STUDY OF GAMS AND RELATED TURBULENT PARTICLE FLUX WITH HIBP IN THE T-10 TOKAMAK

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The new findings in the behavior of geodesic acoustic modes (GAMs) and turbulent particle flux dynamics on the T-10 tokamak are presented. For the first time in T-10 the broadband oscillations ($\le$250 kHz) of electric potential and density in Ohmic and ECRH regimes (B_t = 1.6…2.4 T, I_{pl} = 0.15…0.3 MA, $\bar{n}_e = (0.6…5)\times10^{19}$ m^{-3}) were measured by Heavy Ion Beam Probe (HIBP) in the core plasmas. At the periphery, at r/a > 0.8, the dominated GAM peak with frequency ~ 14 kHz and noticeable peak of quasi-coherent oscillations in the frequency band 40…100 kHz were observed. The multichannel HIBP measurements were performed to measure poloidal electric field E_{pol} and to retrieve the electrostatic turbulent radial particle flux driven by $E\times B$ drift. The preliminary experiment shows that in contrast to the power spectral density of plasma potentials, GAM peak was almost invisible in the E_{pol} power spectrum and on the frequency resolved turbulent particle flux. These results are consistent with the general concept of GAM as a high-frequency branch of zonal flows, having symmetric poloidal structure of potential perturbation, which were supported by earlier observation of poloidal mode number m=0 in T-10.

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INTRODUCTION

Geodesic acoustic modes (GAMs) are the high-frequency branch of zonal flows in toroidal fusion devices. GAMs are actively studied in tokamaks and stellarators as one of possible mechanisms of the plasma turbulence self-regulation by the oscillating radial electric field [1]. GAMs should transform the radial turbulent oscillations, which transfer the energy of plasma turbulence, into the torsional plasma oscillations, which do not transmit the energy radially. The linear theory predicts that the poloidal mode number for GAM potential oscillations is m=0 [2]. Due to this poloidal symmetry, a poloidal component of electric field E_{pol} is expected to be zero for GAMs. Therefore, the radial turbulent particle flux should also be zero at the GAM frequency. However, this theoretical expectation was not yet validated experimentally in the core plasma. The presented report contains the preliminary results of such validation.

1. EXPERIMENTAL SETUP

The GAM oscillations are systematically studied at the circular T-10 tokamak (R = 1.5 m, a = 0.3 m, B_t = 1.5…2.5 T, I_{pl} = 0.15…0.3 MA) using heavy ion beam probing (HIBP) [3, 4]. HIBP is a direct diagnostic for studying the electric potential φ and its oscillations. GAMs are typically observed very clearly as a pronounced monochromatic peak in the frequency power spectra of potential. This diagnostic has an important ability to for study plasma potential oscillations and, specifically, the GAM characteristics in the core region, which is inaccessible for Langmuir probes, which typically used to investigate potential oscillations and the GAM at the edge [5]. Basic principles of HIBP measurements of plasma parameters in T-10 were described in [6]. We use the ions Tl$^+$ with energy E_b up to 280 keV. Varying the beam energy and entrance angle into the plasma, we can spatially scan the sample volume (SV) and form the detector grid: the observation area in plasma. For the registration of the secondary beam I_t we used the energy analyzer with five entrance slits Fig. 1 in [7]. The each slit provides the spatial resolution < 1-2 cm, and the temporal resolution <5 μs in the radial range 6 < r < 30 cm for B_t < 2.1 T. This analyzer allows us to carry out simultaneous measurements in few (up to 5) neighbor SV. The magnetic flux surfaces in poloidal cross-section of T-10 are circular. The adjustment procedure can be performed to get the location of SVs as close as possible to desired magnetic flux surfaces that allows us to estimate the local poloidal electric field

$$E_{pol} = (\varphi_i - \varphi_j)/\delta x, \tag{1}$$

where $\delta x \sim 1$ cm, i, j = 1...5, i ≠ j. This limits the poloidal wave vector, $k_\theta < 3$ cm^{-1}. The radial $E\times B$ drift velocity is

$$V_r = E_{pol}/B_t. \tag{2}$$

The turbulent particle flux is defined as

$$\Gamma_{E\times B}(t) = \tilde{n}_e \tilde{V}_r = 1/B_t\ \tilde{n}_e(t)\ \tilde{E}_{pol}(t). \tag{3}$$

