Study of suprathermal electron dynamics by energy-resolved tomography of hard X-ray emission on the TCV tokamak

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The dynamics of suprathermal electrons play a key role in electron cyclotron resonance heating (ECRH) and current drive (ECCD), and are connected to magnetohydrodynamics (MHD) instabilities such as sawteeth and fishbones.

Fast electron dynamics associated with sawteeth have already been extensively studied on the TCV tokamak [1]. In this paper we report on new observations of bursty modes at constant frequencies, which are regularly observed on TCV and whose amplitude is related to the ECRH power and ECCD injection angle. The suprathermal electron population oscillates spatially with the mode. Fast electron redistribution is, however, not observed during these bursty modes.

We also report on the first observations of electron fishbones, which, by contrast, are found to cause significant fast radial electron redistribution, as theoretically expected. However, electron fishbones have been detected only in a small fraction of TCV discharges. A detailed and dedicated experimental study is planned to investigate this mode further, also in view of its parallels to ion fishbone physics.

Tools

The study of dynamic suprathermal electron - mode interaction requires basically two ingredients which are both available on TCV: flexible, high power ECRH/ECCD systems and high resolution MHD and suprathermal electron diagnostics.

HXRS The key system is the new hard x-ray tomographic spectrometer (HXRS, [2]) allowing energy-resolved measurements of the hard X-ray emission from collisions of fast electrons with plasma ions and electrons. In conjunction with Fokker-Planck modeling (LUKE, [3]) information about the (suprathermal) electron distribution can be extracted. In order to enhance the effective time resolution (down to less than $10\,\mu$s), conditional averaging over ECRH duty cycles and/or MHD events can be performed, exploiting the high-resolution digital acquisition of the full sequence of photon pulses.

Tomography upgrade The second camera of the HXRS system was very recently installed on TCV and is currently in the commissioning phase. Due to its position at the top of the machine, its 24 down-viewing lines of sight cover the whole plasma cross section, thus allowing for high-field-side (HFS) - low-field-side (LFS) asymmetry measurements. In conjunction with the first camera, which has already been reliably operated for several thousand plasma discharges, this installation results in the first tomographic HXR system for non-circular tokamak plasmas. This will enable tomographic inversion on a 2D grid without additional assumptions (such as constant emission on flux surfaces) and a better space resolution than the single camera.

Interaction of suprathermal electrons with the $m/n = 1/1$ internal kink mode

Following a study of suprathermal electron dynamics during sawteeth the focus was shifted towards $1/1$ modes that do not end in a crash but exhibit a bursty behavior in time. Here, two main types of modes can be distinguished: a mode at constant frequency with short bursts of varying duration, and the electron fishbones that show a characteristic frequency chirping in each burst, with the bursts being of constant duration and on a longer timescale. In both cases the main interest lies in the mode excitation (if and how the modes are excited by fast electrons), mode-mode coupling and the influence of the modes on the suprathermal electron population.

Bursty constant frequency mode

The bursty constant frequency mode is regularly observed in TCV discharges with $q_{\min} \lesssim 1$ when high ECRH power is deposited in the plasma core and sawtooth crashes become very weak and rare or disappear completely. In fig. 1 the bursty time evolution and toroidal ($n = 1$) mode structure is shown by a singular value decomposition (SVD) analysis of the toroidal magnetic probe array signals. Surprisingly, the conditional averaging of the poloidal magnetic probe array tells us that we are in the presence of an $m = 2$ mode. The even m is also confirmed by the comparison of the HFS and LFS toroidal array. The frequency of this $m/n = 2/1$ mode is ≈ 7 kHz, which is significantly lower than that of a typical $m/n = 2/1$ NTM in TCV (≈ 12.5 kHz).

