TRANSP modelling of experimentally measured fast particle redistribution and losses on MAST

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I. Introduction

MAST is a mid-size spherical tokamak with $B_T = 0.3 - 0.6$ T and two NBI systems delivering up to 3.5 MW of super-Alfvénic deuterons and therefore suitable for understanding the dynamics of fast particles in ITER-relevant scenarios. It is well known that MHD instabilities can cause redistribution and/or losses of fast ions as observed in many tokamaks (such as PDX, TFTR, DIII-D, JET, ASDEX, NSTX and MAST). In particular, on MAST, the effect of fast particle driven instabilities, such as fishbones and long-lived modes upon the total neutron yield measured by fission chamber (FC) and the neutron count rates measured by Neutron Camera (NC) has been observed [1]. Fishbones are characterized by burst-like behaviour observed in magnetic and SXR diagnostics and by the sweeping of the mode frequency during a burst. The resonant interaction between the toroidal and poloidal motion of the fast ions in the plasma with the $n = 1$, $m = 1$ internal kink mode is the mechanism responsible for driving the fishbone instability [2].

II. Experimental observation and simulation of fishbones in TRANSP

A set of four similar DND plasma discharges 27525 - 27528 has been chosen to study the effect of fishbones on fast ions, in which auxiliary heating, plasma current, electron density and temperature are very similar. These pulses were characterized by plasma current $I_p \simeq 750$ kA, core electron density $n_e \simeq 3 \times 10^{19}$ m^{-3} and temperature $T_e \simeq 1$ keV, toroidal magnetic field $B_T \simeq 0.55$ T. The auxiliary heating consists of 3.5 MW of co-current NBI deuterons with maximum energies of 60 and 66 keV giving rise to the fast ion population. The time evolution of NBI power for pulse 27527 is shown in figure 1 a). During the time interval $0.14 < t < 0.24$ s, when the second NBI was switched on, a noticeable increase of MHD activity was recorded by a midplane outboard Mirnov coil, as shown in figure 1 b). This indicates that observed MHD instabilities are driven unstable by fast ions.

"Small" and more frequent chirping modes (also known as fishbones) appear at time $t = 0.14$ s and last up to $t = 0.19$ s. Then three "large" fishbones clearly visible in the magnetic fluctuation signal occur at $t = 0.197$ s, $t = 0.209$ s and $t = 0.223$ s. The last "large" fishbone evolves into a long-lived internal kink mode. "Small" fishbone activity does not cause large drops in the global neutron yield measured by a fission chamber (Y_n), as shown in figure 1 c). Drops seen in Y_n are clearly correlated with these three "large" fishbones. On the spectrogram of magnetic fluctuation signal presented in figure 2 a), the fishbone oscillations show the characteristic frequency chirp, here from 35 to 20 kHz. The modes visible at twice that frequency are $n = 2$ harmonic oscillations. According to TRANSP calculations for pulse 27527, on average about 83% of the 2.5 MeV neutron emission comes from beam-target, 12% from beam-beam and up to 5% from thermonuclear reactions. The total neutron yield calculated by TRANSP (Y_T) significantly overestimates Y_n and an $AFID$ (Anomalous Fast Ion Diffusion coefficient) of the order of 1.5 m^2s^{-1} applied throughout the pulse is required to match the two, as shown in figure 1 c). The applied $AFID$, which affects passing and trapped ions, was assumed to be constant in time, space and energy and is used to mimic on average the effect of MHD activity on transport of fast ions in the plasma. This model is able to reproduce Y_n apart from the time region $0.199 < t < 0.23$ s, in which three large fishbone are observed. Changes in neutron emission occur when fast ions are redistributed and/or expelled from the plasma.

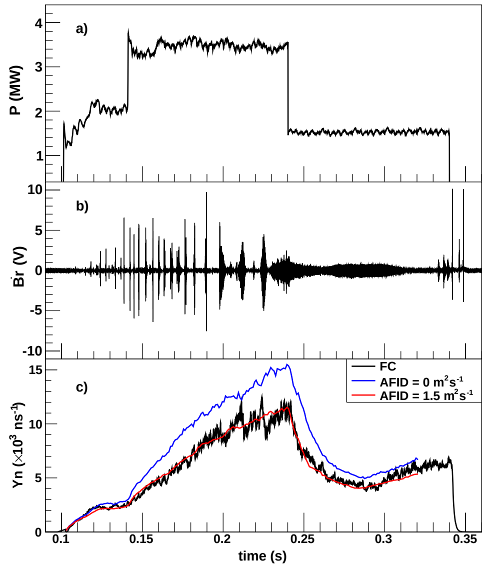

Figure 1: Time evolution of a) NBI power, b) magnetic fluctuation amplitude picked up by a midplane outboard Mirnov coil, c) Y_n in black and TRANSP modelled Y_T for different level of $AFID$ in red and blue.

