Measurement of Radial Structure of Energetic-Ion-Driven MHD Modes with a Fast Response Hα-Detector Array in the Large Helical Device

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In the Large Helical Device, coherent fluctuations related to energetic-ion-driven magneto-hydrodynamic (MHD) instabilities such as Alfvén eigenmodes (AEs) were detected for the first time using an Hα detector array having high-frequency response up to 200 kHz. Correlation analysis between detector and magnetic probe signals has enabled us to successfully extract coherent fluctuations in the AE frequency range. The radial profile of the excess of the coherence from the background value ($\Delta\gamma$) has a clear peak around the predicted toroidal Alfvén eigenmode (TAE) gap.

Keywords: Alfvén eigenmode (AE), fast-response Hα detector, correlation analysis, radial structure, TAE

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Good confinement of fusion-born alpha particles is a crucial issue for the realization of a nuclear fusion reactor [1]. In the course of their slowing down, magneto-hydrodynamic (MHD) instabilities such as Alfvén eigenmodes (AEs) [2] and energetic particle modes (EPMs) [3] may be excited by these energetic ions. These instabilities might induce anomalous transport of energetic ions. Measurement of the radial structure of these instabilities is very important to understand and control anomalous transport of energetic ions induced by them. So far, some advanced fluctuation diagnostic tools have succeeded in obtaining the spatial structure of energetic-ion-driven MHD modes, for instance, electron cyclotron emission (ECE) [4], microwave reflectometry [5], and beam emission spectroscopy [6]. Recently, in the Large Helical Device (LHD), we have succeeded in detecting energetic-ion-driven MHD instabilities with an Hα detector array—a conventional and simple diagnostic tool—having high-frequency response up to 200 kHz. This diagnostic tool has the potential to obtain the radial structure of these MHD modes.

LHD is typically operated at a toroidal field magnitude (B_t) of 0.42 to 2.9 T and a magnetic axis position of vacuum field (R_{ax}) of 3.5 to 4.0 m. The LHD plasmas are heated using three tangential neutral beam (NB) injectors of which beam energy is up to 180 keV. In NB-heated LHD plasmas, toroidal Alfvèn eigenmodes (TAEs) and EPMs are excited typically under the conditions of $B_t \leq 1.5$ T and line-averaged electron density $n_e \leq 3\times10^{19}$ m^{-3} [7, 8].

The Hα emission (ε_α) in a plasma with energetic ions will be the sum of the excitations by electrons ($\varepsilon_{\alpha e}$) and that by energetic ions ($\varepsilon_{\alpha\text{fast}}$), because the energetic ion velocity is comparable to the electron thermal velocity:

$$\varepsilon_\alpha = \varepsilon_{\alpha e} + \varepsilon_{\alpha\text{fast}}, \tag{1}$$

$$\varepsilon_{\alpha e} \cong (n_{\text{n-cold}} + n_{\text{n-fast}})n_e \langle \sigma_{ex} v_e \rangle, \tag{2}$$

$$\varepsilon_{\alpha\text{-fast}} \cong n_{\text{n-cold}} \int \sigma_{ex}(v_{\text{i-fast}})v_{\text{i-fast}} f(v_{\text{i-fast}})dv_{\text{i-fast}} + n_{\text{n-fast}} \int \sigma_{ex}(\Delta v)\Delta v f(v_{\text{i-fast}})dv_{\text{i-fast}}. \tag{3}$$

The first term on right-hand side of Eq. (3) corresponds to the excitation of cold neutrals by energetic ions and the second term to the excitation of energetic neutrals by energetic ions. Here, n is particle density, v is particle velocity, and $\langle \sigma_{ex} v_e \rangle$ is electron-impact excitation rate coefficient averaged over the Maxwell distribution function. Moreover, Δv denotes the relative velocity of energetic ions with respect to energetic neutrals. Note that the velocity distribution function of energetic ions $f(v_{\text{i-fast}})$ is not necessarily Maxwellian. Subscripts "e," "n-cold," "n-fast," and "i-fast" indicate electron, cold neutral coming from the wall, energetic neutral injected by NB and energetic ion, respectively. The electron contribution is thought to be usually dominant, but there may be an appreciable fast-ion contribution under certain conditions. This may arise in the edge region of high-beta LHD plasmas obtained at low B_t (< 1 T) because energetic-ion orbits deviate to the plasma edge where there is high neutral density. The cross-section for electron-impact excitation is al-

