Study of the geodesic acoustic induced modes in T-10 tokamak

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In recent years there has been significant interest in tokamak plasma fluctuations that exhibit scaling with geodesic acoustic frequency $\omega \approx \sqrt{T/m_i}/R$. 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 been realized recently that both GAM and Beta induced Alfven Eigenmodes (BAE), having low, but not zero m and n in potential perturbation [3], may have the same frequency given by the expression:

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

where $\tau_e = T_e/T_i$, $v_{Ti}^2 = 2T_i/m_i$ [4, 5]. In toroidal geometry, the perturbations of ion pressure due to toroidal compressibility are anisotropic resulting in the net adiabatic index of 7/4. The second term τ_e in (1) is related to electron compressibility in the adiabatic limit, $\omega << v_{Te}/qR$ (note that the perturbation of the electron pressure occurs at the m = 1 sideband). The remaining terms with q^{-2} are due to parallel compressibility of ion and electron fluids (such as in slab ion sound modes). The expression (1) describes the local (continuum) spectrum, in which the local $f_{GAM/BAE}$ changes with radius due to the variation of T_e, T_i and q as functions of ρ = r/a. However, some experiments suggest that the observed GAM fluctuations have constant frequency over some radial extent [6, 7] and thus differ from (1).

In the T-10 tokamak (R = 1.5 m, a = 0.3 m, B_t= 1.5–2.5 T) the modes in the geodesic acoustic frequency range have been studied by the heavy ion beam probing (HIBP), correlation reflectometry (CR) and Langmuir probes [8, 9]. Previously we have shown that the mode frequency f^{Exp} scales approximately as $\sqrt{T}$ that confirms that these modes are induced by the geodesic compressibility and belong to the GAM/BAE type. So far we are unable to resolve the polodal mode structure, and we will refer to these modes as GAM/BAE types. The main goal of this work is to study the radial structure of such modes.

Two regimes with low magnetic fields, allowing us to extend the HIBP observation area towards the plasma centre, were studied in details. In these regimes HIBP was able to observe the area from the periphery (ρ = 0.7-1) to the centre (ρ = 0.25). The first regime, (B_t = 1.55 T, I_p = 140 kA,) is characterized by low line-averaged density, slowly evolving from $\bar{n}_e$ = 1.3 to 2.4 × 10^{19} m^{-3} due to the gas-puffing. The time traces of the main plasma parameters are shown in Fig. 1(a). At the lowest density, $\bar{n}_e$ = 1.3 × 10^{19} m^{-3}, the modes are characterized by the main peak and the higher frequency satellite. The radial distribution of the mode frequency peak is shown in Fig. 1 (b), no modes were found at ρ ≥ 0.9. The result shows the uniform structure of the mode: the mode frequency is close to a constant over the investigated interval (0.2<ρ<0.9), showing inconsistency with $f_{GAM/BAE}$ (1) in the absolute value and shape. The constant mode frequency over the large radial extent suggests existence of the global eigenmode. Contrary, theoretically the global eigenmode can occur, if $f_{GAM/BAE}$ profile has a local maximum [4, 5]. Note, the f^{Exp} coincides with $f_{GAM/BAE}$ only at the edge, at ρ = 0.9. With the density rise, the mode frequency is slightly decreasing, the satellite peak disappears at $\bar{n}_e$ = 2.1 × 10^{19} m^{-3}. Later on, the main peak also disappears at $\bar{n}_e$ = 2.4 × 10^{19} m^{-3}. At the edge, ρ = 0.9, slight decay of f^{Exp}, happening with density rise, is consistent with $f_{GAM/BAE}$ prediction due to the evolution of the edge T_e and T_i. The central temperature $T_e(0)$ was obtained with SXR-spectrograph, while $T_e(r)$ and $T_i(r)$ were retrieved by transport code AT with T-11 transport coefficients [10].