To analyze the frequency structure of the flux, we use the flux spectral function [8]:

$$\Gamma_{E\times B}(f,t) = -2/B_t \cdot \mathrm{Re}(S_{n\,Epol}(f,t)), \tag{4}$$

where $\mathrm{Re}(S_{n\,Epol}(f,t))$ is a real part of the complex Fourier power cross-spectral density (CSD) for plasma density and E_{pol}.

To measure $\Gamma_{E\times B}(t)$, the density fluctuations $\tilde{n}_e$ should be obtained simultaneously at the same position as $\tilde{E}_{pol}$ that is provided by combined potential and beam current measurements with HIBP. For the analysis of the flux dynamics in arbitrary units, or for frequency

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spectra analysis, the relative data for density oscillations $\delta n_e(t)=\tilde{I}_t(t)/\overline{I_t}$ is sufficient. In the low-density case, for estimation of the absolute value of $\boldsymbol{\Gamma_{E\times B}}(t)$, $\tilde{n}_e$ may be replaced by $\tilde{I}_t(t)$. In the higher-density case, one should take into account the attenuation effect by the expression: $\tilde{n}_e=\tilde{I}_t/\overline{I_t}\cdot\overline{n}_e$, where oscillatory component $\tilde{I}_t/\overline{I_t}$ is measured by HIBP, and normalization factor $\bar{n}_e$ is provided by other diagnostics like interferometry. This way allows us to extract $\boldsymbol{\Gamma_{E\times B}}$ for the first time in the core plasma of T-10.

2. EXPERIMENTAL RESULTS

Fig. 1 shows the amplitude of GAM activity (over extended frequency domain covering GAM and satellite) obtained from difference of potentials between neighboring poloidally shifted sample volumes as function of radial difference between them. Figure shows that for Δr<1 cm (the beam diameter) the radial component E_r may be omitted, and the GAM amplitude is invisible on the noise background. When Δr increases, the role of E_r becomes more important, and the measured GAM amplitude grows.

Fig. 2 shows the time evolution of power spectral density (PSD) for potential oscillations measured at the central slit φ_3 (*a*); and PSD for difference of potentials oscillations between the central and edge slits φ_1 - φ_3, i.e. the electric field (*b*). The time evolution of the frequency resolved flux spectral function calculated as cross-spectral density (CSD) for difference of potentials φ_1 and φ_3 and density oscillations (eq. 4) is shown in (*c*). We see that GAM is clearly pronounced on the potential spectrum, but is not seen on *E* and so in the flux spectra.

Fig. 3,a shows the time evolution of spectral function of turbulent particle flux (4). The quasi-coherent (QC) modes are dominated on the spectrum. The total turbulent particle flux driven by QC modes is shown in Fig. 3,b. It is determined as follows:

$$\Gamma_{QC}(t)=-2/B_t\cdot\int_{f_1}^{f_2}\mathrm{Re}(S_{n\,Epol}(f,t))df\,, \qquad (5)$$

where f_1=100 kHz, f_2=175 kHz for the considered case.

