GAM FREQUENCY STRUCTURE AND PROPERTIES IN OHMIC AND POWERFUL ECR-HEATED PLASMAS IN A TOKAMAK

[1,2,3]A.V. MELNIKOV, [1]L.G. ELISEEV, [1,2] Ya.M. AMMOSOV, [1]S.E. LYSENKO

[1] NRC “Kurchatov Institute", Moscow, Russia
[2] Moscow Institute of Physics and Technology (NRU), Moscow, Russia
[3] National Research Nuclear University "MEPhI", Moscow, Russia

Email: Melnikov_AV@nrcki.ru

For the first time it was shown that GAM has a complex frequency structure with three frequency peaks evolving together with equal frequency shift of ~ 3 kHz between them. Under high-power ECR-heating (0.5 MW<P_{EC}≤2.2 MW) all three GAM peaks, deviate from the square root dependencies of GAM frequency on temperature $f_{GAM}(T_e)$ = $c_s/2\pi R$ and become saturated, reaching an upper limit for f_{GAM}.

The geodesic acoustic mode (GAM) is a high-frequency branch of Zonal Flows (ZFs) considered as a mechanism of self-regulation of turbulence, affecting the radial transport of energy and particles in toroidal fusion devices [1]. In the T-10 tokamak (B_0=1.5-2.42 T, R=1.5 m, a=0.3 m), an advanced high sensitivity heavy ion beam probing (HIBP), measuring the fluctuating component of plasma potential, density, and poloidal magnetic field with a high spatial (~1 cm) and temporal (1 μs) resolution was used to study GAM [2, 3]. Tl^+ ions with energy E_b≤330 keV probed the plasma from the edge to the central area [4]. Deuterium plasma with ohmic and powerful ECR-heating (P_{EC} ≤ 2.2 MW) was studied in a wide range of plasma parameters T_e < 3.1 keV, T_i < 0.6 keV, $\bar{n}_e$~0.7-4×10^{19} m^{-3}, I_{pl} = 150-300 kA.

Advanced HIBP with improved signal sensitivity allows us to observe the fine frequency structure of GAM. It was shown for the first time that GAM consists of three separated frequency peaks: the main GAM peak with f_{GAM}, the HF-satellite with f_{HF_sat} and the LF-satellite with f_{LF_sat}, Fig. 1. As a rule, the frequency differences between the GAM and its satellites are equal $f_{GAM} - f_{LF\_sat} = f_{HF\_sat} - f_{GAM} = \Delta f$ and amounts to Δf ~ 3 kHz. This frequency structure of the GAM corresponds to a nonlinear model of interaction between the GAM and low-frequency ZF, suggesting the ZF frequency f_{ZF} is equal to Δf [5, 6]. GAM main peak and its satellites dominate the plasma potential power spectra in the OH and ECRH stages of discharge. With ECRH, the amplitude of the GAM increases.

The GAM main peak and both satellites have a uniform structure with constant frequency and amplitude in a wide radial region shown in Fig. 2 (a), which corresponds to the global plasma oscillation mode, where f_{GAM}=18 kHz, f_{HF_sat}=21 kHz, f_{LF_sat}=15 kHz. The almost constant frequency difference between the three peaks allows us to interpret the HF satellite as the second branch of the GAM, originated in a deeper region of plasma at r_{HF_sat} = 23 cm with a higher temperature, and the LF-satellite as the third one, born in more outer region at r_{LF_sat} = 27 cm with a lower temperature, while main peak originates in between at r_{GAM} = 25 cm. Following [7], we consider the origin point for each GAM peak as an outer radius of the area of constancy of its amplitude, since the absolute values of the measured GAM frequencies correspond to $c_s = \sqrt{(T_e + 7/4T_i)/m_i}$, taken at these radii. As a rule, the amplitude of the LF-satellite is significantly (2-4 times) lower than the amplitudes of the main peak and the HF-satellite. The amplitude of each of the GAM peaks begins to fade monotonously from the origin point towards the edge, down to the noise level, Fig. 2 (b). The origin point radii for each of the peaks are different, but they are quite constant over wide range of plasma parameters under study in both OH and ECRH plasmas.

For plasma with ohmic heating and low-power ECR-heating (P_{EC} < 0.5 MW) all three frequency peaks of the GAM: the main, LF-, and HF-satellites have a square root temperature dependence on (T_e+7/4T_i), taken at the origin points, different for each peak. For plasma with high-power ECR-heating (0.5 MW < P_{EC} ≤2.2 MW) or when (T_e+7/4T_i) at r_{GAM} exceeds 0.55 keV, the frequencies of the main peak of the GAM, as well as of LF- and HF-satellites deviate from the prediction of the local theory [1], and the square root dependencies of f_{GAM} on (T_e+7/4T_i) at r_{GAM} become saturated. Thus, there is an upper limit for the GAM frequency. In this parameter range, as the power of the ECR-heating or T_e increases, the frequencies of the main peak and the HF-satellite merge into one.
Bispectral analysis indicates the three-wave interaction for each of three GAM frequency peaks with background turbulence in a wide frequency band from 0 to 330 kHz, that is, in the range of quasi-coherent modes. Each GAM peak has its own characteristic frequency range of interaction, including low-frequency quasi-coherent mode, high-frequency quasi-coherent mode and stochastic low frequency mode.

