Consideration of Density Fluctuation Measurement using Heavy Ion Beam Probe on Large Helical Device

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Heavy ion beam probe (HIBP) can measure density, potential, magnetic field and their fluctuations, simultaneously, in high temperature magnetic confinement plasma. However it is well-known that local density fluctuation is measured with difficulty due to a path integral effect. Ionization cross-sections of HIBP beam particles affects a detected beam current, which informs density. The ionization cross-sections due to not only electron impact but also proton impact are important for MeV-range beam. Take into account the proton ionization, the path integral effect becomes twice larger than that only due to electron impact. And the path integral effect can decrease by less than half, when phase difference between proton and net electron fluctuations is finite.

Keywords: heavy Ion beam probe, fluctuation measurement, path integral effect, proton impact ionization

1 Introduction

A fluctuation transport closely relates magnetic plasma confinement performance. This transport is represented fluctuations of density, temperature, and electric and magnetic fields. To measure them is one of the most important study in the magnetic plasma confinement. Heavy ion beam probe (HIBP) is one of powerful diagnostics which can measure density, potential, magnetic field, and their fluctuations, simultaneously. However, density, magnetic field and their fluctuations cannot be measured locally due to the path integral effects. Measured fluctuation amplitudes are simulated in previous paper [1, 2], and local density fluctuation amplitude is accomplished to be reconstructed under a specific condition [3].

A HIBP system on a large confinement device needs a few MeV order beam energy, like HIBP system on Large Helical Device (LHD) [4]. This HIBP system makes a difference from previous HIBP systems which have a few hundreds keV in beam energy. In the case of MeV order HIBP, beam particles ionize by mainly not only electron impact but also proton impact [5]. In this paper, we discuss influences of proton impact ionization on density fluctuation measurement, and simulate the path integral effect in this measurement on some conditions.

2 Brief description of density fluctuation measurements of HIBP

HIBP system consists of an accelerator, energy analyzer, and beam sweepers. In principle, a singly charged heavy ion beam (Rb^+, Cs^+ and Au^+, etc), called primary beam, is injected into a plasma. In the plasma, the beam ions are ionized to doubly (or higher) charged ions through the collisions with plasma particles. The doubly charged ions, called secondary beam, come out from the plasma, and are detected with the energy analyzer.

The detected beam current I_d, which has density informations, is expressed in the following form:

$$I_\mathrm{d} = I_0 l_\mathrm{sv}(r_*)\left\{n_\mathrm{e}(r_*)S_\mathrm{e}^{12} + n_{\mathrm{H}^+}(r_*)S_{\mathrm{H}^+}^{12}\right\} \times \exp\left[\left\{-\sum_{i=1,2}\int\left(n_\mathrm{e}(r)S_\mathrm{e}^{i} + n_{\mathrm{H}^+}(r)S_{\mathrm{H}^+}^{i}\right)\mathrm{d}l_i\right\}\right] \quad (1)$$

where r_* is an ionization position, I_0 is an initial primary beam current, l_sv is a sample volume length, n_e and n_{H^+} are electron and proton density, respectively. The terms $S_\alpha^{12} = \langle\sigma_\alpha^{12} v_\mathrm{the}\rangle_\mathrm{M}/v_\mathrm{b}$ and $S_\alpha^{i} = \langle\sigma_\alpha^{i} v_\mathrm{the}\rangle_\mathrm{M}/v_\mathrm{b}$, where $\alpha = (\mathrm{e}, \mathrm{H}^+)$, and σ_e and σ_{H^+} are ionization cross-sections of electron and proton impacts, respectively. The terms v_the and v_thi are electron and proton thermal velocity, respectively. And v_b is beam particle velocity. Superscript 12 of σ_α means ionization from single charged ion to double charged ion, and superscripts 1 and 2 of σ_α express ionization from single and double charged ions to higher charged ions, respectively. Subscript M of bracket represents a Maxwellian average. And $\mathrm{d}l_1$ and $\mathrm{d}l_2$ are length elements of primary and secondary beam orbits, respectively. The term $l_\mathrm{sv}(r_*)\left\{n_\mathrm{e}(r_*)S_\mathrm{e}^{12} + n_{\mathrm{H}^+}(r_*)S_{\mathrm{H}^+}^{12}\right\}$ and exponential term are brightness and attenuation of detected beam current, respectively.

