Evaluation of Measurement Signal of Heavy Ion Beam Probe of Energetic-Particle Driven Geodesic Acoustic Modes*)

Makoto SASAKI[1,2], Kimitaka ITOH[2,3], Takeshi IDO[4], Akihiro SHIMIZU[4], Tatsuya KOBAYASHI[4], Hiroyuki ARAKAWA[5,a], Naohiro KASUYA[1,2], Akihide FUJISAWA[1,2] and Sanae-I. ITOH[1,2]

[1] *Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan*

[2] *Research Center for Plasma Turbulence, Kyushu University, Kasuga 816-8580, Japan*

[3] *Institute of Science and Technology Research, Chubu University, Kasugai 487-8501, Japan*

[4] *National Institute for Fusion Science, Toki 509-5292, Japan*

[5] *Teikyo University, Fukuoka 836-8505, Japan*

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In order to observe spatial profiles of energetic particle driven modes, measurement signal of Heavy Ion Beam Probe (HIBP) is formulated theoretically, focusing on effects of the fast ion density fluctuation and attenuation of the injected beam (line-integral effect). Obtained formula is applied to the density fluctuation measurement of energetic-particle driven geodesic acoustic modes (EGAMs). Intensity of the fluctuation obtained by the HIBP can be up-down asymmetric in the poloidal cross-section due to the effect of the fast ion density fluctuation, when the electron loss cross-section of HIBP due to fast ions is comparable to that due to electrons. A possibility to measure the fast ion density by HIBP is discussed, and the experimental guideline for the specification of the resonance which drives the EGAM is presented.

Keywords: EGAM, spatial structure, HIBP, EP driven mode

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1. Introduction

In magnetically confined plasmas, energetic-particle driven modes, such as Alfven eigenmode and geodesic acoustic modes (EGAMs), affect confinement of fast ions [1, 2], and properties of bulk plasmas [3, 4]. EGAM interacts with turbulence [5, 6], and can contribute to ion heating [4], and toroidal rotation drive [7], which is the so-called GAM channeling. When a resonance due to the magnetic drift of the fast ions is taken into account, up-down symmetry of the fluctuation intensity in the poloidal cross-section is violated, especially in the fast ion density fluctuation [8]. In such a case, the GAM channeling becomes significant. Therefore, the up-down asymmetry of the EGAM is important to be measured.

Heavy Ion Beam Probe (HIBP) is a powerful tool to observe spatial profiles of the electrostatic potential and the electron density [9]. Important observations related to plasma transport by HIBP has been reported, such as the observation of turbulence driven flux [10, 11], zonal flows [12,13], and dynamics of L-H transition [14]. Spatial profile of the EGAM have been observed in Large Helical Device (LHD) [15,16]. In this experiment, up-down asymmetry of the EGAM density fluctuation has been observed [17]. Up-down asymmetry could be caused by the geometrical effect, such as the beam attenuation effect (line-integral effect) [18,19]. In addition, it has been pointed out that the ionization of HIBP beam by the fast ions can be important [20]. Therefore, in order to distinguish the real signal (including the fast ion effect) with the geometrical effect, it is necessary to evaluate both of the effects of the fast ions and the line-integral.

In this study, the detected signal of HIBP is formulated theoretically with the effects of the fast ion and the line-integral. The obtained expression is applied to the measurement of the EGAM density fluctuation. Assuming that the electron loss cross-section of the HIBP beam by the fast ions is comparable to that by the electron, we evaluate these effects, and show that the intensity of the fluctuation detected by HIBP can be up-down asymmetric in the poloidal cross-section. In a low electron density case, similar to the LHD experiment [15–17], the line-integral effect is not important, and the fast ion contribution is significant for the up-down asymmetry. In such a case, the direct measurement of the fast ion density fluctuation could be possible by HIBP. The rest of the paper is organized as follows. In section 2, the detected signal of HIBP in the presence of the fast ion density fluctuation is formulated. The obtained expression for the measurement signal is applied to EGAM, and the spatial structure of the detected signal is described in section 3. Discussion and summary are given in sections 4 and 5, respectively.

author's e-mail: sasaki@riam.kyushu-u.ac.jp

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a) present address: Shimane University, Matsue 690-8504, Japan

