MHD phenomena as Trigger for the Formation of Internal Transport Barriers on ASDEX Upgrade

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1. Introduction

Advanced tokamak scenarios with the formation of internal transport barriers (ITBs) in discharges with low or negative central magnetic shear are very promising with respect to steady state tokamak operation, or to a reduced size tokamak reactor with pulsed operation. Whereas the reduced turbulent transport in the stationary phase after the formation of the ITB can be explained by the sheared perpendicular rotation resulting from the improved confinement within the ITB itself, the dynamics of the formation of the ITB is not yet well understood. In various tokamaks an influence of low order rational surfaces has been observed [1-4]. In JET positive shear discharges external kink modes coupled to inner rational surfaces have been shown to be able to trigger ITBs [4].

In ASDEX Upgrade reversed shear discharges, the onset of internal transport barriers is usually accompanied by fishbone activity. In the 80 discharges studied (with both ion and electron heating), there is not a single one in which a clear ITB forms without the presence of MHD activity. If an ITB forms, its onset occurs right after the first fishbone oscillations. This general observation suggests that the fishbone activity is instrumental for the formation of ITBs on ASDEX Upgrade.

2. Suppression of turbulent transport by fishbones

In most of the discharges it is (m,n)=(2,1) fishbone activity which acts as a trigger for the ITB formation. The reason for this effect is probably the ability of this kind of MHD to suppress the turbulent transport. To illustrate this, in Fig. 1 reflectometry data measuring the total amount of turbulent fluctuations is given together with the observed (m,n)=(2,1) MHD activity. It is seen that as soon as the (2,1) activity starts (at about 0.41 s) the turbulence level is strongly reduced. The turbulence reaches its minimum at about 0.45 s, when the (2,1) activity is strong and the fishbone character of the mode activity becomes obvious. Afterwards the turbulence level slightly rises, possibly due to the increase in heating power. The turbulence level remains then constant until it increases again at about 0.6 s. In Fig. 1b the radial location of the reflectometry measurements is given. Due to the density increase in time, the cut-off layer moves outwards. Thus, the increase of the turbulence level after 0.6 s is not surprising as the measurements are located already outside the ITB region.

In Fig. 2 the profiles of the ion temperature are given at a time right after the onset of the (2,1) fishbone activity ($t = 0.49$ s) and just before the fishbone activity of (2,1) helicity disappears. For these two times the regions of improved confinement are indicated. These regions have been defined as those in which the logarithmic temperature gradient ($\nabla T/T$) exceeds the maximum value observed in a comparison discharge with very similar plasma parameters but without the onset of fishbone activity, and in which no ITB develops. Whereas the foot of the ITB, located in the positive magnetic shear region, does not move in time, the inner boundary of the ITB moves inwards. As can be seen the inner boundary of the ITB agrees within the error bars with the location of the inner $q = 2$ surface, and it moves inwards with the same velocity as this rational surface. This observation supports the hypothesis of fishbones acting as a trigger for ITBs, as the fishbone eigenfunctions in the presence of two rational surfaces should behave like a double kink mode. Therefore it should be large only in between these surfaces. Thus in the region of weak or reversed magnetic shear, the inner boundary of the ITB should be close to the corresponding inner rational surface. In the positive magnetic shear region however, the ITG modes are expected to be more unstable. There the fishbone activity might not be sufficient to suppress the turbulent transport.

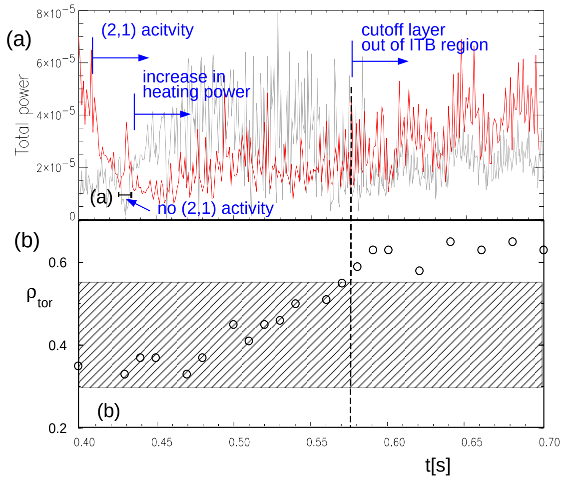

Fig. 1.
(a) Time evolution of the total reflectometry signal (red) in the frequency range between 80 and 250 kHz, and of the n=1 Mirnov activity (grey). Indicated are the onset of the (2,1) mode activity at about 0.41 s, the increase in heating power (0.44 s). At about t= 0.57 s the cutoff layer moves out of the ITB region. (b) Radial location of the cutoff layer for the reflectometry measurements. The hatched area indicates the region of improved confinement.

