Measurement of geodesic acoustic modes and the turbulent particle flux in the T-10 tokamak plasmas

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Abstract. Geodesic acoustic modes (GAMs) and the turbulent particle flux were studied in the T-10 tokamak in discharges with Ohmic (OH) and electron cyclotron heating (ECRH). The broadband oscillations of electric potential and density with frequencies up to 250 kHz were measured using a heavy ion beam probe (HIBP) in the plasma core. At the plasma edge, at a relative radius \( r > 0.8 \), the dominant GAM peak with a frequency of approximately 20 kHz and the noticeable peak of quasicoherent oscillations in the 40–100 kHz range were observed. Using a multislit energy analyzer, we estimate the poloidal electric field \( E_{pol} \) and the radial electrostatic turbulent particle flux, which is driven by drift in crossed \( E \times B \) fields. The GAM peak was observed in the spectrum of potential oscillations, but it was practically absent in the spectrum of \( E_{pol} \) oscillations and in the frequency-resolved particle flux. However, the flux was observed in the broadband range. These results agree with the theoretical concept of GAM and our earlier measurements of symmetric poloidal structure of GAM potential perturbations.

1. Introduction

Zonal flows (ZF) and their high-frequency counterpart, the geodesic acoustic modes (GAMs), are considered as a possible mechanism of the high-temperature plasma turbulence self-stabilization [1]. Therefore, ZFs and GAMs have been intensively studied in many fusion devices, see review [2]. According to modern theoretical concepts, turbulent transport has a complicated structure caused by the interplay of fine-scale turbulence (e.g., ITG, TEM and other modes) via middle-scale turbulence (ZF and GAM) with global events (e.g., L-H transitions) [3]. The experiments and theory show that GAMs convert the radial turbulent flux, which exhausts the plasma energy to the wall, into the torsional oscillations of potential [4], which do not transfer energy to the wall. GAMs are driven by the broadband turbulence, and after its depletion, GAMs are saturated and die from ‘starvation’. So, GAMs have an oscillating character, and their interplay with turbulence is dubbed as ‘prey-predator’.

The radial turbulent particle flux \( \Gamma_r \) is a product of density \( n_e \) and radial velocity \( V_r \) oscillations, which are averaged over some frequency domain:

\[
\Gamma_r = \langle \tilde{n}_e \cdot \tilde{V}_r \rangle.
\]

In turn, \( V_r \) is driven by the \( E \times B \) drift that is linked to the poloidal electric field \( E_{pol} \) and toroidal magnetic field \( B_t \) as follows:

\[
\tilde{V}_r = \tilde{E}_{pol} / B_t.
\]

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The paper presents first measurements of the GAM dynamics together with the radial turbulent particle flux at the T-10 tokamak. These measurements are possible only in the core plasma using a unique diagnostic tool, a heavy ion beam probe (HIBP).

2. Experimental setup
Experiments were performed in the T-10 tokamak (major and minor radii are \( R = 1.5 \) m and \( a = 0.3 \) m, respectively, toroidal magnetic field is \( B_t = 1.6-2.4 \) T, plasma current is \( I_p = 0.15-0.3 \) MA, line-average plasma density is \( n_e = (0.6-5) \times 10^{19} \) m\(^{-3}\). The shots with Ohmic and electron cyclotron resonance heating (ECRH), with a power \( P_{EC} = 0.5 \) MW were studied.

The T-10 tokamak is equipped with a multichannel heavy ion beam probe (HIBP) [5], which measures the oscillating components of density \( n_e \) and potential \( \varphi \) in a wide radial interval, \(+0.2 < \rho < 1\), where \( \rho = r/a \). HIBP operates as follows. The primary beam of \( \text{Tl}^+ \) ions with the energy \( E_{b1} = 200-300 \) keV is injected into the plasma at an entrance angle \( \alpha \) and moves along the Larmor orbit. At some point (sample volume or \( SV \)), the \( \text{Tl}^+ \) ions are ionized, and the secondary current \( I_{tot} \) of \( \text{Tl}^{++} \) ions with the energy \( E_{b2} \) moves along another orbit and reaches the energy analyzer. The local potential in \( SV \) is equal to the energy difference: \( \varphi = E_{b2} - E_{b1} \), while the local density is proportional to \( I_{tot} \). To estimate the absolute level of density fluctuations, we need to calibrate \( I_{tot} \) using the interferometer data. The T-10 energy analyzer has 5 entrance slits. Now, we use the lateral and central slits, which are denoted as \( S_1 \), \( S_2 \) and \( S_3 \). Each slit observes its SV. The SV position depends on \( E_{b1}, \alpha, B_t \), and device geometry. The set of \( SVs \) forms the detector grid. A sketch of the experiment and the points of detector grid are shown in figures 1 and 2, respectively. If we measure the potentials in \( SVs \) that are observed by slits \( S_1 \) and \( S_3 \), which are located at the same flux surface at a distance \( \Delta x \), then, \( E_{pol} = (\varphi_1 - \varphi_3) / \Delta x \). In reality, the line \( S_1-S_3 \) does not coincide with the flux surface. Thus, apart from \( E_{pol} \), we measure the radial component \( E_r \). Therefore, we try to choose such position of \( SVs \), where \( E_{pol} \gg E_r \).