By taking variations and square of Eq. (1), the instantaneous normalized measured fluctuation power is represented as

$$\left(\frac{\widetilde{I}_\mathrm{d}(r_*)}{I_\mathrm{d}(r_*)}\right)^2 = T_0 - S_\mathrm{C} + A_\mathrm{C} \quad (2)$$

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with expression of

$$
\begin{aligned}
T_0 &= \frac{\left(\widetilde{n}_{\mathrm{e}}(r_*)S_{\mathrm{e}}^{12} + \widetilde{n}_{\mathrm{H}^+}(r_*)S_{\mathrm{H}^+}^{12}\right)^2}{\left(n_{\mathrm{e}}(r_*)S_{\mathrm{e}}^{12} + n_{\mathrm{H}^+}(r_*)S_{\mathrm{H}^+}^{12}\right)^2}, \\
S_{\mathrm{C}} &= \frac{2\left(\widetilde{n}_{\mathrm{e}}(r_*)S_{\mathrm{e}}^{12} + \widetilde{n}_{\mathrm{H}^+}(r_*)S_{\mathrm{H}^+}^{12}\right)}{n_{\mathrm{e}}(r_*)S_{\mathrm{e}}^{12} + n_{\mathrm{H}^+}(r_*)S_{\mathrm{H}^+}^{12}} \qquad (3) \\
&\times \sum_{i=1,2}\left(\int \widetilde{n}_{\mathrm{e}}(r_i)S_{\mathrm{e}}^{i}\mathrm{d}l_i + \int \widetilde{n}_{\mathrm{H}^+}(r_i)S_{\mathrm{H}^+}^{i}\mathrm{d}l_i\right), \\
A_{\mathrm{C}} &= \left[\sum_{i=1,2}\left(\int \widetilde{n}_{\mathrm{e}}(r_i)S_{\mathrm{e}}^{i}\mathrm{d}l_i + \int \widetilde{n}_{\mathrm{e}}(r_i)S_{\mathrm{H}^+}^{i}\mathrm{d}l_i\right)\right]^2,
\end{aligned}
$$

where a tilde expresses fluctuation.

The term $\widetilde{n}_\alpha$ are statistical variables, hence we will consider an ensemble of fluctuations $\widetilde{n}_\alpha$ with $\langle\widetilde{n}_\alpha\rangle_{\mathrm{E}} = 0$, where $\langle\rangle_{\mathrm{E}}$ means an ensemble average. If $n_{\mathrm{e}} = n_{\mathrm{H}^+}$ and $\widetilde{n}_{\mathrm{e}} = \widetilde{n}_{\mathrm{H}^+}$, by taking ensemble average of Eq. (2), we obtain

$$\langle\widetilde{\eta}^2(r_*)\rangle_{\mathrm{E}} = \langle T_0\rangle_{\mathrm{E}} - \langle S_{\mathrm{C}}\rangle_{\mathrm{E}} + \langle A_{\mathrm{C}}\rangle_{\mathrm{E}} \qquad (4)$$

with the expression on a condition of $S_\alpha^{12} \equiv S_\alpha^1$ of

$$
\begin{aligned}
\langle T_0\rangle_{\mathrm{E}} &= \langle\widetilde{\xi}^2(x_*)\rangle_{\mathrm{E}} \\
\langle S_{\mathrm{C}}\rangle_{\mathrm{E}} &= 2\sum_{i=1,2}\int \langle\widetilde{\xi}(x_*)\widetilde{\xi}(x_i)\rangle_{\mathrm{E}}\hat{S}^i w_i(x_i)\mathrm{d}x_i \qquad (5) \\
\langle A_{\mathrm{C}}\rangle_{\mathrm{E}} &= \sum_{i=1,2}\sum_{j=1,2}\iint \langle\widetilde{\xi}(x_i)\widetilde{\xi}(y_j)\rangle_{\mathrm{E}}\hat{S}^i\hat{S}^j w_i(x_i)w_j(y_j)\mathrm{d}x_i\mathrm{d}y_j
\end{aligned}
$$

