Role of MHD activity triggered by fast ions in tungsten transport in JET hybrid discharges

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1. Introduction

Neo-classical and turbulent transports have been identified as major causes of tungsten transport in the plasma core [1, 2]. MHD activity also acts on impurity transport and in particular the sawtooth crash is found to flush out the tungsten accumulated inside the q=1 surface. On JET, when ICRH power is added to a NBI-heated H-mode discharge, the resulting increase of fast ion pressure gradient inside the q=1 surface may trigger the fishbone instability. When a regime with large amplitude and frequency span of the fishbones is achieved, the tungsten profile peaking decreases strongly and flat profiles are observed before the sawtooth crash [3, 4]. The effect of the m=1, n=1 MHD mode on the core tungsten transport in the hybrid scenario has already been investigated on JET [5, 6, 7] and it is found that in the early phase of high normalized beta (β_N>2.5) discharges, the continuous saturated mode strongly peaks the tungsten profile when the fishbone can either flatten this profile or moderately peak it. We here address the effect of the (1,1) mode on the longer term. As the current profile evolves, fishbones which are sensitive to the current profile in the core can be triggered quite late, up to 3.6s after the start of the high power phase.

2. Effect of ICRH on tungsten accumulation and fishbone activity

A set of 23 hybrid discharges (B_t=2.8-3.2T, I_p=2.0-2.4MA) with a weak variation of the NBI power (P_{NBI} =24-27MW) and on-axis ICRH with power varying between 1 and 6MW is used

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for the study of W transport and the link with the activity of the (1,1) mode. When P_{ICRH} exceeds 3MW, a significant level of fishbone activity is triggered in 53% of the discharges. A typical scenario is a period with fishbone activity followed by the growth of the continuous mode, sometimes interrupted by a short sequence of fishbones as shown in figure 1 where high amplitude and frequency span fishbones are triggered until the second sawtooth crashes (t=10.36s). After this event, a short period of low amplitude fishbones is followed by the development of the continuous internal kink mode. The core tungsten concentration evaluated from the soft X-ray diagnostic starts peaking 100ms after the fishbone activity starts decaying.

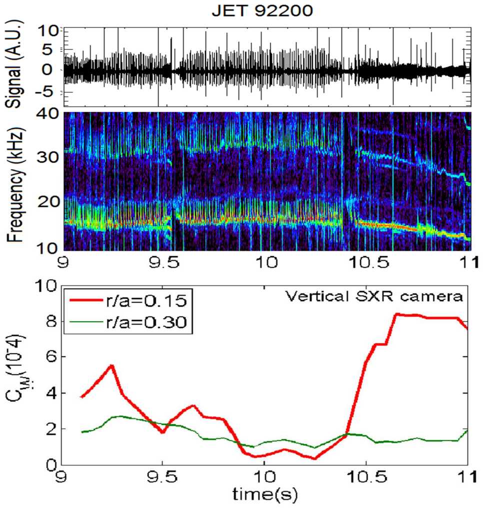

Figure 1. Raw signal (top), spectrogram (middle) of an outboard Mirnov coil and tungsten concentration (bottom).

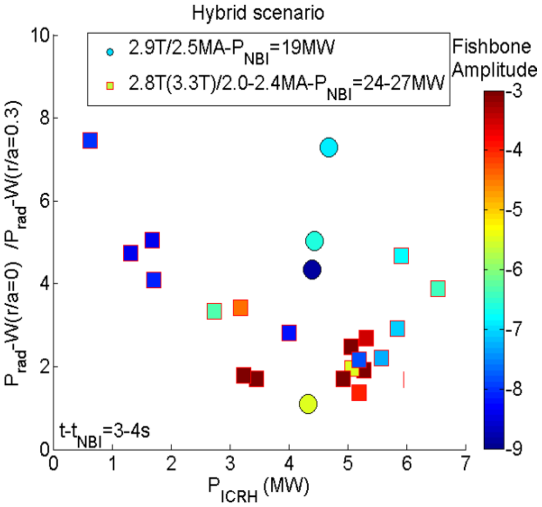

Figure 2. Tungsten peaking as a function of the ICRH power (t-t_{NBI}=3-4s). Fishbone amplitude is on a logarithmic scale.

The core tungsten peaking factor (PF), defined as the ratio between the power radiated by tungsten at a normalized radius r/a=0 and 0.3, is found to decrease strongly with the ICRH power in most cases, in agreement with previous work for standard scenario with much larger q=1 surface [4] (figure 2). It should be mentioned that whereas the core W concentration, approximatively varying like the peaking factor (PF=1 corresponding to $c_W(0)\sim1\times10^{-4}$), decreases with P_{ICRH}, the W concentration measured at mid-radius of the plasma by VUV spectroscopy, increases by a about a factor 2 when P_{ICRH} increases from 0 to 6MW. The colour code highlights the correlation between the fishbone amplitude and the flattening of the W profile. In particular rather flat W profiles (PF=1.7-1.8) are obtained with only 3MW concomitantly with large amplitude fishbones. On the opposite, no or very low fishbone activity (dark to light blue colour) is related to high PF. This is in particular true for the discharges performed in 2014 at lower power (circles) although for this series, the flat profile (PF=1.1) discharge has a strong continuous mode lasting 0.9s before the mode evolves into fishbones confirming that the continuous mode has not always a deleterious effect on tungsten transport [5]. The effect of the current profile on fishbone activity is revealed from the 2.8T discharges with P_{ICRH}~6MW and strong W accumulation (PF=4-5). These discharges have flatter current profile (the internal inductance is 0.78 compared to 0.85 for other discharges at same plasma current) caused by the early timing of the high power phase and no fishbone activity.