The situation is clarified by the soft X-ray tomography (XTOMO) which detects primarily the $m = 1$ mode, but sees also the $m = 2$ mode revealed by the magnetics (fig. 1). The comparison of the time evolution of the $m = 1$ mode from XTOMO and $m = 2$ from magnetics shows that these modes are correlated in amplitude, have the same frequency and a constant phase difference. This indicates a close coupling between the two modes, with the $m/n = 2/1$ mode being located more radially outward. Another soft X-ray diagnostic (DMPX) confirms the existence of both modes. By contrast, the HXRS camera shows that the suprathermal electron population is oscillating radially with the $m/n = 1/1$ mode (fig. 1). The $m/n = 2/1$ mode does not affect the fast electrons appreciably; if it did, the horizontal viewing camera would see a widening and narrowing of the profiles as the mode oscillates, additionally to the up-down movement indicating the $m/n = 1/1$ mode. It cannot yet be determined whether the modes are ideal displacements or islands.

The excitation of the mode is studied using ECRH/ECCD modulation and varying the ECCD toroidal injection angle. The average mode amplitude becomes higher and rises faster as the current drive component decreases, being maximum for pure ECRH. With strong current drive

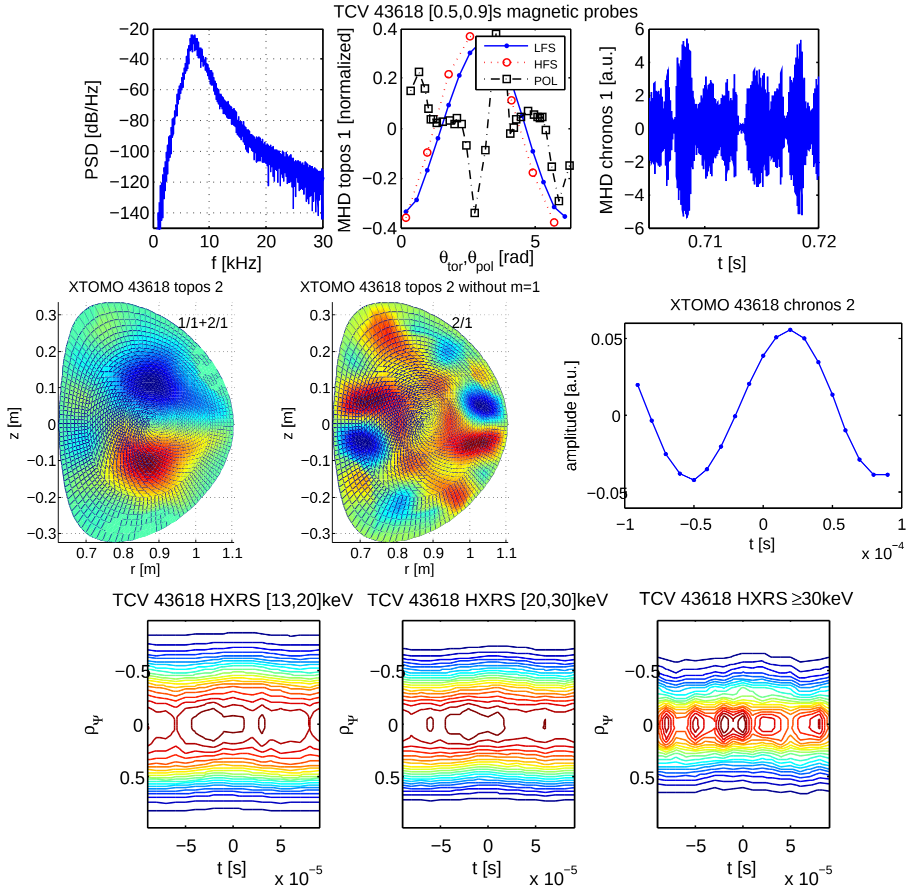

Figure 1: Bursty constant frequency mode: an SVD analysis of the magnetic probe array signals shows only the $2/1$ mode while both the $1/1$ and the $2/1$ mode appear in the soft X-ray tomographic inversion (XTOMO, cond. avg.). The HXR emission profiles (HXRS, cond. avg.), inverted separately for chords lying below and above the magnetic axis (negative and positive ρ_ψ), show that only the $1/1$ mode affects the radial suprathermal electron distribution.

(both co- and counter) the mode is quenched and sawteeth dominate.

