MHD phenomena in advanced scenarios on ASDEX Upgrade and the influence of localized electron heating and current drive

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Abstract MHD instabilities in advanced tokamak scenarios on the one hand are favourable as they can contribute to the stationarity of the current profiles and act as a trigger for the formation of internal transport barriers. In particular fishbone oscillations driven by fast particles arising from neutral beam injection (NBI) are shown to trigger internal transport barriers in low and reversed magnetic shear discharges. During the whistling down period of the fishbone oscillation the transport is reduced around the corresponding rational surface, leading to an increased pressure gradient. This behaviour is explained by the redistribution of the resonant fast particles resulting in a sheared plasma rotation due to the return current in the bulk plasma, which is equivalen to a radial electric field. On the other hand MHD instabilities limit the accessible operating regime. Ideal and resistive MHD modes such as double tearing modes, infernal modes and external kinks degrade the confinement or even lead to disruptions in ASDEX Upgrade reversed shear discharges. Localized electron cyclotron heating and current drive is shown to significantly affect the MHD stability of this type of discharges.

1. Introduction

Advanced tokamak scenarios are very promising with respect to a reduced size tokamak reactor in pulsed operation or even to steady state tokamak operation [1-5]. The improved confinement reduces the necessary plasma current I_p for sufficiently high fusion performance (Q = fusion power/externally supplied plasma heating power). The flat and reversed q profiles allow the formation of internal transport barriers (ITBs) as well as the access to second stability with respect to the ideal $n \to \infty$ ballooning modes [6], and therefore large pressure gradients. The resulting large fraction of I_p provided by the intrinsic bootstrap current allows steady state operation if the bootstrap-driven current density can be sufficiently aligned with the one required to maintain an ideal current profile.

A wide variety of magnetohydrodynamic (MHD) instabilities has been observed in advanced tokamak experiments. Most of them limit the accessible operating regime, in particular the maximum achievable normalized plasma pressure β_N ($\beta_N = \beta_t/(I_p/aB_t), \beta_t = \langle p\rangle/(B_t^2/(2\mu_0))$, where a is the minor radius, B_t is the toroidal magnetic field, and $\langle p\rangle$ is the volume averaged plasma pressure) by either terminating the improved confinement or even causing disruptions.

Here we report on the MHD phenomena in advanced scenarios observed on ASDEX Upgrade. Besides the above mentioned unfavourable role of MHD instabilities, they have been shown to be helpful in achieving improved confinement and quasi-stationary discharge conditions. In Section 2 the contribution of MHD instabilities to quasi-stationary profiles is discussed. In Section 3 the dynamics of the formation of ITBs on ASDEX Upgrade is investigated. It is found that fishbones can act as trigger for ITBs by reducing the turbulent transport due to the redistribution of the resonant fast particles resulting in a sheared plasma rotation due to the return current in the bulk plasma, which is equivalen to a radial electric field. Section 4 is devoted to the investigation of the observed confinement limiting MHD instabilities and the influence of localized current drive and heating on stability. Possibilities for a further extension of the accessible operating regime will be discussed.

2.MHD phenomena supporting quasi-stationary profiles

The beneficial effect of sawteeth and edge localized modes (ELMs) for achieving quasi-stationary discharge conditions in conventional H-mode is well known. It has been shown in [7] that fishbones can play a similar role, limiting the peaking of impurity density and electron temperature profiles. An effect also on the current profile was infered indirectly from the necessity of assuming a reconnection process to explain the observed stationary current profiles in H-mode discharges with improved confinement [8]. In the absence of sawteeth such a reconnection process could only be provided by the strong fishbone activity which is characteristic for this type of discharge.

An island structure of the fishbone oscillations has been found already from soft-X ray tomography at JET [9], and a direct proof of the resistive character of fishbones can be given by considering the eigenfunction ($\tilde{T}_e/\nabla T_e$) as derived from electron cyclotron emission (ECE), see Fig. 1. During the frequency whistling down time, the phase of the eigenfunction does not change, indicating an ideal mode. For the case of fishbone oscillations, which continue afterwards at nearly constant frequency, a clear island structure develops with a phase jump, located at about $\rho_{tor} = 0.2$ for the fishbone considered.

In reversed shear discharges fishbones with higher mode numbers $(m,n > 1)$ have been observed, in agreement with theoretical predictions [10,11]. These fishbones have a similar effect on the q profile. Often (2,1) fishbones clamp the current profile locally, keeping the minimum q value (q_{min}) in the vicinity of 2 for about 100 ms. As for the fishbones in the improved H-mode discharges with flat shear, no degradation in confinement occurs [12].