where the normalized fluctuations $\widetilde{\eta}(r) = \widetilde{I}_{\mathrm{d}}(r)/I_{\mathrm{d}}(r)$ and $\widetilde{\xi}(r) = \widetilde{n}_{\mathrm{e}}(r)/n_{\mathrm{e}}(r)$. The normalized ionization rate $\hat{S} = n_{\mathrm{e}}S_\alpha^i a$ which depends on beam energy, electron and proton temperature, and density, where $S_\alpha^i = S_{\mathrm{e}}^i + S_{\mathrm{H}^+}^i$. The term a is minor radius. And the weight in the integral $w_i(x_i) = \partial\hat{l}_i(x_i)/\partial x_i$, where $\hat{l}_i = l_i/a$. The ensemble average of two fluctuation is represented as

$$\langle\widetilde{\xi}(x)\widetilde{\xi}(y)\rangle = |\widetilde{\xi}(x)||\widetilde{\xi}(y)|\gamma(x,y)\Psi(x,y), \qquad (6)$$

where $\gamma(x,y)$ and $\Psi(x,y)$ are coherence and phase between fluctuations at points x and y, respectively. Equation (4) and (5) are the same formula as those of previous HIBP system which has a few hundreds keV beam energy and beam particles are mainly ionized by electron impact [1], thus the ionization rate in Eq. (5) is only raised by proton impact ionization.

There are two kinds of path integral effects; screening effect S_{C} and accumulation effect A_{C} [3]. The term $\langle S_{\mathrm{C}}\rangle_{\mathrm{E}}$ has negative sign in Eq. (4), and is a local path integral effect which screens the local fluctuation. The other way, $\langle A_{\mathrm{C}}\rangle_{\mathrm{E}}$ has positive sign in Eq. (4), and is a long range path integral effect which is the same as well-known type effect in other line integral diagnostics.

3 Simulation of Measured Fluctuation

The measured fluctuation is simulated with linear beam orbit shown in Fig. 1 as the same as previous paper [1]. Using parameter s and t, the primary and secondary beam orbit are described as

$$\vec{\hat{l}}_1(s) = (0, -s+1), \quad \vec{\hat{l}}_2 = (t, -\hat{\zeta}t + \hat{\zeta}) \qquad (7)$$

The corresponding weight factors are $w_1 = 1$, $w_2 = \sqrt{1+\zeta^2}$. In the calculation, minor radius a is assumed 600 mm, and profiles of density and electron temperature T_{e} are assumed as

$$
\begin{aligned}
n_{\mathrm{e}} &= n_{\mathrm{e},0}(1+\rho^4)^2 \qquad (8) \\
T_{\mathrm{e}} &= T_{\mathrm{e},0}\exp\left[-\frac{1}{2}\left(\frac{\rho}{0.5}\right)^2\right], \qquad (9)
\end{aligned}
$$

where $n_{\mathrm{e},0}$ is calculated as the line averaged density is kept to be $1\times10^{19}\ \mathrm{m}^{-3}$, $T_{\mathrm{e},0} = 2\mathrm{keV}$ (Fig. 2), and $\rho = |r/a|$. The primary and secondary beam are selected Au^+ and Au^{2+}, respectively. Ionization cross-sections of electron and proton impacts are calculated using Lot'z empirical formula and results in Ref. [5], respectively. Electron temperature contribution to the path integral effect is assumed to be ignored.

First, we will examine dependence on a position of fluctuation peak and coherence. The local fluctuation profile is assumed $0.1\exp[-0.5(\rho-\rho_0)^2/0.2^2]$, and three patterns; $\rho_0 = 0.0$, 0.5 and 0.9, are simulated. The coherence γ is assumed $\gamma(x,y) = \exp(-|x-y|^2/\hat{l}_{\mathrm{C}}^2)$, where $\hat{l}_{\mathrm{C}} = l_{\mathrm{C}}/a$ is a normalized correlation length expressed with correlation length l_{C}. And using delta function $\delta(x,y)$, the phase difference Ψ is assumed $\Psi(x,y) = \cos\delta(x,y) = 1$. The beam

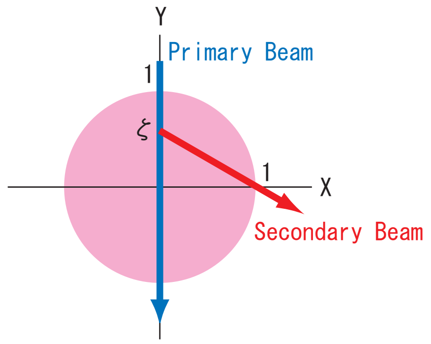

Fig. 1 Beam orbit model.

