Radial mode structure of plasma fluctuations in the GAM frequency range in OH and ECRH plasmas in the T-10 tokamak

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In the recent years there has been significant interest in tokamak plasma fluctuations that exhibit scaling with geodesic acoustic frequency $f_{GAM} \sim \sqrt{T}$. Geodesic Acoustic Modes (GAMs) being the high-frequency counterpart of zonal flows, have been intensively studied as a possible mechanism of the plasma turbulence self-regulation [1]. GAMs involving $m=0$ component of the electrostatic potential and $m=1$ component of the plasma pressure were first introduced in [2] within the ideal MHD model. It has also been noted that electromagnetic Beta induced Alfvén Eigenmodes (BAE), with finite poloidal m and toroidal n mode numbers have the same (as GAM) local mode frequency given by the expression:

$$f_{GAM/BAE} = \frac{V_{Ti}}{2\pi R} \sqrt{\frac{7}{4} + \tau_e + q^{-2} \left(\frac{23}{2} + 8\tau_e + 2\tau^2_e \right) \left(7 + 4\tau_e \right)^{-1}} \ , \tag{1}$$

where $\tau_e = T_e / T_i$, $V_{Ti}^2 = 2T_i / m_i$ [3, 4].

In the T-10 tokamak ($R = 1.5$ m, $a = 0.3$ m) the modes in the GAM frequency range have been studied by the heavy ion beam probing (HIBP) [5, 6]. The regimes with Ohmic, on-axis and off-axis electron cyclotron resonance heating (ECRH) were studied ($B = 1.5$–2.4 T, $I_p =$ 140–300 kA, $\bar{n}_e = (0.6 - 3) \times 10^{19}$ m^{-3}, $P_{EC} < 1.2$ MW). We have previously shown [7] that the mode frequency f^{exp} approximately scales as $\sqrt{T}_e$ confirming that these modes belong to the GAM/BAE type. So far we are unable to resolve the poloidal mode structure, and we will refer to these modes as GAM/BAE type.

Figure 1(a) shows the typical GAM/BAE mode evolution in the discharge with auxiliary ECRH heating. The mode is more excited during ECRH, when the typical frequencies were seen in the narrow band from 22 to 27 kHz for the main peak, and 25-30 kHz for the higher frequency satellite peak. Figures 1 (b) and (c) show power spectral density for plasma potential oscillations in Ohmic (b) and ECRH phases (c) of discharge.

We see that the f_{GAM} evolves together with T_e. As a reference frequency we will use the

simplified expression, which has only T_e dependence:

$$f^e_{GAM/BAE} = \sqrt{2T_e/m_i}\,/\,2\pi R\ , \tag{2}$$

Figure 2 shows the T_e dependence of f^{exp}, which was obtained in various discharges with ohmic and ECRH heating by one or two gyrotrons. The HIBP data were obtained in the fixed position at r=21-22 cm in the Low Field Side of the torus. There is significant density evolution, typically pump-out during the ECRH pulse. We see that the observed main frequency peak follows the local GAM/BAE scaling with some reduction factor about 0.4.

The radial structure of oscillations disagrees with the local $f_{GAM/BAE}$ scalings (1), (2). Figure 3 presents the example of HIBP measurements in the discharge with $B_t = 1.55$ T, $I_p =$ 140 kA and the line-averaged density, gradually evolving from $\overline{n}_e = 1.3$ to 2.4×10^{19} m^{-3} due to the gas-puffing. Evolution of the average values of plasma potential φ in this discharge was described in [8]. We see that the frequency of the both main peak and satellite is constant over the large radial extent that suggests the global mode structure. Note, the f^{exp} coincides with local $f_{GAM/BAE}$ expression (2) only at the edge, at $\rho = 0.9$. The evolution of the amplitude of potential fluctuations $\delta\varphi$ for the discharge with rising density is shown in Figure 4 as a function of radius. It is shown that both $f_{GAM/BAE}$ and $\delta\varphi$ are almost uniform over the all observed radial interval, and $\delta\varphi$ has a scale of hundred Volts and decreases with density raise. As far as T_e decreases with the density raise, the $f_{GAM/BAE}$ decreases accordingly. The similar uniform radial structure of the GAM frequency and amplitude was observed in all other observed regimes, covering the operational limits of T-10 (B_t =1.55–2.4 T, I_p = 140–300 kA). Decrease/increase of GAM amplitude with the density growth/fall was observed in all regimes under study with varying and steady-state density. This is illustrated by Figure 5, which presents GAM amplitudes measured at radii $10 < r < 24$ cm in ohmic regime with varying gas puffing.

