# The Fishbone-Instability in ASDEX Upgrade

T Kass, HS Bosch, F Hoenen*, K Lackner, M Maraschek, H Zohm,
ASDEX Upgrade Team, NI Team, ICRH Team and ECRH Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association,
Boltzmannstr. 2, D-85748 Garching, Germany
*IPP Forschungszentrum Jülich GmbH, EURATOM Association,
D-52425 Jülich, Germany

## 1. Introduction

Stability and confinement are important features of tokomak fusion plasmas. It has been shown, that the fishbone instability [1,2] directly deteriorates the confinement of fast ions in a fusion plasma. As for example the $\alpha$-particles from the $D(T,n)\alpha$-reaction are responsible for the heating of a future fusion reactor, this instability can affect ignition of a fusion plasma. Understanding the fishbone instability is therefore an important topic in nuclear fusion research. As all experiments presented here have been examined in pure deuterium discharges the $\alpha$-particles were simulated throughout by fast deuterium particles injected with an energy of 60 keV.

## 2. General Features of the Fishbone-Instability

The fishbone instability can be easily identified because of its (namegiving) typical burstlike structure on the signal of the magnetic probes. Fishbones not only vary in amplitude but also in frequency. The temporal variation of the frequency within one single fishbone burst can be calculated with the help of a wavelet analysis (differential Fourier analysis). The result of such an analysis is shown in Fig. 1.

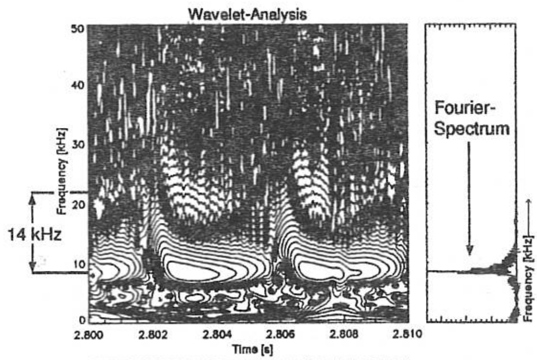


**Fig. 1:** *A wavelet analysis (differential Fourier analysis) during a fishbone burst shows clearly a frequency decrease within each single burst. Furthermore it exhibits, that the mode amplitude reaches its maximum right at the time, when the mode frequency has whistled down [3].*

In the bottom box the raw signal of a magnetic probe during two fishbone bursts is shown. The plot above displays the result of the wavelet analysis. The vertical axis represents the frequency in kHz, whereas the horizontal axis represents the time in sec. The lines connect areas with equal spectral power. This analysis shows, that a fishbone burst starts with an oscillation frequency of approximately 22 kHz, which decreases continuously within one third of the duration of the burst to the much lower frequency of the plasma rotation ($\approx$ 8.5 kHz in the lab-frame). Thus the difference of 14 kHz represents the actual start frequency of the fishbone burst in the plasma rest frame. Furthermore it can be observed, that the mode amplitude reaches its maximum right at the moment, when the mode frequency has whistled down. Integrating this 2-dimensional distribution over time, one gets the known Fourier spectrum shown in the right box.

A mode analysis exhibits, that the fishbone mode has a toroidal number of n=1 and a poloidal number of m=1 mainly. However higher poloidal mode numbers are also observed during each single burst. The rotation direction of this mode is the ion-diamagnetic drift direction. The amplitude distribution of magnetic probes located at different poloidal positions shows, that the fishbone activity is enhanced at the low-field side of the mid-plane plasma. As the fast trapped ions stay in majority in this area too, a coupling between these ions and the fishbone mode is indicated. During each fishbone burst an ejection of fast ions is detected via a correlated (up to) 20%-reduction of the neutron flux. Measurements of the charge exchange flux confirm this fact directly in showing, that fast particles are ejected from the plasma [4].

