Investigation of GAM dynamics and spatial structure in the FT-2 tokamak

A.D. Gurchenko, E.Z. Gusakov, A.B. Altukhov, S. Leerink[*],

E.P. Selyunin, L.A. Esipov, M.Yu. Kantor, D.V. Kouprienko, S.I. Lashkul, A.Yu. Stepanov

Ioffe Physical-Technical Institute of the RAS, St. Petersburg, Russian Federation

[*]*Aalto University, Euratom-Tekes Association, Helsinki, Finland*

Geodesic acoustic mode (GAM), which manifests itself in toroidal plasmas as a symmetric oscillation of the electrostatic potential (with poloidal and toroidal mode numbers m = n = 0) coupled with a minor density perturbation (with m = 1, n = 0), as well as low-frequency zonal flows, is considered nowadays as a factor of micro-turbulence induced self-control. Experimental information on GAM is usually obtained either via direct measurement of the plasma potential by probes or HIBP technique, or of oscillating component of plasma rotation velocity by Doppler reflectometry [1] and is already very detailed. However information related to GAM spatial structure and correlation properties is still missing. In the present paper we are making an attempt to fill in this gap. The complete data set on GAM behaviour is obtained at the FT-2 tokamak and compared against the results of full-wave gyro-kinetic modelling. Two microwave methods are utilised for investigation of the GAM. In the first one the Doppler frequency shift f_D of the signal, backscattered (BS) in the upper hybrid resonance (UHR), is measured by the quadrature method. The Doppler UHR BS technique utilizes X-mode microwave plasma probing out of the tokamak's equatorial plane from high magnetic field side. It is benefiting from the effects of the electric field and both poloidal and radial wave numbers growth in the UHR resulting in enhancement of the scattering signal, sub-mm radial resolution and substantial f_D increase. The technique allows to perform the correlation analysis of f_D temporal variation for two UHR BS signals at different probing frequencies and to implement it for GAM spatial structure investigation. The second method is based on correlative analysis of the f_D-signal obtained by UHR BS and the homodyne detected signal of the O-mode reflectometer with top launching and vertical probing.
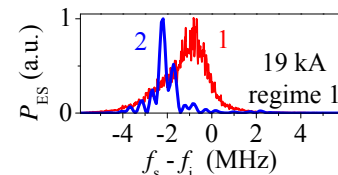

Fig. 1. The UHR BS spectra.

The measurements were carried out at FT-2 tokamak (R = 55 cm; a = 7.9 cm) in hydrogen plasma and with additional helium puffing in regimes with different plasma currents 19-32 kA at $B_T \sim 2.2$ T. In the hydrogen discharge ($I_p \sim 19$ kA, $n_{e0} \sim 4.5 \times 10^{19}$ m^{-3}, $T_{e0} \sim 470$ eV, $T_{i0} \sim 110$ eV, $Z_{eff} \sim 3.5$ (the main impurity is O^{8+}), the safety factor $q(x = 5\text{-}8$ cm$) = 2.5\text{-}6)$ the ES spectrum for f_i = 66 GHz averaged over 1.6 ms (see red curve 1 in Fig. 1) is wide.

However when calculated without averaging in 3.2 mks window it appears to be narrow (blue curve 2), oscillating during 1.6 ms and filling the first one. The f_D behaviour estimated from spectra 2 as $f_D(t) = \int f |P_{ES}(f)| df / \int |P_{ES}(f)| df$ is presented on Fig. 2a by grey curve, whereas the mean values determined in the 1.6 ms window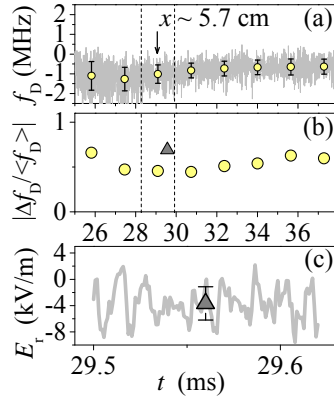s are shown by circles. Typical features of $f_D(t)$ dependence are significant levels of its mean value $<f_D>$ and rms value Δf_D, (shown by black error bars in Fig. 2a). The ratio of rms to mean value is shown by circles on Fig. 2b.

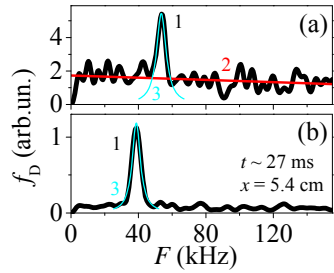Fig. 2. The f_D-signal (a), normalised rms (b) and E_r (c) in regime 1.

