INTRODUCTION

Energetic ions with velocities comparable to Alfvén velocity V_A can destabilize Alfvén Eigenmodes in tokamaks through resonant wave-particle interaction. At low magnetic field, $B \leq 1T$, the Alfvén velocity is sufficiently small for resonance, $V_{||beam} \approx V_A$, between the wave and NBI-produced ions at E_{NBI} ~ 80-160keV typical for present-day tokamaks. Experiments on the destabilization of TAEs by NBI at low B have been performed on TFTR [1], DIII-D [2], and JET [3]. The experiments on JET [3] have shown that TAEs and very high amplitude n = 1 fishbones are destabilised by NBI with $V_{beam} \approx 0.85\ V_A$ and powers up to 10MW, if the safety factor is below one, q(0)<1. It was found that the fishbones significantly affect both the neutron rate determined by the beam-plasma reactions (Fig.1) and the total energy content of the plasma (Fig.2).

A similar experiment dedicated to measurements of the NBI power deposition profile and its redistribution by TAEs/fishbones was performed in 2003 Trace Tritium campaign. The experiment was based on using neutron profile monitor on JET for measuring the profiles of Tritium NBI injected in blips into deuterium plasma with TAEs/fishbones.

1. EVIDENCE OF FAST ION REDISTRIBUTION TAE IN DEUTERIUM PLASMAS

Reference deuterium plasma and NBI discharges were investigated first. TAEs were found to be unstable in JET limiter plasmas with B = 0.8 T and I = 0.9MA, when TAEs and large amplitude fishbones were destabilised by 5MW of NBI. TAEs with toroidal mode numbers n = 4, 5 and 6 were seen in the absence of fishbones, while n = 2 and 3 TAEs appear in the presence of fishbones (Figs 3, 4). This observation is consistent with a fishbone localised mainly inside q = 1 redistributing fast ions and providing a steeper dpbeam/dr outside q = 1 [3]. A steeper dpbeam/dr outside q = 1 destabilises TAEs with lower n.

2. REDISTRIBUTION OF TRITIUM NBI-PRODUCED IONS DURING FISHBONES

A scenario similar to the deuterium reference then was used during the Trace Tritium campaign. Deuterium NBI of power 5.5 MW and $V_{beam} \approx 0.73\ V_A$ was injected first and destabilized TAEs/ fishbones in JET plasmas with B = 0.86 T, I = 0.9MA (Fig.5). Four 50 msec tritium NBI blips were added then on top of the deuterium NBI as shown in Fig.5. The T-blips generated high yield of DT neutrons, which allowed the assessing of the beam deposition profile from the neutron profile measured with high resolution in time.

Due to the very high sensitivity of the cross-section of the DT reaction on the T-beam energy (it falls by an order of magnitude for energies 105keV to 40keV), the most significant source of DT neutrons was associated with T-beam ions of highest energy. Such T-beam ions were the ones closest to the wave-particle resonance as well, so they were the best for detecting a redistribution of the resonance ions. Two cases were investigated: with on-axis and off-axis blips of Tritium NBI.

Due to lower NBI power and lower V_{beam} / V_A ratio, a smaller amplitude fishbones were excited in the recent experiment (e.g. in Pulse No: 61507) than in experiment shown in Figures 1,2. Direct comparison of the two signals showing the magnetic perturbations due to fishbones in the 'old' and 'new' cases is given in Figure 6. The fishbones of smaller amplitude and higher repetition rate were not causing such dramatic changes in total neutron rate or in the plasma energy contents as these in Figures 1, 2.

However, a direct comparison of total DT neutron yield per amount of tritium injected by T-NBI, shows that time-integrated number of neutrons is smaller in plasmas with fishbones than in MHD-stable plasmas. For the case shown in Fig.5, the normalised amount of neutrons after first NBI-blip at t = 21.95sec (fishbones) is less than 0.95 of the total amount of neutrons after the blip at t = 22.85sec (no fishbones). This is contrary to 'classical' expectations as the plasma was hotter when fishbones were present,

The radial profile of DT neutron emission was measured with a time resolution of 25msec. Tomographic reconstruction of the neutron emissivity was performed for both cases of on-axis NBI (Fig.7) and off-axis NBI (Fig.9).