An attempt to reproduce the large drops in global neutron emission in this time interval has been performed using the TRANSP 'fishbone loss' model. The 'fishbone model' allows the fishbone onset time, the repetition time T_{FB} and the total duration of the burst W_{FB} to be specified. The loss model can be used in two different ways: a) Loss Model 1 (LM1): can expel all fast ions (passing and trapped) whose energy and pitch angle belong to specified ranges or b) Loss Model 2 (LM2): allows to specify which energy and ion orbits will be affected i.e. barely, deeply or fully trapped. Note that LM2 does not affect passing ions. Both fishbone loss models have been used and the following settings were kept the same in modelling: $T_{FB} = 12$ ms, $W_{FB} = 4$ ms and characteristic loss time for affected ions $T_{LOSS} = 0.1$ ms, hereby assuming that these three "large" fishbones have all the same properties which is approximately what is observed (see figure 1 b) and 2 a)). In LM1, pulse 27527 has been divided into 3 time intervals $0 < t < 0.199$

s, $0.199 < t \leq 0.23$ s and $t \geq 0.23$ s, in which $AFID$ takes the following values 1.5 m^{2}s^{-1}, 0 m^{2}s^{-1} and 1.5 m^{2}s^{-1}, respectively. Parameter $\sigma_{LM1,2} = \sqrt{\sum_{i=1}^{n} \frac{(Y_{ni}-Y_{Ti})^2}{n}} \Big/ \sum_{i=1}^{n} \frac{Y_{ni}}{n}$, where n is the number of data points in time interval $0.199 \leq t \leq 0.23$ s, was defined to assess the agreement between Y_n and Y_T modelled using fishbone models LM1 and LM2. Reasonable agreement for LM1, $\sigma_{LM1} = 7.15\%$ was found when all fast ions (both trapped and passing) with energy > 55 keV and pitch angle in the range $(-0.5, 0.5)$ were expelled from plasma, as depicted in figure 2 b).

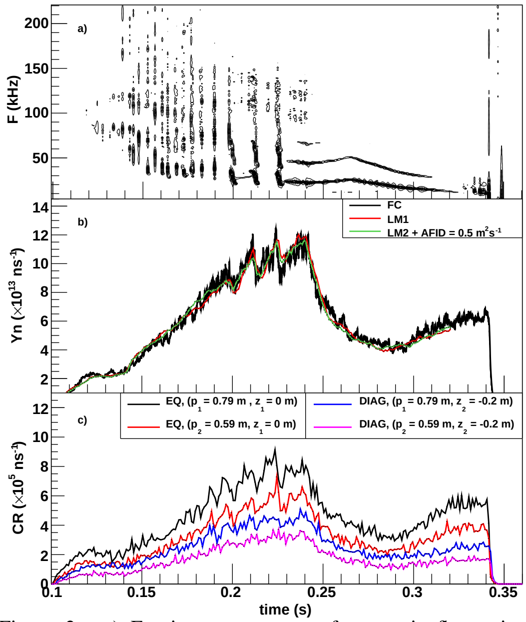

Figure 2: a) Fourier spectrogram of magnetic fluctuation picked up by a Mirnov coil, b) Y_n and Y_T modelled using LM1 and LM2 c) Neutron count rate measured by NC for four channels whose radial position is characterized by impact parameter $p_1 = 0.79$ m and $p_2 = 0.59$ m.

In LM2, even removing all fast ions regardless of their energy and trapping depth, TRANSP overestimates Y_n. This suggests that passing ions could also be ejected by the fishbones. In fact, by combining LM2 with small diffusion $AFID = 0.5$ m^{2}s^{-1} in the time interval $0.199 < t < 0.23$ s gives also satisfactory agreement $\sigma_{LM2} = 6.05\%$, as shown in figure 2 b). Neutron emission profiles as a function of impact parameter p delivered by NC can be used to further validate TRANSP modelling. The experimental pre- and post-fishbone neutron emission profiles were obtained from the neutron count rates measured with the NC collimated chords, which for the pulse 27527 are shown in figure 2 c). TRANSP modelled neutron emission profiles required simulating pre- and post-fishbone non flux averaged neutron emissivities. The pre- and post-fishbone time intervals were defined as 1 ms before the maximum amplitude of magnetic signal and from 2 to 3 ms after it, respectively.

