§38. Measurement of Radial Structure of Energetic-Ion-Driven MHD Modes with a Fast Response Hα-Detector Array

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Confinement of energetic ions/alpha particles is an important issue for efficient heating and sustainment of a burning plasma. However, steep gradient of energetic ion pressure causes energetic ion driven instabilities such as toroidal-Alfvèn engenmodes (TAEs[1)]) and energetic particle modes (EPMs[2)]). These instabilities are of practical importance because transport and/or loss of energetic particles leads to low efficiency of heating. Measurement of the space structure of these instabilities is important to clarify the transport mechanisms and minimize their loss. Although there are many advanced diagnostic techniques for this purpose, we have adopted an Hα-detector array as a simpler but useful method on LHD[3)]. In NB-heated LHD plasmas, TAEs and EPMs are excited typically under the conditions of $B_t \leq 1.5$T and line-averaged electron density $n_e \leq 3\times10^{19}\text{m}^{-3}$[4, 5)].

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:

$$\varepsilon_\alpha = \varepsilon_{\alpha e} + \varepsilon_{\alpha\text{fast}} \qquad ,(1)$$

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

$$\begin{aligned}\varepsilon_{\alpha\text{-fast}} &\cong n_{\text{n-cold}} \int \sigma_{\text{ex}}\left(v_{\text{i-fast}}\right) v_{\text{i-fast}} f\left(v_{\text{i-fast}}\right) \mathrm{d}v_{\text{i-fast}} \\ &+ n_{\text{n-fast}} \int \sigma_{\text{ex}}\left(\Delta v\right) \Delta v f\left(v_{\text{i-fast}}\right) \mathrm{d}v_{\text{i-fast}}\end{aligned} \qquad .(3)$$

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. Subscripts "e," "n-cold," "n-fast," and "i-fast" indicate electron, cold neutral coming from the wall or supplied by gas-puff, energetic neutral injected by NB and energetic ion, respectively. Contribution of fast ions is negligibly small compared with that of electrons in high beta plasma in LHD. Density fluctuations caused by energetic ion driven MHD modes will be detected with an Hα-detector array.

Typical spectrograms of magnetic probe (MP) and Hα (HA) signals obtained in a hydrogen plasma are shown in Fig. 1 a) and b), together with the volume-averaged toroidal beta <β_{dia}>, line-averaged electron density $\overline{n}_e$, and HA signal, where B_t is 0.425 T[3)]. Time evolution of the coherence between MP and HA signals is shown in Fig.1 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. 1 c). 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.

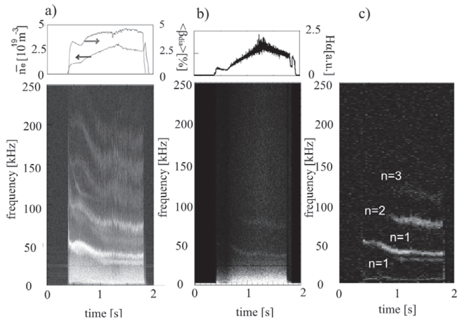

Fig.1 a) Spectrogram of MP together with <β_{dia}> and $\overline{n}_e$; b) time evolution and spectrogram of the HA signal; c) spectrogram of the coherence between HA and MP signals.

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 (Δγ) for MD_1 and MD_2 is plotted for the time slice at t = 1.3 s in Fig. 2 a) as a function of the normalized minor radius (ρ). The mode MD_3 has a peak in the region of 0.6 < ρ < 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 Δγ is not identified for the other mode MD_4, presumably due to its very small amplitude. In Fig. 2, the radial profiles of Δγ 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 Δγ have peaks around the gap of the n = 1 TAE formed by poloidal mode coupling of the m = 1 and m = 2 Fourier components (ρ ~ 0.6). Note that the appreciable increase in Δγ near the plasma core region (ρ < 0.5) is caused by the path integral effect along the line of sight.

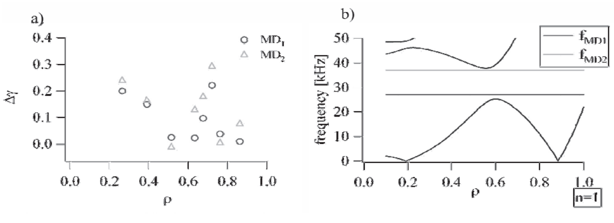

Fig.2 a) Radial profile of Δγ of n = 1 modes at t = 1.3 s. (b) n = 1 SAS calculated for this LHD plasma without toroidal mode coupling.

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