

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

EX-C 2865

A.V. Melnikov<sup>1,2,3,\*</sup>, L.G. Eliseev<sup>1</sup>, Y.M. Ammosov<sup>1,2</sup> and S.E. Lysenko<sup>1</sup>

<sup>1</sup> NRC "Kurchatov Institute"

<sup>2</sup> Moscow Institute of Physics and Technology (NRU)

<sup>3</sup> National Research Nuclear University «MEPhI»

\*Melnikov\_AV@nrcki.ru

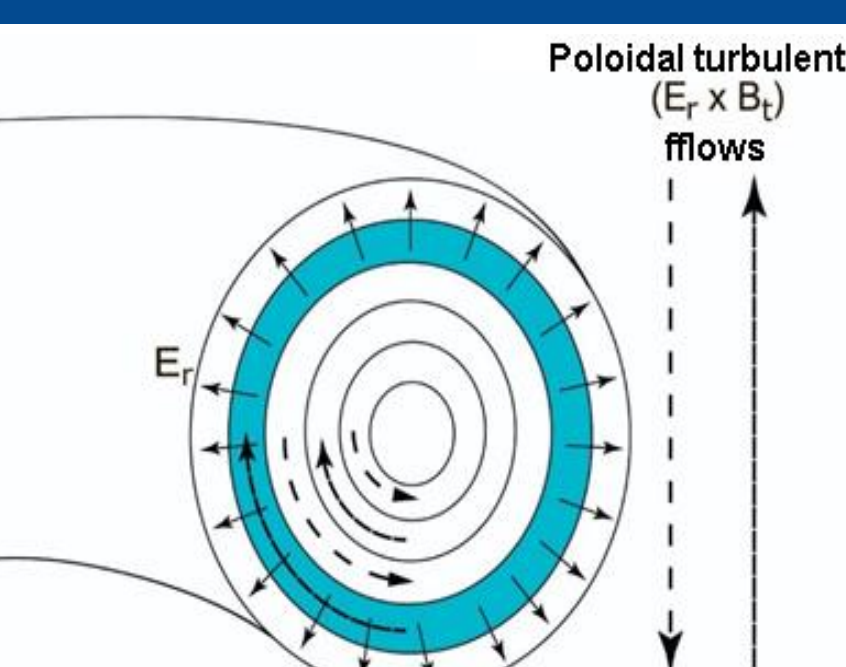


## Abstract

Using an advanced heavy ion beam probe (HIBP) diagnostics in the T-10 tokamak ( $R=1.5$  m,  $a=0.3$  m,  $B_z=2.5$  T,  $I_{pl}<330$  kA,  $D_2$ ), we have shown that:

- The geodetic acoustic mode (GAM) has a complex frequency structure consisting of three separate frequency peaks: the main GAM peak with the frequency  $f_{GAM} \sim 20$  kHz, and two satellite peaks, High-Frequency and Low-Frequency, shifted from the main peak at  $\Delta f \sim 4$  kHz.
- The radial dependence of the GAM frequency is not described by the local Winsor formula ( $f_{GAM} \sim C_s/R$ ,  $C_s$  - the ion-sound speed,  $R$  - major plasma radius). In ohmic discharges and at the moderate ECRH power ( $P_{EC} < 0.5$  MW) the frequencies of each of the three GAM peaks follow the Winsor formula for  $f_{GAM}$ . With a further power or temperature increase at the strong ECRH ( $0.5$  MW  $< P_{EC} \leq 2.2$  MW) the frequencies of the GAM main peak and both satellites deviate from the theoretical dependence and saturate.
- Near the highest achieved ECRH power (or the temperature), the frequency difference between the main GAM peak of the HF-satellite decreases, and two peaks merge into the single one.
- The bicoherence analysis indicates the three-wave coupling of GAM with quasiscoherent (QCM) and stochastic low-frequency (SLF) turbulent modes in a wide spectral range, and each of three GAM peaks has its own frequency range of coupling.