2. Formulation of HIBP Signal

The detected signal of HIBP is formulated theoretically, taking the effects of the fast ion and the line-integral into account. The situation corresponds to cases of the plasma where the fast ions exist to excite energetic-particle driven modes. The injected HIBP beam is assumed to be ionized by the electrons and the fast ions. In such a case with the multiple ionization processes, the intensity of the detected signal of HIBP, I, can be expressed as [18]

$$I = I_0 \Delta \sum_j C_j n_j \exp\left(-\sum_j \int C_j n_j \mathrm{d}l \right), \tag{1}$$

where I_0 is the intensity of the injected beam current, Δ is the sample volume, j denotes the particle species, j = e, h (e and h represent electron and fast ion, respectively), C_j is defined by $C_j = \langle \sigma v \rangle_j / v_\mathrm{b}$. Here, v_b is the speed of the beam, and $\langle \sigma v \rangle_j$ is the ionization rate coefficient for HIBP beam by the particle of the j-th species. The integration is performed along the trajectory of the beam, which attenuates the intensity (line-integral effect).

The fluctuation of the detected signal of HIBP due to the density fluctuation in different spices is calculated. The density of the j-th species is expressed with the sum of the mean and fluctuating components, $n_j = n_j^{(0)} + \tilde{n}_j$. Assuming $n_j^{(0)} \gg \tilde{n}_j$, the fluctuating component of the HIBP beam intensity, $\tilde{I}$, normalized by the intensity without the fluctuation, $\langle I \rangle$, is obtained as

$$\frac{\tilde{I}}{\langle I \rangle} \approx \frac{\sum_j C_j \tilde{n}_j}{\sum_j C_j n_j^{(0)}} - \sum_j \int C_j \tilde{n}_j \mathrm{d}l. \tag{2}$$

The first term in the right hand side (RHS) of Eq. (2) is the local information of the density fluctuation, which becomes the electron density fluctuation, $\tilde{n}_\mathrm{e}/n_\mathrm{e}^{(0)}$, in the case when only the electron is dominant for the ionization of the HIBP beam. In the case of energetic-particle driven modes, where the fast ion density fluctuation exists, the effect of the fast ion density fluctuation appears in this term. The second term in RHS of Eq. (2) is the line-integral effect for the fluctuation. Equation (2) is a general form for multiple ionization processes, and it can be rewritten as following, by considering the ionization processes by the electrons and the fast ions.

$$\frac{\tilde{I}}{\langle I \rangle} \approx \frac{\tilde{n}_\mathrm{e} + \alpha \tilde{n}_\mathrm{h}}{n_\mathrm{e}^{(0)} + \alpha n_\mathrm{h}^{(0)}} - \left(\int C_\mathrm{e} \tilde{n}_\mathrm{e} \mathrm{d}l + \int C_\mathrm{h} \tilde{n}_\mathrm{h} \mathrm{d}l \right), \tag{3}$$

where α is defined as the ratio between the ionization rate coefficient of the beam by the electrons and that by the fast ions, $\alpha = C_\mathrm{h}/C_\mathrm{e}$, which determines the strength of the fast ion effect. The fast ion density fluctuation affects the HIBP signal significantly when α is the order of $|\tilde{n}_\mathrm{e}|/|\tilde{n}_\mathrm{h}|$. The obtained expression for the HIBP signal is applied to EGAM in the next section.

3. Application to EGAM Measurement

In this section, the formulation of HIBP signal, Eq. (3), is applied to EGAM density fluctuation measurement. First, we introduce the EGAM eigenfunction for the density fluctuation briefly. Then, a spatial profile of the fluctuation intensity measured by HIBP is discussed.

EGAMs are driven by the resonance of the fast ions. Depending on the energy distribution of the fast ions, the unstable branch of EGAMs changes. When the parallel motion of the fast ions is important, the transit resonance destabilizes the EGAM with the transit frequency [21]. When the perpendicular motion of the fast ion is important (this can be realized when the energy of the fast ions becomes large), the magnetic drift resonance destabilizes a branch with the magnetic drift frequency [22]. The branch with the standard GAM frequency, which is determined by the sound speed, can be driven by the both resonances. When the resonance of the magnetic drift frequency of the fast ion is important, the bump structure appears in the poloidal eigenfunction [22]. Here, the condition that the magnetic drift frequency is dominant can be written as [22]

$$u_0 \gg \left| \frac{2\Lambda_0}{k_\mathrm{r} q (1 + \Lambda_0^2)} \right|, \tag{4}$$

where u_0 is the speed of the fast ions normalized by the ion thermal velocity, q is the safety factor, k_r is the radial wavenumber of the EGAM, and Λ_0 is the pitch angle of the fast ions. Thus, the magnetic drift resonance becomes important when the energy of the fast ions is large. The resonance condition for a simple tokamak is given by