III. Results and discussion

The comparison of the pre- and post-fishbone experimental and TRANSP modelled neutron emission profiles obtained from LM1 and LM2 is depicted in figure 3. The overall reduction in the neutron emission is seen for post-fishbone profiles for EQ and DIAG lines of sight (LoS). It is more pronounced in the plasma core region ($0.9 < p < 1.1$), indicating fast ion redistribution and/or losses. No significant increase of neutron emission is observed outside the core region. Reproducing the large drops in the global neutron rate Y_n can be

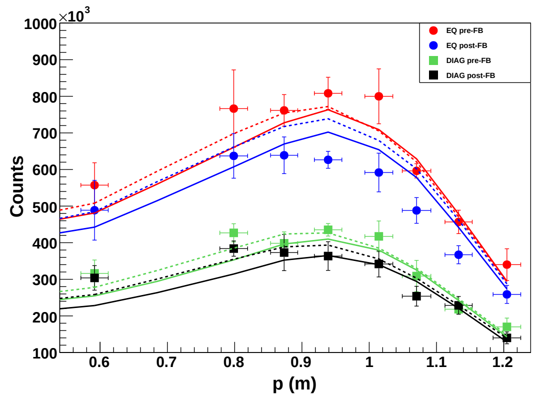

Figure 3: Pre- and post-fishbone experimental (points) and TRANSP modelled using LM1 (solid line) and LM2 (dashed line) neutron emission profiles as a function of impact parameters p for EQ ($p, z = 0$ m) and DIAG ($p, z = -0.2$ m) LoS.

achieved either by using LM1 and removing passing and trapped particles from the plasma or LM2 which in addition to ejection of all trapped particles requires adding a small level of diffusion. Although, the agreement between Y_n and TRANSP modelled Y_T using both fishbone loss models is acceptable, the simulated pre- and post-fishbone neutron emissivity profile do not reproduce the drop in the experimental neutron emission profiles, especially for EQ LoS.

Simulations of the effect of a generic fishbone, with a peak relative amplitude $\delta B/B = 5\times10^{-3}$, on the profile of the neutron emission for pulses 26789, 27920 and 27927 have been carried out using LOCUST-GPU and HAGIS (L&H) codes [3, 4] and is shown in figure 4 together with NC experimental measurements. The L&H model predicts a 20% drop of the core neutron emission which matches the drop observed experimentally. This effect of fishbones on the neutron emission is what is also observed in the plasma studied here and which are very similar to the one used in the L&H model. According to L&H, the change in the neutron emission due to fishbones is caused mainly by redistribution. A similar conclusion was obtained in LM2 but not LM1 where losses alone were sufficient to reproduce the experimental observations. However, TRANSP is not able to reproduce the NC observations indicating that for a more realistic simulation of fishbones it is necessary to model the mode wave-particle interaction effect on the fast ion distribution function, in particular these results demonstrate the importance of spatially resolved neutron emission profile measurements. In order to better understand the observations here reported a more detailed comparison between TRANSP, NC and L&H will be carried out.

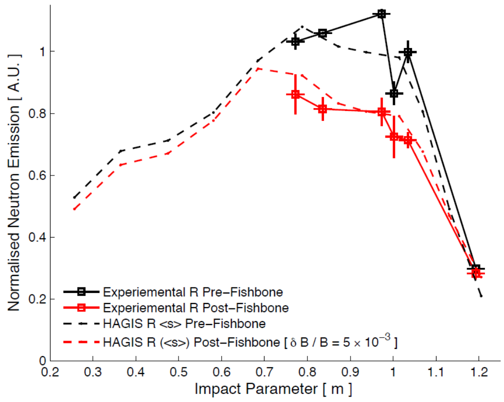

Figure 4: Pre- and post-fishbone NC experimental (points) and HAGIS modelled (dashed line) neutron emission profiles as a function of impact parameter.

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References

[1] M. Cecconello et al, Nucl. Fusion **52**, 094015 (2012)
[2] W. W. Heidbrink et al, Phys. Rev. Lett. **57**, 835 (1986)
[3] S. D. Pinches et al, Comput. Phys. Commun. **111**, 133 (1998)
[4] R. Lake, PhD thesis, University of Warwick, 2013.