## Introduction

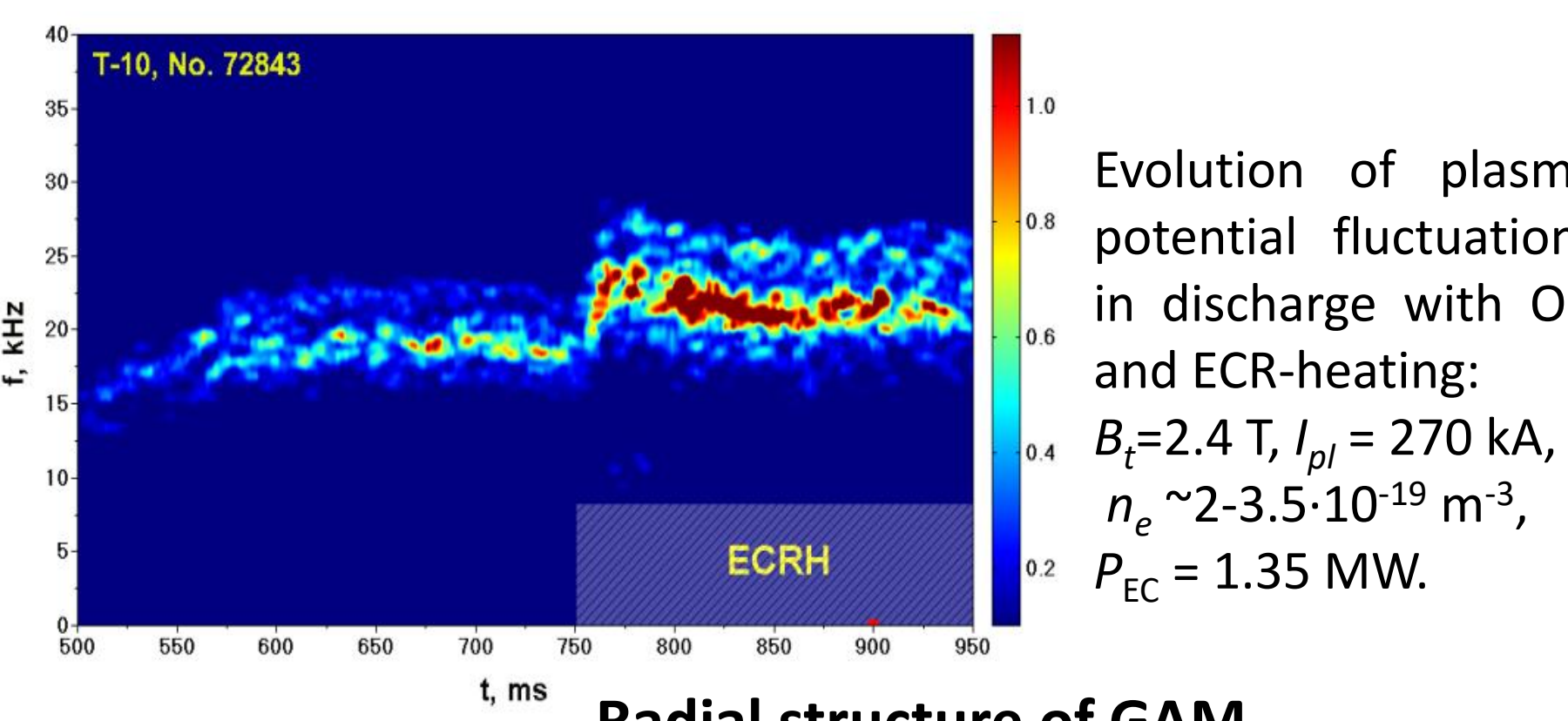


Geodetic acoustic mode (GAM) is a high-frequency branch of zonal flows (ZF). It manifests itself in the form of torsional poloidal oscillations along magnetic surfaces excited by an oscillating radial electric field. The occurrence of zonal flows and GAMs is associated with the nonlinear interaction of various spectral components of turbulence, or with the effect of fast particles (e-GAMs). ZF and GAM are considered as an effective mechanism for the turbulence self-regulation, having a significant effect on the radial transport of energy and particles. ZF/GAM is also considered as a mechanism influencing L-H transitions.

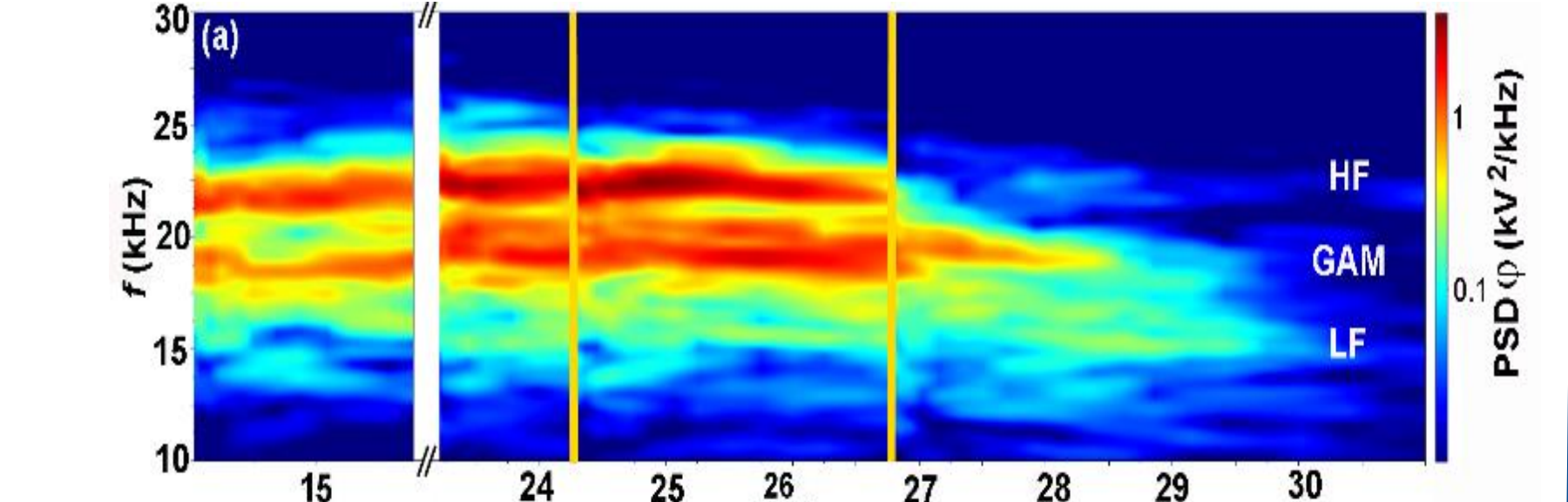
$$f_{GAM} = [10 - 30] \text{ kHz}, m=n=0, \Delta n_e/n_e \ll e\Delta\phi/T_e, f_{GAM} \approx \frac{C_s}{\sqrt{2\pi R}}, C_s = \sqrt{(T_e + 7/4 T_i)/m_i}$$