3. MHD instabilities as a trigger of internal transport barriers

The stationary large pressure gradient after the formation of an ITB can be explained by the sheared perpendicular rotation resulting from neoclassical effects due to the large temperature gradient at the ITB itself. This leads to a radial electric field

$$E_r = \nabla_r p/(en_e) - v_\phi B_\theta + v_\theta B_\phi, \tag{1}$$

and the resulting $E \times B$ shearing rate [13]

$$\omega_{E\times B} = \left| \frac{RB_\theta}{B_\phi} \frac{\partial}{\partial r} \left(\frac{E_r}{RB_\theta} \right) \right| \tag{2}$$

(B_θ and B_ϕ: poloidal and toroidal components of the magnetic field, n_e: electron density, v_ϕ and v_θ: toroidal and poloidal rotation velocities). The dynamics of the ITB formation, however, is not yet well understood. An influence of MHD phenomena in this process appears probable, as the existence of low order rational surfaces has been found to support the ITB formation in various tokamaks [14 - 16].

3.1. Experimental observations

On ASDEX Upgrade a strong influence of fishbone activity on the formation of ITBs has been discovered. In nearly all discharges with a clear ITB its onset occurs right after the first fishbone oscillations, radially located in the vicinity of q_{min}. At the same time and radial location

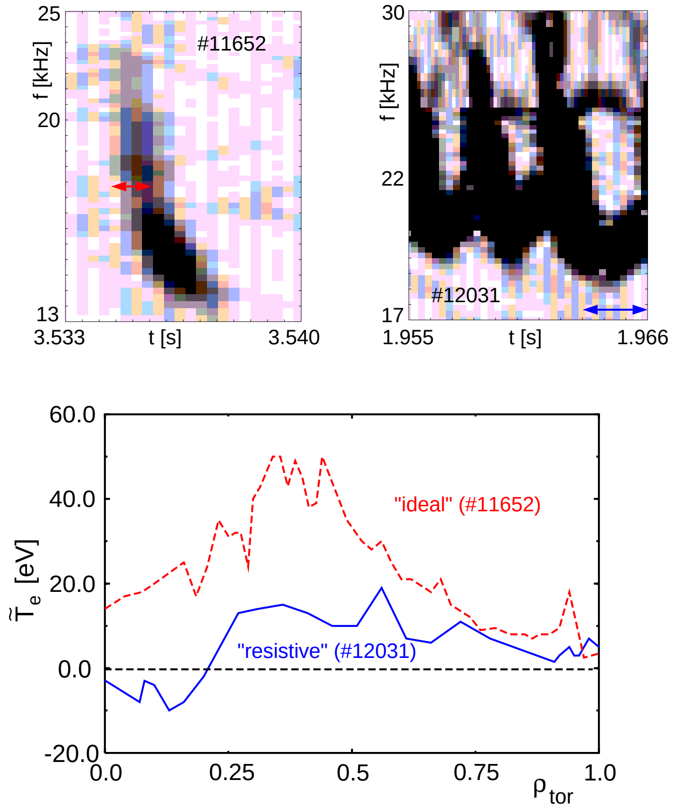

Figure 1: *Eigenfunction of a (1,1) fishbone during the frequency whistling down time (dashed line) and the period of nearly constant frequency (solid line) as measured by ECE.*

the turbulence becomes suppressed, as measured by reflectometry [17]. In discharges without significant MHD phenomena, however, usually no formation of ITBs is observed.

In order to show that fishbones indeed can suppress the turbulent transport, in Fig. 2 the effect of (5,2) fishbones on the electron temperature (measured by the ECE diagnostic) is shown for different radial positions. In between two fishbones, the electron temperature remains constant outside $\rho_{tor}(q_{min}) \approx 0.4$. The fishbone activity itself, however, strongly modifies the temperature profile. During the period of frequency whistling down, the temperature rapidly rises in the region close to the outer $q = 5/2$ surface ($\rho_{tor} \approx 0.5$). This increase in temperature is obviously caused by a local transport reduction as the temperature outside $\rho_{tor} = 0.5$ decreases, and no temperature reduction in the plasma centre is observed. Subsequent to the frequency whistling down, a fast temperature decrease at $\rho_{tor} = 0.5$, and an increase outside this radius are observed, consistent with a reconnection induced by the fishbone. This decrease in temperature is, however smaller than its increase during the frequency whistling down phase.

In the discharge considered, besides a transport barrier located at q_{min}, at the $q = 5/2$ radius another one forms. The radial location of the latter moves outwards together with the $q = 5/2$ surface as long as the (5,2) fishbone activity is present [17]. Obviously, this transport barrier, located in the positive magnetic shear region, cannot be sustained without the fishbone activity which periodically reduces the transport.

