Velocimetry aided wavelet cross-phase analysis of type-I ELM precursors in ASDEX Upgrade

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Introduction

Edge localized modes (ELMs) are bursty quasiperiodic expulsions of energy and particles from the plasma edge into the scrape-off layer (SOL) in the state of high confinement (H mode) of magnetically confined fusion plasmas. ELMs are believed to be triggered by MHD instabilities either the ideal peeling mode (IPM) or the ideal ballooning mode (IBM), depending which stability boundary (the current or the pressure) is reached [1]. Prior to the ELM, fluctuations appear, which are called ELM precursors in general. The role of these ELM precursors is not understood at all.

Previously ELM precursors were investigated by means of 2D ECE measurements in ASDEX Upgrade [2]. Off-midplane fluctuations appear about 2 ms before the ELM crash in the range of 20–50 kHz at poloidal mode numbers $m = 112 \pm 12$ and toroidal mode numbers $n = 28 \pm 7$. These off-mid-plane fluctuations do not trigger the ELM crash [2]. The ELM is triggered about 200 μs before the actual ELM onset by fluctuations with mode numbers $m = 74 \pm 9$ and $n = 18 \pm 4$ [2]. In both cases the temperature fluctuations propagate into the electron diamagnetic direction [2]. In this contribution we will focus on the off-midplane fluctuations.

Precursors were also observed in NSTX with 2D gas puff imaging [3]. The precursors appear at frequencies around 20 kHz with wave numbers of 0.05-0.2 cm^{-1}, propagate into the electron diamagnetic direction and are correlated with magnetic fluctuations with mode numbers of $n = 5 - 10$ [3]. It is stated that this is consistent with peeling-ballooning modes.

To actually characterize different instabilities the cross-phase between pressure and potential fluctuations is one of the key quantities. Unfortunately, in particular potential measurements are difficult to obtain and practically unavailable at the same temporal and spatial resolution as pressure fluctuations in high temperature plasmas, where ELMs occur. Here, we deduce potential fluctuations $\tilde{\phi}$ from radial velocity fluctuations assuming $\tilde{v}_r = \tilde{E}_r/B = -\nabla\tilde{\phi}/B$ estimated by a velocimetry technique [5] from two-dimensionally measured electron temperature fluctuations $\tilde{T}_e$. This allows to estimate the cross-phase between $\tilde{\phi}$ and $\tilde{T}_e$ of ELM precursors.

Experimental setup

Experiments were carried out on the ASDEX Upgrade tokamak, which has major and minor horizontal radii of $R_0 = 1.65\,\text{m}$ and $a = 0.5\,\text{m}$, respectively. Electron temperature fluctuations $\tilde{T}_e$ were measured with a 2D imaging (ECEI) diagnostic [4] at ASDEX Upgrade. The ECEI diagnostic consists of an array of 16 detectors, where 12 have been used for the present study. Each of the detectors acts as a (1D) ECE radiometer measuring the intensity of emitted electron cyclotron radiation from different vertical positions in second harmonic X-mode (100-140 GHz). 16 lines of sight (LOS) are focused on the low-field side (LFS) plasma edge. Per LOS 8 local oscillator frequencies allow measurements on 8 different radial positions. The radial resolution was 1.36 cm, where four channels per LOS measure inside the last-closed flux surface (LCFS) and four channels in the scrape-off layer (SOL). The sampling rate of the diagnostic was 200 kHz. The ECEI is calibrated against the 1D-ECE diagnostic sharing the same viewing window. Details on the diagnostic can be found in Ref. [4]. The calibration and the influence of decreasing optical thickness are discussed in Ref. [2]. A typical type I ELMy H-mode plasma (# 24793) is studied, which was previously analysed in Ref. [2]. The plasma current was $I_p = 1$ MA, the magnetic field strength was $B = -2.5$ T at an edge safety factor of $q_{95} = 4.7$. The plasma parameters were $T_e = 500$ eV, $T_i = 700$ eV (measured at $R = 2.1$ m), core line-integrated electron density $n_e = 8 \cdot 10^{19}$ m^{-3}. The plasma was heated by 7 MW of neutral beam injection and 750 KW of electron cyclotron resonance heating. More details on the discharge are given in Ref. [2].

Results

As the fluctuations are two-dimensionally resolved the velocity field can be estimated via velocimetry, where sections of two consecutive images are compared for similar structures. The displacement of the structures gives the velocity field. Velocimetry has been widely used for the interpretation of gas-puff-imaging data [6, 3, 7]. The technique avoids

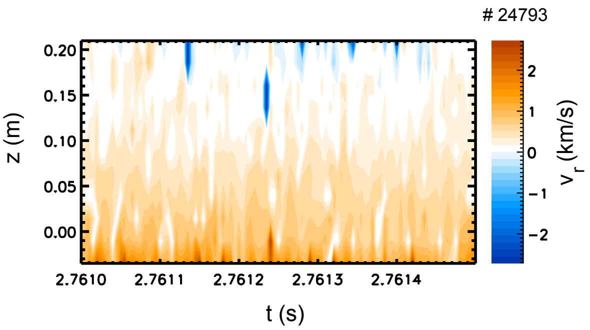

Figure 1: Radial velocity fluctuations estimated via velocimetry at the innermost radial position ($\rho = 0.94$).

misinterpretation due to tilted structures in the plasma edge present in the standard time delay estimation approach used often to estimate the velocity [8].