The second regime (B_t = 2.08 T, n_e = 2.5 × 10^{19} m^{-3}, I_p = 160 kA, P_{EC} = 0.9 MW) with off-axis ECRH (ρ_{ECRH} = 0.5) has the current ramp-up to the I_p = 212 kA at the ECRH phase. The time traces of the main plasma parameters are shown in Fig. 2(a). The GAM/BAE modes are characterized by the main peak and the higher frequency satellite. The examples of the Power Spectral Density (PSD) for potential perturbation are shown in Fig. 2 (b). Figure shows that GAM/BAE presents the strongly dominating peak in the potential PSD in all four main phases of the regime. The time evolution of the GAM/BAE frequency is shown in the lower box of Fig. 2(a). The mode frequency is evolving with T_e rise due to the ECRH and the increase of the OH power. It scales with T_e as predicted by eq. (1) for $f_{GAM/BAE}$, and consistent with the absolute values of frequency (with a factor of 0.5). The radial distribution of f^{Exp} is shown in Fig. 3 (a). Similar to the first regime with B_t=1.55 T, we see the uniform radial structure: the mode frequency is constant over the investigated interval, showing the feature of the global eigenmode. Radial distribution of the amplitude of the potential perturbation, corresponding to GAM/BAE frequency band, containing both main peak and satellite, is shown in Fig. 3 (b). The amplitude of the induced potential perturbation in this regime is quite pronounced, having a range of a few dozens of Volts, which is comparable with the earlier measurements in other regimes on T-10 [8]. The amplitude increases towards the plasma center. Radial distribution of f^{Exp} shows inconsistency with $f_{GAM/BAE}$ as a function of ρ in this regime. On the other hand, the increase of f^{Exp}, happening over the whore observed radial interval with the increase of the heating power, is consistent (with a factor of 0.5) with prediction of equation (1) due to the evolution of the edge T_e at ρ = 0.7, where T_e was estimated by the 2ω-ECE signal, while T_i was assumed to be unchanged due to the constancy of n_e.

In summary, on T-10 the modes in the geodesic acoustic range are found to be present in the plasma potential as a main peak, and in some cases have a higher frequency satellite. The modes are more pronounced during ECRH, when the typical frequencies are seen in the band from 22-27 kHz over the whole plasma cross-section. The modes demonstrate the features of the spatially global eigenmodes. At the outer edge, ρ = 0.95, f^{Exp} absolute value and evolution is consistent with $f_{GAM/BAE}$ prediction, which may be indicative these mode are the edge driven eigenmodes. So far the observed modes did not show frequency dependence on the magnetic field and plasma density.

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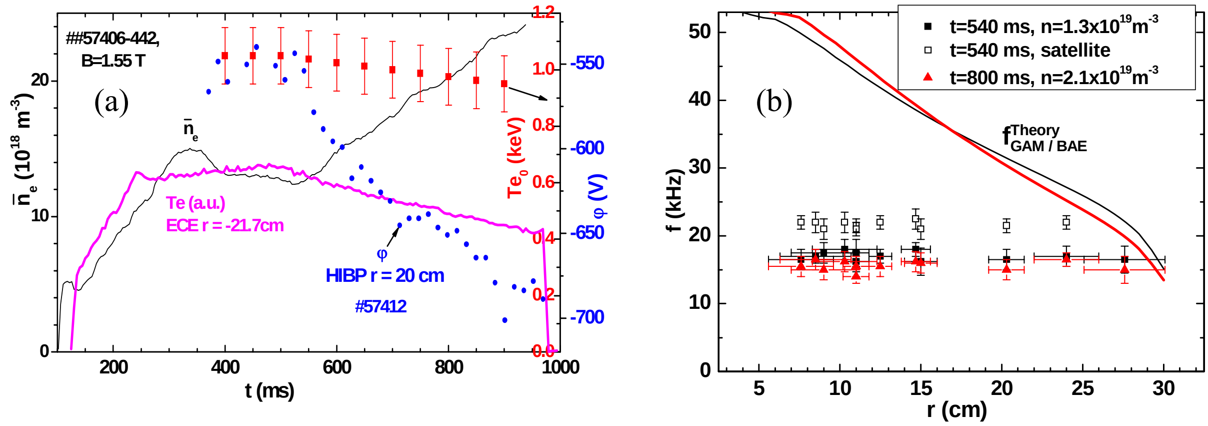

Fig. 1 (a) B= 1.55 T. Evolution of plasma density (black), potential (blue dots) and electron temperature T_{e0} (red) from SXR and from $2\omega_{ECE}$ (magenta) in the regime with density ramp-up. (b) Radial distribution of GAM frequency. Black ■, $\bar{n}_e$=1.3×10^{19} m^{-3} , red ▲, $\bar{n}_e$=2.1×10^{19} m^{-3}, closed 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}.