## The fine frequency structure of GAM

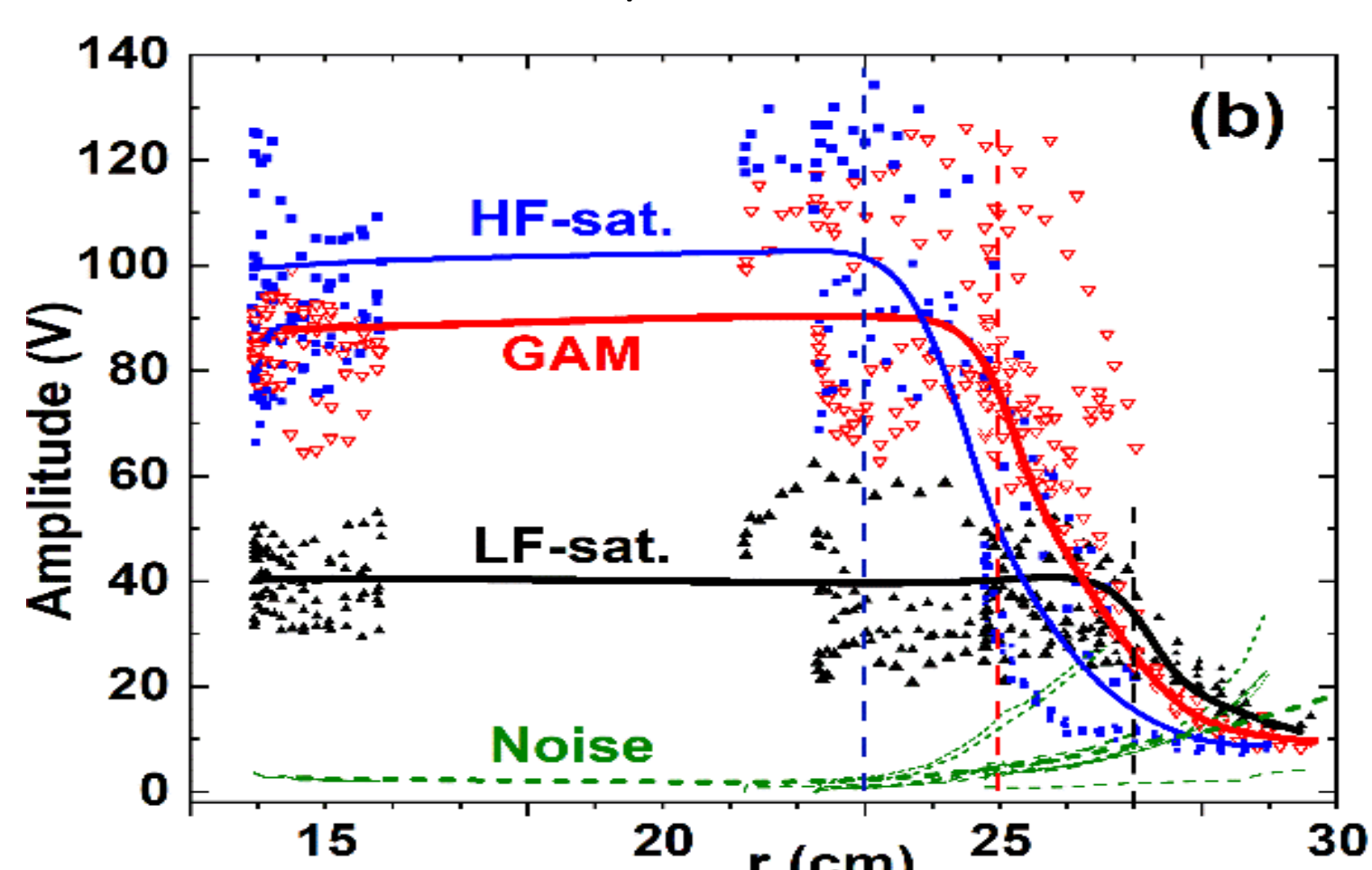
Advanced HIBP diagnostics with improved signal sensitivity allowed us to observe the fine frequency structure of the GAM and its temporal evolution. For the first time it was shown that GAM consists of three peaks with separated frequencies: the main GAM peak, LF- and HF-satellites, while previously only two peaks were observed.