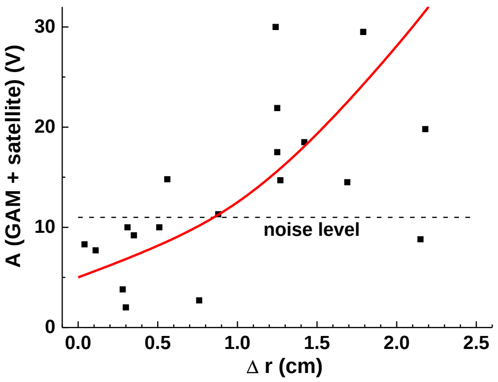

Fig. 1. Dependence of potential difference vs the distance between the sample volumes for GAM+satellite frequency domain

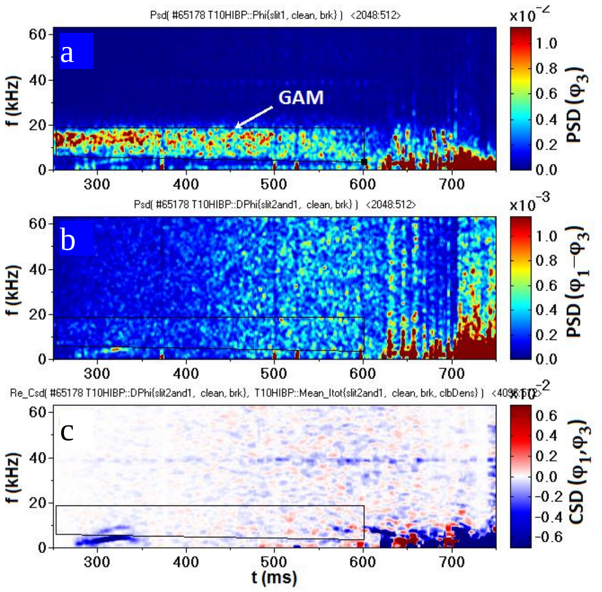

Fig. 2. Time evolution of: power spectral density (PSD) of potential oscillations measured by the central slit φ_3 (a); PSD for difference of potentials on central and edge slits (φ_1- φ_3) (b); the frequency resolved flux spectral function (c)

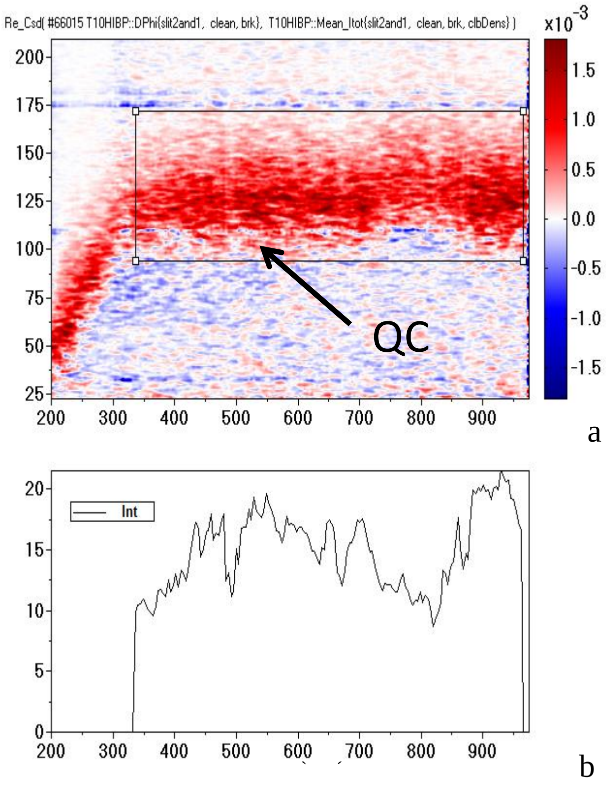

Fig. 3. Time evolution of: spectral function of turbulent particle flux (a); turbulent particle flux driven by quasicoherent (QC) modes (b)

The time-frequency domain for QC mode is shown in Fig. 3,a as a black rectangle. Figure shows that QC mode generates pronounced outward particle flux, contrary to GAM, which does not generate neither outward nor inward flux for the examined experimental conditions.

