Three dimensional measurements of Geodesic Acoustic Mode with correlation Doppler reflectometers

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ABSTRACT: Correlation Doppler reflectometers have been newly developed in the HL-2A Tokamak. Owing to the flexibility of the diagnostic arrangements, the multi-channel systems allow us to study, simultaneously, the radial properties of edge turbulence and its long-range correlation in both the poloidal and toroidal direction. With these reflectometers, three-dimensional spatial structure of Geodesic Acoustic Mode (GAM) is surveyed, including the symmetric feature of $E_r$ fluctuations in both poloidal and toroidal directions, and the radial propagation of GAMs. The bi-coherence analysis for the $E_r$ fluctuations suggests that the three-wave nonlinear interaction could be the mechanism for the generation of GAM. The temporal evolution of GAM during the plasma density modulation experiments has been studied. The results show that the collisional damping plays a role in suppressing the GAM magnitudes, and hence, weakening the regulating effects of GAM on ambient turbulence. Three dimensional correlation Doppler measurements of GAM activity demonstrate that the newly developed correlation Doppler reflectometers in HL-2A are powerful tools for edge turbulence studies with high reliability.

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1 Introduction

Doppler reflectometry was dedicated to measure the perpendicular rotation velocity of plasma turbulence and the density fluctuation simultaneously in magnetically confined plasmas [1–3]. Hence, this diagnostic can measure the radial electric field ($E_r$) and its fluctuations with high spatiotemporal resolution. Thus, it is a powerful tool for the study of Zonal flow, which has a $E_r$ perturbation radially localized in toroidal plasmas [4–6]. Because of the flexibility of the diagnostic arrangements, the spatiotemporal characteristics of Zonal flows were obtained in both L-mode and H-mode plasmas [7–10], even the spatial distribution of GAM in density fluctuation was evidenced by poloidal correlation reflectometry [11].

One of the main differences between conventional or radial reflectometry and Doppler reflectometry is the tilt angle of the launched microwave beam relative to the normal of the cut-off layer. The principle can be derived from the the energy and momentum conservation laws for coherent microwave scattering [3]. According to the Bragg selection condition, the scattered wave vector is $k_{\perp} = 2k_i \sin(\theta_s)$, where $k_i$ is the incident wave vector and $\theta_s$ is the tilt angle. If the turbulence moves in poloidal direction, a Doppler shift $f_D$ is induced in the frequency domain of the scattered wave and is determined by $f_D = V_\perp 2k_i \sin(\theta_s) / 2\pi$, where $V_\perp$ is the perpendicular velocity of turbulence. Then radial electric field $E_r$ can be revealed from $E_r = -V_{E_x B}$ ($B$ is the local magnetic field) by ignoring the phase velocity of the edge drift wave turbulence [7]. Hence, $E_r$ is proportional to the Doppler shift ($E_r = -\frac{2\pi f_D}{2k_i \sin(\theta_s)} B$). With the Doppler reflectometry, the mean and fluctuant $E_r$ can be measured routinely. In this paper, the diagnostic setup and data processing methods for $E_r$ fluctuations study will be introduced firstly. Then the investigation of GAM characteristics will be presented.

2 Diagnostic setup and data processing methods

Recently, the microwave reflectometers, especially the Doppler reflectometers have been developed in the HL-2A Tokamak [12], whose major and minor radius are $R = 1.65$ m and $a = 0.4$ m [13]. The
Figure 1. Characteristic frequencies on the equatorial plane for a HL-2A plasma with magnetic field 1.3 T and electron density profile $n_e(\rho) = 2 \times (1 - \rho^2)$: $L$ and $R$ wave frequencies ($f_L$ and $f_R$), electron cyclotron frequency ($f_{ce}$), plasma frequency ($f_{pe}$) and upper hybrid frequency ($f_{UH}$).

Multi-channel systems are dedicated to routinely measure the turbulence with high spatiotemporal resolution not only in the edge but also in the core of plasma. Figure 1 shows the characteristic frequencies on the equatorial plane for a HL-2A plasmas. For the study of GAMs in low magnetic field ($B_t = 1.3$ T) plasma, the frequency $f_R$ is used for extraordinary mode (X-mode) measurement of Doppler reflectometer.

Figure 2 illustrates the schematic diagram of the Doppler reflectometer, which is a homodyne system. Each multi-channel system has four microwave frequencies with the spacing of 2 GHz. The microwave is generated from a novel filter-based feedback loop microwave source, which has low phase noise [14]. And the four frequencies are combined in a low insertion loss multiplexer ($< 2$ dB). The combined microwave with output power $> +15$ dBm is launched into the target plasma. Then, the four filtered waves from the power divider are separately demodulated with the reference waves in the microwave I/Q mixers.

