Radially Propagating High-n/High-m Mode Cascades During Flattening or Inversion of Central q-Profile in ASDEX Upgrade

A. Gude, K. Hallatschek, M. Bessenrodt-Weberpals, S. Günter, A. Kallenbach, K. Lackner, S.D. Pinches, S. Sesnic, M. Sokoll, and the ASDEX Upgrade Team,
Max-Planck-Institut für Plasmaphysik, EURATOM-Association,
D-85748 Garching, Germany

1 Introduction

The discovery of neoclassical tearing modes ((3,2), (4,3), (5,4), etc.) has shown that modes of $n > 1$ can be excited in the core [1,2]. Moreover, advanced tokamak concepts with increased core confinement have opened new possibilities for higher-n modes in the vicinity of integer q surfaces and renewed the interest in core MHD modes [3,4]. This is especially true for reversed magnetic shear experiments, where q_{min} can be localized near $q = 1, 2$ or 3 [3,4]. In such a case, the local shear around these surfaces can be rather low. This, combined with the high β's in the modern experiments, could affect the stability of higher-n modes. The most probable modes to be destabilized in the area of an integer q surface ($q = k$, where $k = 1,2,3$), will have the poloidal and toroidal mode numbers linked by the expression $m = k \cdot n \pm 1$. In this paper we report on a new kind of high-n mode activity in the plasma core, which has similar attributes and is characterized by a cascading process.

2 Phenomenology of mode cascades

2.1 General properties of cascades

We define a cascade as a series of short mode bursts in order of increasing n. The cascade commences with the lowest n, typically 5 or 6, and can reach n values of 22 or higher. The relationship between the poloidal and toroidal mode numbers is given by $m = n + 1$, so that the q range of the cascade modes is $\approx 1.045 < q \leq 1.2$. This q range corresponds to a radial shell from $r = 11$ to 27 cm. At least two, sometimes even more, of the neighbouring modes in a cascade overlap partially in time, so that it can be assumed that the lower mode triggers the next higher one.

Fig. 1 gives examples for the two kinds of cascading processes observed in ASDEX Upgrade. In both cases the cascades begin with a mode of lower frequency, signifying a lower n number. The main difference between the two cases is that for co-injection a very low, but still positive, magnetic shear (PMS) develops in the central region and for counter-injection a low reversed magnetic shear (RMS) evolves. This low shear allows the cascades to appear in both PMS and RMS regions. The mode positions obtained from soft X-ray mode profiles differ for the two cases. The highest modes for PMS are established at lower minor radii and for RMS at larger radii than the lower cascade modes. There is also a difference in the radial progression of the cascades: In the PMS case, the cascading process (of a single cascade) advances from outside toward inside. For the RMS case the direction of progression is opposite. During the cascades, continuous low-n modes ((3,2), (4,3), (5,4)), not displayed in Fig. 1, appear. From their n numbers the lowest cascade n numbers (5 or 6) can be deduced using the fact that the frequency difference between two neighbouring modes does not change much with the n number.

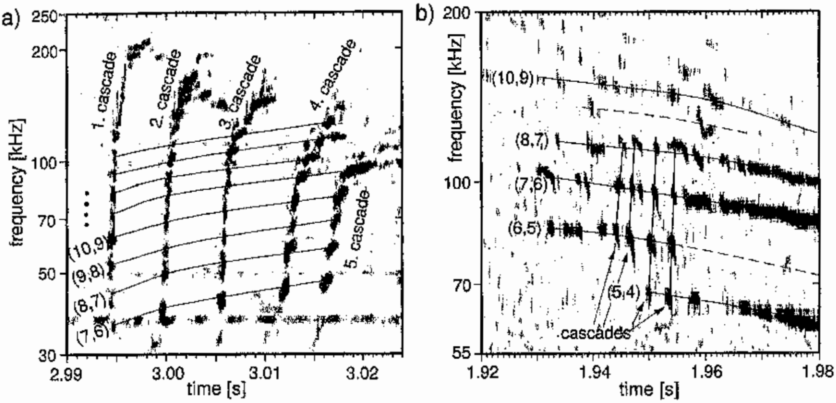

Figure 1: *MHD cascades observed in wavelet spectrum of soft X-ray radiation: a) positive magnetic shear case (co-injection) b) reversed magnetic shear case (counter-injection). Dark areas represent mode activity. Mode numbers for b) are estimated.*