Presented new experimental findings require a theoretical analysis, which complements the works [5, 6].

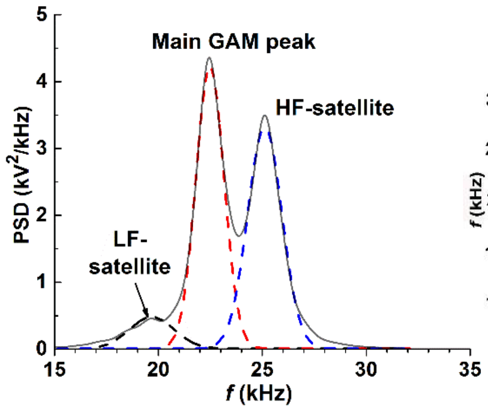
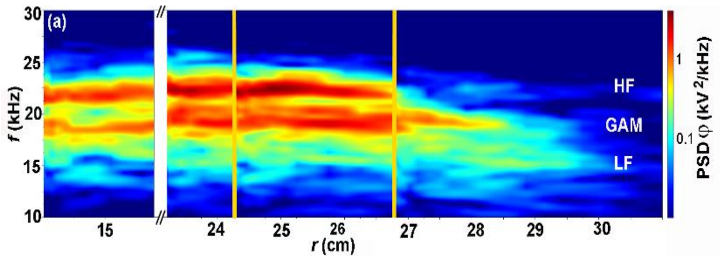


Fig. 1. The frequency structure of the GAM on a typical power spectrum of plasma potential fluctuations with ECRH.



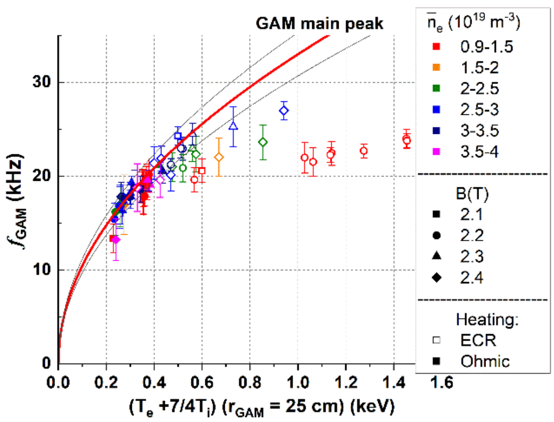


Fig. 3. Dependence of the main GAM peak frequency on the temperature. Red curve - f_{GAM}, black curves – its upper and lower estimation for ±10% T_e and T_i variation.

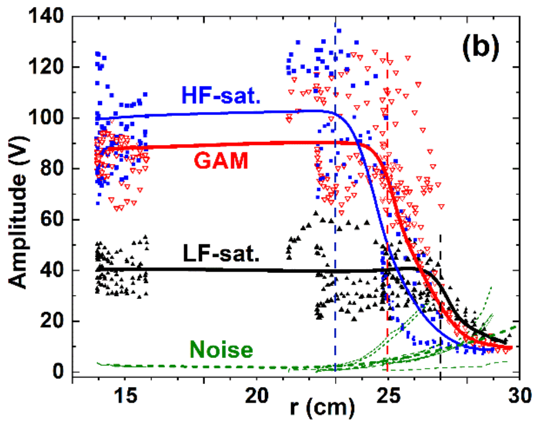


Fig. 2. Radial distribution of power spectral density of plasma potential fluctuations (a); of amplitudes for three GAM peaks (b), in OH plasma with B_0 = 2.3 *T*, I_{pl} = 230 kA, $\bar{n}_e \approx 0.6\text{-}1.0\times10^{19}$ m^{-3}. Vertical dash lines designate origin points for three GAM peaks.

ACKNOWLEDGEMENTS

Authors acknowledge continuous support of T-10 team.

REFERENCES

[1] Convay G.D., Smolyakov A.I., and Ido T., Geodesic acoustic modes in magnetic confinement devices, Nucl. Fusion **62** (2022) 013001.

[2] Melnikov A.V., Krupnik L.I., Eliseev L.G., et al., Heavy ion beam probing – diagnostics to study potential and turbulence in toroidal plasmas, Nucl. Fusion **57** (2017) 072004.

[3] Sergeev N.S., Melnikov A.V. and Eliseev L.G., Magnetic component of quasi-coherent mode of plasma fluctuations in ohmic plasma of the T-10 tokamak, JETP Letts. **119** N 11 (2024) 852-859.

[4] Melnikov A.V., Drabinskiy M.A., Eliseev L.G., et al., Heavy ion beam probe design and operation on the T-10 tokamak, Fusion Eng. and Des. **146**, Part A (2019) 850-853.

[5] Sorokina E.A., Transformation of a geodesic acoustic mode in the presence of a low-frequency zonal flow in a tokamak plasma, JETP Letts. **120** (2024) 642-649.

[6] Lakhin V.P., On the nonlinear interaction of geodetic acoustic modes and zonal flows in tokamaks with toroidal plasma rotation, JETP submitted, (2025).

[7] Melnikov A.V., Eliseev L.G., Perfilov S.V., et al., The features of the global GAM in OH and ECRH plasmas in the T-10 tokamak, Nucl. Fusion **55** (2015) 063001.