially in the presence of a large pressure gradient, a difference is expected between the Carbon velocity profile and that of deuterium [5]. The deuterium rotation is, together with the diamagnetic frequency, responsible for the observed mode frequency. The deuterium rotation and radial electric field have been calculated according to the principles presented in Ref. [5]. The calculation may be inaccurate in the centre ($R<3.1$m).

In Fig.4a deuterium toroidal rotation profiles are shown for the discharge presented in Fig.2(a). At the time the modes are coupled, the rotation is locally reduced, producing a hollow rotation profile. It gives a confirmation that the inner mode position is located at $R\approx3.2$m. The carbon rotation, measured by CXS directly, also show a definite hollow profile caused by mode coupling.

The plasma rotation, at the position of the inner mode, is able to increase after the modes have de-coupled. In Fig.2a the frequency of the $n=2$ is seen to spin up while the outer mode decreases in frequency. Calculated deuterium rotation profiles, for the discharge with locked modes (see Fig. 2(b)), showed that the whole plasma outside $R>3.2$m is brought to a stand still. The effect of the coupled modes on the radial electric field can be seen in Fig.4(b). The field is locally reduced at the position of the modes, while at the position of the ITB a large field has to balance the strong pressure gradient.

CONCLUSIONS.

Discharges featuring high-density ITBs in JET were found to coincide with the presence of large coupled tearing modes. The MHD modes, triggered when the minimum q crossed $q=3$, were able to grow to large amplitude due to the high density and low rotational shear at the start of the main heating phase. However, the MHD activity did not deteriorate the ITB. In due course the modes de-couple and stabilise. A reduced torque on the plasma will decrease the acceleration of the plasma rotation. Hence, it was found more difficult to de-couple the modes at higher densities or lower NBI input power. It suggests that at lower densities, small modes may be triggered but a fast stabilisation prevents them growing to large amplitudes.

Coupled or locked modes can have a large impact on the toroidal rotation profile. It has been suggested in Ref. [7] that strong braking of the local poloidal plasma rotation by MHD modes could trigger an ITB. However, it was not possible to determine the real poloidal rotation component for these experiments. The initial toroidal rotational shear, at the moment the ITB started to grow, was a factor of *4* lower than in standard ITB discharges in JET. It indicates that toroidal rotational shear did not contribute to turbulence suppression as a trigger to high-density ITBs.

Both the formation of the ITB and the growth of MHD modes may have a mutual cause: pellet injection and the resulting peaked density profile and lower plasma rotation. The rotational shear and the perturbation of the radial electric field profile, caused by the coupling and locking of MHD modes, may play a role in additional turbulence reduction. The formation of and internal transport barrier in a tokamak plasma is a highly non-linear process. A detailed discussion on transport analysis in high-density ITBs is given in Ref. [2].

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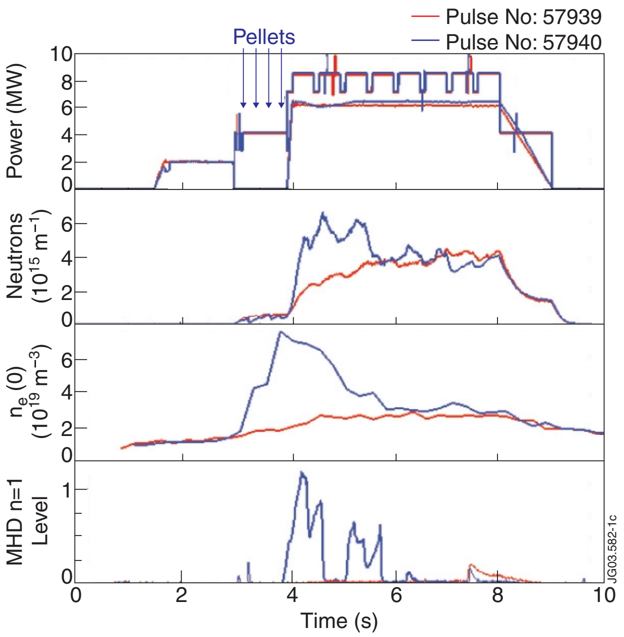

Figure 1: The JET high-density ITB scenario. Heating and current drive is applied by LHCD during the current-ramp phase of the discharge ($t < 4s$)*. During a short period with low power NBI heating* ($3s < t < 4s$) *pellets are injected to attain a peaked density profile. By applying high power NBI and ICRH* ($t > 4s$) *an ITB is triggered (Pulse No: 57940). The increased neutron rate, compared to an identical discharge without an ITB (Pulse No: 57939) indicates the improved confinement. The high-density discharge shows large* n=1 *MHD activity, detected by magnetic diagnostics.*