3.2. The trigger mechanism

The mechanism by which fishbone activity can lead to the supression of turbulent transport has been more thoroughly investigated in a discharge with a monotonic q-profile in which a transport

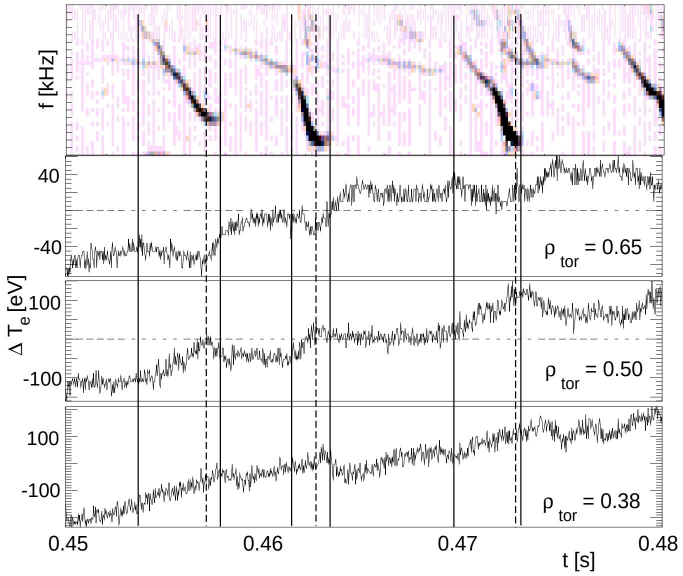

Figure 2: *Wavelet plot of (5,2) fishbone activity together with the time traces for the electron temperature measured by the ECE diagnostic at different radial positions. Indicated are the beginning and the end of the fishbone bursts (solid lines) as well as the end of the whistling down phase (dashed lines).*

barrier is formed right after the occurance of a large (1,1) fishbone burst [17]. The frequency of this fishbone is sufficiently small to allow the eigenfunction of the (1,1) mode to be determined using the ECE measurements. Combining the measured eigenfunction as given in Fig. 3 (a) with the observed mode frequency, the non-linear interaction between the fishbones and a population of fast particles has been investigated using the HAGIS code [18]. For this investigation a slowing down velocity distribution (isotropic in the pitch angle) for the neutral beam injected particles has been used, taking the experimental beam energy of 60 keV. 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 is shown in Fig. 3 (b). Its return current in the bulk plasma gives rise to a sheared plasma rotation, equivalent to a radial electric field. As the corresponding poloidal rotation is damped by neoclassical effects, after a few ms only the resulting toroidal rotation

$$\Delta\Omega_E = \frac{\Delta E_r}{\langle RB_\theta \rangle} = \int \frac{RB_\theta\, j_r}{m_i n_i \langle R^2 \rangle} dt \tag{3}$$

(j_r : radial current density, m_i and n_i: ion mass and density) contributes to the shearing rate given in Eq. 2. Damping of the toroidal rotation is not considered here, as this happens on the momentum confinement time scale which is large compared to the fishbone repetition time. For the discharge considered, this shearing rate exceeds by a factor of 3 the maximum linear growth rate of the ITG modes, calculated according to [19] (see Fig. 3 (c)). Therefore, even weaker fishbones should be able to suppress the turbulent transport, which is in agreement with the experimental observations.

4. Limitation of the operational regime due to MHD instabilities

The flat or reversed q profiles required for the ITB formation give rise to MHD phenomena not observed under conventional discharge conditions. These instabilities lead to a significant limitation of the accessible operating regine, in particular of the maximum achievable β_N value.