Radial structure of GAM

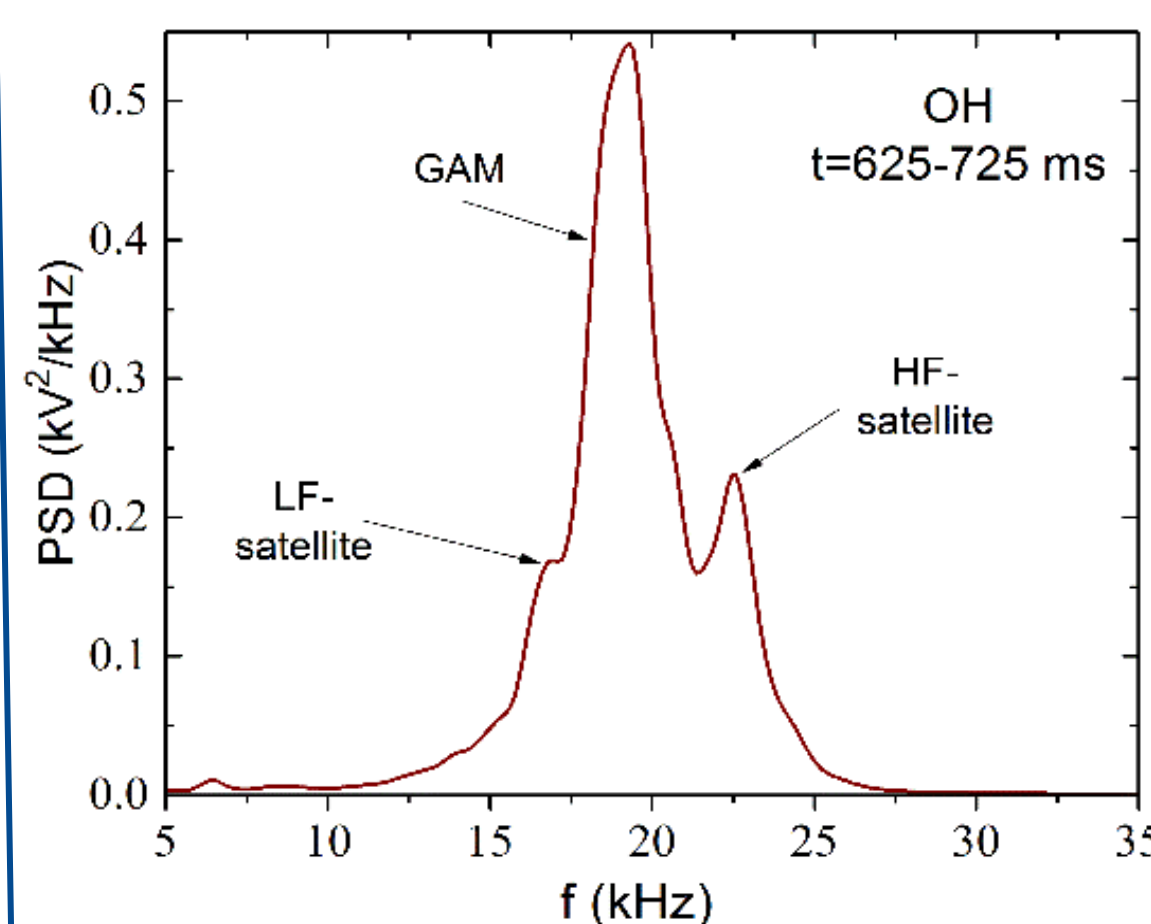


(a) The frequency for each of the three GAM peaks is constant in the observation area  $r/a = 0.55-1.0$ .

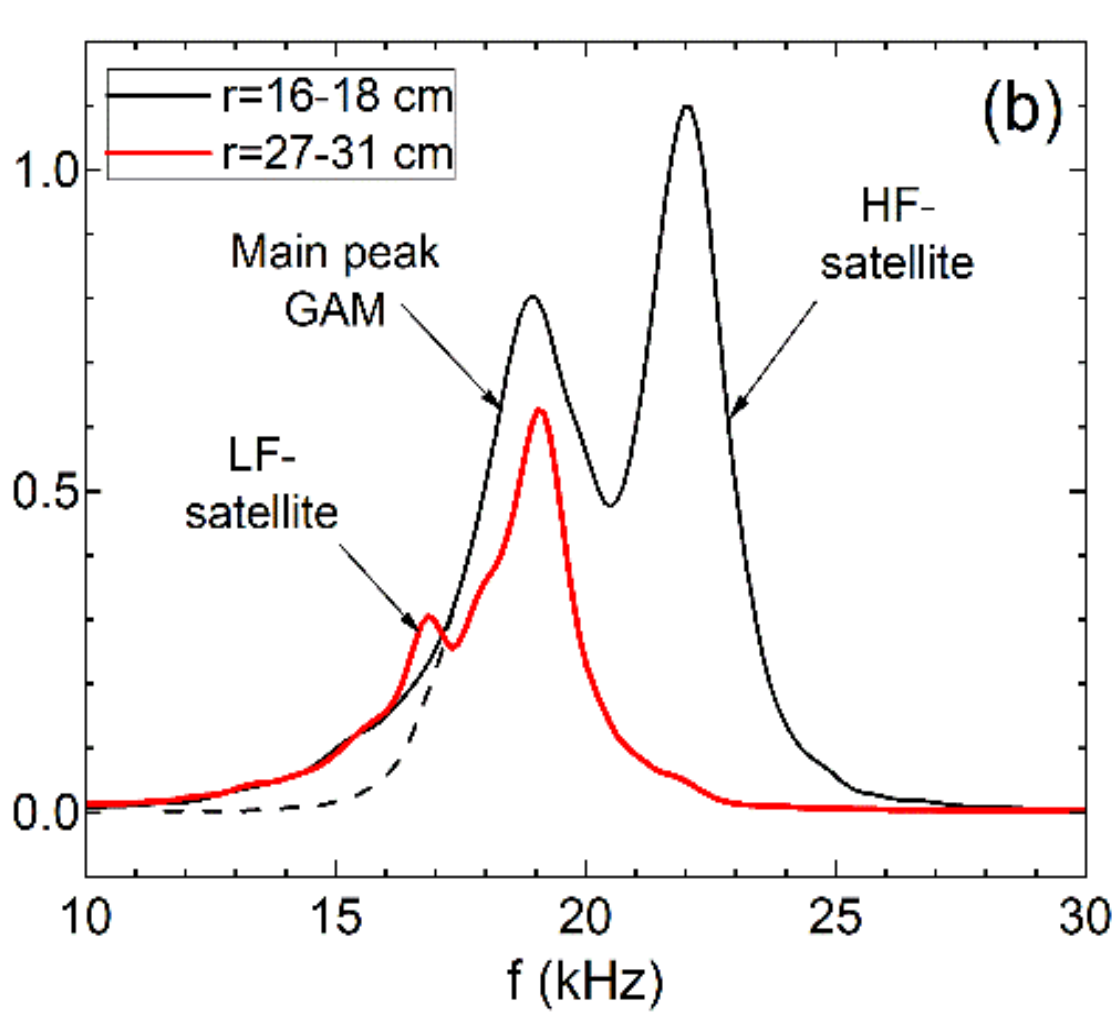


(b) Radial distribution of the GAM amplitude. The amplitude of each of the three peaks is constant over a wide radial range. As it approaches to the edge, it begins to fall down to the noise level. The region of constant amplitude for the HF satellite is the narrowest, for the LF- it is the widest, and for the main peak it is the average between them.  $B_z=2.3$  T,  $I_{pl}=230$  kA,  $n_e \approx 0.6 \cdot 10^{19} \text{ m}^{-3}$ , OH plasma

