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Geodesic acoustic mode (GAM) [1] is a turbulence-driven high-frequency branch of zonal flows, which can play a role in self-regulation of turbulent transport. It is a toroidaly symmetric, $n = 0$, oscillating flow with potential constant on a flux surface, $m_\phi = 0$. Due to geodesic curvature the flow couples to a pressure perturbation with $m_p = 1$ standing wave pattern. Even though GAM is mainly an electrostatic mode, its magnetic component has been recently described both in experiment and theory. While in the circular plasmas the magnetic component has $m_B = 2$ poloidal mode number, other Fourier components can be induced by plasma shaping [2]. The GAM oscillations are driven by non-linear three-wave coupling with ambient turbulent oscillations [3]. In practice, the coupling is typically detected using bicoherence analysis. Frequency of the mode scales with the ion sound speed c_s and tokamak major radius R_0, $2\pi f_{GAM} = Gc_s/R_0$, where G is a factor dependent on plasma shape. In ciruclar plasmas $G = (2+q^{-2})^{1/2}$ [1] but lower values are expected in elongated plasmas [2, 4].

In this paper, we present observation of GAM-like oscillations in D-shaped discharges on the COMPASS tokamak. The mode is detected in a form of long range correlations of plasma potential between pair of reciprocating probes and the oscillations are clearly correlated with oscillations of poloidal magnetic field.

Experimental setup

COMPASS ($R = 0.56$ m, $a = 0.2$ m) is a tokamak with ITER-like divertor plasma configuration. It is equipped with two pneumatic reciprocating probe manipulators, located at the top of the vessel and at the low-field side (LFS) midplane, toroidally shifted by 22.5°. Typically the manipulators are not directly magnetically connected. Both probe heads consist of combination of Langmuir probes (LP) measuring floating potential V_{fl} and/or ion saturation current I_{sat}, and ball-pen probes (BPP) providing fast measurement of a potential that can serve as a close proxy to the plasma potential ϕ [5]. Moreover, combination of LP and BPP allows fast sub-microsecond measurement of electron temperature $T_e = (V_{BPP} - V_{fl})/2.2$ [6]. All the probe measurements are available with 5 MHz sampling rate. Both manipulators allow deep reciprocation inside the last closed flux surface, without overheating the probe head. However, position of the probes and EFIT reconstruction are not fully in agreement, with a shift at LFS of D-shaped plasmas of about ~ 2 cm. As both probes provide fast measurement of T_e, we therefore carry out surface labeling using an assumption that T_e is constant over flux surface.

The probe diagnostics was supplemented by Mirnov coils, that allowed measurement of fluctuations of poloidal magnetic field B_p with 2 MHz sampling rate along full poloidal cross-section, and a set of saddle loops, covering the whole toroidal angle, with the same sampling rate.

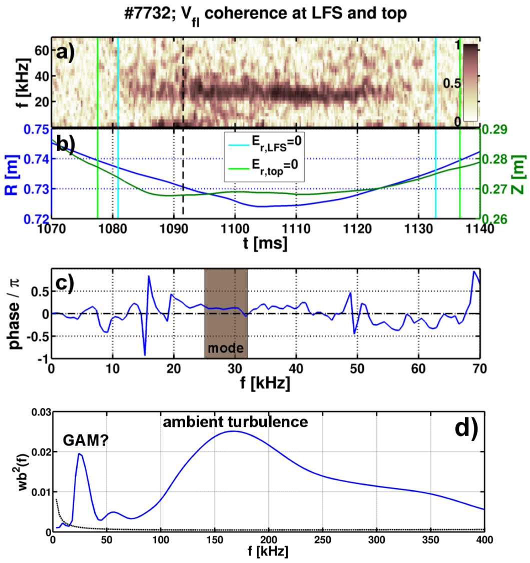

Figure 1: *Coherence of V_{fl} at LFS and top during simultaneous probe reciprocation a), position of the probes in time b), phase shift c) between probes when crossing the same flux surface - marked by dashed black line in a). Summed squared wavelet bicoherence of V_{fl} at LFS d), dashed black line shows level of statistical significance.*

Mode properties

Fig. 1 shows cross-coherence between V_{fl} during simultaneous deep plunge of the probes. Correlated oscillations are detected in V_{fl} as well as ϕ around ~ 30 kHz whenever both probes get inside the radius with zero radial electric field (i.e. local maximum of radial profile of plasma potential). When the probes are at the same flux surface, mutual phase shift is close to zero (Fig. 1c). This is consistent with $m_\phi = 0$ expected for GAMs. This is further supported by estimation of wavenumber-frequency spectra from two-point probe measurements [8] that rules out poloidal mode numbers with $m_\phi > 2$. I_{sat} measurements at midplane show no or very weak oscillations at this frequency, consistent with GAM oscillations, but the $m_p = 1$ structure needs to be further verified by I_{sat} measurement at the top. Further, wavelet bicoherence [7] (Fig. 1d) confirms non-linear coupling of the mode to the ambient turbulent fluctuations in a broad 100-400 kHz range of frequencies. The turbulent drive of the mode may explain its observation in L-mode only, disappearing during L-H and reappearing shortly after the H-L transition. Note that in some cases we detected significant bicoherence also bellow 5 kHz, i.e. in the expected range of the low-frequency zonal flows. These fluctuations are, however, out of the scope of this paper.