The temporal behaviour of the DT neutron profile was compared with the TRANSP code modelling based on classical Coulomb collisions. Figures 8, 10 show a marked departure of the measured DT neutron profile from TRANSP in discharges with T-blips of NBI into plasma with fishbones, with the central region of the plasma inside q = 1 being the most affected. This departure is in contrast to the good agreement found in cases with T-blips of NBI into plasmas at higher magnetic field 3T, when fishbones/TAEs were not excited.

CONCLUSIONS

Fishbones and TAEs were excited by NBI with V beam ~ VA at low B in JET. Lower amplitude higher repetition rate fishbones were found to be less damaging to global plasma parameters such as neutron yield and plasma stored energy. Indirect evidence for beam ions redistributed by fishbone was first derived from lower-n TAEs excited during fishbones outside q=1, in deuterium reference discharges. In trace Tritium discharges, a somewhat lower neutron yield was observed in plasmas with fishbones than in plasmas without fishbones. Marked departure of beam-plasma DT neutron profile from that from TRANSP, which is based on classical transport and was validated against T-blips of NBI in [4], was found in discharges with T-blips of NBI into plasma with fishones/TAEs. This departure is in contrast to cases with T-blips of NBI into JET plasma without fishbones/TAEs, where significantly better comparison of DT neutron profiles is common. Thus the deviations between the neutron profiles measured experimentally and obtained from TRANSP gives a quantitative estimate of the redistribution effect of T-beam ions resonating with fishbones/TAEs.

ACKNOWLEDGEMENTS

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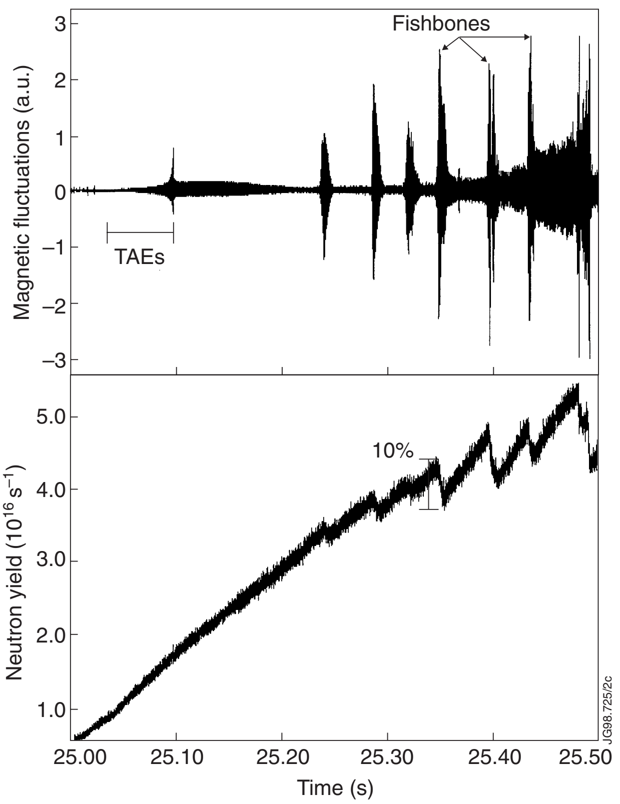


Figure 1. Measured magnetic perturbations (top) and neutron rate (bottom) during T-beam (10 MW at 160 keV) injection into T-plasma at B=0.9 T (JET pulse #43014, [3]).