A correlation between the fishbone instability and the ELM (Edge Localized Mode) instability located on the plasma edge (far away from the fishbones at the q=1-flux surface) was observed in a high-$\beta$-discharge. This might be due to the ejection of the resonant fast trapped particles through the fishbone instability. These ions may enhance the plasma gradient on the plasma edge and thus cause an ELM. But to clear up this issue fully further investigations have to be done.

### 3. Mechanism

The initial frequency of the fishbone oscillation in the plasma rest frame is identified as the toroidal precession frequency of the injected fast trapped ions. From this, and the observation that the trapped content of the injected fast particles plays the dominant role in destabilizing the fishbone instability, a more detailed understanding of the basic fishbone mechanism can be derived.

The underlying destabilization mechanism is based on the fact, that the deeply trapped ions always stay in the bad curvature region of the magnetic field. Hence they can cause plasma interchange on the resonant q=1-surface, resulting in a resistive (m=1,n=1)-interchange mode. In this case the gradient of the spatial fast trapped ion distribution at the q=1-surface drives the fishbone instability. Because of the precessional movement of the fast trapped ions, the fishbone mode oscillates with the same frequency. Since the fishbone instability continuously ejects the resonant and driving ions it is successively driven unstable by lower energetic ions in the fast-ion-distribution. The fact, that the precession frequency is proportional to the energy of the fast trapped ions explains the observed whistling down of the frequency. If the gradient has been removed, the mode will not be driven any longer and slows down, as shown in Fig 1. It vanishes within the resitive time scale.

The inherent mechanism of successive fishbone cycles can be described in good accordance with the experimental data, if the mode amplitude and the destabilizing fast trapped ions are considered as predator and prey [5]. With this relationship it is possible to model the fishbone instability quite well.

## 4. Operational Regime

An evaluation of the experimental data leads directly to a stability diagram for the fishbone instability. Fig. 2 plots the toroidal precession frequency of the fast trapped ions against the fast particle pressure $\beta_{\rm fast} = \beta_{\rm tor}/(1+\tau_{\rm E}/\tau_{\rm sd})$, where $\tau_{\rm E}$ represents the energy confinement time and $\tau_{\rm sd}$ the slowing-down time of the fast ions) of several discharges showing fishbone activity (full symbols) and some without (open symbols). It exhibits clearly, that a distinct threshold in the fast particle pressure exists ($\beta_{\rm fast} > 0.009$), above which the fishbone instability can be destabilized in ASDEX Upgrade.

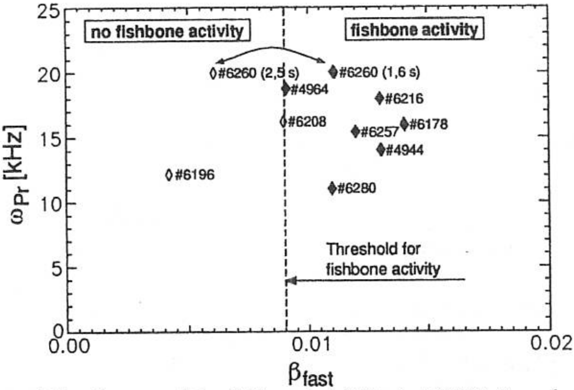


**Fig. 2:** *The stability diagram of the fishbone instability in ASDEX Upgrade [3]. It shows directly, that the fishbone activity occurs only above a distinct threshold in the fast particle pressure $\beta_{fast} = \beta_{tor}/(1 + \tau_E/\tau_{sd})$ (where $\tau_E$ is the energy confinement time of the plasma and $\tau_{sd}$ the slowing-down time of the fast injected deuterium particles).*