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most constant around $5 \times 10^{-17}\,\mathrm{cm}^2$ in the energy region of the electron energy (energy of electrons is less than 500 eV). On the other hand, the excitation cross-section by fast ions does not exceed $10^{-19}\,\mathrm{cm}^2$ (energy of fast ions is greater than 150 keV). Moreover, the energetic-ion density n_{fast} is estimated to be $\sim 1 \times 10^{18}\,\mathrm{m}^{-3}$, as evaluated from $n_{\mathrm{fast}} \sim P_{\mathrm{NBabs}}(\tau_s/2)/(eT_{\mathrm{fast}})$ with NBI absorbed power $P_{\mathrm{NBabs}} \sim 5$ MW, energy slowing down time $(\tau_s/2) \sim 5$ ms, Coulomb charge (e), and $T_{\mathrm{fast}} \sim 150$ keV. It is one order of magnitude lower than the electron density ($n_e \sim 10^{19}\,\mathrm{m}^{-3}$). This estimation suggests that $\varepsilon_{\alpha\mathrm{fast}}$ is negligibly small ($\sim 0.2\%$), compared with $\varepsilon_{\alpha e}$. Consequently, Hα fluctuation signals will reflect the electron density fluctuations induced by energetic-ion-driven MHD modes in the plasma core region, because the fluctuations of $\langle \sigma_{\mathrm{ex}} v_e \rangle$ and n_n can be ignored.

Hα fluctuations are measured using an array comprising 16 Hα detectors (HAs). The sight lines of the HA array installed on the horizontally elongated section of LHD are shown in Fig. 1. The radial width of each sight line is restricted to 10 mm using an optical collimator, where an 8-mm-diameter lens and an interference filter are attached. The wavelength bandpass of the filter is from 655.00 to 658.04 nm. The filtered light is transmitted by the optical fiber of core diameter 400 µm and length 25 m. A photomultiplier tube (PMT) is employed to detect the light. The wavelength response of the PMT is from 185 to 900 nm. The signal from the PMT is amplified by a factor of 10^5 using a current amplifier having fast time response up to 5 µs (up to 200 kHz). The Hα data are acquired by an analog-to-digital converter with a sampling rate of 1 MHz and 14-bit dynamic range.

Typical spectrograms of magnetic probe (MP) and HA signals obtained in a hydrogen plasma are shown in Fig. 2 a) and b), together with the volume-averaged toroidal beta $\langle \beta_{\mathrm{dia}} \rangle$, line-averaged electron density $\bar{n}_e$, and Hα signal, where B_t is 0.425 T. Time evolution of the coherence between MP and HA signals is shown in Fig. 2 c). In this figure, four coherent fluctuations above 20 kHz in the range of the Alfvèn eigenmode frequency are clearly seen, whose frequencies at $t = 1.3$ s are respectively 27, 37, 74, and 111 kHz. The toroidal mode numbers (n) of these modes derived by a toroidal MP array are 1, 1, 2, and 3; we denote these as coherent modes MD$_1$, MD$_2$, MD$_3$, and MD$_4$, respectively as shown in Fig. 2 c). Coherent fluctuations also exist below 10 kHz, and are thought to be pressure-driven interchange modes [9]. MD$_1$ and MD$_2$ are individual $n = 1$ TAEs. However, MD$_3$ and MD$_4$ are the second and third harmonics of the $n = 1$ TAE (MD$_2$). The poloidal asymmetry of MD$_2$ strongly excited in a high-beta plasma having a noticeable Shafranov shift will generate these higher harmonics.