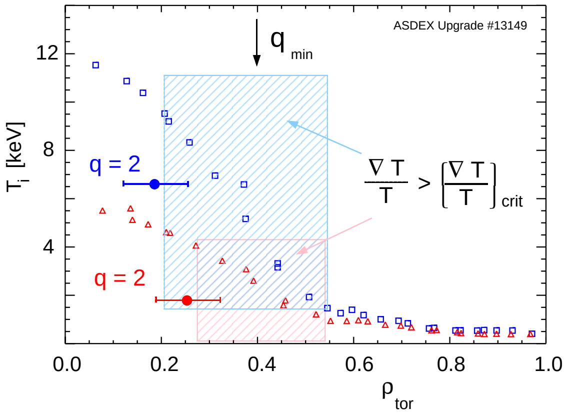

Fig. 2.
Profiles of the ion temperature right after the onset of (2,1) fishbone activity (t=0.49 s) and just before the fishbone activity of (2,1) helicity disappears. In addition the location of the minimum q-value (q_{min}) and that of the inner $q = 2$ surface are given. Furthermore the radial extend of the ITB for the two times is shown by the hatched areas.

In Fig. 3 it is shown how a single fishbone affects the energy confinement. During the frequency whistling down phase the central soft X-ray (SXR) signal increases whereas it decreases outside. Obviously the fishbone locally reduces the transport creating - at least for a short time - a transport barrier. Inside the location of this transport barrier the temperature increases, whereas it decreases outside due to the resulting reduced outward heat flux.

In advanced scenario discharges, even if an ITB already has been formed, often the confinement spontaneously improves with the onset of additional fishbone activity or when the repetition frequency of the existing fishbones increases. Such an example is shown in Fig. 4. Without any changes in heating power or density, the energy confinement in this discharge suddenly increases at about 0.75 s together with an increase in the fishbone repetition frequency. Fig. 4b shows time traces of a central SXR channel before and during the confinement improvement. It is seen that in both time traces each fishbone increases the central SXR signal at least shortly. After about 1 . . . 3 ms the signal decreases again. Only if the fishbone repetition frequency is large enough ($\tau_{FB} \leq 2.5\ ms$) a net increase in the SXR signal can be observed.

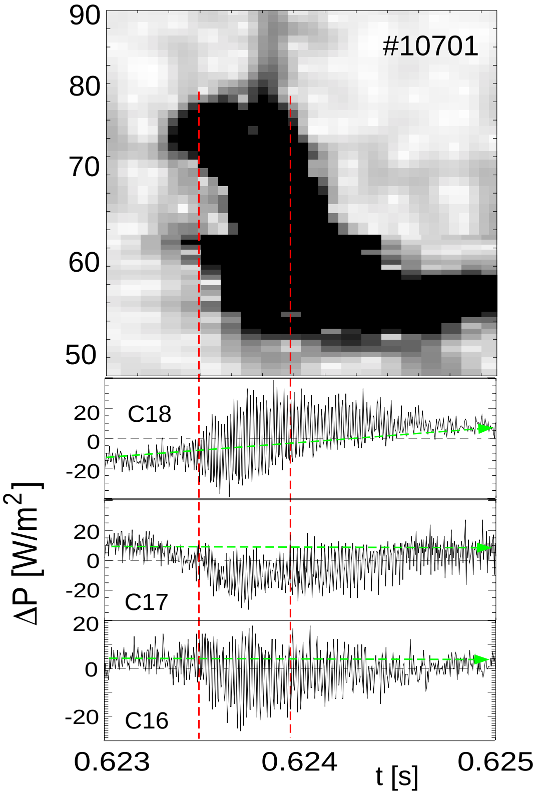

Fig. 3.
Wavelet plot of a single fishbone together with SXR measurements. It is seen that the central SXR signal (C18) increases during the frequency whistling down phase. At the same time the SXR signal outside is decreased, indicating a transport barrier induced by the fishbone.