For the study of GAM in the typical discharge with low toroidal magnetic field ($B_t = 1.3$ T), the X-mode polarization is set for the multi-channel Doppler reflectometers with launching frequencies of 32, 34, 36 and 38 GHz. The sensitive perpendicular wave-number of the density fluctuation is predicted by ray tracing calculation, and the density profile is measured by the frequency modulated continuous wave reflectometry [15]. Here, two different electron density profiles are used for the ray tracing calculation as figure 3a shown. The corresponding wave-number is in the range of $k_\perp \sim 3.5 - 5.5$ cm$^{-1}$ as shown in figure 3b. In HL-2A, there are several ports available for the arrangement of Doppler reflectometers in different poloidal and toroidal locations. Figure 4a shows the poloidal arrangement of two systems, both can operate as extraordinary mode (X-mode) and ordinary mode (O-mode) polarization.
Figure 2. A schematic diagram of the multi-channel Doppler reflectometer system on HL-2A.

Figure 3. Wave-number sensitivities of the multi-channel Doppler reflectometer in the cases of different electron density profiles. (a) two different electron density profiles (labelled as A and B) used for the ray tracing calculation of the perpendicular wave-number $k_{\perp}$, (b) the probed $k_{\perp}$ and locations of the Doppler reflectometer with X-mode (32, 34, 36, and 38 GHz) polarization in the cases of two density profiles (A and B as shown in left figure), the specified color of each symbol represents the electron density at the backscattering location of each probing microwave.
As mentioned above, $E_r$ is proportional to the Doppler frequency shift $f_D$. Generally, the time evolution of $f_D$ is extracted by the Centre of Gravity (CoG) of a double-sided Doppler spectrum, which is given by a sliding Fast Fourier Transform (FFT) of the complex amplitude signal from the I/Q detector [7]. It is derived by $f_D(t) = \frac{\int f S(f) \, df}{\int |S(f)|^2 \, df}$. Another commonly used method is to estimate the instantaneous frequency from a phase derivative (the phase is obtained by $\phi(t) = \tan^{-1}\left\{ \frac{Q(t)}{I(t)} \right\}$ from the In-phase ($I = A \cos \phi$) and Quadrature ($Q = A \sin \phi$) fluctuation signals). It is given by $f_D(t) = \frac{1}{2\pi} \frac{d\phi}{dt} = \frac{1}{2\pi} \frac{\phi(t+\Delta t) - \phi(t)}{\Delta t}$. In CoG method, the equivalent sampling frequency of $f_D$ is determined by the interval of two sliding FFT realizations. While, it is determined by $\Delta t$ in the method of phase derivative. Figure 4 shows the compared $f_D(t)$ by using these two methods. The radial position of the measurement is about 4 cm inside the LCFS. Here, an Ohmic discharge is selected. Main plasma parameters of the discharge: the toroidal magnetic field is $B_t = 1.3$ T, the plasma current is $I_p = 150$ kA, the line averaged electron density is $n_{e,l} = 0.8 \times 10^{19}$ m$^{-3}$. Two $f_D$ curves in figure 4b show the small difference mainly caused by the different equivalent sampling frequencies. The phase derivative method costs less calculation time than that of the FFT based CoG method. However, the difference does not affect the analysis of $E_r$ fluctuation. As shown in figure 4c, the cross-power spectra of two poloidal Doppler signals with same sampling frequencies. The phase derivative method costs less calculation time than that of the FFT based CoG method. However, the difference does not affect the analysis of $E_r$ fluctuation. Two poloidal separations are about 30 cm. There are artificial higher frequency components ($30 - 50$ kHz) in the spectrum from phase derivative method, which could be induced by the zero order of the reflected signal as discussed in ref. [16]. A coherent peak of 12 kHz is observed from the spectra. The mode frequency is close to the geodesic acoustic frequency $\omega_{\text{GAM}} = \sqrt{2(T_e + 7T_i/4)/M_i/R}$, suggesting that it is a GAM oscillation, which was usually observed by electrostatic probes in HL-2A edge plasma region. The demonstration and characteristics of GAM will be presented in next section.

3 Characteristics of GAM

3.1 Spatial structure

With poloidally and toroidally equipped Doppler reflectometers in HL-2A, the long range correlation measurements for $E_r$ fluctuations can be realized. Figure 5a and 5b shows the poloidal and toroidal cross-power and cross-phase spectra of $E_r$ fluctuations. The distance between two poloidally separated ports is about 30 cm. In toroidal direction, the distance is about 150 cm. Two cross-power spectra in figure 5a show clear coherent peaks ($f \simeq 12$ kHz). Corresponding to the frequencies of the peaks, the phase shifts (figure 5b) in both poloidal and toroidal directions are near zero, demonstrating the two dimensional symmetry feature ($m = 0$ and $n = 0$) of GAM appeared in the fluctuation component of $E_r$.