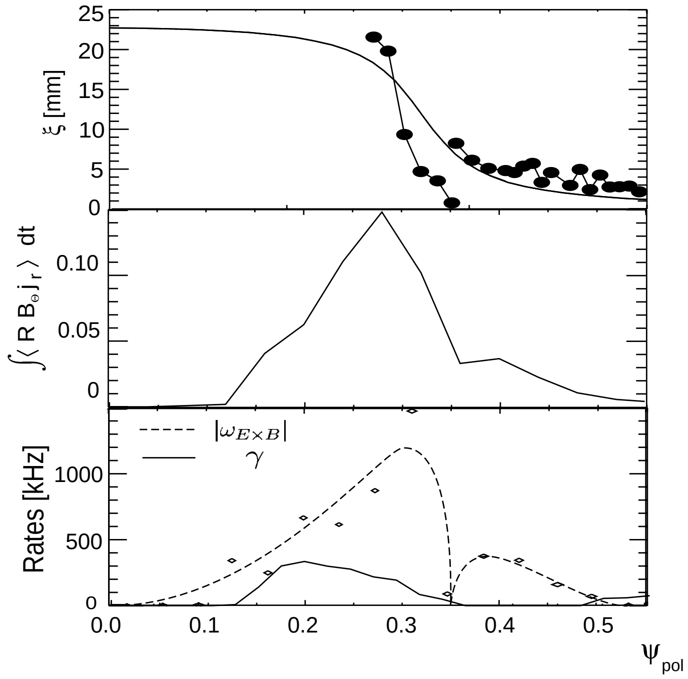

Figure 3: *(a) Eigenfunction of the (1,1) fishbone oscillation as derived from the ECE data ($\xi = \tilde{T}_e/\nabla T_e$), (b) the time integrated current density normal to the magnetic surfaces, and (c) the sheared flow resulting from this current density compared to the maximum linear growth rate of the ITG.*

We will summarize here the corresponding instabilities observed in ASDEX Upgrade reversed shear discharges (described in more detail in [20]) and the influence of localised current drive and heating on the stability of the observed MHD modes. Furthermore, the prospects of the more tangential NBI injector, being right now installed on ASDEX Upgrade, with respect to steady state operation will be investigated.

4.1. Double tearing modes (DTMs)

In ASDEX Upgrade reversed shear discharges, subsequent to the (2,1) fishbones described in Sec. 2, often continuous (2,1) mode activity appears when the minimum q-value is close to 2. In contrast to the fishbone activity, these modes lead to the break down of the internal transport barrier as well as to decreased electron temperatures. During the mode activity, the current profile is clamped, at least in the vicinity of q_{min}. The end of the (2,1) activity coincides with a sudden drop of q_{min} well below two.

A stability analysis based on an equilibrium reconstruction using the MSE diagnostic has been performed with the CASTOR code [21], but generalised to include the effect of differential rotation [22]. The plasma rotation has been included furthermore into the equilibrium reconstruction since the measured rotation frequencies are of the order of the sound velocity. The observed mode has been shown to be a double tearing mode, vanishing about 70 ms after its onset due to the decoupling of the two rational surfaces [23]. Non-linear simulations, performed in cylindrical geometry, using the code described in [24], show that the coupled islands are able to flatten the current profile in between the two rational surfaces.

Additional electron heating leads to high central electron temperatures ($T_e \approx T_i \approx 10$ keV) [24,25], and significantly changes the MHD stability of the discharges considered. With central electron heating applied, the DTM either does not appear if the electron heating is provided before the expected onset of the DTM, or disappears as soon as the ECRH is switched on [20].

A tentative explanation for this effect could be the increased pressure gradient at the inner $q = 2$ surface, giving rise - in inversion to the dynamics leading to the neoclassical tearing modes in positive shear regions - to a stabilisation of the mode due to the combined effect of bootstrap current reduction in the island and of the negative magnetic shear.

To investigate the efficiency of additional current drive using electron cyclotron current drive (ECCD) and its effect on the MHD stability, EC power has been applied to the plasma centre not only in pure heating, but also in current drive mode, using a movable mirror system. The effect of co-current drive was much larger than that of counter-current drive, as in this case both effects, the increased current density in the plasma centre due to the electron heating (resulting in an increased conductivity) and the current drive, are additive in increasing the central current density. In contrast to discharges without external current drive, co-ECCD reduces the shear reversal significantly affecting the MHD stability [20].

4.2. Limitation of the pressure gradient in the weak magnetic shear region

In discharges with combined neutral beam injection (NBI) and EC heating, ideal (2,1) mode activity (growth time about 200 μs) appears. This mode has been shown to be an infernal mode, driven by the large pressure gradient in the weak magnetic shear region. It does not always destroy the ITB, the time evolution of the central electron temperature, however, sometimes seems to be similar to that of a sawtoothing discharge with (2,1) instead of (1,1) mode activity limiting the peaking of the temperature profile [20].

4.3. Disruptions due to global modes

Even without additional electron heating, ideal modes often appear in reversed shear discharges when a low order rational q-value at the plasma edge allows the coupling of the (2,1) infernal mode to an external kink mode. The resulting mode mostly causes a disruption about 1 ms after its onset due to the global character of the eigenfunction as measured by electron cyclotron emission, which agrees very well with that derived from the stability analysis [20].