## Fine frequency structure of GAM



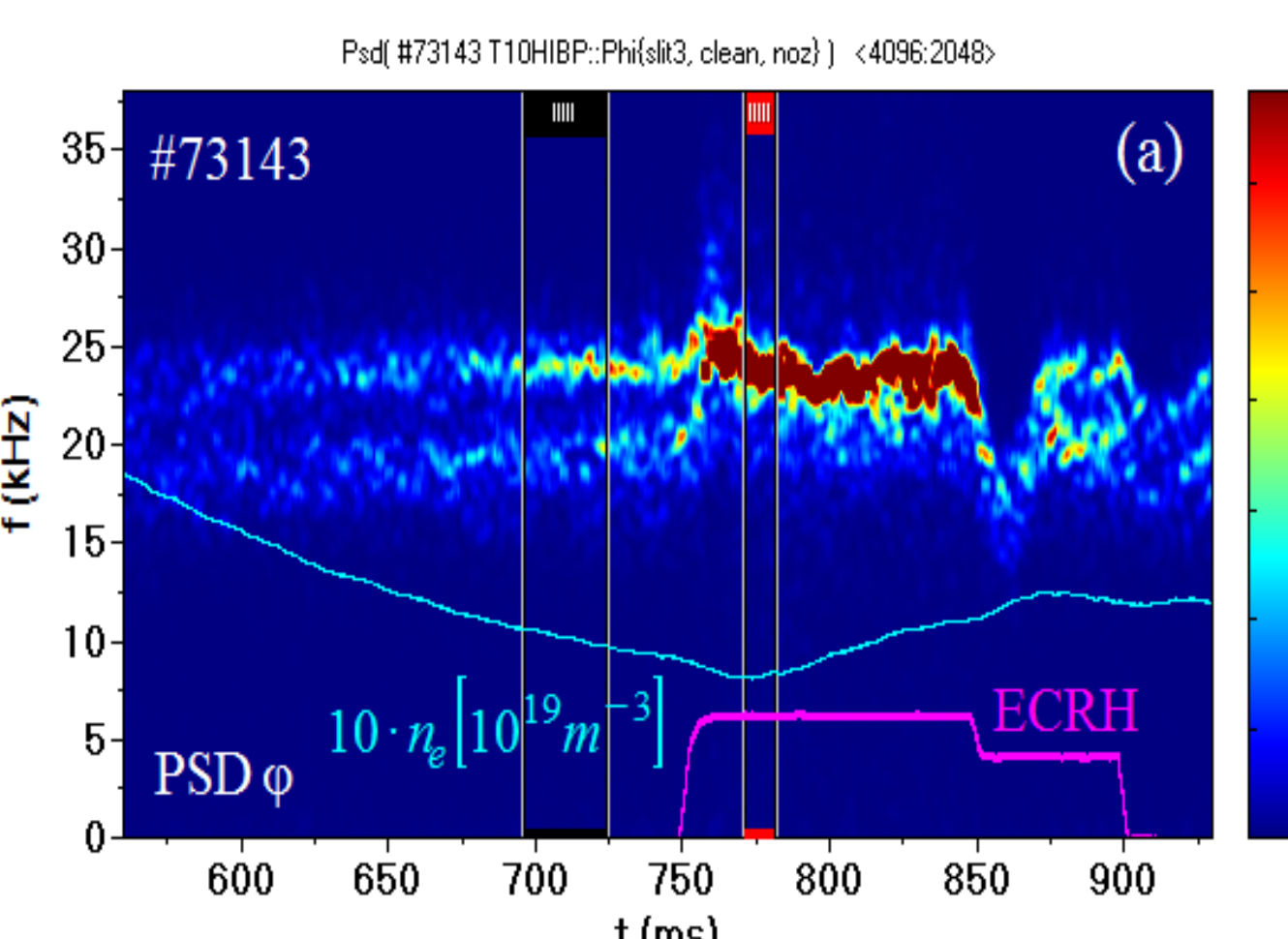
Main GAM peak, LF-, and HF-satellites on the power spectral density of potential fluctuations. An example for OH plasma.



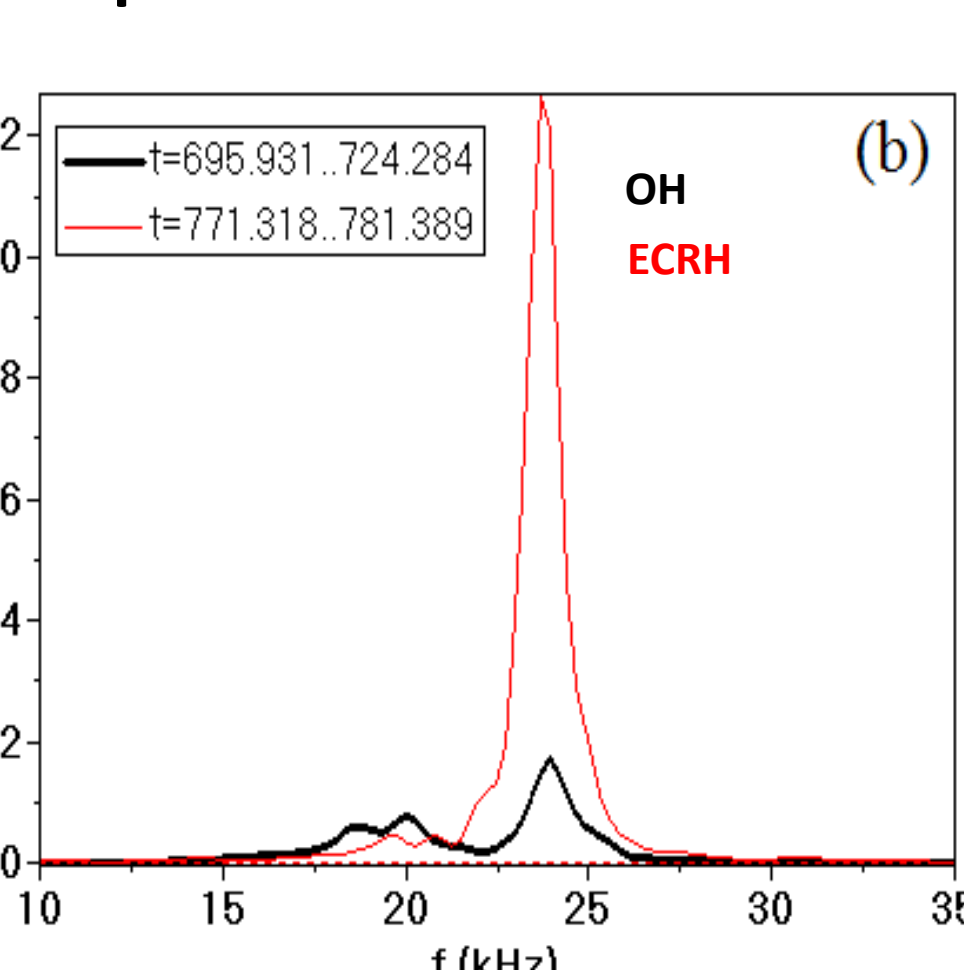
Power spectrum of potential fluctuations depends on the observation point. The HF-satellite peak is not observed in the outermost observation position. An example for OH plasma.