Electron fishbones

Ion fishbones are of significant importance for experiments with a large population of fast ions (such as ITER). Electron fishbones have also been reported from several experiments [4, and references therein], usually at low or negative central shear with $q_{\text{min}} > 1$ and ECRH deposition on the HFS. The instability appears in regularly repeating bursts with chirping mode frequency. Occurrence without any $q = 1$ surface indicates a non-resonant mode. A detailed study of electron fishbones and an assessment of their relation with ion fishbones remains to be performed. Subsequently, electron fishbone physics could contribute to the understanding of ion fishbones. The first observations of electron fishbone features on TCV show significant effects on the suprathermal electron distribution. The inverted HXR emission profile evolution in fig. 2 indicates that the fast electrons are moved radially outwards as the mode amplitude reaches its maximum and continue to move outwards as the mode amplitude subsequently decreases.

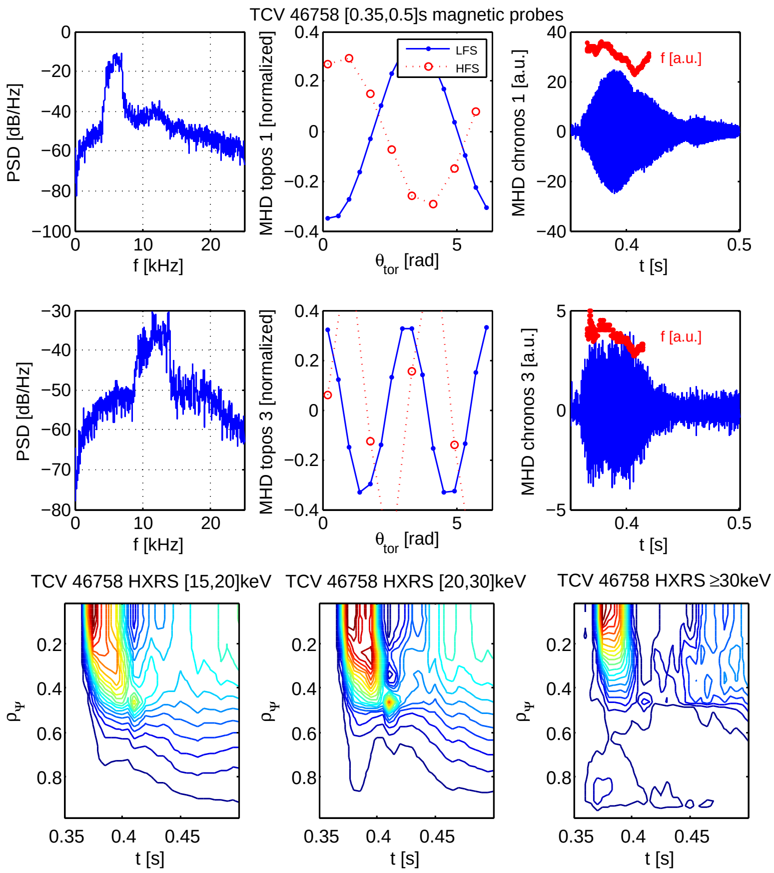

Figure 2: Fishbone-like burst: an SVD analysis of the magnetic probe array signals shows the 1/1 and 2/2 mode components chirping; the HXRS inversion indicates that the suprathermal electrons are redistributed radially outwards.

Plasma scenarios conducive to the appearance of electron fishbones have rarely been pursued on TCV in the past. However, TCV is ideally placed to contribute to these studies as its shaping capabilities allow it to explore the continuum between results from other tokamaks. The high-power and highly flexible ECRH/ECCD system, piloted by a new, highly versatile digital control system, can effectively tailor the q-profile and the (suprathermal) electron distribution independently, both of these being crucial ingredients in fishbone physics. The newly commissioned tomographic HXRS diagnostic could quantify the fast electron evolution and redistribution, in even more detail than shown in fig. 2 for a single fishbone-like burst and a single camera.

This work was supported in part by the Swiss National Science Foundation.

References

[1] J. Kamleitner, S. Coda, S. Gnesin, Ph. Marmillod and J. Decker, ECA **36F** (2012) P1.010

[2] S. Gnesin, S. Coda, J. Decker and Y. Peysson, Rev. Sci. Instrum. **79** (2008) 10

[3] Y. Peysson and J. Decker, Phys. Plasma **15** (2008) 092509

[4] Z. O. Guimarães-Filho et al., Nuclear Fusion, **52** (2012) 094009