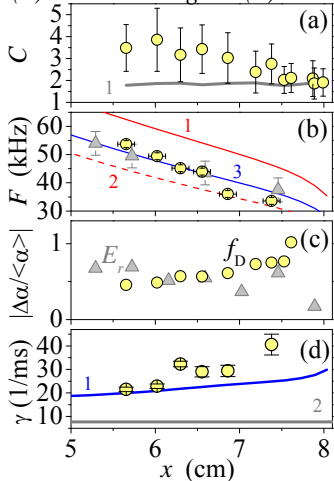Fig. 3. f_D-spectra in regime 1 (a) and in He-regime (b).

Fig. 4. (a) The contrast, (b) line frequency, (c) normalised rms of f_D and E_r, (d) aproximating parameter γ_0 in regime 1. (2 – f_D-spectrum resolution $\pi\Delta F$).

The spectrum of $f_D(t)$ dependence, calculated with 8 averages in 1.6 ms window (within dashed lines on Fig. 2a) is presented on Fig. 3a by black curve 1. An intense spectral line is clearly seen in this spectrum at $F \sim 54\pm1.2$ kHz. The red line 2 corresponds to a noise level, which can be attributed to radial electric field E_r and density perturbations, as well as distortions of UHR and magnetic surfaces. The ratio of the line amplitude $A_m \sim 5.41\pm0.03$ to noise level $A_n \sim 1.55\pm0.47$ is a contrast $C = A_m/A_n \sim 3.5\pm1.1$. The radial profiles of the spectral line's contrast C, frequency F and its normalised rms $\Delta f_D/<f_D>$ at $t \sim 29$ ms are shown on Fig. 4 by circles. The line frequency F was determined only for cases when the contrast error bars were not crossing the error level for noise (grey curve 1 on Fig. 4a).

The theoretical estimations of GAM frequency are also plotted on Fig. 4b. The red curve 1 was obtained with formula:

$$\omega_G^2 R^2 \sim \frac{2}{m_i}\left(\frac{7}{4}T_i + Z_i T_e\right), \quad (1)$$

where $Z_i = 1$ (for H$^+$). The dashed red curve 2 corresponds to (1) with $T_i = 0$. The blue curve 3 is based on a formula accounting for impurities [2], in which we assumed two-component (H$^+$ and O^{8+}) plasma. It could be easily seeing on Fig. 4b that experimental frequencies are very close to theoretical estimations. As for the C-level, it decreases to plasma periphery, where (for $x > 7.5$ cm) the line becomes invisible against the background noise level. The GAM spectral line (see Fig. 3a) is well approximated by the Lorenzian dependence (cyan curve 3) describing excitation of the dissipative oscillator by a random force: $A_G = F_{turb}/[(\omega-\omega_0)^2 + \gamma_0^2]$, with

$\omega_0 = \omega_G$ and $\gamma_0 = 21.5 \pm 0.9$. The radial dependence of approximation parameter γ_0 is shown by circles on Fig. 4d, where it is compared against the sum of collisional $\gamma_c \sim 4\nu_i/7$ and Landau $\gamma_L \sim \omega_G \exp(-q^2)$ damping rate (blue curve 1) responsible for GAM damping in warm plasma estimated for $Z_{\text{eff}} \sim 3.5$ according to theory [2]. As it is seen in Fig. 4d, parameter γ_0 is close to the theoretical prediction in the gradient zone and exceeds it by a factor of 2 at the edge where accuracy of γ_c determination is poor. It should be mentioned that the observed γ_0 growth is consistent with decrease of the GAM line contrast seen at the edge in Fig. 4a.

   The experimental data obtained in regime 1 was compared to results of FT-2 tokamak gyro-kinetic modelling using ELMFIRE code [3]. An example of the E_r temporal behaviour obtained in this modelling is shown on Fig. 2c by grey curve. It is characterised by very strong modulation. Its mean value and rms are shown by triangle with error bars. The spatial distribution of frequency of the dominating spectral line of this dependence is shown on Fig. 4b by grey triangles. The normalised level of E_r rms is plotted on Fig. 4c. Both dependencies appear to be in nice agreement with those measured experimentally.
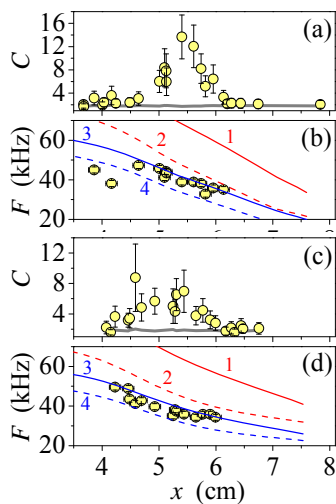

Fig. 5. The contrast and frequency in He-regime.