Figure 5c is the squared auto-bicoherence of the $f_D$ fluctuations. It is calculated by $b^2(f_1, f_2) = \frac{\langle \hat{X}(f_1) \hat{X}(f_2) \hat{\chi}^*(f_1+f_2) \rangle^2}{\langle |\hat{X}(f_1) \hat{X}(f_2)|^2 \rangle \langle |\hat{X}(f_1+f_2)|^2 \rangle}$, where $\hat{X}(f)$ is the Fourier transform of the $f_D$ and $\hat{\chi}^*(f)$ is the complex conjugate. The angular bracket represents the ensemble average. The squared bi-coherence $b^2(f_1, f_2)$ is an indicator for the strength of nonlinear coupling of three wave at $f_1$, $f_2$ and $f_1 + f_2$ [17]. There are three noticeable peaks with higher values of $b^2(f_1, f_2)$ are shown in figure 5c, the frequency $f_1 + f_2 = 12$ kHz and $f_2 = \pm 12$ kHz is corresponding to GAM frequency in figure 5a, suggesting that the nonlinear interaction is responsible for the generation of the GAM.
Figure 4. (a) Poloidal arrangement of Doppler reflectometers in the HL-2A tokamak. Two ports (A and B) are used for X-mode measurements in this paper, (b) time traces of the $f_D$ estimated by CoG and phase derivative methods, (c) cross-power spectra of the $f_D$ signals between two poloidally separated ports.

Figure 5. (a) Poloidal and toroidal cross-power spectra of $E_r$ fluctuations between two separated ports, (b) and corresponding cross-phase spectra, (c) squared bi-coherence spectrum of the $f_D$ fluctuations plotted in the $f_1 - f_2$ plane.
In additional to the symmetry property of GAM structure in both poloidal and toroidal directions, its radial characteristics are also described by radially separated measurements of multi-channel Doppler reflectometers. Figure 6 shows the wave-number spectrogram $S(k_r, f)$ obtained from 36 GHz and 38 GHz channel of the Doppler reflectometry. The radial separation is 1 cm. A noticeable peak, which corresponds to the GAM, is clearly observed. The spectral-averaged wave-number can be estimated by $k_r(f = f_{GAM}) = \sum k_r S(k_r | f = f_{GAM})$, here the $S(k_r | f = f_{GAM})$ is the conditional wave-number spectral density. For the GAM in figure 6, $k_r$ is 0.68 cm$^{-1}$. The positive value of the wave-number indicates a radial outward phase velocity of the GAM oscillation.

3.2 Collisional damping

Theoretical work predicted that the GAM would be strongly damped at high collisional plasmas owing to the collisional damping mechanism. The collisional damping rate of GAM intensity is proportional to the ion-ion collisional frequency $\gamma_{damp} \sim v_{ii}$ [18].

Experimentally, the collisionality can be increased by increasing the ion density and/or decreasing the ion temperature. This requirement is met by plasma fueling method, such as gas puff. As figure 7a shown, the modulated fuelling by gas puff is carried out in HL-2A. The measurement location of Doppler reflectometer is about 4 cm inside the LCFS. Owing to the X-mode polarization, the radial movement of the measurement position is less than 1 cm. Figure 7b is the Doppler spectrogram. Preliminary, both the turbulence poloidal velocity and intensity is modulated by the gas puff. Figure 7c is the spectrogram of $E_r$ fluctuations obtained from Doppler reflectometer. The noticeable mode is the GAM. Obviously, the GAM intensity (figure 7d) is also modulated by gas puff. The fueling increases the collisionality. Then the GAM intensity is reduced. In return, the stronger GAM is accompanied by the decreased collisionality. The result suggests that the collisional damping is responsible for the decrease of the GAM intensity. The modulated GAM intensity is inversely correlated with the turbulence intensity as figure 7e shown, suggesting that the GAM has the regulating effect on turbulence.
Figure 7. Collisonal damping for GAM. (a) gas puff monitor, (b) Doppler spectrogram, (c) spectrogram of $E_r$ fluctuations, (d) GAM intensity and (e) turbulence intensity obtained from Doppler reflectometer.

4 Conclusion

Recently, several correlation Doppler reflectometers have been newly developed in the HL-2A Tokamak. The multi-channel systems allow studying radial properties of edge turbulence and its long range correlations in both poloidal and toroidal directions, simultaneously. Specifically, the non disturbing diagnostic is used to routinely measure the perpendicular rotation velocity of turbulence and the density fluctuations with high spatial resolution. For the extraction of $E_r$ fluctuations from the Doppler reflectometry signal, two data processing methods (CoG and phase derivative) are introduced and compared. With these reflectometers, three dimensional spatial structure of GAM zonal flow is characterized, including the symmetry feature of poloidal and toroidal $E_r$ fluctuations, and the radial propagation of GAM. The advanced bi-coherence analysis suggests that the three wave nonlinear interaction would be the mechanism for the generation of GAM. The temporal behaviors of GAM during gas puff modulation experiments are investigated, which suggests that the collisional damping plays a role in suppressing the GAM oscillation level, and hence, weakening the regulating effects of GAM on ambient turbulence.

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