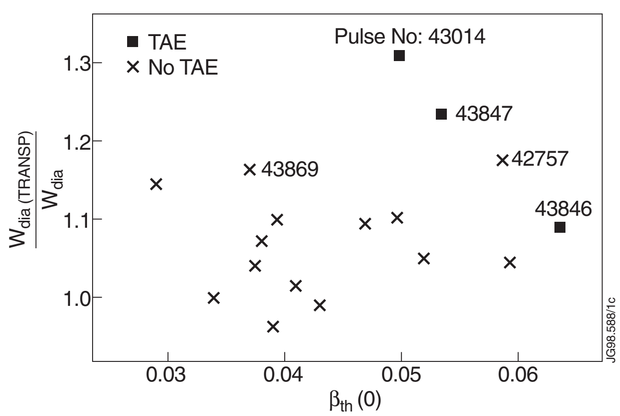


Figure 2. Significant difference was found between measured Wdia and Wdia from TRANSP (which does not account for anomalous transport due to fishbones) in discharges with TAEs and fishbones.

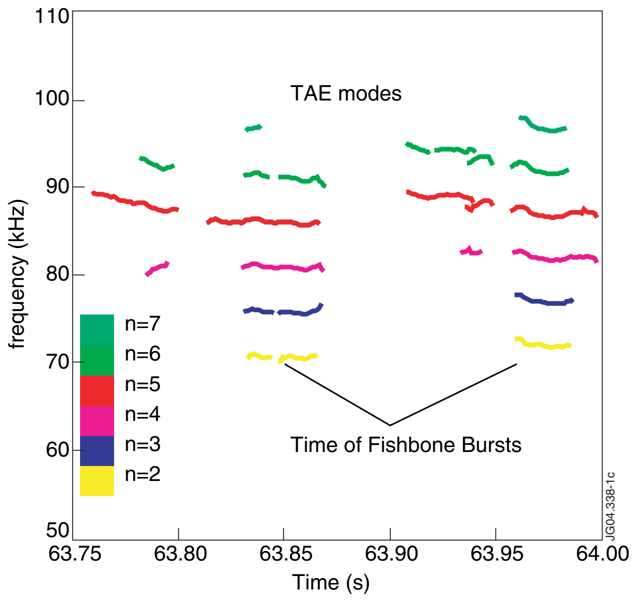


Figure 3. TAE mode spectrum with different toroidal mode numbers (n), during the fishbone bursts.

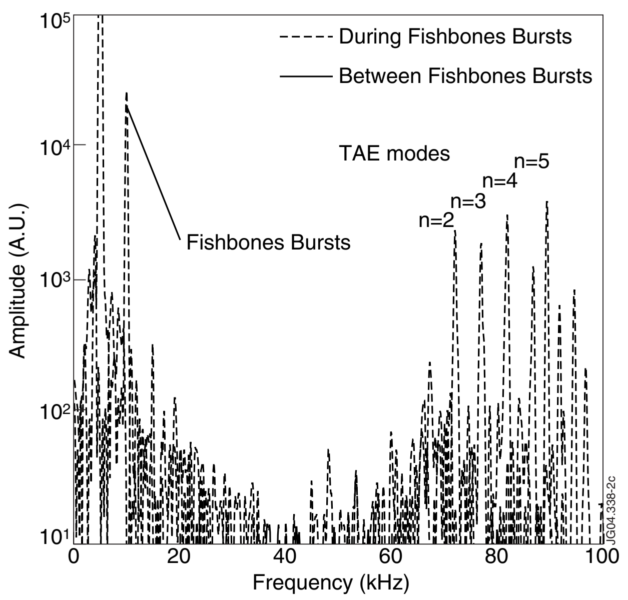


Figure 4. TAE mode spectrum with different toroidal mode numbers (n), during the fishbone bursts and in between the fishbone bursts.