## Merging of GAM with HF-satellite at the powerful ECRH

### GAM evolution under powerful ECRH



Power spectrogram of plasma potential

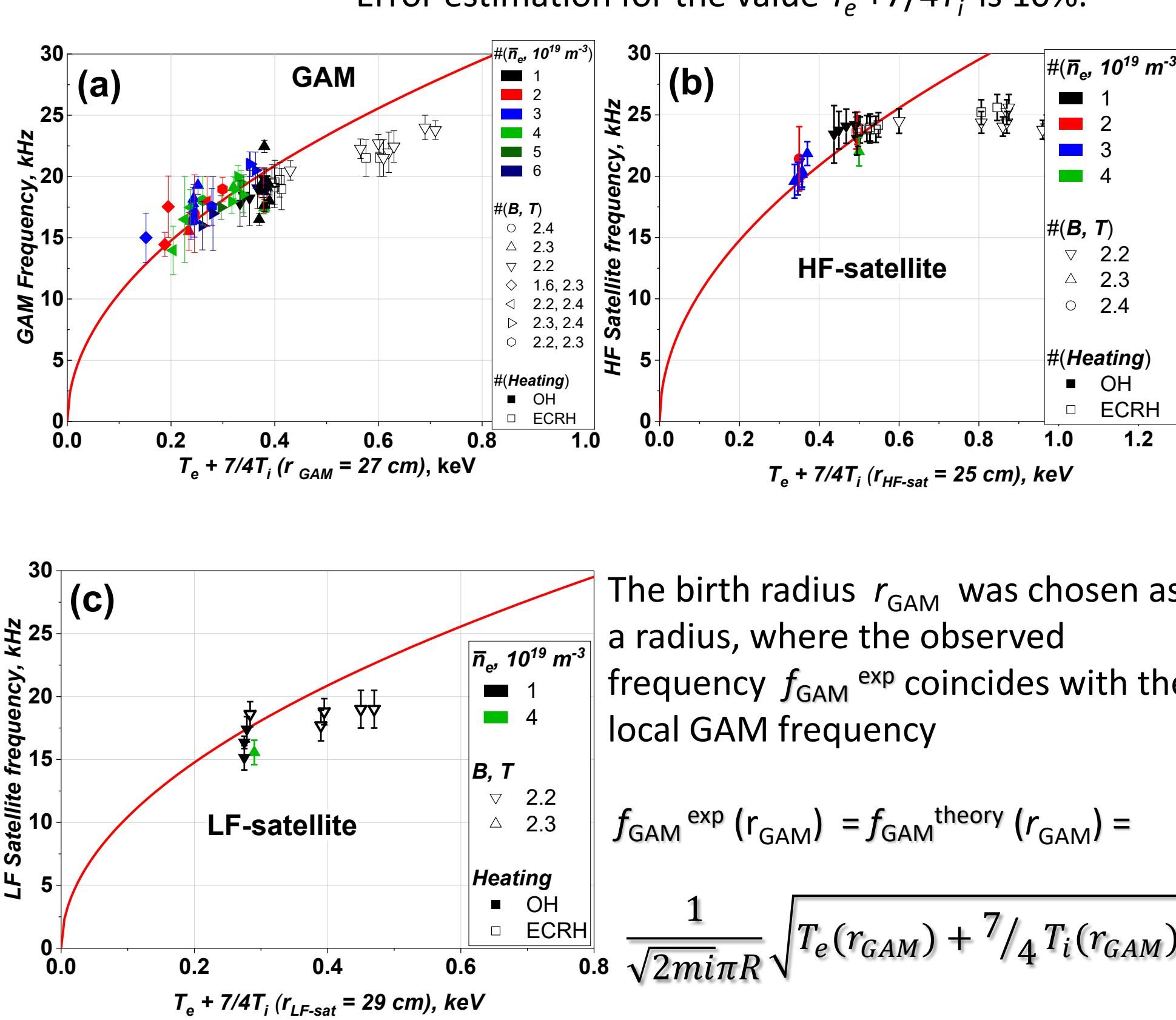


Power spectrum of plasma potential

At  $P_{EC} > 1.7$  kW, the temperature value  $T_e + 7/4 T_i$  ( $r_{GAM} = 27$  cm) approaching 0.7 keV, a convergence of the main GAM and HF satellite peaks is observed, up to their complete merging.

## Dependence of the GAM frequency on the plasma temperature

In OH and low-power ECRH ( $P_{EC} < 0.5$  MW) plasmas, all three frequency peaks: the main GAM peak, LF- and HF- satellites have a square-root temperature dependence on the value  $(T_e + 7/4 T_i)$ , taken at the points of birth, different for each peak. For plasma with powerful ECRH ( $0.5$  MW  $< P_{EC} < 2.2$  MW) or when  $(T_e + 7/4 T_i)$  at the birth radius  $r_{GAM}$  exceeds 0.55 keV, the frequencies of the main GAM peak (a), as well as HF- and LF-satellites (b, c) deviate from prediction of the local theory, and reach a limit, saturate.