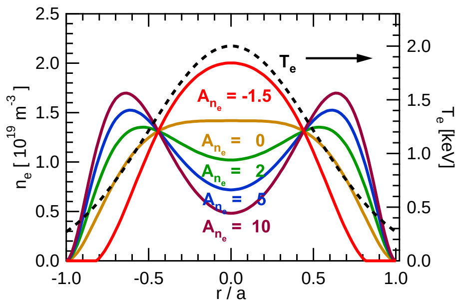

Fig. 2 Profiles of electron density (solid lines) and temperature (dashed line). $A_{n_{\mathrm{e}}}$ is hollow factor in Eq. (10). A case of $A_{n_{\mathrm{e}}} = 0$ expressed Eq. (8)

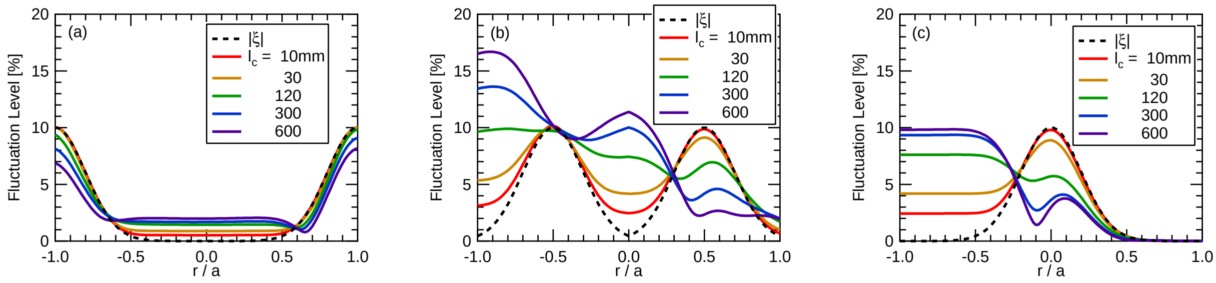

Fig. 3 Dependence of path integral effect on fluctuation peak position and coherence. Coherence is assumed $\gamma(x, y) = \exp(-|x - y|^2/\hat{l}_C^2)$, where $\hat{l}_C = l_C/a$ is the local correlation length. No phase difference is assumed; $\Psi(x, y) = 1$. Radial profile of the local density fluctuation and the measured fluctuation are indicated dashed and solid lines, respectively. (a) Edge (pattern A), (b) half of minor radius (pattern B), and (c) center (pattern C) peaks local density fluctuation profiles.

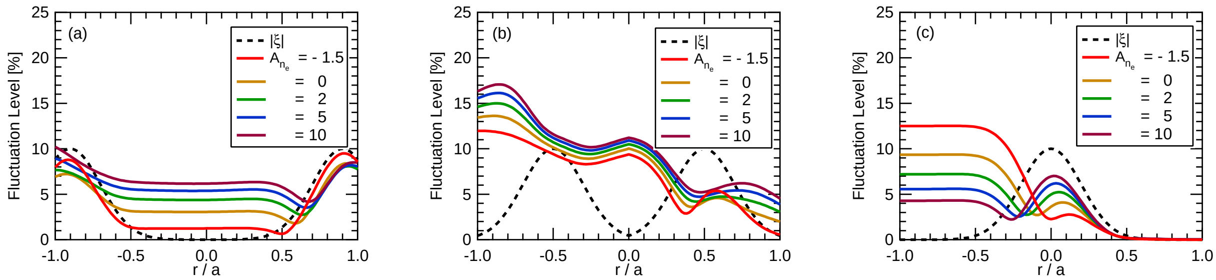

Fig. 4 Dependence of the path integral effect on density profile. The correlation length is 300mm, and other parameters are the same as Fig. 3 except density profile (Fig. 2). Radial profile of the local density fluctuation and the measured fluctuation are indicated dashed and solid lines, respectively.

energy is assumed to be 1.5 MeV. Figure 3 shows three profile patterns of local fluctuation $\widetilde{\xi}$ with several correlation lengths; l_C = 10mm, 30mm, 120mm, 300mm and 600mm. The short and long correlation lengths are the cases of drift wave turbulence and MHD fluctuation, respectively. The primary beam is injected from right hand side in Fig. 3.