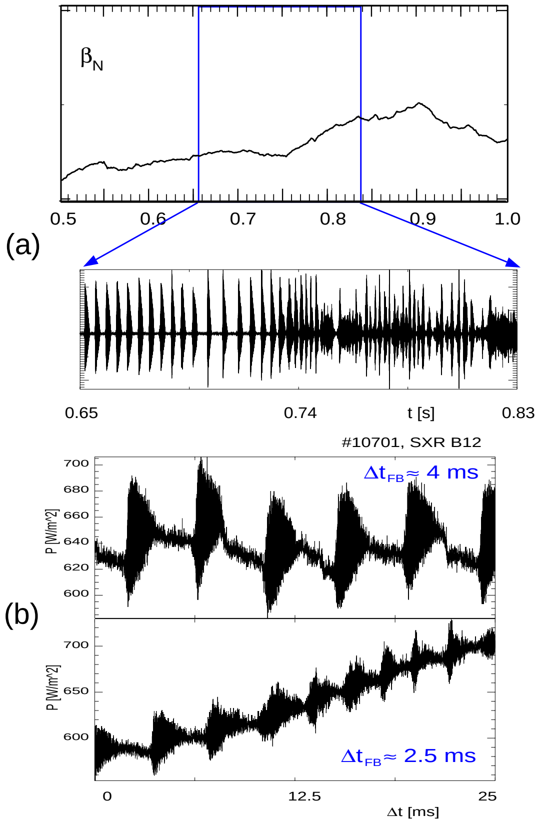

Fig. 4.
(a) Wave forms of the normalized plasma pressure, and Mirnov signal for a discharge with a confinement improvement at increased fishbone repetition frequency. The heating power does not change during the given time intervall. (b) Time traces of a central SXR signal before and during the confinement improvement. Each fishbone increases the SXR signal. As it deacreases about 1 . . . 3 ms after its rise, the time averaged SXR signal only increases for sufficient frequent fishbones.

A possible explanation for fishbones reducing the turbulent transport and thus creating a transport barrier is the interaction between the fishbones and the fast particles arising from NBI injection. As is well known, the interaction between fishbones and fast particles leads to a redistribution of the resonant fast particles. The resulting current carried by them across the corresponding magnetic surfaces causes a return current in the bulk plasma which gives rise to a sheared plasma rotation, equivalent to a radial electric field. The observed time scales are consistent with this explanation: (i) The transport is reduced during the fishbone frequency whistling down phase, in which the redistribution of the fast particles is known to be strongest. (ii) The transport is again increased after a few milliseconds which is in agreement with the time in which the poloidal rotation induced by the fishbone is damped by neoclassical effects. Only if the next fishbone occurs before the poloidal rotation is damped, the central temperature can increase (as seen in Fig. 4), and an ITB develops.

Nonlinear calculations for the interaction of fishbones with the fast particles arising from neutral beam injection have been perfomed using the HAGIS code [5]. It has been demonstrated that fishbones are able to redistribute the resonant fast particles causing a net current of fast ions outwards. The resulting return current in the bulk plasma leads to a sheared poloidal plasma rotation (see Fig. 5). The total sheared flow generated by fishbones can become comparable to the linear growth rate of the ITG modes if the fishbone repetition time is smaller than the time required for the neoclassical damping of the poloidal plasma rotation.

3. Summary and Conclusions

Fishbones have been shown to reduce the turbulent transport during their frequency whistling down time. For a sufficiently large fishbone repetition frequency they cause an increase in the temperature gradient, and thus trigger internal transport barriers. Nonlinear calculations for the interaction of fishbones with the fast particles arising from neutral beam injection have demonstrated that a possible explanation for the role of fishbones in triggering ITBs on ASDEX Upgrade is the sheared plasma rotation due to the resulting return current within the background plasma. As the poloidal plasma rotation is damped by neoclassical effects this mechanism can be successful only if the fishbone repetition frequency is larger than the damping rate of the poloidal rotation.

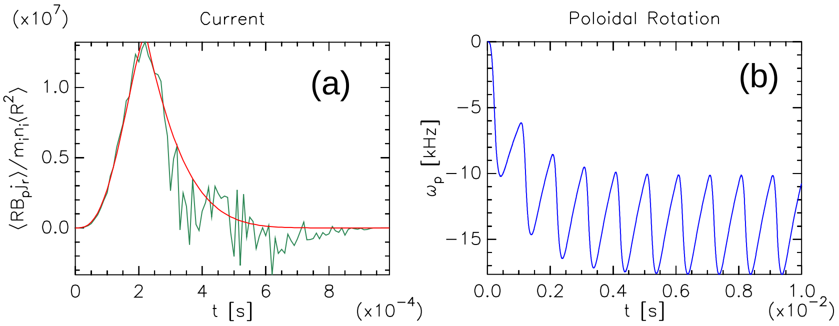

Fig. 5.

(a) Radial current arising from HAGIS simulations due to one fishbone. If one assumes such fishbones repeated every millisecond one arrives at a poloidal rotation given in (b). The shearing rate of this poloidal rotation within a factor of 2 agrees with the ITG linear growth rate.

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