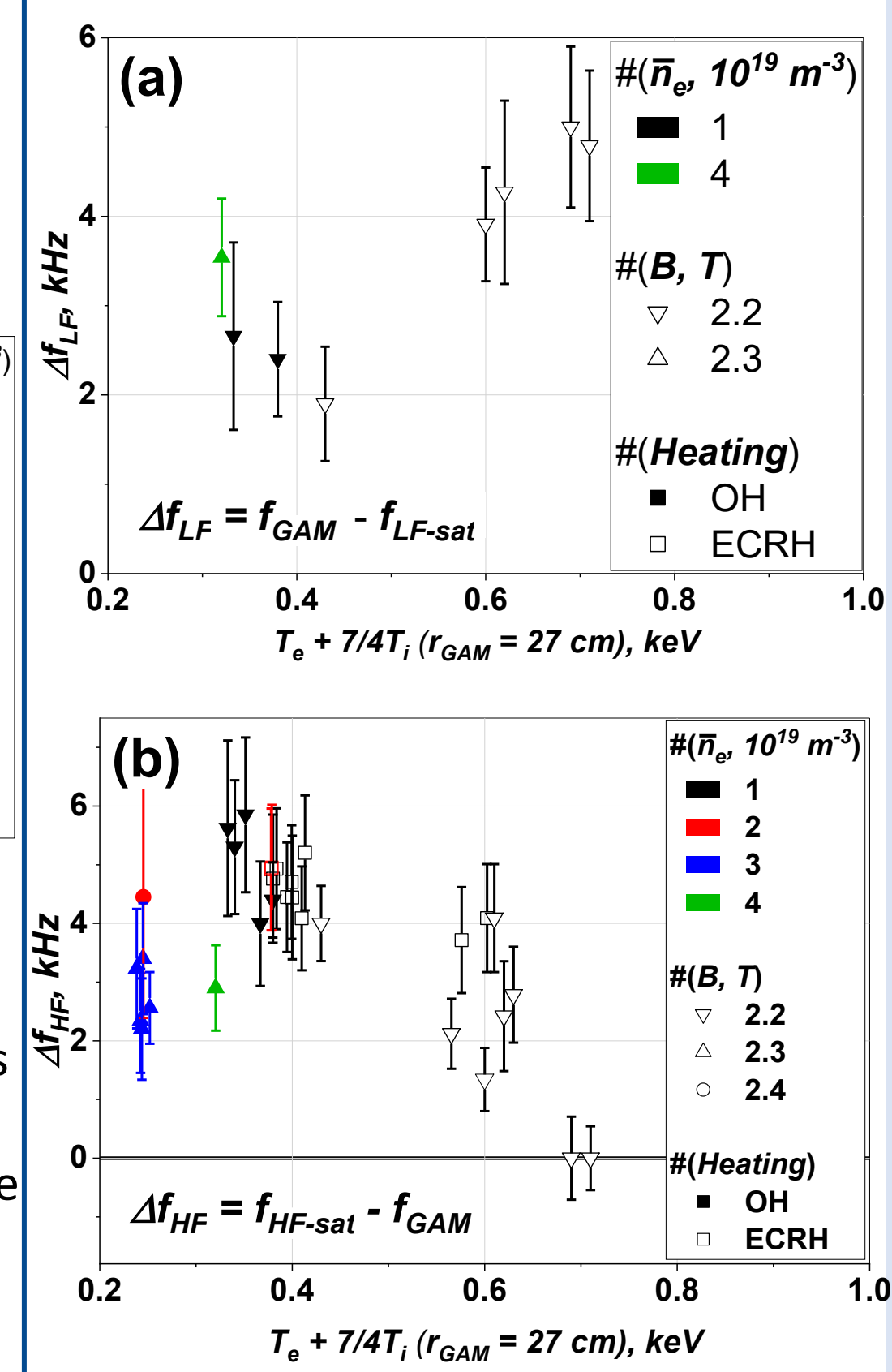


The birth radius  $r_{GAM}$  was chosen as a radius, where the observed frequency  $f_{GAM}^{exp}$  coincides with the local GAM frequency

$$f_{GAM}^{exp}(r_{GAM}) = f_{GAM}^{theory}(r_{GAM}) = \frac{1}{\sqrt{2\pi m_i R}} \sqrt{T_e(r_{GAM}) + 7/4 T_i(r_{GAM})}$$

### Frequency difference for GAM peaks

For OH and low-power ECRH plasmas, the frequency differences  $\Delta f_{LF}$  (a), and  $\Delta f_{HF}$  (b), are close to each other.

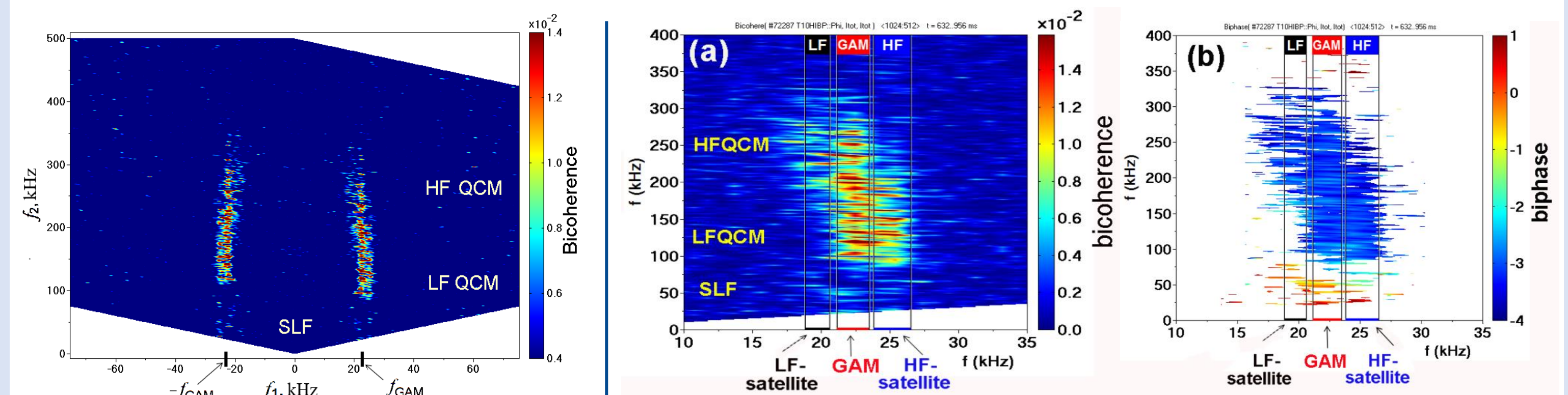


When the temperature value  $T_e + 7/4 T_i$  ( $r_{GAM} = 27$  cm) approaches 0.7 keV, the main GAM and HF-satellite peaks are merging.