In all three cases, as correlation length becomes shorter, profile distortions of the measured fluctuation amplitudes from original local fluctuation amplitudes become smaller. The measured fluctuation profiles mostly correspond to the local fluctuation profiles in the cases of l_C = 10mm in upstream of the original peak. In pattern A, the measured fluctuation amplitude in the area of upstream ($r/a < 0.6$) remains finite amplitude $\sim$ 2% in the case of l_C = 600mm due to the path integral effects of the plasma edge fluctuation (10%). The accumulating effect is larger than the screening effect in this area; $S_C/A_C < 1$. On the other hand, in pattern C, the peak of measured fluctuation amplitude reduces and shifts to upstream as l_C becomes large. The reduction of the measured fluctuation amplitude is calculated less than half of the original local fluctuation amplitude in the case of l_C = 600mm, and represents that the screening effect is larger than accumulating effect; $S_C/A_C > 1$. An amount of the local maximum shift is $r/a = 0.1$ in the case of l_C = 600mm. The shift arises as a result of which the accumulating effect along primary beam orbit is larger than that along the secondary beam orbit. In pattern B, a upstream peak of the measured fluctuation is reduced and shifts as the same as pattern A. An apparent peak, which can be larger amplitude than the original peak, can appear near the center. This is generated as the result of the screening effects around two original peaks and the accumulating effect originated from upstream peak of the local fluctuation. The qualitative property of the measured fluctuation profiles is the same as HIBP system considered only electron impact ionization [1], this is because model equations, Eq. (4) and (5), are the same formulae. However, the path integral effect considered electron and proton ionization can be twice larger than that considered only electron ionization in these case.

The dependence of measured fluctuation amplitude on density profile is simulated. Hollow and parabolic density profile are supposed for center heating of ECRH and NBI plasma, respectively. Here, Eq. (8) is instead of

$$n_e(\rho) = n_{e,0}\left(1 + \rho^4\right)^2\left(1 - A_{n_e}\rho^2\right), \qquad (10)$$

where A_{n_e} is hollow factor. Hollow depth becomes deep as hollow factor increases (Fig. 2). Figure 4 shows amplitude profiles of the measured fluctuations calculated for several hollow factors; $A_{n_e} = -1.5, 0, 2, 5$ and 10. The correlation length is assumed 300mm and other parameters are the same as Fig. 3 except density profiles. If density is calculated negative, density replaces sufficiently small positive value.

The measured fluctuation profiles change as density profile, even though in the same line average density (Fig. 4). In pattern A, contaminations of the measured fluctuation amplitudes in center region due to edge fluctuation amplitudes become large as the hollow factor increases. This is because the density around local fluctuation peak is relatively higher, then the path integral effect become large. For the same reason, in pattern C, distortions of measured fluctuation profiles become small as hollow factor increases. In pattern B, the distortion is medium between pattern A and C, and variation of the distortion is small for hollow factor. In the three case, although the amounts of the distortions are different, a tendency of distortion of measured fluctuation profile is the same as the simulation of Fig. 3.

4 Discussion

In a case of low frequency range fluctuation, like MHD fluctuation, net electron fluctuation is the same phase as proton fluctuation. However, in the case of higher frequency range fluctuation or the plasma including impurities, the net electron fluctuation cannot be the same phase as proton fluctuation.