CONCLUSIONS

The multichannel energy analyzer makes the heavy ion beam probing an effective tool to study $\tilde{E}_{pol}$ up to 250 kHz. In combination with simultaneously measured density perturbation HIBP allows us to retrieve the electrostatic radial turbulent particle flux driven by $E\times B$ drift. The preliminary data shows that GAM-driven $\tilde{E}_{pol}$ oscillations happen to be below experimental accuracy, and could be considered as negligibly small for the regimes under study. Thus, one can conclude that in the GAM frequency range, the turbulent $E\times B$ particle flux is not observed. This experimental observation agrees with theoretical predictions [2] and with the previous results that GAMs in T-10 have the poloidal mode number $m = 0$ [7]. Note that the similar absence of the turbulent $E\times B$ particle flux for electrostatic modes was observed in the TJ-II stellarator [9].

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ИССЛЕДОВАНИЕ ГАМ И ТУРБУЛЕНТНОГО ПОТОКА С ПОМОЩЬЮ ПУЧКА ТЯЖЁЛЫХ ИОНОВ В ТОКАМАКЕ Т-10

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Представлены новые результаты исследований геодезических акустических мод (ГАМ) и турбулентного потока частиц на токамаке Т-10. Впервые на Т-10 в разрядах с омическим и ЭЦР-нагревом (B_t = 1,6…2,4 Тл, I_{pl} = 0,15…0,3 МА, $\bar{n}_e$ = (0,6…5)×10^{19} $м^{-3}$) в горячей зоне плазмы с помощью зондирования пучком тяжёлых ионов (ЗПТИ) измерены широкополосные колебания электрического потенциала и плотности с частотами до 250 кГц. На периферии, r/a > 0,8, наблюдался преобладающий пик ГАМ с частотой ~ 14 кГц и заметный пик квазикогерентных колебаний с частотами 40…100 кГц. Многоканальные ЗПТИ измерения позволили оценить полоидальное электрическое поле E_{pol} и найти радиальный электростатический турбулентный поток частиц, возбуждаемый $E\times B$ дрейфом. Предварительные эксперименты показали, что ГАМ пик виден на спектре колебаний потенциала, но практически не виден на спектре E_{pol} и на частотно разрешённом потоке частиц. Эти результаты согласуются с общей теоретической концепцией, что ГАМ – это высокочастотная ветвь зональных потоков с симметричной полоидальной структурой возмущений потенциала, а также с прежними наблюдениями полоидального модового числа m = 0.

ДОСЛІДЖЕННЯ ГАМ ТА ТУРБУЛЕНТНОГО ПОТОКА ЗА ДОПОМОГОЮ ПУЧКА ВАЖКИХ ІОНІВ У ТОКАМАЦІ Т-10

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Представлено нові результати досліджень геодезичних акустичних мод (ГАМ) і турбулентного потоку часток на токамаці Т-10. Вперше на Т-10 в розрядах з омічним і ЕЦР-нагрівом (B_t = 1,6…2,4 Тл, I_{pl} = 0,15...0,3 МА, $\bar{n}_e$ = (0,6…5)×10^{19} $м^{-3}$) у гарячій зоні плазми за допомогою зондування пучком важких іонів (ЗПВІ) виміряні широкосмугові коливання електричного потенціалу та щільності з частотами до 250 кГц. На периферії, r/a > 0,8, спостерігався переважаючий пік ГАМ з частотою ~ 14 кГц і помітний пік квазікогерентних коливань з частотами 40…100 кГц. Багатоканальні ЗПВІ виміри дозволили оцінити полоїдальне електричне поле E_{pol} і знайти радіальний електростатичний турбулентний потік часток, збуджуваний $E\times B$ дрейфом. Попередні експерименти показали, що ГАМ пік видно на спектрі коливань потенціалу, але практично не видно на спектрі E_{pol} і на частотно дозволеному потоці часток. Ці результати узгоджуються із загальною теоретичною концепцією, що ГАМ – це високочастотна гілка зональних потоків з симетричною полоїдальною структурою обурень потенціалу, а також з колишніми спостереженнями полоїдального модового числа m = 0.