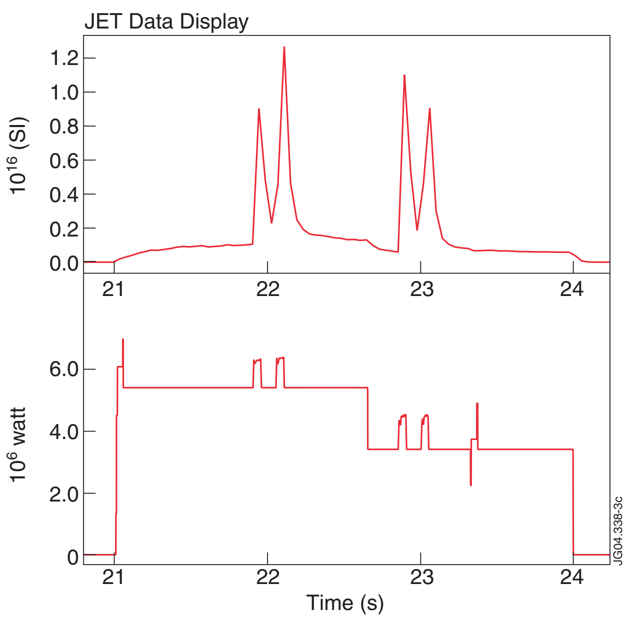


Figure 5. Neutron rate (top) and NBI power (bottom) in Pulse No: 61507 ($B = 0.86T$, $I = 0.9MA$, $P_{D\text{-}NBI} = 5.5MW$, $V_{||beam}/V_A \sim 0.73$, $E_{NBI} = 105keV$.

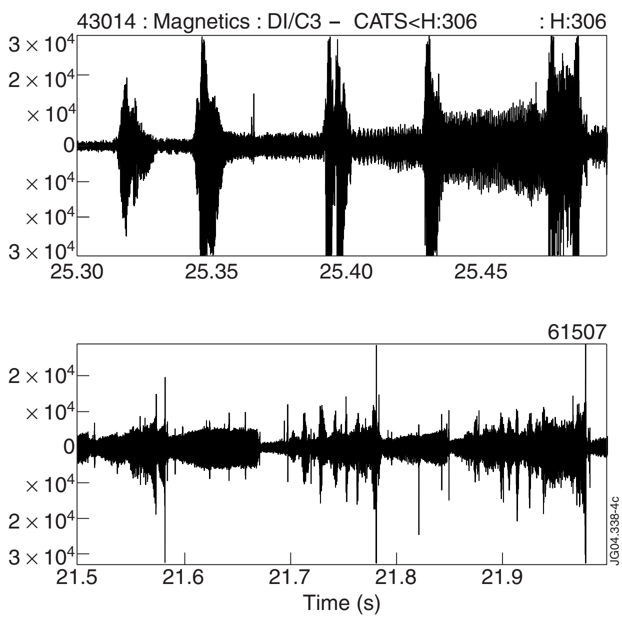
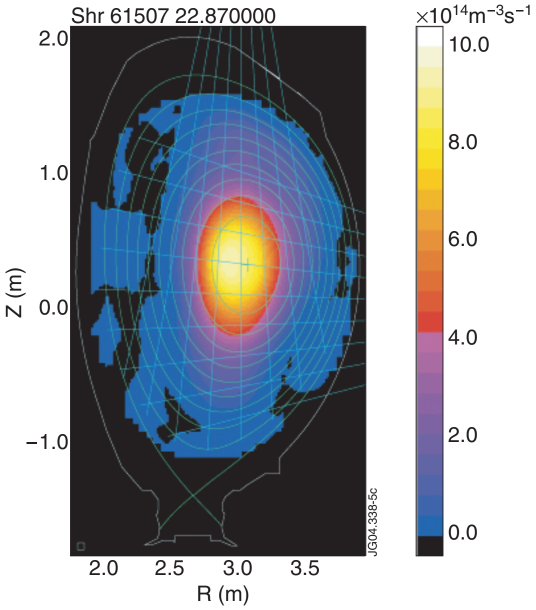


Figure 6. Fishbones in Pulse No: 43014 (top) and in Pulse No: 61507 (bottom). Higher amplitudes (factor 3-5) and lower repetition rate (by 3-4 times) observed in Pulse No: 43014.