$$\omega = \omega_\mathrm{D} \sin\theta, \tag{5}$$

where ω, ω_D and θ are the EGAM frequency, magnetic drift frequency, and the poloidal angle, respectively. The resonance condition has poloidal angle dependence, and there are special angles, which satisfy the resonance condition; $\theta_* = \arcsin(\omega/\omega_\mathrm{D})$. The density fluctuation for the fast ion is localized at the resonance location $\theta = \theta_*$. The eigenfunctions for the electron density and the fast ion density are illustrated in Fig. 1, which corresponds to the case with $\omega_\mathrm{D} > 0$. The eigenfunction of the fast ion density fluctuation is completely up-down asymmetric in the poloidal cross-section, while the intensity of the electron density fluctuation is almost up-down symmetry. The density fluctuations of the electron and the fast ion are out of phase. The absolute value of the fast ion density fluctuation is comparable to that of the electron at the resonance locations. When the frequency is chirped in time, as was observed in the experiment [15], the resonant location, $\theta = \theta_*$, is expected to change temporally, according to the chirped frequency. In such a case, the up-down asymmetric fluctuation can be observed in a wider poloidal region.

We describe the spatial structure of the EGAM density fluctuation measured by HIBP. For simplicity, we consider a situation that the HIBP primary beam is injected from bottom to top of the torus with a straight trajectory, and the beam passes through the resonance location. The frequency chirping is not considered. The HIBP signal is calculated from Eq. (3), by using the LHD experimental parameters [15]: $T_e = 8$ [keV], $T_i = 0.6$ [keV], $n_e^{(0)} = 1\times10^{18}$ [m^{-3}], $B = 1.375$ [T], the minor radius $a = 0.65$ [m], the energy of the fast ion $E_h = 175$ [keV] (that is supplied by the neutral beam injection (NBI) heating), and the radial wavenumber of the EGAM $k_r^{-1} = 0.2a$. It is noted that the energy of the fast ions in LHD experiment is so large that the magnetic drift frequency can be comparable or larger, compared to the transit frequency. In this study, as a first step, we assume that the EGAM is driven by the magnetic drift resonance in such a condition, and investigate what can be observed in experiments. The ionization rate coefficient of the primary beam with the electron is $\langle\sigma v\rangle_e = 0.6\times10^{-12}$ [m^3/s] [23]. The energy of the HIBP primary beam consisted of Au is $E_{\rm beam} = 1.134$ [MeV], which corresponds to $v_b = 1.1\times10^6$ [m/s]. The electron loss cross section of the HIBP beam increases with the increase of the energy of the beam, and the cross section is roughly the order of $\sigma_h \sim 10^{-19}$ [m^2], and it corresponds to $\langle\sigma v\rangle_h \sim 10^{-13}$ [m^3/s] [20]. The ionization rate coefficient by the fast ions can be comparable to that by the electron. However, there is ambiguities for the cross-section by the fast ions. Thus, the strength of the fast ion effect, α, is

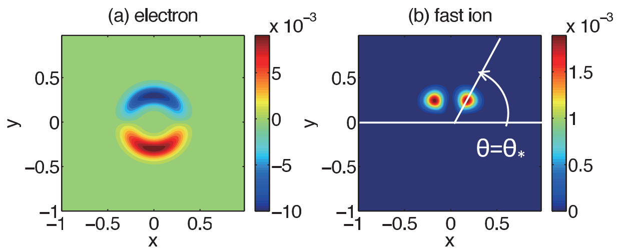

Fig. 1 Density eigenfunction of EGAM in poloidal cross section. (a) Electron density and (b) Fast ion density are shown.

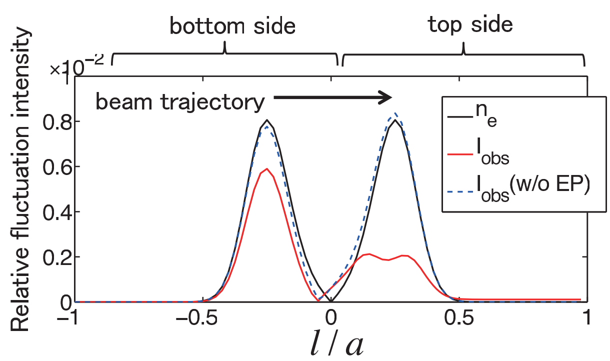

Fig. 2 Comparison of the density fluctuation with the simulated signal of HIBP in the case of $\alpha = 3$. Electron density fluctuation, simulated signal with and without the fast ion effect are shown by the black, blue and magenta lines, respectively.

