Correlation properties of Geodesic Acoustic Modes in the T-10 tokamak

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Abstract. Geodesic acoustic mode (GAM) of electrostatic potential and density fluctuations are simultaneously measured by Heavy Ion Beam Probe (HIBP) and Correlation Reflectometry (CR). The regimes with Ohmic and electron cyclotron resonance heating (ECRH) were studied (\(B = 2.2\) T, \(I_p = 210 - 240\) kA, \(n_e = (2.3 - 3.7) \times 10^{19}\) m\(^{-3}\), \(P_{EC} < 0.6\) MW). GAMs are more pronounced 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. The local values of electric potential and density fluctuations show the significant coherency and constant phase shift at GAM frequency range. The existence of the long-distance (one quarter of the torus) correlations of core electric potential and density for GAM implying that GAM is a global mode, was shown for the first time in tokamaks.

1. Introduction

It is believed that the transport processes in the toroidal plasmas are dominated by the turbulence. The studies of the turbulent transport processes and the phenomena of the turbulence self-regulations like Zonal Flows (ZF) and Geodesic Acoustic Modes (GAMs) are of crucial importance to understand the physical picture of anomalous transport. It has been recently observed experimentally the correlation between GAM and high frequency turbulence, unless the level of the modulation was not found to be high [1-3]. The correlation properties of GAMs are important issues in the transport and turbulence studies. The most direct and powerful tool to study GAM in the core plasmas is HIBP [4], which is routinely used in T-10 for both mean potential profiles and oscillations [5]. It has been recently shown by HIBP that GAM poloidal mode number \(m = 0\) [6]. The first experimental characterization of the correlation properties of ZF in stellarator plasma was done with dual HIBP in CHS [7].

The paper is dedicated to the first result of the core correlation measurements of the GAM oscillations made by different diagnostics in a tokamak. It reports the characterization of the GAMs on T-10, the correlation between the local values of potential and density, and the long-distance potential/density correlation.

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2. Experimental set-up

Geodesic acoustic modes (GAM) were investigated in the T-10 tokamak using Heavy Ion Beam Probe (HIBP) [8, 9], Multipin Langmuir Probe (MLP) and Correlation Reflectometry (CR) [10] diagnostics. Regimes with Ohmic heating and with on- and off-axis ECR heating were studied ($B = 2.2$ T, $I_p = 210 - 240$ kA, $n_e = 2.3 - 3.7 \times 10^{19}$ m$^{-3}$). HIBP observed upper quadrant of the plasma column cross-section at the Low Field Side of the torus with radial position of Sample Volumes $r_{SV}$, varying as wide as $16 < r_{SV} < 30$ cm. One CR antenna was located at the High Field Side of the same cross section as HIBP, another one has a toroidal shift of one quarter of the torus at the Low Field Side. This layout was focused to the future study of the spatial mode structure of GAM.

3. Experimental results

3.1. GAM observation

HIBP is a powerful diagnostics to study GAMs in various toroidal devices [11]. It is able to get simultaneously the oscillatory components of two parameters: plasma electric potential $\phi$ by the energy of secondary ions and electron density $n_e$ by total secondary beam current, $I_t$, the latter works, if the beam attenuation does not affect the signal (path integral effect) [12, 13]. This is the case of low density, which was studied here. It was shown that the GAMs are more pronounced in the plasma potential rather than in density, as presented in figure 1. Figure shows the potential and density power spectra, obtained by HIBP at the same time. It is clearly seen that GAM peak dominates the potential spectra, while MHD $m=2$ mode peak dominates the density spectra. Note that the GAM peak has dual structure, the lower frequency main peak and the higher frequency satellite, which is very typical for T-10 [2, 10].

![Figure 1. Power density spectra measured by HIBP for potential $\phi$ and total current $I_t$ (or $n_e$) in discharge with ECRH. GAMs are more pronounced on the potential than on the density. In contrast, the amplitude of 7 kHz MHD $m=2$ mode oscillations is larger on the density and much smaller on the potential.](image)

3.2. GAM intermittent character in OH and ECRH plasmas

Earlier observation had shown that the GAM frequency increases with $T_e$ after the switching on the ECRH according to the GAM frequency scaling [14]. The recent experiments in OH regimes with auxiliary ECR heating shows that GAM might have a complex structure, not similar to harmonic oscillations with a single frequency. The wavelet spectrogram, presented in figure 2 (a) shows that GAM has an intermittent character presenting the stochastic sequence of the wave packages. Note that this feature holds for both the main GAM peak and the higher frequency satellite.
Figure 2 (a) Wavelet spectrogram for HIBP potential $\phi$.

Figure 2 (b) Example of the GAM intermittent behaviour for ECR heated plasma

Figure 3. Local potential-density correlation. HIBP shows the high correlation at the GAM frequency range and the permanent cross-phase. For 7 kHz MHD mode $m=2$, the cross-phase differs from that of GAM. #44166, $B=2.2$ T, $E_{\text{beam}} = 210$ keV, $r_{SV} = 22.1$ cm.