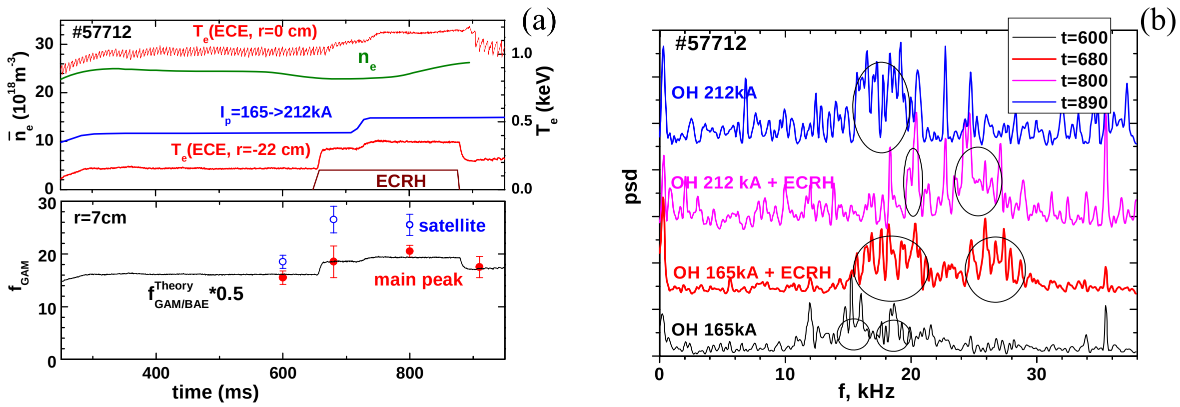

Fig. 2 (a) B_t= 2.08 T. Upper box: time traces of line-averaged density (green), plasma current (blue) and electron temperature (red) in the regime with current ramp-up. Lower box: time evolution of the GAM frequency $f^{\,Exp}$ for main peak (full squares) and satellite (open circles). The error bars denotes the width of the frequency peaks; $0.5{\cdot}f_{GAM/BAE}^{\ Theory}$ (r = 21cm) is shown by black curve. (b) PSD of plasma potential for four stages of the regime. The main peak with lower frequency and the satellite, highlighted by circles, are evolving with T_e.

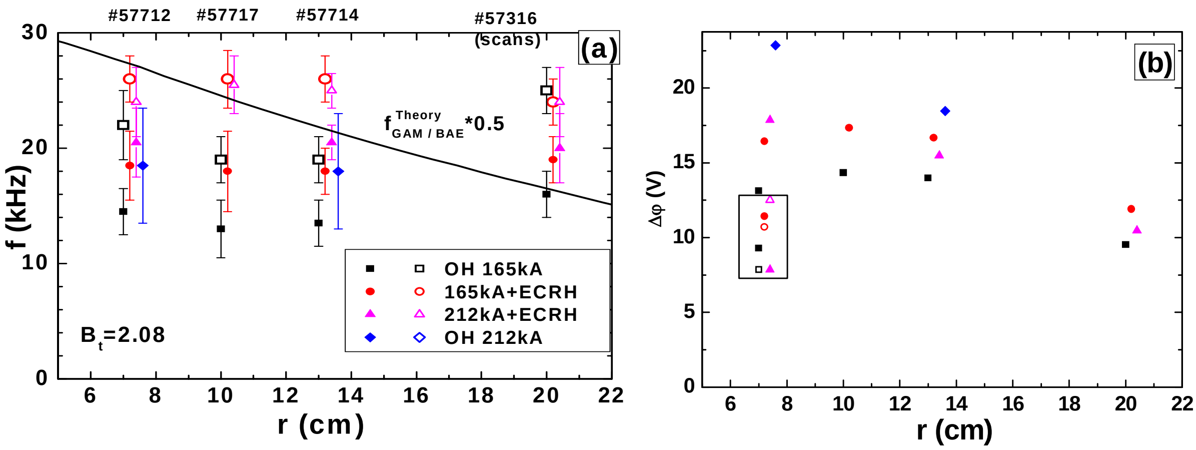

Fig. 3 (a) Radial distribution of the GAM frequency peak for four stages of the discharge. Full symbols are main peaks, open symbols - satellites. Dots in each group are radially shifted a bit for clearance. Black line is $0.5{*}f_{GAM/BAE}^{\ Theory}$ for OH, 165 kA. (b) Radial distribution of the potential amplitude, averaged over GAM main peak and satellite frequency band. Separate amplitudes of main peak and satellite are shown in the rectangle.