Characterisation of Pulsations Close to The L-H Transition in AUG

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In fusion plasmas, a regular pulsation of the perpendicular flow velocity $\mathbf{u}_\perp$ and the density fluctuations $\tilde{n}$ can occur at the transition from low to high confinement regimes (L-H transition). These pulsations, sometimes referred to as limit-cycle oscillations [1], I-phase [2] or dithering cycles [3], have frequencies in the low kilohertz range and are associated with an improved confinement with respect to the L-mode.

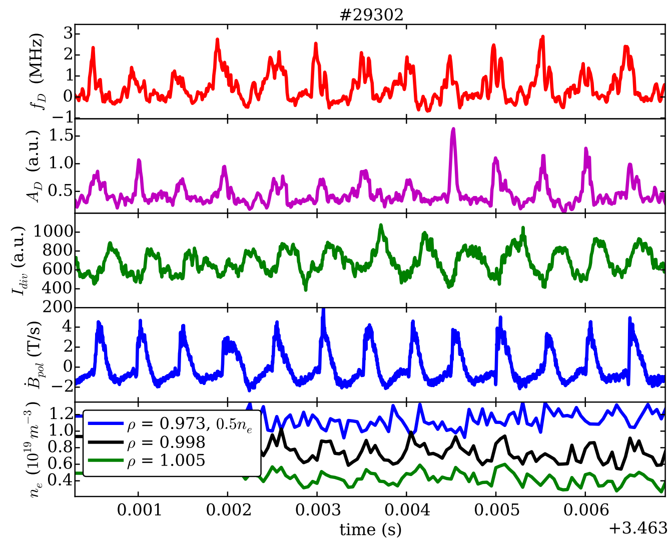

Figure 1: *The appearance of the I-phase pulsation in the Doppler shift $f_D \sim \mathbf{u}_\perp$ and amplitude $A_D \sim \tilde{n}$ of the Doppler reflectometer signal, the divertor shunt current I_{div}, the poloidal magnetic field coil $\dot{B}_\theta$, and the electron density n_e at three different radial positions.*

It is discussed whether an interaction between edge turbulence and zonal flows [4, 5] regulate the I-phase pulsation. However, there are also indications that the Reynolds stress drive of zonal flows is too weak in order to explain the measured flows in some cases [6]. Therefore, it is still an open question whether the turbulence-flow interaction is the dominant mechanism to explain the experimental findings or whether there are other mechanisms at work as proposed in theoretical models [7, 8]. The experimental results presented in the following indicate that the I-phase pulsations are accompanied by electromagnetic phenomena which point to physics beyond the flow-turbulence interaction picture.

The I-phase is typically studied with Doppler reflectometry [2] since the pulsation of the turbulence amplitude $\tilde{n}$ and the flow velocity $\mathbf{u}_\perp$ during this intermediate phase between L-mode and H-mode can easily be detected by the Doppler shift $f_D \sim u_\perp$ and the amplitude $A_D \sim \tilde{n}$ of the backscattered microwave. An example of an I-phase 6 ms after the L-I transition at medium density is shown in Fig. 1 (first two rows). During the phase of high turbulence level (peaks in A_D) the particle transport is increased resulting in a modulation of the divertor shunt current I_{div} (third row in Fig. 1) with the same frequency of about 2 kHz. As already described in Ref. [3], the pulsations are accompanied by a magnetic response visible in signals of magnetic pick up coils measuring $\dot{B}_\theta$ (Fig. 1, second last row). In lower single null configuration, this magnetic response seems to originate from the X-point region and propagates along the high-field side from bottom to top. The outer part of the electron density profiles reconstructed from lithium beam emission spectrocscopy (Li-BES) data every 50 μs is modulated during an I-phase cycle. The separatrix and scrape-off layer density is increased while the inner parts of the profile ($\rho_{pol} < 0.98$) stay unchanged or are slightly reduced during the turbulence burst of the I-phase (last row in Fig. 1). This indicates that the density gradient is reduced during the high turbulence phase.

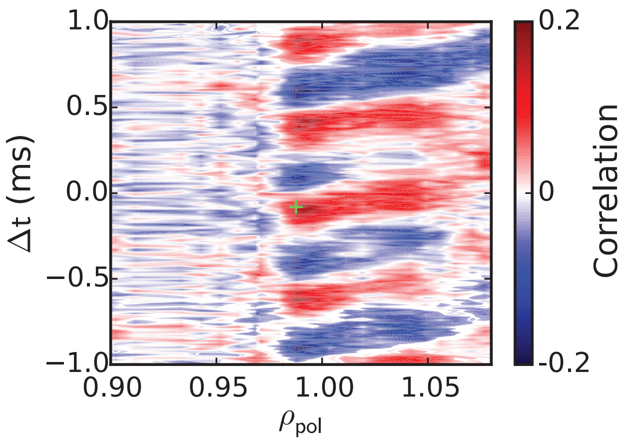

Figure 2: *Correlation between Doppler reflectometry velocity signal and radial channels of Li-BES rawdata ($\sim n_e$).*

The modulation of the electron density profile seems to propagate from inside to outside and is strongest slightly inside the sparatrix. This can be deduced from the slightly oblique stripes in the spatio-temporal cross-correlation of the Doppler velocity signal f_D with different radial channels of the Li-BES system (Fig.2). The highest correlation is found at $\rho_{pol} = 0.99$ (green plus sign) and the time shift of the maximum is negative $\Delta t \approx -100$ μs indicating that the flow velocity at the probing position rises before the density profile change takes place.