Histograms of the potential-density cross-phase for the main peak and satellite are shown in Figure 6. The maximum of cross-phase is $\pi/2\pm0.15\pi$ both for the main peak and satellite, which agrees with the theoretical prediction [2].

The ratio between relative amplitudes of the potential and density oscillations (the Boltzmann ratio) $e\,\delta\varphi/T_e = k\,\delta n_e/n_e$ is about $k \sim 10{-}60$ for the considered regimes. It is worth noting that for GAM polarization, this ratio in the m=1 component is expected to be close to unity, while for m=0 component density perturbation is much smaller than the potential. For BAE mode, which has polarization similar to Alfvén modes, the density perturbation is expected to be much smaller compared to the potential.

In summary, on T-10 the modes in the GAM frequency range are seen on the potential as a main peak, and a higher frequency satellite. The modes are more pronounced during ECRH with typical frequencies 22-27 kHz over the whole plasma cross-section and demonstrate the

features of the global modes. The global GAM can be obtained theoretically for the specific plasma conditions [9], however such conditions differs from the ones, which takes place in the considered experiments. The absolute value f^{exp} is consistent with $f_{GAM/BAE}$ prediction at the outer edge, $\rho = 0.95$, which may be an indication that these modes are the edge-driven modes. The amplitude of the mode is almost constant over the radius. The theoretical local mode frequency is independent on density and the magnetic field. The observed frequency decrease with rising density is assumed to be the result of temperature drop, when the density increases.

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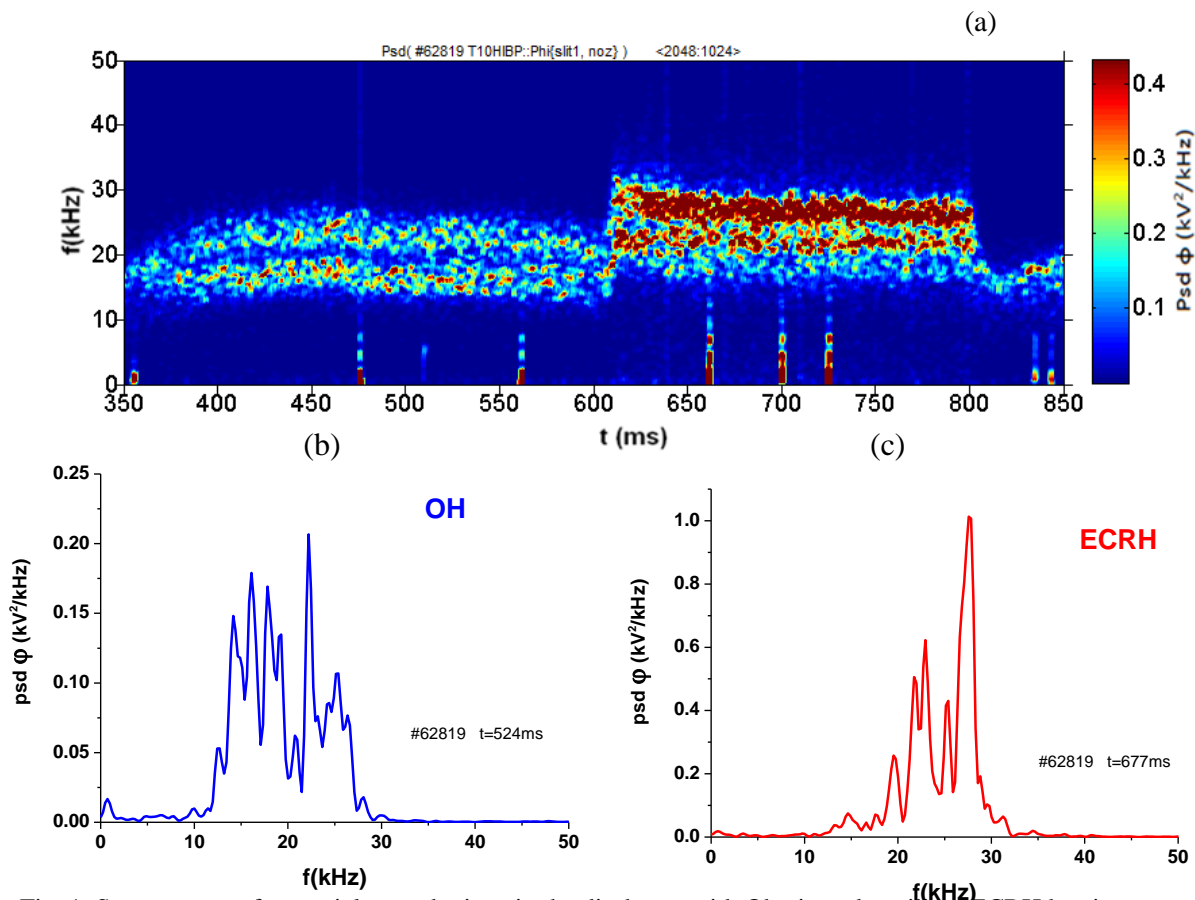