As $\beta_{\rm fast}$ is a very inconvenient parameter it is useful to express the information of this diagram in terms of adjustable plasma parameter in order to derive a general operational regime of the fishbone instability. This can be achieved by replacing all parameter in the equation for $\beta_{\rm fast}$ through their explicite terms. For the confinement time $\tau_{\rm E}$ one has to insert the ITER H92P scaling law [6]. Thus it is possible to calculate the operational regime via an evaluation of the following expression [3]:

$$\beta_{\rm fast} = \frac{2\mu_0 n_e T_e/B_t^2 \cdot 3,1\cdot 10^8 A_b T_e^{2/3}/n_e \ln\Lambda}{0,051\cdot A_i^{0,51}\cdot I_P^{0,83}\cdot P_{\rm tot}^{-0,51}\cdot R^{1,87}\cdot (\frac{a}{R})^{0,11}\cdot \kappa^{0,5}\cdot B_{\rm tor}^{0,1}\cdot n_e^{0,05}} > 0.009 \qquad (1)$$

It can be seen, that the destabilization of the fishbone mode is more or less independent of the plasma density $n_e$ at constant heating power $P_{\rm tot}$. Figure 3 displays the calculated general operational regime (for $n_e = 5\cdot 10^{19}$ m$^{-3}$ and $P_{\rm tot} = 6$ MW) including the location of some discharges with and without fishbone activity. By means of this diagram it is possible to predict the appearance of the fishbone instability depending on the plasma current $I_P$, the toroidal magnetic field $B_{\rm tor}$ and the central plasma temperature $T_e$.

Following from that, within the flattop phase of a plasma discharge with constant current, toroidal magnetic field and additional heating power the single free parameter for destabilizing the fishbone mode is the plasma temperature. Thus in a discharge located very close to the destabilization region for fishbones, only small changes in the plasma temperature are necessary to suppress or to destabilize fishbone activity.

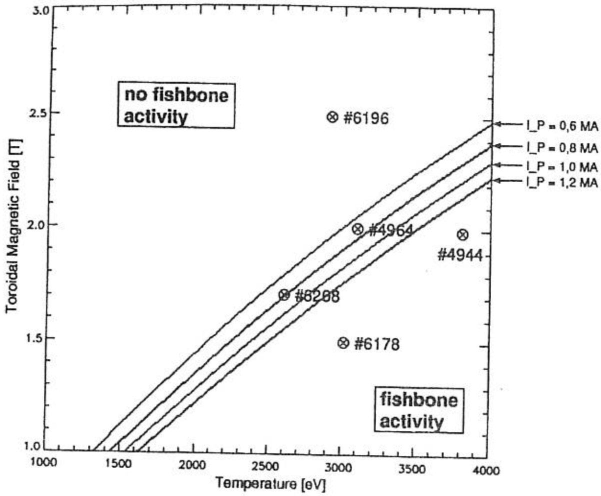


**Fig. 3:** *The calculated operational regime of the fishbone instability in ASDEX Upgrade [3]. The parameter space is divided into two regions by the line for the plasma current ranging between 0.6 - 1.2 MA. In the upper left area (above the corresponding plasma current line) no fishbone activity is possible, wheras in the lower right area (below the corresponding plasma current line) fishbone activity can be observed.*

## 5. Summary

The fishbone instability has been investigated in the tokamak experiment ASDEX Upgrade. It can easily be identified due to its burstlike structure on the magnetic probes and the characteristic frequency reduction within each single burst. The basic destabilization mechanism is essentially based on the fact, that the fast trapped ions always stay in the bad curvature region of a toroidal plasma. Thus they can destabilize interchange. Because of their toroidal precession these ions transport this magnetic perturbation in the same direction. As the toroidal precession frequency depends on the energy of the fast trapped ions, the ejection of these particles results in a frequency reduction during each burst. Fishbones occur in ASDEX Upgrade only above the threshold $\beta_{fast} > 0.009$. From this it is possible to calculate generally the operational regime in terms of adjustable plasma parameters like plasma current, toroidal magnetic field and temperature. It turns out, that the destabilization depends only marginally on the plasma density. Thus within the flattop phase of a discharge the single free parameter for destabilizing fishbone activity is the plasma temperature [3].

## References

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