Fig. 2 depicts the PMS cascading example of Fig. 1a, as observed in soft X-ray diodes. Cascades are indicated by different shadings. The shading marks two neighbouring diodes where the mode bursts cause a loss of energy and particles from inside (inner diode with a signal drop) to outside (outer diode with a signal rise). This also denotes the position of the modes. Due to the limited resolution of the diode array, several modes can be responsible for the signal drop. It is also evident from the figure that these cascades progress inward.

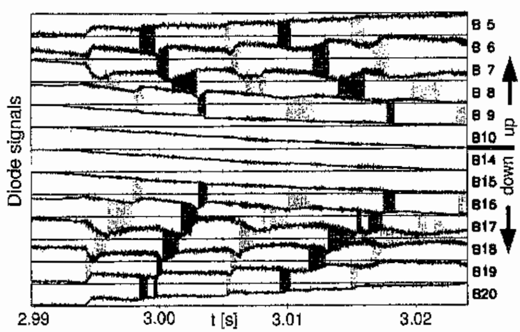

Figure 2: *Signals from a soft X-ray diode array showing the same cascades as in Fig. 1a. Shaded areas demonstrate inward progression of cascades.*

The mode cascading in ASDEX Upgrade occurs during a transient process in a discharge, where the central current profile is going through a strong modification brought about by low-Z (Ne, C) and/or high-Z (e.g., W) central accumulation. This accumulation leads to peaking of Z_{eff} (for low-Z) or flattening of the T_e profile caused by high central radiation (for high-Z impurities). In all discharges with cascades we observed both a peaking of Z_{eff} and a flattening of the T_e profile. During the later cascades the T_e profiles can even become hollow. The cascades are, therefore, observed in some of the CDH discharges, where Neon peaking sometimes occurs and in counter-injection discharges, which tend occasionally to accumulate impurities. All discharges where cascades have been detected were auxiliary heated with a medium β_{pol} between 0.6 and 0.9.

2.2 Evolution of q profiles

Knowing the mode location, corresponding n number, and the relationship $m=n+1$, one can construct the q profile in the cascade region. $m=n+2$ or $m=n-1$ are not applicable, because these relations would result in a large break in the q profile between low-n and cascade modes. The q profile including the $q=1$ surface is shown in Fig. 3 for the PMS case for three times during the cascades. The modes at $q=1.33$ and 1.25 are non-cascading low-n modes. This figure also demonstrates the inward movement of the central q profile. The magnetic shear, $s=r/q\cdot dq/dr$, becomes small in the region of cascade modes with values of $s=0.5$ down to 0.26 for the (6,5) and 0.2 down to 0.07 for the (10,9) mode.

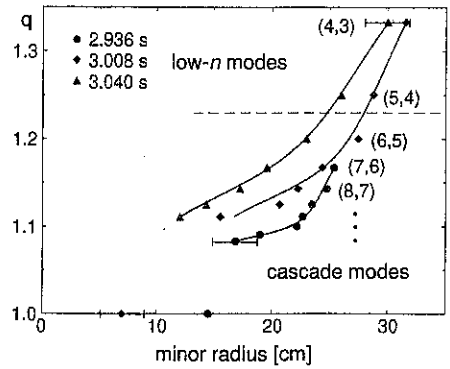

Figure 3: *Time evolution of the q profile during the cascading process determined from mode positions. The time sequence illustrates the inward movement of the q profile.*

From the change in mode location in the RMS case one can conclude that the RMS region progresses outward and most probably the q_{min} value increases. This can also be inferred from the lowering of the maximum and minimum n numbers observed for the cascades. In addition to the cascade modes there are low-n modes in the outer PMS region (of the RMS discharges). From the evolution of their location, we can conclude that this part of the q profile progresses inward as in the PMS case.