3. Tungsten transport in high power hybrid discharges

The experimental neoclassical flux of tungsten is generally estimated from the proxy $R/L_{ne} - 0.5R/L_{Te}$ where L_{ne} and L_{Te} are the gradient length for the density and the temperature, respectively, when the same temperature is assumed for the electrons and the ions. Four (possibly five considering error bars) discharges out of the six discharges with high fishbone activity (figure 3, dark brown symbols) have a negative neoclassical proxy indicating an outward tungsten flux. When these results are compared to those performed with baseline discharges (q_{95}~3.5) at relatively low plasma pressure ($\beta_N<1.4$) [4], which have weak to medium fishbone activity (with no statistical correlation on tungsten peaking), the peaking factor varies with the neo-classical proxy quite identically and no specific behaviour is observed.

4. Control of the fishbone activity

By replacing ion cyclotron resonance heating (π phasing of the antenna straps) by ion cyclotron current drive ($\pm\pi/2$ phasing), the current profile can be changed in the very core The driven current inside the r/a=0.3 surface is expected to be in the 10-20kA range with 5MW of ICCD which could be sufficient to act on the fishbone instability. An example is shown in figure 4. When the strap phasing is changed from 180 deg. (a) to +90 deg. (b), the fishbone amplitude is reduced, a n=2 mode grows and the tungsten tends peaking. Keeping the $\pi/2$ phasing and increasing the minority concentration n_H/n_D from 4% to 6% (c) suppresses the fishbone activity, strongly enhances the n=2 mode and the tungsten peaking. By increasing n_H/n_D, the fast ion pressure is not computed to increase [4] but the slight reduction of the electron temperature (~0.5keV) may result in a change of the current profile large enough to stabilize the (1,1) mode. ICRF-induced pinch of the resonating ions may also contribute in reduction of FB [8].

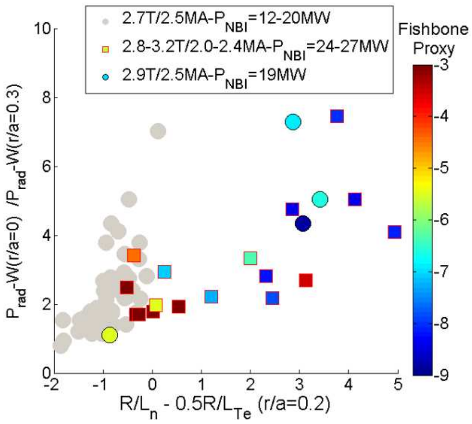

Figure 3. Tungsten peaking versus the neo-classical transport proxy for hybrid discharges (coloured symbols) and standard discharges (grey symbols) (t-t_{NBI}=3-4s). Fishbone amplitude is on a logarithmic scale.

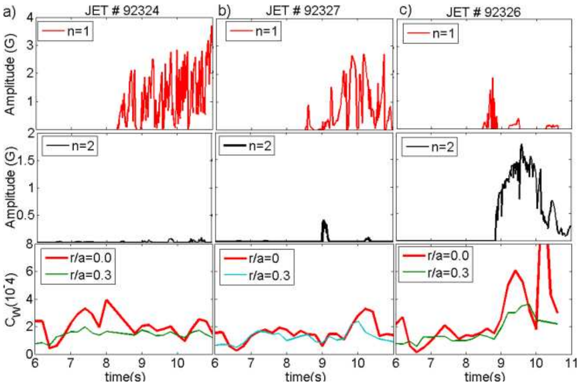

Fig.4. MHD mode amplitudes and tungsten concentration for 3 discharges (P_{NBI}=20.5MW)
a) P_{ICRH}=5.8MW, 180° phasing, n_H/n_D=4%,
b) P_{ICRH}=4.7MW, +90° phasing, n_H/n_D=4%,
c) P_{ICRH}=4.6MW, +90° phasing, n_H/n_D=6%.

5. Conclusions. Strong reduction of tungsten concentration in the plasma core is obtained in high power hybrid discharges when ICRH power is increased. This observation is generally correlated to the increase of the fishbone activity and a decrease of the continuous (1,1) mode. The fine details of the current profile in the core (r/a<0.2-0.3) seems to be determinant for the tungsten transport. Current drive phasing of the ICRF antennas could be an effective actuator aiming at further control of the tungsten contamination of the plasma core.

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