Fig. 1. Spectrogram of potential perturbations in the discharge with Ohmic and auxiliary ECRH heating. $B = 2,27$ T, $I_p = 200$ kA, $r = 17$ cm. Power spectra in Ohmic (b) and ECRH (c) phases of discharge.
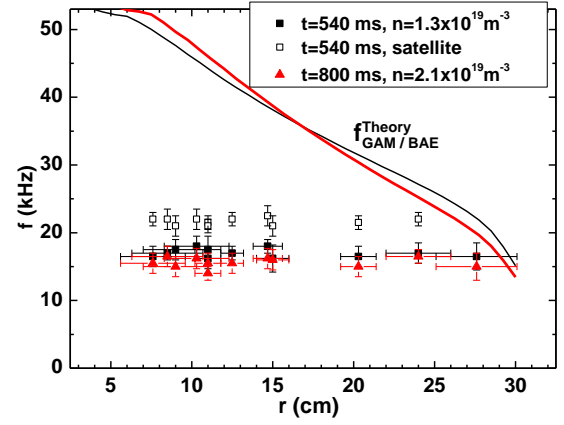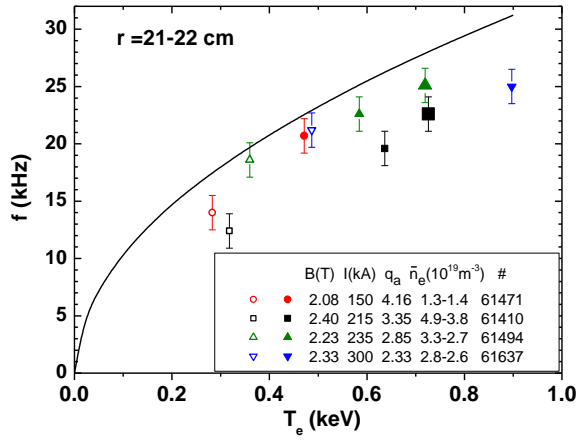
Fig. 2. T_e dependence of f^{exp} for r = 21-22 cm. Open symbols – OH phase, full symbols – ECRH phase of the discharge, small symbols– one gyrotron, large ones – two gyrotrons. Solid curve is Eq. (2), $f \sim \sqrt{T_e}$, T_e (0) ~ 1 keV in OH phase.