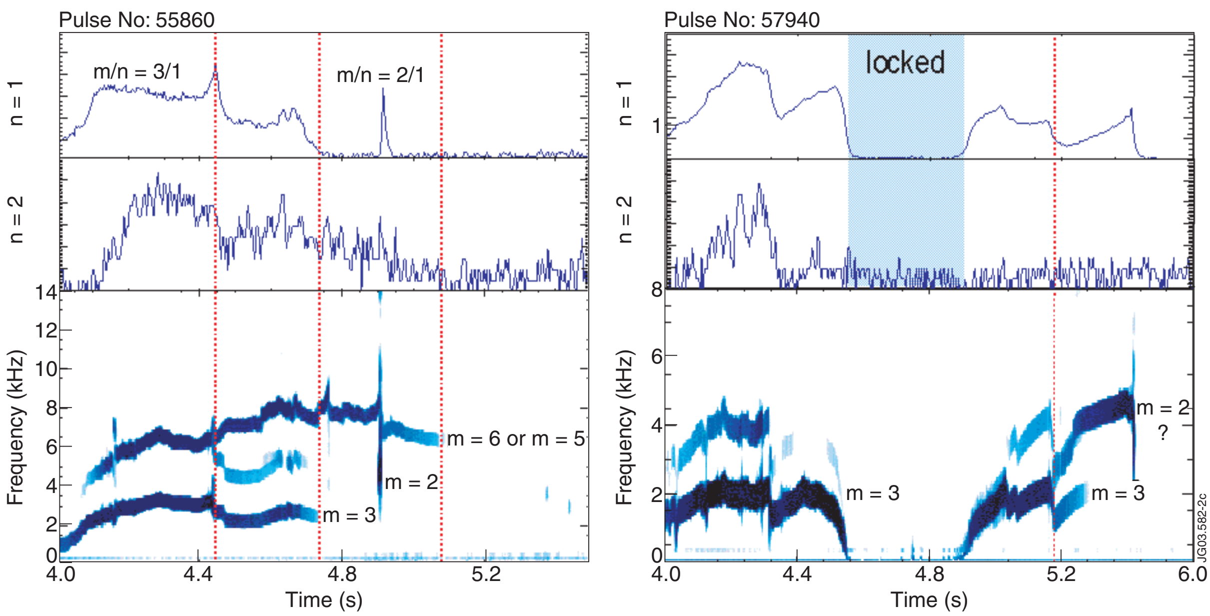

Figure 2: The mode amplitude and frequency during the main heating phase for two similar discharges: (Pulse No's: 55860 and 57940) but with a different mean volume integrated density: a) $\langle n_e \rangle \approx 2.8 - 2.1 \times 10^{19} m^{-3}$*, b)* $\langle n_e \rangle \approx 4.2 - 2.2 \times 10^{19} m^{-3}$*, respectively. In both discharges a NBI input power of P = 8MW is applied.*

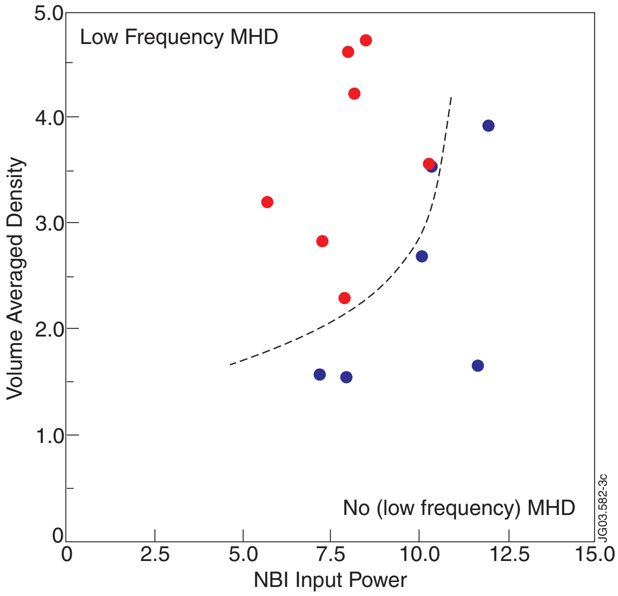

Figure 3: ITB discharges with coupled MHD modes are shown in red, others in blue.

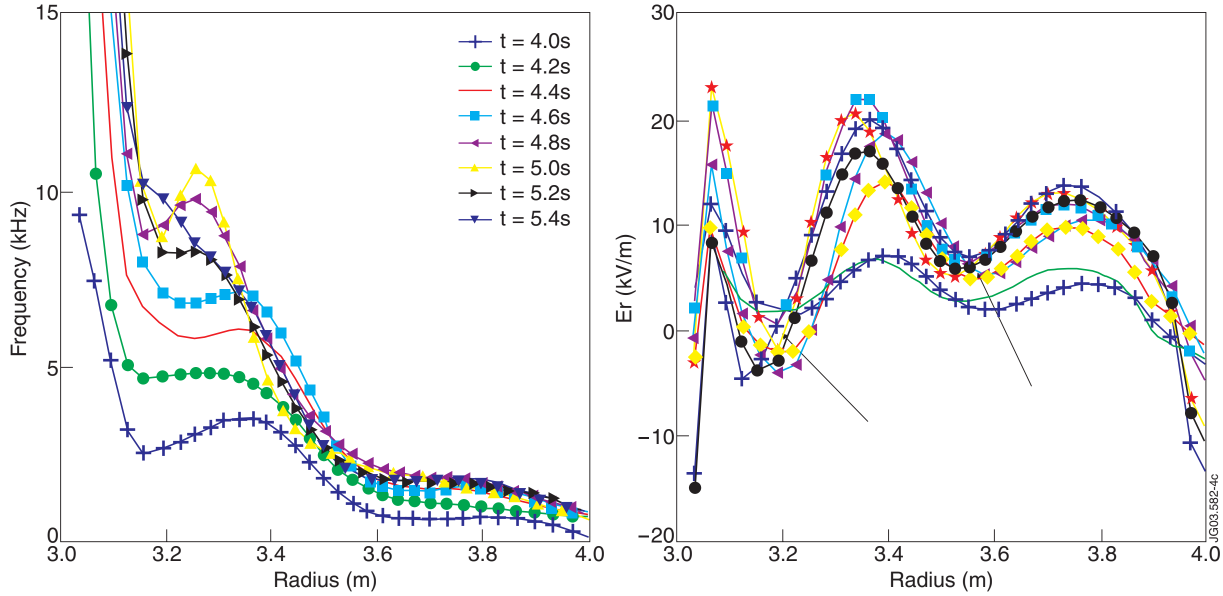

Figure 4: (a) The deuterium rotation and (b) the corresponding radial electric field profiles of Pulse No: 55860 (See Fig.2(a). The ITB was located at approximately R = 3.4*m.*