3. Experimental results
After processing the HIBP signals in the frequency range of less than the Nyquist frequency, \( f_N \sim 250 \) kHz, we find their Fourier-transforms or power spectral densities PSD for \( \tilde{n}_y \) and \( \tilde{V}_r \), their coherence \( \text{coh}(\tilde{n}_y, \tilde{V}_r) \), cross-phase, \( \theta = \text{Arg}(F_n, F_r) \), (* means the complex conjugate), cross-spectral...
density \( CSD(\tilde{n}_e, \tilde{V}_r) \), flux spectral function \( \text{Re}CSD(\tilde{n}_e, \tilde{V}_r) \) and the total frequency-averaged particle flux.

\[
\Gamma(t) = \langle 1/f \rangle \int_{f_1}^{f_2} \text{Re}(F_{n_e}(f,t) \cdot F_{V_r}(f,t)) df
\]  

(3)

Figure 3 presents PSD for the potential \( \phi_1 \) (a), electric field \( E_{pol} \sim \phi_1 - \phi_2 \) (b) and the spectral function of flux (c) fluctuations measured at \( \rho = 0.57 \). At this radius, the high-frequency broadband turbulence is absent. Therefore, we show only the low-frequency part \( (f < 60 \text{ kHz}) \) of the spectra. The GAM peak, which is marked by a black rectangle, is visible on the spectrum of potential, but it is practically absent on the spectrograms of \( E_{pol} \) and the flux. Note that at \( t > 650 \text{ ms} \), the large-scale instabilities are seen on the density (c) and all HIBP signals.

For the quasicoherent (QC) oscillations \( (100 < f < 170 \text{ kHz}) \), the coherence between \( E_{pol} \) and density \( n_e \) is rather high, \( coh > 0.6 \), the phase between \( E_{pol} \) and \( n_e \) is \( \theta \sim 1.5\text{–}3 \text{ rad} \) and increases with frequency. Thus, the intense flux, which is directed outward, is observed for QC, figure 4. In this shot, we also see the weak flux in the GAM frequency range [6]. For this shot, we estimated the root mean square of \( E_{pol} \), \( \text{RMS}(\phi_1, \phi_2) = 13 \text{ V} \), RMS of the flux

\[
\langle \tilde{\phi}_1 - \tilde{\phi}_2 \rangle \cdot \frac{I_{pol}}{I_{tot}} = \frac{\Gamma_x B \Delta x}{n_e} \approx 0.05 \text{ B},
\]  

where \( n_e(\rho = 0.78) = 2.3 \times 10^{19} \text{ m}^{-3} \). Therefore, the total specific flux averaged over the QC frequency range is \( \Gamma_x(0.78) \lesssim 4 \times 10^{16} \text{ m}^2 \text{ s}^{-1} \). The HIBP measurement for a similar shot gives \( \Gamma_x(\rho = 0.87) \lesssim 2 \times 10^{20} \text{ m}^{-2} \text{ s}^{-1} \), while the Langmuir probe in a different regime gives \( \Gamma_x(\rho = 1) \lesssim 2 \times 10^{20} \text{ m}^{-2} \text{ s}^{-1} \) [7], i.e., the flux increases with radius. If we suppose the poloidal and toroidal homogeneity of the flux, and multiply \( \Gamma_x(0.87) \) by the lateral surface of T-10, \( S = 2\pi R^2 \), we
obtain the total outflow \( Q_r = 3 \times 10^{21} \text{ s}^{-1} \), which is comparable with the total particle influx, or the Mukhovatov number \( N_M = (2.5–3) \times 10^{21} \text{ s}^{-1} \) [8].

4. Conclusions
Using HIBP with a multislit analyzer, we performed the first simultaneous measurements of the potential, electric field and density oscillations at the core and edge of tokamak plasmas, and their correlations. We estimate that the radial turbulent particle flux is driven by the \( E \times B \) drift. The absence of flux in the GAM frequency range agrees with a theoretical concept of GAM, as the high-frequency branch of zonal flow with a symmetrical poloidal structure of potential perturbations [1], and with our previous measurements of the poloidal mode number \( m = 0 \) for GAM [9, 10]. The broadband quasicoherent turbulence of plasma forms a considerable part of the total particle outflow.

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