2.3 Frequency evolution of cascade modes

As can be seen from Fig. 1, there is a rather slow change in frequency of a given (m,n) mode from cascade to cascade but one can also notice a fast change of roughly 10 % during a mode burst. There are three contributions in the slow frequency change: an increase in the plasma rotation velocity, the inward (PMS) or outward (RMS) movement of the q surfaces, and the flattening of the pressure profile. These three terms contribute differently from discharge to discharge and from mode to mode. The pressure profile flattening decreases the electron diamagnetic drift contribution, f_{*e}, to the mode frequency. In the PMS case (co-injection) f_{*e} has a negative sign, which causes the mode frequency to increase. For RMS (counter-injection) the f_{*e} contribution has a positive sign, and, therefore, the frequency of the mode decreases. The same arguments apply for the fast change in frequency during the mode burst: the burst flattens the pressure profile in the mode region and the mode frequency increases for the co-injection (PMS) case and decreases for the counter-injection (RMS) case.

3 Theoretical considerations

Fig. 4 shows a spline-fitted q profile together with the inferred current density profile. High gradients at the outer edge of a peak in the current density meet very low shear right at the position of the cascading modes (between vertical lines). Cylindrical tearing mode calculations for the shown profiles result in instability for mode numbers up to $n \approx 12$, as observed in the corresponding discharge. Stability analysis of realistic ASDEX Upgrade equilibria with the same current profiles using the resistive MHD code CASTOR also proved instability up to high-n modes even at finite pressure. Moreover, with increasing pressure gradient, the high-n growth rate increases due to mode-coupling, yielding modified tearing modes [5].

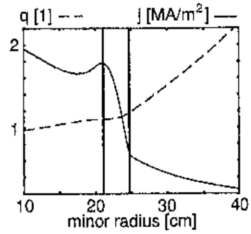

Figure 4: *q profile and corresponding current density*

For the development of a cascade an (m, n) mode has to destabilize the $(m+1, n+1)$ and stabilize the $(m-1, n-1)$. To model a cascading mechanism depending on the current, the evolution of a number of modes and their effect on the equilibrium current profile were calculated in a cylinder, neglecting higher harmonics, nonlinear coupling and pressure. That way, cascading could be simulated, which carries on over several stabilizing/destabilizing events (see Fig. 5). A detailed description of these findings will be published elsewhere.

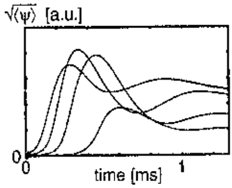

Figure 5: *Flux amplitudes of 4 cascading modes*

4 Summary

Core MHD cascades with a long series of mode bursts in order of increasing n have been observed in certain ASDEX Upgrade discharges. A cascade is initiated by a low-n mode, typically of $n = 5$ or 6, and can reach maximum n values of 22 or higher. Cascade modes satisfy the relationship $m = n + 1$. They have been found in discharges with positive and reversed magnetic shear. In the positive shear case the cascade modes progress radially inward and in the reversed shear case outward. The common features of these cascades are that they are excited in a low magnetic shear region and that $0.6 < \beta_{pol} < 0.9$. Cascades are observed in discharges with high-Z/low-Z accumulation, where the current and the pressure profile are being rearranged. Parts of the q profile with positive shear are shifted inward and those with reversed shear outward. The frequency of the cascade modes changes due to the variation in the toroidal plasma rotation velocity and pressure gradient and because of the radial movement of the central q profile.

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