The frequency of the I-phase pulsation in individual discharges decreases linearly with the density and temperature in the edge during the evolution from L-mode to type-I ELMy H-modes indicating a weaker drive or a stronger damping of the pulsation at higher density and temperature. In a series of discharges with varying magnetic field B, plasma current I_p and density n_e the I-phase frequency was studied in order to find a determining quantity for the pulsation frequency across various discharges. The model presented in Ref. [7] predicts an I-phase frequency scaling proportional to the neoclassical poloidal damping rate ν_{pol}.

The data set from ASDEX Upgrade, however, does not follow this trend as shown in Fig. 3 (upper left box). Different colors indicate the covered I-phase frequency range in different discharges. The frequency likewise does not clearly scale with the poloidal Alfvén speed $v_A \sim I_p/\sqrt{n}$ as proposed by Solano *et al.* [9] based on JET data (lower right box). Furthermore, it does not scale with single parameters (e.g. B, T_e, n_e) and shows a weak dependence on the normalized Larmor radius ρ^* (lower left box) and the normalized pedestal pressure $\beta_{ped} = 2\mu_0 p_{ped}/B^2$ (upper right box). It is therefore unclear by which quantity the I-phase frequency is determined.

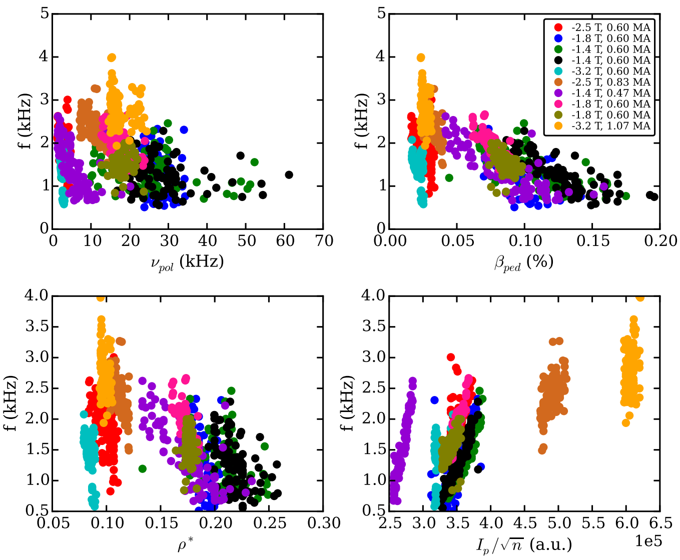

Figure 3: *I-phase frequency f versus poloidal damping rate ν_{pol}, normalized pedestal pressure β_{ped}, normalized Larmor radius ρ^*, and poloidal Alfvén speed $v_A \sim I_p/\sqrt{n}$.*

In the very late phase of the I-phase, the frequency is typically very low due to high density and temperature, and the pulsation becomes very intermittent and spiky. In this phase, each spike is accompanied by a magnetic precursor clearly visible in magnetic pick up coils measuring $\dot{B}_r$ sharing the characteristics of type-III ELM precursors. Its frequency ranges from 50 to 100 Hz as shown in the spectrogram of $\dot{B}_r$ (Fig. 4). Even before the precursor appears in the $\dot{B}_r$-signal, it is already detectable in the phase signal of the reflectometer which probes the (movement of the) cutoff-layer close to the separatrix (Fig. 4, third row).

In the early I-phase, magnetic precursors are hardly distinguishable. In the phase signal of the reflectometer, however, very small but significant quasi-coherent oscillations can be found (Fig. 5, third row). We interpret these findings as follows: each I-phase pulse has a precursor similar to a type-III ELM which is, however, too weak to be detected with the magnetic pick up coils in the early I-phase but always existing and in principle detectable as a modulation of the separatrix density. The existence of precursors in all phases of the pulsation points to a dynamic as it is known from magnetohydrodynamic instabilities which grow in a linear phase and result in a crash after a certain amplitude is exceeded [10].

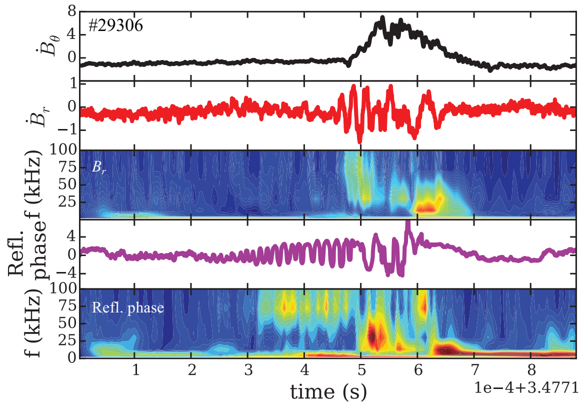

Figure 4: *Late I-phase: precursor modes are clearly visible in the $\dot{B}_r$-signal (red and spectrogram below) and even earlier in the reflectometer phase signal (purple and spectrogram below) prior to each I-phase pulse (black).*

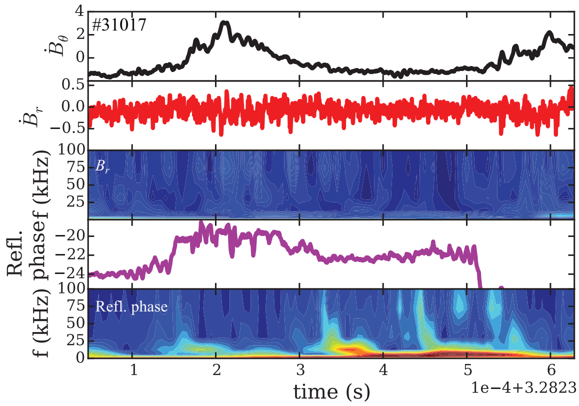

Figure 5: *Early I-phase: There are no precursors in the $\dot{B}_r$-signal but small oscillations in the reflectometer phase indicating a small precursor activity already at the beginning of the I-phase.*

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