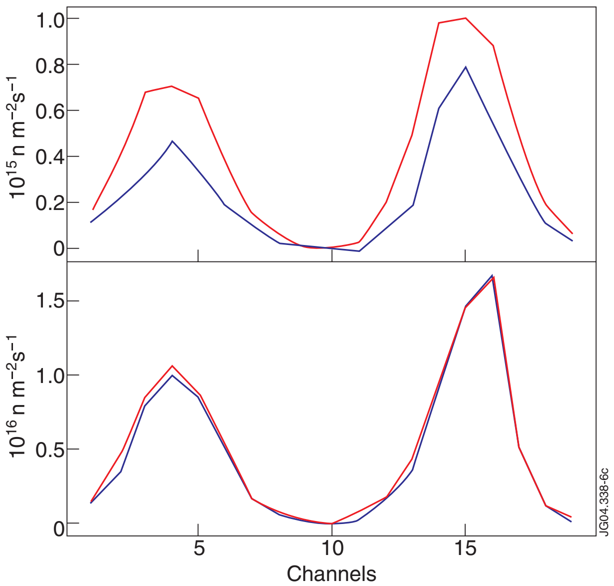
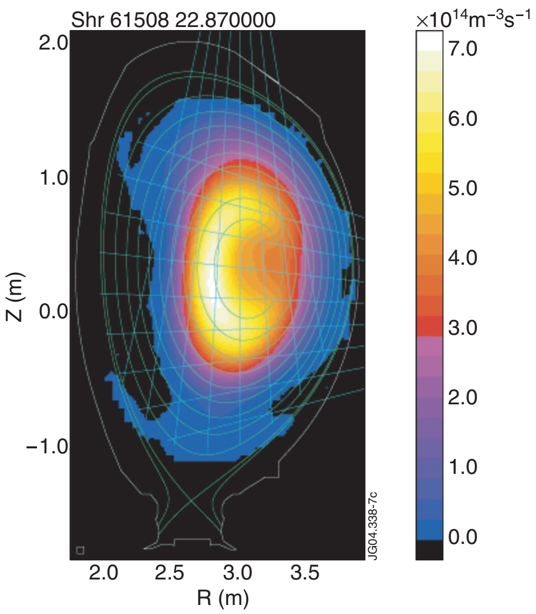


Figure 7. Tomographic reconstruction of DT neutron profile for on-axis NBI (Pulse No: 61507). Horizontal channels: 1 (top) to 10 (bottom), vertical ch.: 11 (inboard) to 19 (outboard).

Figure 8. Comparison of measured (blue) vs TRANSP (red) profiles of DT neutrons 10msec before end of T-blip: ***top: Pulse No: 61507 with fishbones and on-axis T-blip****; bottom: an example of on-axis T-blip case without fishbones/TAEs (Pulse No: 61341, B/I=3T/3MA).*



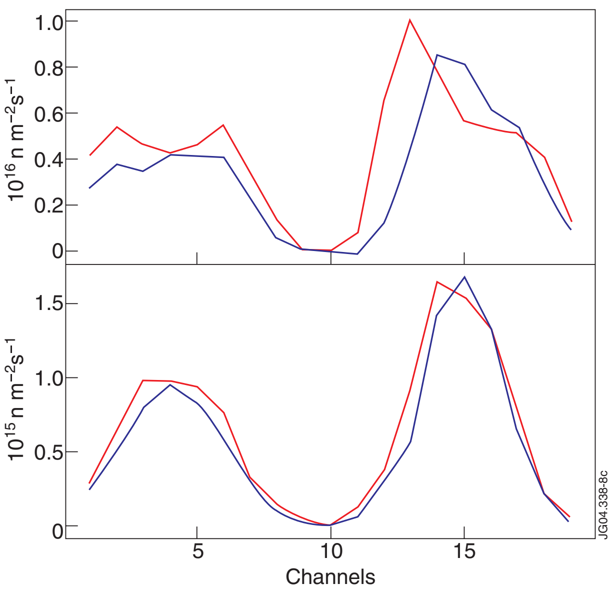


Figure 9. DT neutron profile for off-axis NBI into plasmas with n=1 fishbones (Pulse No: 61508).

Figure 10. Measured vs TRANSP neutrons: top: ***Pulse No: 61508 with fishbones and off-axis T-bli****p; bottom: off-axis T-blip case without fishbones/TAEs (Pulse No: 61344, B/I=3T/3MA).*