   The dependence of the GAM frequency on the ion mass was clearly observed, in accordance with theoretical predictions [2], in the experiment in the discharge with He puffing ($I_p \sim 22$ kA, $n_{e0} \sim 2.1$-3.4×10^{19} m^{-3}, $T_{e0} \sim 350$-520 eV, $T_{i0} \sim 150$-160 eV, $Z_{\text{eff}} \sim 2$-3.2). Profiles of contrast and the line frequency (F) measured at $t = 26.3$-27.6 ms are shown on Fig. 5a,b and at $t = 36.8$-38.1 ms – on Fig. 5c,d. As it is clearly seen on Fig. 5b,d F-values have shifted from the region between red lines 1 and 2 to a region between blue lines 3 and 4, calculated in the same manner with the formula 1 with $Z_i = 2$ (for He^{2+}). As it seen from the $C(x)$ profiles in Fig. 5a and Fig. 5c the GAM oscillation is observed in a narrower zone, compared to Fig.4a, which is explained by growth of the Landau damping in the gradient zone and by suppression of low frequency turbulence at $x > 5.5$ cm which was registered by ES correlative measurements [4].

   The radial spatial structure of the GAM was investigated with dual-frequency UHR BS correlative approach [5] possessing sub-mm spatial resolution. Two signals at probing frequencies with difference $|f_2 - f_1| < 4$ GHz, corresponding to spatial separation $|\Delta L| < 2$ cm in plasma, were measured simultaneously by two homodyne channels. Because of considerable Doppler frequency shift of the quadrature spectrum (Fig. 1) the corresponding line is also
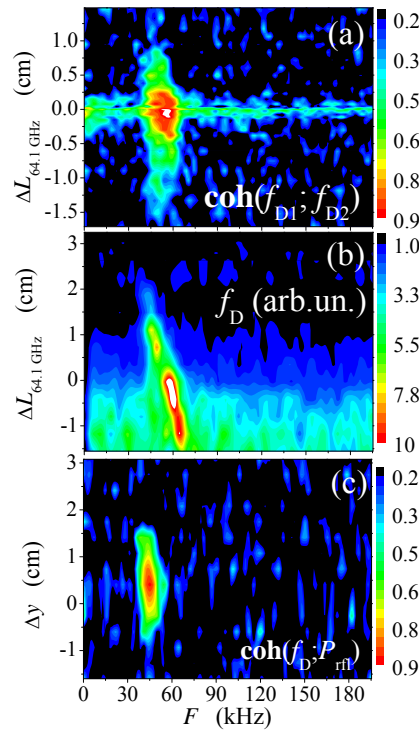
Fig. 6. The coherence between f_{D1} and f_{D2} (a), f_D and reflectometer signal (c). The f_D-spectrum (b).

seen in both homodyne spectra, therefore two signals $f_{D1/2}(t)$ were reconstructed in the same manner as it was done for quadrature spectrum. Due to GAM influence on $f_{D1/2}$ it is quite natural to expect the high level of correlation between $f_{D1}(t)$ and $f_{D2}(t)$ signals at GAM frequency. An example of the coherence frequency spectrum of the above signals for reference frequency $f_1 = 64.1$ GHz in 19 kA discharge is shown on Fig. 6a, (noise level: $coh \sim 0.14$). The maximum of $coh \sim 0.91$ corresponds to $F \sim 56.9$ kHz and drops by a factor of e at $\Delta L = +0.72\pm0.01$ cm (-0.94 ± 0.01 cm). The f_D-spectrum, measured by quadrature scheme for 19 kA case, is shown on Fig. 6b. It could be concluded from this figure that suppression of the GAM coherence is determined by decrease of the GAM's spectra overlap at a spatial shift.

The coherence spectrum of the UHR BS f_D-dependence and O-mode reflectometer signal at $f_i = 27.74$ GHz is shown on Fig. 6c. The maximum of $coh \sim 0.88$ corresponds to $F \sim 45.2$ kHz and drops by a factor of e at $\Delta y = +1.6\pm0.17$ cm (and -0.8 ± 0.17 cm). The resulting correlation length in the radial direction in this case $l_c \sim 1.3\pm0.2$ cm is larger than in the previous case: $l_c \sim 0.7\pm0.01$ cm. This difference is probably explained by the poor locality of the reflectometry diagnostics. The cross-phase of these signals was $\pi/2$ which is natural for E_r and density components in GAM.

Summarising we would like to stress that application of highly localised ES technique to GAM studies has resulted in detailed investigation of their characteristics and, in particular, in measurement of radial correlation length which appear to be determined by spectral overlapping of GAM in different spatial points and therefore estimated by relation $l_c \sim 2\sqrt{\pi} L_{T_e} \gamma_G / \omega_G$.

1. A. Fujisawa, *Nucl. Fusion* **49**, 013001 (2009)
2. W. Guo, S. Wang and J. Li, *Phys. Plasmas* **17**, 112510 (2010)
3. S. Leerink et al., *this conference.*, P4.121
4. A.D. Gurchenko et al., *this conference*, P2.128
5. A.D. Gurchenko et al., 36th EPS Conf. on Plasma Phys., Sofia 2009 ECA Vol.**33E**, P-5.207