The radial profile of the coherence (γ) between MP and HA signals can give information on the eigenfunction of the MHD modes. The excess of γ from the background value ($\Delta\gamma$) for MD$_1$ and MD$_2$ is plotted for the time slice at $t = 1.3$ s in Fig. 3 a) as a function of the normalized minor radius (ρ). The mode MD$_3$ has a peak in the region of $0.6 < \rho < 0.8$, the same as MD$_2$. This is consistent with the idea that MD$_3$ is the second harmonic of MD$_2$. However, any obvious peak of $\Delta\gamma$ is not identified for the other mode MD$_4$, presumably due to its very small amplitude. In Fig. 3 b), the radial profiles of $\Delta\gamma$ for MD$_1$ and MD$_2$ have been compared with the $n = 1$ shear Alfvèn spectrum (SAS) calculated using experimentally obtained density profiles and predicted rotational transform profiles. These profiles of $\Delta\gamma$ have peaks around the gap of the $n = 1$ TAE formed by poloidal mode coupling of the $m = 1$ and $m = 2$ Fourier components ($\rho \sim 0.6$). Note that the appreciable increase in $\Delta\gamma$ near the plasma core region ($\rho < 0.5$)

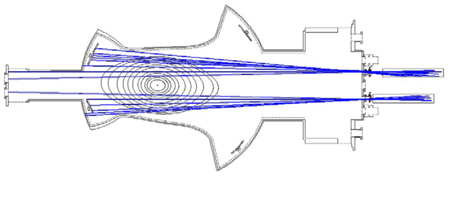

Fig. 1 Sight lines of the HA array in LHD.

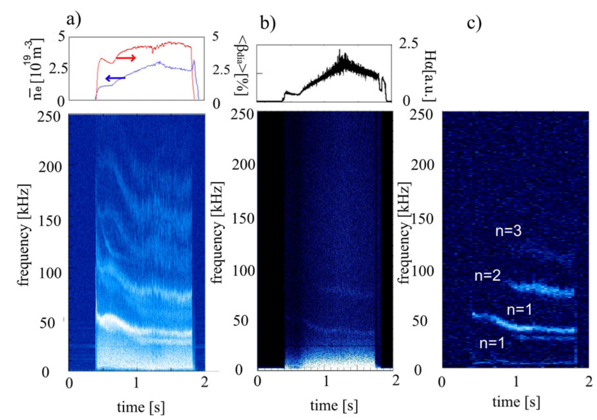

Fig. 2 a) Spectrogram of MP together with $\langle \beta_{\mathrm{dia}} \rangle$ and $\bar{n}_e$; b) time evolution and spectrogram of the HA signal; c) spectrogram of the coherence between HA and MP signals.

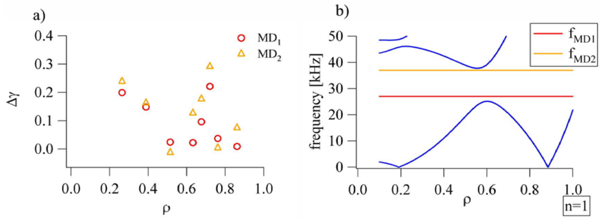

Fig. 3 a) Radial profile of $\Delta\gamma$ of $n = 1$ modes at $t = 1.3$ s. (b) $n = 1$ SAS calculated for this LHD plasma without toroidal mode coupling.

is caused by the path integral effect along the line of sight. The MD_1 and MD_2 modes, whose frequencies are close to the lower and upper bound of the TAE gap, respectively, are thought to be TAEs with odd/even radial parity, as predicted in LHD [7, 10].

In conclusion, coherent Hα fluctuations of TAEs were detected for the first time by using an array of Hα detectors with fast time response in high-beta plasmas on LHD. The Hα fluctuations reflect electron density fluctuations induced by energetic-ion-driven AEs. The radial profile of the $\Delta\gamma$ obtained by correlation analysis gives important information on the radial structure of the energetic-ion-driven modes such as TAE.

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