Fig. 3. Radial distribution of GAM frequency in discharge with density rise, B= 1.55 T, I_p=140 kA. Black ■, $\bar{n}_e$=1.3×10^{19} m^{-3}, red ▲, $\bar{n}_e$=2.1×10^{19} m^{-3}, full symbols are main peak, open symbols are satellites. Black thin line - $f_{GAM/BAE}^{Theory}$ for $\bar{n}_e$=1.3×10^{19} m^{-3}, fat red line for n_e=2.1×10^{19} m^{-3}.
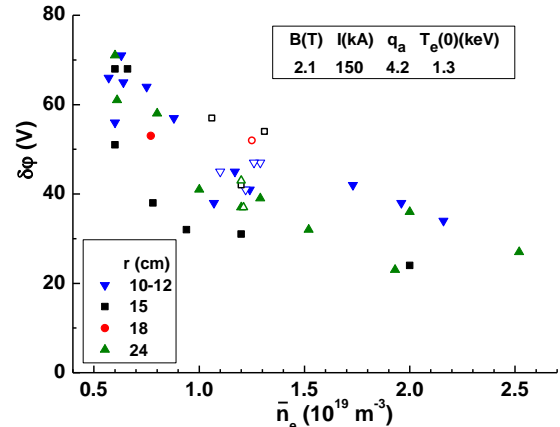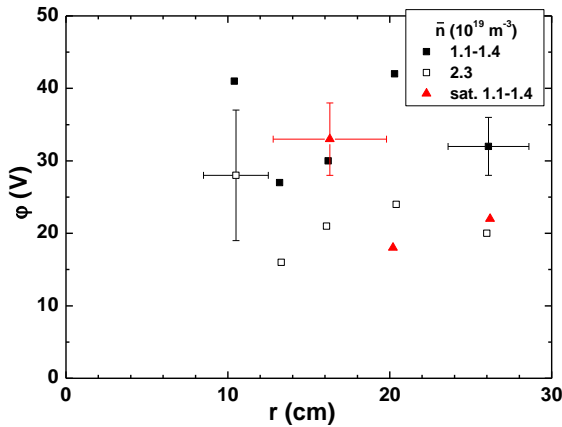

Fig. 4. Radial distribution of GAM amplitude in discharge with density rise, B= 1.55 T, I_p=140 kA. Full symbols are main peak and satellite for n_e=1.1-1.4×10^{19} m^{-3}, open symbols are $\bar{n}_e$=2.3×10^{19} m^{-3}.

Fig. 5. Dependence of the mode amplitude at r = 10-24 cm on the density in ohmic discharges. Open symbols corresponds to the density fall, full symbols - the density growth.
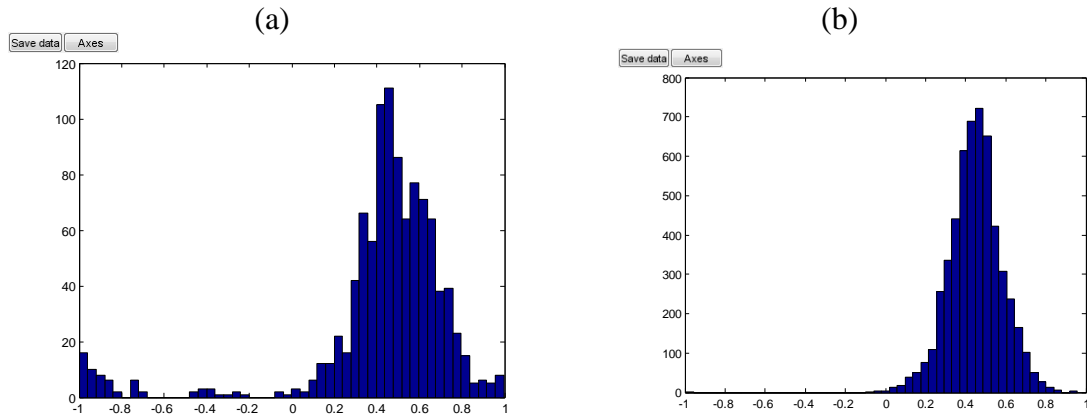

Figure 6. Potential-density cross-phase histograms for the main peak (a) and satellite (b) #61458. The mean cross-phase is $\pi/2\pm0.15\pi$ for both main peak and satellite. B=2.1 T, I_p=150 kA, q_a=4.2, $T_e(0)$=1.3 keV, r=15 cm.