Here the radial propagation velocity of turbulent structures has been estimated with a rather simple particle image velocimetry (PIV) algorithm optimized for noisy data [5], including a pattern matching technique, subpixel interpolation and denoising by removing displacement vectors which seem quite different from any of their neighboring displacements. The obtained radial velocity fluctuations are shown in Fig. 1 for the innermost radial position. Assuming the magnetic perturbation localized at the outboard midplane, the potential for modes with tearing parity would exhibit an up-down asymmetry around the midplane. The corresponding radial $E \times B$ velocity fluctuations for modes with tearing parity have a maximum around the midplane due to the phase shift. The already documented up-down asymmetry in the fluctuations amplitude [2] is here completed by the observation of tearing parity conform potential fluctuations.

In order to distinguish between the different instabilities, the cross-phase between plasma potential and pressure fluctuations is the key quantity. Assuming that the radial propagation velocity of the fluctuations is due to $E \times B$ advection, the potential can be deduced from the velocity field. We correlate this potential field with the electron temperature fluctuations. As the ELM cycle is very dynamic and inherently non-stationary we favor the wavelet transformation of electron temperature and radial velocity fluctuations, which provides the frequency information for every point of the time series. The Morlet wavelet is used here. The spectra are calculated for every LOS and the four inner channels. Afterwards the data is averaged over the ensemble of all channels. The upper part of Fig. 2 shows the wavelet auto spectrum of T_e fluctuations in a logarithmic representation. The off-midplane fluctuations as studied in Ref. [2] appear around 2.761 s in the range of 20–40 kHz.

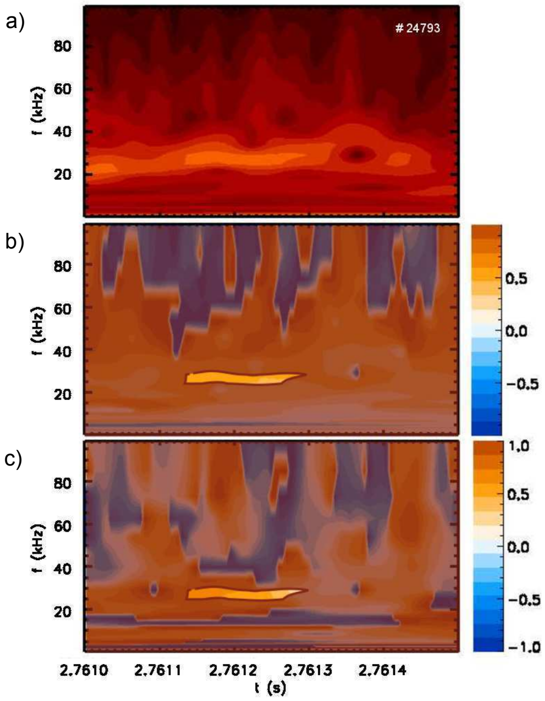

Figure 2: Wavelet auto spectrum of electron temperature fluctuations (a), cross-phase between poloidally separated channels (b) and between temperature and radial velocity fluctuations (c). To guide the eye the cross-phases at small intensities are shaded.

The wavelet cross spectrum between two poloidally separated channels can be used to estimate the propagation direction of a distinct frequency mode. As we already know the propagation direction this is a consistency test. As a complex quantity, the cross spectrum can be represented by its amplitude and its phase, which is called the cross-phase. A positive cross-phase represents a positive time lag and therefore the present choice of poloidally separated channels indicates propagation in the electron-diamagnetic direction. The cross-phase is shown in Fig. 2b. As observed in Ref. [2] the off-midplane fluctuations propagate in the electron diamagnetic direction.

The wavelet cross spectrum between temperature and radial velocity fluctuations is close to zero for interchange modes and close to $\pi/2$ for drift waves. The cross-phase is shown in Fig. 2c. The off-midplane fluctuations have a cross-phase around $\pi/2$ pointing to drift waves.

Conclusion

As these fluctuations do not show interchange characteristics (a cross phase of zero between radial velocity and temperature fluctuations) ideal or kinetic ballooning modes, linear ion and electron temperature gradient modes can be ruled out. The drift-wave nature of the fluctuations together with the up-down asymmetry of the amplitudes point to tearing or micro-tearing modes (MTMs). More details can be found in Ref. [9].

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