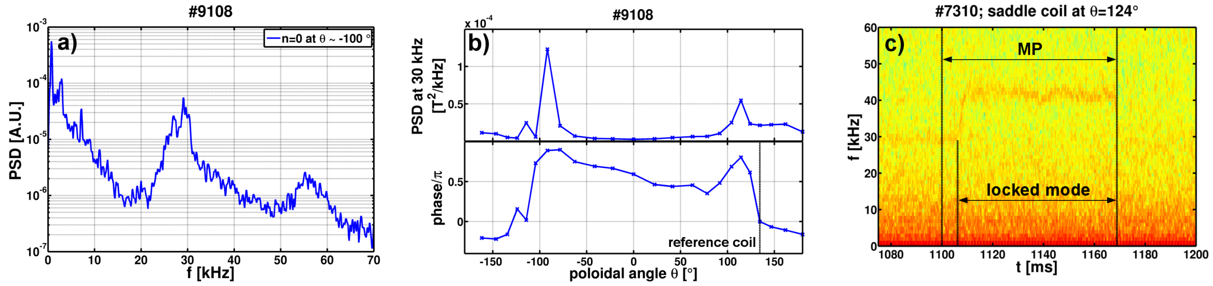

Figure 2: *Spectrum of toroidal $n_B = 0$ component a) and poloidal structure of magnetic fluctuations b). The frequency peak in a) is broadened by oscillations with sawtooth period. Change of mode frequency simultaneously with generation of locked mode by MP c).*

Magnetic component

Magnetic sensors show oscillations of B_p correlated with the potential oscillations measured by the probes. In toroidal direction, saddle coils spanning over the whole toroidal circumference confirm toroidal symmetry $n_B = 0$ (Fig. 2a) of the mode. Poloidally spaced coils confirm its non-rotating nature and show poloidal structure different from $m_B = 2$ (Fig. 2b). While $m_B = 2$ is expected for GAM in circular plasmas, [2] predicts that additional Fourier components can be excited due to plasma shaping.

Mode frequency

Frequency of the mode in D-shaped discharges is observed in the range $\sim 25-35$ kHz. With typical edge temperature $T_e \gtrsim 30$ eV this is in the range expected for GAM frequency in circular plasmas provided $T_e = T_i$ and $\gamma_i = 1$, but empirical AUG scalings for D-shaped plasmas [4] would require rather high value of ratio $\gamma_i T_i / T_e \sim 7$, where γ_i is ion specific heat ratio and T_i is ion temperature. The frequency does not significantly change with radius within ~1-2 cm layer penetrated by the probes, consistent with non-local eigenmode structure reported on some devices, e.g. [9, 10]. However, in discharges with sawtooth activity (all shots shown here), the frequency peak of the mode is broadened by temporal oscillations of the frequency. This is best demonstrated on the magnetic component of the mode that shows clear periodic oscillations of the frequency by $\delta f \sim 2$ kHz with period similar to that of sawtooth instability (Fig. 3). This could be related to the temperature dependence of GAM frequency and to the heating of edge plasma by energy released from the core after each sawtooth crash, as observed e.g. on T-10 [11]. Note the relatively

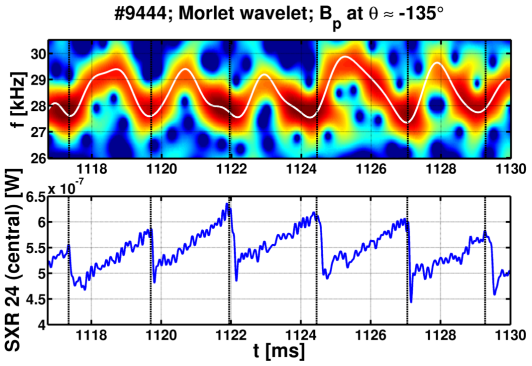

Figure 3: *Wavelet periodogram showing oscillations of frequency and amplitude of the mode compared with central soft-X ray (SXR) channel. White line marks instantaneous frequency estimated from Hilbert transform.*

small dimensions of COMPASS plasma allowing non-negligible core-edge interactions.

Magnetic perturbations

COMPASS is equipped with set of $n = 2$ coils used for magnetic perturbation (MP) studies [12]. While MP typically does not affect frequency of the GAM-like mode, Fig. 2c shows that when MP generated locked mode is present, the frequency sharply but still continuously rises by $\sim$15 kHz and returns back when MP coils are turned off and the locked mode disappears. Poloidal and toroidal structure of the magnetic fluctuations changes during presence of the locked mode towards dominant $n_B = 2$ and $m_B \geq 6$ components. While mechanism responsible for the transformation of the mode is still not fully clear, we note that very similar observation has been recently made during MP experiments on ASDEX Upgrade [13].

Summary

An oscillatory mode has been observed at the edge of COMPASS plasma, inside of the radius with $E_r = 0$, that provides a reference point for the position of the edge sheared flows. Frequency of the mode is in the range of frequencies expected for GAMs and bicoherence analysis confirms non-linear coupling of the mode with broad spectrum of turbulent fluctuations. Also poloidal and toroidal structure of the magnetic component and poloidal mode number of the potential oscillations are in favor of conclusion that it could be classified as a GAM. Characteristic temperature dependence of GAM frequency needs, however, yet to be confirmed. We note that presence of the mode was detected also on several other diagnostics, such as soft-X ray detectors or divertor ball-pen probes, whose analysis will follow.

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