## Interaction of GAM with broadband turbulence

Bispectral analysis indicates a three-wave interaction for each of three GAM frequency peaks with background turbulence in a wide frequency range  $0 < f < 330$  kHz. The each GAM peak has a characteristic frequency range of interaction, including a low-frequency quasi-coherent mode (LF QCM), a high-frequency quasi-coherent mode (HF QCM), and a stochastic low-frequency mode (SLF).

### Three-wave interaction of GAM and satellites with turbulence

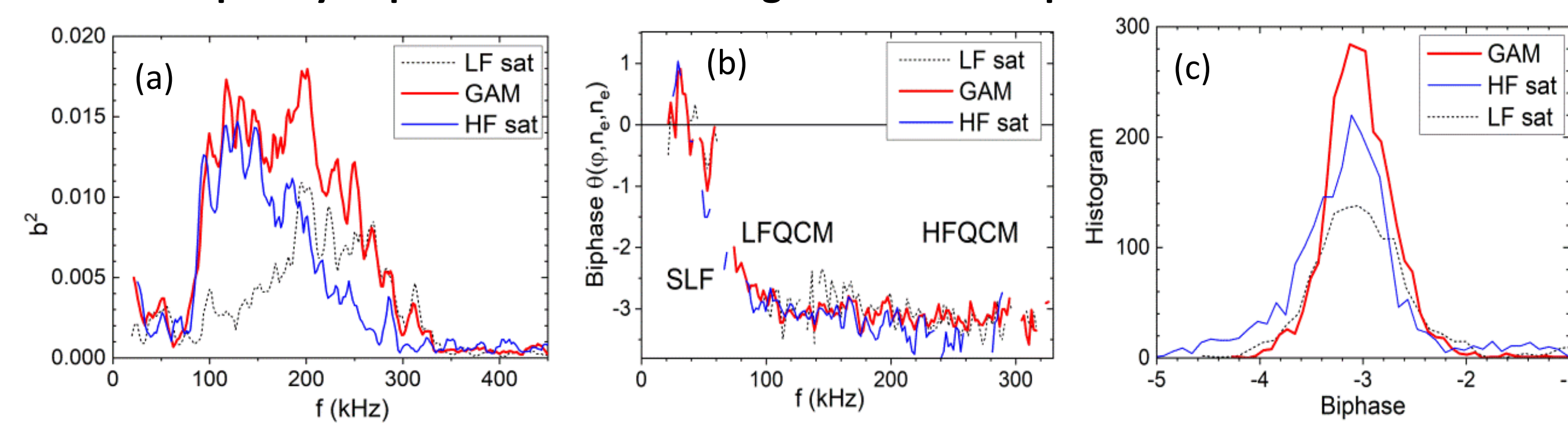


Statistically significant quadratic bicoherence coefficient  $b^2$  indicates the presence of a three-wave interaction between GAM and SLF, LF + HF QCM frequencies;

shot No. 72287, OH,  $\bar{n}_e \sim 0.7 \cdot 10^{19} \text{ m}^{-3}$ .

Bicoherence  $b^2$  (a) and biphas  $\theta$  (b) for  $(\phi, I_{tot}, I_{tot})$  (potential, density, density) in shot No. 72287. Three-wave interaction of GAM and satellites with SLF, QCM is observed in a wide frequency range 0 - 330 kHz.

### Frequency dependence of the integrated $b^2$ and biphas for GAM and satellites



(a) integrated bicoherence spectra for GAM and satellites interactions with QCM;  
(b) the biphas spectra for interactions with various types of turbulence;  
(c) biphas histogram for the GAM interactions with QCM has a maximum of about  $\pi$ .

## CONCLUSIONS

- We found that GAM has not only HF-, but also an LF-satellite. Thus, the GAM consists of three separate frequency peaks: the main GAM peak, the HF-satellite, and the LF-satellite. As a rule, the amplitude of the LF-satellite is significantly (2-4 times) lower than the amplitudes of the main peak and HF-satellite.
- For plasmas with ohmic and low-power ECR heating ( $P_{EC} < 0.5$  MW), all three GAM peaks: the main one, LF-, and HF- satellites have a square root temperature dependence of their frequencies, which is typical for GAM.
- A three-wave interaction of all three GAM frequency peaks with turbulence in the wide frequency band from 0 to 330 kHz (stochastic low frequency mode and quasiscoherent modes, both LF- and HF-) has been detected. Each GAM peak has its own typical frequency range of interaction.
- The almost constant frequency difference between the three peaks makes it possible to interpret the HF-satellite as the second GAM, born in a deeper plasma region with a higher temperature, and the LF-satellite as the third GAM, born in an outer region with a lower temperature.
- For plasma with high-power ECR heating ( $0.5$  MW  $< P_{EC} < 2.2$  MW), the frequencies of the main GAM peak, as well as LF- and HF satellites deviate from the prediction of the local theory, the square root dependence of the frequency on temperature  $f(T)$  goes into saturation. Thus, an upper frequency limit for GAM has been found.
- An increase of the ECRH power (plasma temperature) leads to the merging of the main GAM peak and HF satellite into the single peak.
- These new experimental findings need the further theoretical analysis, based on [V.I. Ilgisonis and E.A. Sorokina, #3268, This Conference].

## Acknowledgements

This work was carried out within the State assignment for the NRC "Kurchatov Institute". The authors thank the T-10 team, as well as M.A. Drabinskiy, O.D. Krokhalev, F.O. Khabanov and N.K. Kharchev for their help and support. Y.M. Ammosov and S.E. Lysenko are supported by the RSF grant 23-72-00042.