4.4. Possibilities for an extension of the operational regime

The stability analysis of ASDEX Upgrade reversed shear discharges has shown that confinement degrading MHD activity appears due to the occurrence of two low-order rational surfaces of the same helicity (double tearing modes) or due to a large pressure gradient within a weak magnetic shear region (infernal modes). An optimised q-profile with respect to the stability of core localised modes, has to avoid therefore, close double rational surfaces. The shear at the low order rational surfaces should be as large as possible, especially in regions with large pressure gradients. Furthermore, in order to avoid the occurrence of neoclassical tearing modes, q_{min} should be larger than 1.5, and the pressure gradient at the $q = 2$ surface as small as possible.

Possibilities for an active control of the current profile are rather limited. On ASDEX Upgrade, at present, a significant modification of the plasma current profile has been achieved so far only by early heating and current ramp up (reversed shear scenarios) or in low density discharges by electron cyclotron current drive (ECCD). In some discharges of the latter type, and with low plasma current ($I_p = 0.4$ MA), the whole current was driven non-inductively [26]. The rotation of one of the NBI injectors into a more tangential direction carried on right now, will offer the possibility of off-axis NBI current drive. This way we expect to achieve stationary current profiles with $q > 1$, or even $q > 1.5$ [27]. To estimated the expected current profiles, besides the current drive due to NBI, also the bootstrap current has to be taken into account. Unfortunately the bootstrap current itself depends on the current profile via the transport coefficients which determine the pressure profile. Assuming a typical H-mode pressure profile, the q profiles expected for the new injector geometry ensure $q_{min} > 1.5$, avoiding close double low order rational surfaces (see Fig. 4). Compared to the reversed shear q profiles obtained by early heating, the q profiles of Fig. 4 are improved with respect to MHD stability. While in the reversed shear discharges the achieved normalized plasma pressures, in agreement with theoretical predictions, are quite low ($\beta_N \leq 1.7$), the theoretical β limits significantly rise for the current profiles expected with the new injector geometry ($\beta_N \approx 3$ for a bootstrap current fraction of 35%).

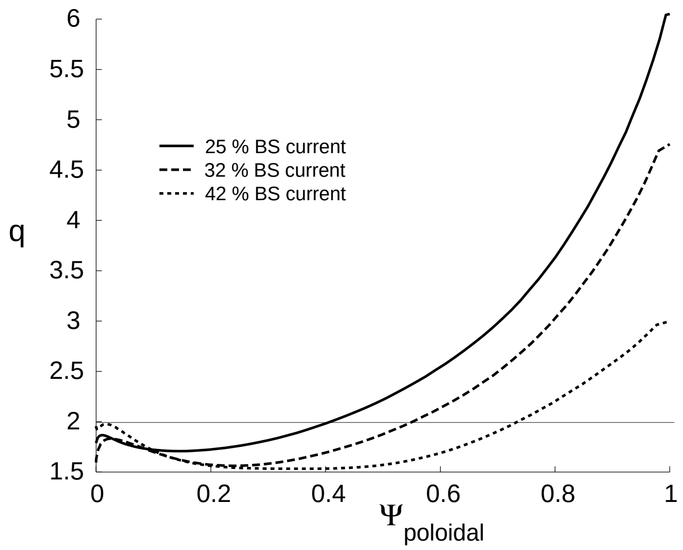

Figure 4: *profiles expected for the more tangential neutral beam injector assuming different bootstrap current fractions.*

5. Summary and conclusions

MHD instabilities have been shown to play a significant role in advanced tokamak scenarios on ASDEX Upgrade. Besides their well known unfavourable role in limiting the operating regime, they contribute to the quasi-stationarity of the current density profile, and can even act as a trigger for the formation of internal transport barriers. In particular, fishbone-type modes have shown to be able to induce the suppression of turbulent transport by expelling fast resonant particles causing a sheared plasma flow. It appears plausible that also other MHD instabilities, forming magnetic islands, could have a similar effect, as also the formation of magnetic islands at least transiently should affect the radial electric field. This would explain the preferential formation of transport barriers in the proximity of low order rational surfaces, observed in several other tokamaks.

To extend the operating regime, active control of the current profile is necessary. If one can optimize the current profiles with respect to the stability of core localized modes, the ultimate limit to the normalised plasma pressure would be given by the onset of external kink modes, as l_i is rather small for q-profiles in advanced scenarios. External modes, however, could be stabilised by a conducting wall, in combination with a feedback system, which would have to react on the resistive wall time. On ASDEX Upgrade, at present, the wall is too far away from the plasma edge to provide a significant stabilising contribution. Installing additional wall structures inside the vacuum vessel on ASDEX Upgrade is therefore under discussion right now. Since such a wall would have a 3-dimensional structure, of course, the resulting influence on MHD stability has to be investigated using 3D stability codes. This will be done in the near future using the 3D ideal MHD code CAS3D [28].

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