treated as a parameter of the order unity. By using these parameters, the detected signal of HIBP is simulated from Eq. (2). The spatial structure of the simulated fluctuation intensity is shown in Fig. 2. The horizontal axis is the distance along the trajectory of the primary beam. The regions of $l < 0$ and $l > 0$ correspond to the bottom and top sides of the torus. Although the electron density fluctuation is symmetric, the up-down asymmetric fluctuation is expected to be obtained by HIBP, which is similar to that observed in LHD [17]. This asymmetry, the reduction of the fluctuation signal in $l > 0$, is due to the fast ion density fluctuation. For the case when the cross-section by the fast ions is neglected, $\alpha \to 0$, only the line-integral effect by the electron is obtained, which is plotted by the dashed magenta line. The line-integral effect due to the electron is almost negligible.

4. Discussion

We discuss the possibility to measure the fast ion density by using HIBP. In the low density experiment, where the line-integral effect is not significant as the case in the LHD experiments [15–17], the detected signal of HIBP can be written as

$$\frac{\tilde{I}}{\langle I\rangle} \approx \frac{\tilde{n}_e + \alpha\tilde{n}_h}{n_e^{(0)} + \alpha n_h^{(0)}}. \tag{6}$$

If one knows the value of the coefficient α (the electron loss cross-section of HIBP by the fast ions), one can estimate the fast ion density as follows.

The mean of the fast ion density, $n_h^{(0)}$, can be evaluated from $\langle I\rangle$, which is the sum of $n_e^{(0)}$ and $\alpha n_h^{(0)}$. The difference of $\langle I\rangle$ with $n_e^{(0)}$ is $\alpha n_h^{(0)}$. Here, $n_e^{(0)}$ can be measured by other instruments such as reflectometer or Thomson scattering. Thus, $n_h^{(0)}$ is possible to be measured by comparing $\langle I\rangle$ and $n_e^{(0)}$. In order to validate the measurement, it is useful to use the response of $\langle I\rangle$ when the NBI is turned on/off. $\langle I\rangle$ is expected to increase/decrease with the scale of the slowing down time, when the power of NBI is on/off.

The fluctuation of the fast ion density is also possible to be measured. The ratio of $\tilde{I}$ at upper-side ($\tilde{I}^{(\rm up)}$) and down-side ($\tilde{I}^{(\rm down)}$) can be written as

$$\frac{\tilde{I}^{(\rm up)}}{\tilde{I}^{(\rm down)}} \approx \frac{\tilde{n}_e^{(\rm up)} + \alpha\tilde{n}_h^{(\rm up)}}{\tilde{n}_e^{(\rm down)}} \approx -\left(1 + \alpha\frac{\tilde{n}_h^{(\rm up)}}{\tilde{n}_e^{(\rm up)}}\right), \tag{7}$$

assuming the relation, $\tilde{n}_e^{(\rm up)} \approx -\tilde{n}_e^{(\rm down)}$, where $\tilde{n}_j^{(\rm up)}$ and $\tilde{n}_j^{(\rm down)}$ are the values of the density fluctuation at upper-side and down-side, respectively. It is possible to change the ionization rate coefficient α by changing the HIBP beam energy. This ratio can be plotted as in Fig. 3. $\tilde{n}_h$ can be obtained from the slope, where the slope is given as $\tilde{n}_h^{(\rm up)}/\tilde{n}_e^{(\rm up)}$. The negative slope indicates that the density fluctuations of the fast ion and the electron are out of phase.

It is noted that the asymmetry discussed here is due to the magnetic drift of the fast ion so that up-down asymmetry can be reversed by changing the sign of the magnetic

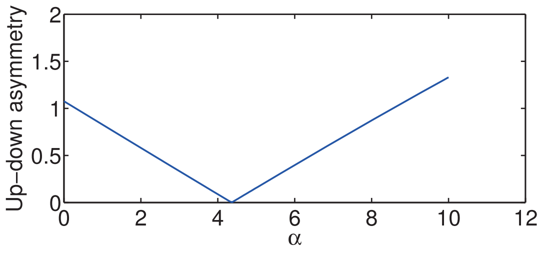

Fig. 3 Up-down asymmetry of intensity of simulated signal, $|\tilde{I}^{(\mathrm{up})}|/|\tilde{I}^{(\mathrm{down})}|$.