For the considered T-10 experimental conditions the “lifetime” of the package lies in a range of 0.5–2 ms. This data shows that, the wavelet analysis used to be the most direct data processing tool to study the GAM properties. Figure 2 shows that in comparison with OH plasma, GAMs are more pronounced in ECRH plasmas, where the typical frequencies of the wave packages are observed in a narrow interval from 20-30 kHz at the outer one third of the plasma minor radius, as shown in figure 2 (a, b).

3.3. GAM potential-density cross-phase. Local HIBP correlations

Fourier coherence analysis with long time series (> 200 ms) shows clear coherence between local values of potential and density simultaneously measured by HIBP at the sample volume. The phase shift is found to be $\pi/2$ for GAMs in the presented example. In contrast, figure 3 shows that for MHD $m=2$ peak the phase shift is zero. Fourier coherence analysis with short time series (10 ms) shows the constant frequency and a bursty character of the coherence between HIBP potential and density at the GAM frequency, figure 4.
Figure 4. Fourier spectrogram for local HIBP potential-density coherency. Example of the GAM intermittent behaviour for Ohmic heated plasma. GAM frequency is around 20 kHz. MHD \(m=2\) mode frequency is 7 kHz. \(B=2.2\) T, \(E_{\text{beam}} = 250\) keV, \(r_{SV} = 16.1\) cm.

Figure 5. Time evolution of the cross-phase for local HIBP potential-density correlation, shown in figure 4. The threshold coherency \(\text{coh}_t = 0.3\). If coherency > 0.3, the cross-phase is marked in colors, if coherency <0.3, the cross-phase is marked in green (zero).

The cross-phase between potential and density presents generally stochastic behavior over the observed frequency range. However, for quasicoherent modes, like MHD \(m=2\) mode and GAMs the cross-phase is more systematic, see figure 5. To make the figure more clear and free from stochastic component, the only phase, which corresponds to the coherency exceeding some limit is presented with its color. For the lower coherency the cross-phase was marked as zero (green color in figure 5). To analyze the cross-phase for GAM, the histogram was made for the values, exceeding the threshold coherency \(\text{coh}\). The result is shown in figure 6. The histogram method gives the same value as the long time series, as shown in figures 3 and 6.
Figure 6. The examples of the cross-phase histogram for data taken from figures 4 and 5. The most frequent value for GAMs is $\pi/2$. (a) $t = 760-780$, (b) $t = 920-940$ ms.

Figure 7. Long-distance potential-density coherency between HIBP and CR. #43285. $B=2.2$ T, $E_{\text{beam}} = 250$ keV, $r_{SV} = 25\pm0.5$ cm.

3.4. GAM potential-density cross-phase. Global HIBP-CR correlations

To study the long-distance correlations the following experiment was performed: both HIBP and CR were located at the same fixed radial position. Fourier correlation analysis with long time series (>200 ms) reliably shows a clear correlation between HIBP potential and CR density at the GAM frequency, see figure 7. This observation suggests a global character of the GAMs.

Fourier correlation analysis with short time series (4 ms) shows the constant frequency and a bursty character of the correlation between HIBP potential and CR density at the GAM frequency, figure 8. To study the radial range of the long-distance correlations the following experiment was performed: HIBP was located at the fixed position, while CR observation are (reflection layer) varied during a shot with the decay of the local density, presented in figure 9 (a) at 500 ms < $t$ < 1000 ms. Figure 9 (b) shows the reliable existence of the correlation between the HIBP potential and CR density at the GAM frequency during all the shot. The coherency remains almost unchanged around 1 cm radial variation of CR, while HIBP position was 1 cm shifted outwards. This observation shows that the radial correlation length for GAM is higher than 2 cm. This agrees with our earlier CR estimation of $k_r = 3-5$ cm [2] and more recent observations of the large radial extend of the GAM [15].
Figure 8. Time evolution of long-distance potential-density correlations. HIBP versus CR.

Figure 9. Radial evolution of the long-distance potential-density correlations. (a) Time trace of the central chord line-averaged density evolution in the OH discharge. (b) Potential-density correlation for different radii for one shot, HIBP versus CR. Top box: evolution of line-averaged density. Middle box: corresponding evolution of the CR observation radius. Bottom box: potential-density coherency. Density in this figure is normalized to the radius of vacuum chamber. Actual density should be enhanced by factor 4/3. HIBP radial position is $r_{SV} = 25 \pm 0.5$ cm.
4. Summary
GAM correlation study was performed by HIBP and CR. It shows that GAM is mainly manifested in
the plasma potential and much less pronounced on the plasma density fluctuations. GAM has an
intermittent character in amplitude and frequency, potential and density presents high correlations with
a constant phase shift for GAMs. The existence of the long-distance correlations for GAM was shown
for the first time in the core tokamak plasmas. This suggests that GAM is a global mode. Radial
correlation length for GAM has a range of a few cm at least.

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