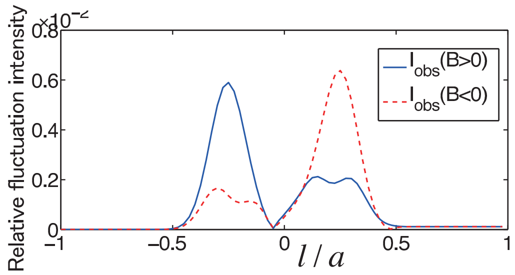

Fig. 4 Simulated signals of HIBP in the case of $\alpha = 3$ for the positive and negative magnetic fields.

field, which is shown by the red line in Fig. 3. The detected signals for the positive and negative magnetic field cases are illustrated in Fig. 4. It should be noted that the positive direction of the magnetic field is the toroidal direction in the usual toroidal coordinate. Reversing the sign of the magnetic field is useful to validate the kinds of the resonances which causes the asymmetry. There is a different resonance which can excite the EGAMs; the transit resonance, which does not cause the asymmetry of the fast ions in poloidal direction. In the case of this branch, no change for the fluctuation is expected by changing the sign of the magnetic field. Due to poloidally homogeneous resonance, the measurement of $\tilde{n}_{\mathrm{h}}$ is difficult for this branch. In helical plasmas with the complex magnetic filed, there are other fast ion resonances exist, for instance, the precession drift (which is expected to cause the in-out asymmetry). A unified theory of the EGAMs to include such kinds of the multiple resonances is required for the future study.

5. Summary

Measurement signal of Heavy Ion Beam Probe (HIBP) is formulated theoretically, focusing on effects of the fast ion density fluctuation and the line-integral. Obtained formula is applied to the density fluctuation measurement of the EGAMs in LHD. In experiments in LHD, where the ionization rate coefficient of the HIBP beam by the fast ion could be comparable to that with the electron, the intensity of the fluctuation detected by HIBP can be up-down asymmetric in the poloidal cross-section due to the effect of the fast ion density fluctuation. A possibility to measure the fast ion density by HIBP is discussed, and the experimental guideline for the specification of the resonance which drives the EGAM is presented.

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[1] Y. Todo *et al.*, Phys. Plasma **24**, 081203 (2017).
[2] N. Gorelenkov *et al.*, Nucl. Fusion **54**, 125001 (2014).
[3] N.J. Fisch and J.M. Rax, Phys. Rev. Lett. **69**, 612 (1992).
[4] M. Sasaki, K. Itoh and S.-I. Itoh, Plasma Phys. Control. Fusion **53**, 085017 (2011).
[5] M. Sasaki *et al.*, Scientific Reports **7**, 16767 (2017).
[6] D. Zarzoso *et al.*, Phys. Rev. Lett. **110**, 125002 (2013).
[7] M. Sasaki *et al.*, Nucl. Fusion **57**, 036025 (2017).
[8] M. Sasaki *et al.*, Phys. Plasmas **23**, 102501 (2016).
[9] A. Shimizu *et al.*, Plasma Fusion Res. **11**, 2402123 (2016).
[10] G.A. Hallock, A.J. Wootton and R.L. Hickok, Phys. Rev. Lett. **59**, 1301 (1987).
[11] Ch. P. Ritz *et al.*, Phys. Rev. Lett. **62**, 3099 (1989).
[12] A. Fujisawa *et al.*, Phys. Rev. Lett. **93**, 165002 (2004).
[13] T. Ido *et al.*, Plasma Phys. Control. Fusion **48**, S41 (2006).
[14] T. Kobayashi *et al.*, Phys. Rev. Lett. **111**, 035002 (2013).
[15] T. Ido *et al.*, and the LHD Experiment Group, Phys. Rev. Lett. **116**, 015002 (2016).
[16] T. Ido *et al.*, Nucl. Fusion **55**, 083024 (2015).
[17] T. Ido *et al.*, IAEA FEC, EX/P8-13 (2016).
[18] D.W. Ross *et al.*, Rev. Sci. Instrum. **63**, 2232 (1992).
[19] N. Kasuya *et al.*, Plasma Sci. Technol. **13**, 326 (2011).
[20] M. Nishiura *et al.*, Plasma Fusion Res. **2**, S1099 (2007).
[21] G.Y. Fu, Phys. Rev. Lett. **101**, 185002 (2008).
[22] M. Sasaki *et al.*, Phys. Plasmas **23**, 102501 (2016).
[23] NIFS database for the atomic and molecular process: http://dbshino.nifs.ac.jp/nifsdb/amdis_ion/top