We consider the two cases that net electron fluctuations are in-phase and anti-phase to ion fluctuations, as a extreme case. Assuming infinitesimal correlation in a homogeneous plasma, $\gamma(x, y) = \delta(x, y)$ and $dx_i dy_i = \delta(x_i - y_i) dx_i dy_i$. In the case of the net electron and proton fluctuation are in-phase, the ensemble averaged Eq. (4) is deformed, $\overline{\eta}^2 = \overline{\xi}^2 \left[\overline{T}_0 - \overline{S}_\mathrm{C} + \overline{A}_\mathrm{C}\right]$, where $\overline{T}_0 = 1$, $\overline{S}_\mathrm{C} = 2\sqrt{2\pi}\hat{\overline{l}}_\mathrm{C}\overline{n}_\mathrm{e} \sum_{i=1,2}\left\{S^i_\mathrm{ei} + S^i_\mathrm{Loss}\right\}$ and $\overline{A}_\mathrm{C} = \sqrt{2\pi}\hat{\overline{l}}_\mathrm{C}\overline{n}^2_\mathrm{e} \sum_{i=1,2}\left\{(S^i_\mathrm{ei})^2 + (S^i_\mathrm{Loss})^2\right\}\hat{L}_i$. Overline expresses constant in the homogeneous plasma. The terms $\hat{L}_1$ and $\hat{L}_2$ are normalized lengths of primary and secondary beam, respectively. A path integral coefficient $\overline{\Phi}$ is defined as $\overline{\Phi} \equiv (\overline{S}_\mathrm{C} + \overline{A}_\mathrm{C})/\overline{T}_0$, and furthermore, a distortion coefficient $\overline{D}_\mathrm{ist}$ is defined as $\overline{D}_\mathrm{ist} \equiv (-\overline{S}_\mathrm{C} + \overline{A}_\mathrm{C})/\overline{T}_0$. The distortion ratio indicates the measured fluctuation distorts the local fluctuation. In the case of anti-phase on the same assumptions, the ensemble averaged Eq. (4) is deformed, $\overline{\eta}^2 = \overline{\xi}^2 \left[\overline{T'}_0 - \overline{S'}_\mathrm{C} + \overline{A'}_\mathrm{C}\right]$, where $\overline{T'}_0 = \left(S^{12}_\mathrm{ei}/S^{12}\right)^2 + \left(S^{12}_\mathrm{Loss}/S^{12}\right)^2$, $\overline{S'}_\mathrm{C} = 2\sqrt{2\pi}\hat{\overline{l}}_\mathrm{C}\overline{n}_\mathrm{e} \sum_{i=1,2}\left\{(S^i_\mathrm{ei})^2 + (S^i_\mathrm{Loss})^2\right\}/S^{12}$ and $\overline{A'}_\mathrm{C} = \sqrt{2\pi}\hat{\overline{l}}_\mathrm{C}\overline{n}^2_\mathrm{e} \sum_{i=1,2}\left\{(S^i_\mathrm{ei})^2 + (S^i_\mathrm{Loss})^2\right\}\hat{L}_i$. A path integral coefficient in the case of anti-phase $\overline{\Phi'}$ is defined as $\overline{\Phi'} \equiv (\overline{S'}_\mathrm{C} + \overline{A'}_\mathrm{C})/\overline{T'}_0$.

Figure 5 (a) shows D_ist with $\hat{L}_1 = \hat{L}_2 = 1$ and $l_\mathrm{C} = 120$mm. The distortion coefficient $D_\mathrm{ist} = 0$ means that the measured fluctuation amplitude can be the same as the local fluctuation amplitude, as a result of the screening and accumulating effects. Positive or negative D_ist represent that the measured fluctuation amplitude can increase or decrease from the local fluctuation amplitude. In the case of $n_\mathrm{e} = 1 \times 10^{19}\mathrm{m}^{-3}$ and $T_\mathrm{e} = 2$keV, the distortion ratio is negative ($D_\mathrm{ist} = -0.8$), which is consistent with the measured fluctuation amplitude reduced at center in the case Fig. 3 (c). The ratio $\overline{\Phi'}/\overline{\Phi}$ shown in Fig. 5 (b) increases as the density increase, and is 0.2 at $n_\mathrm{e} = 1 \times 10^{19}\mathrm{m}^{-3}$ and $T_\mathrm{e} = 2$keV. This means that the path integral effect in the case of the anti-phase is 20 % of that in the case of in-phase. Hence, the case of anti-phase is more local measurement than that of in-phase.

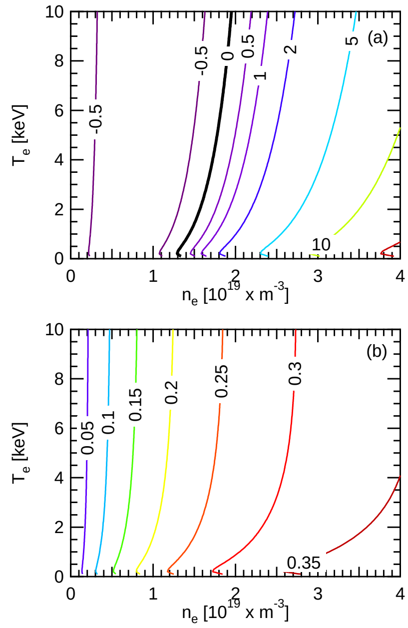

Fig. 5 (a) Contours of the distortion coefficient $\overline{D}_\mathrm{ist}$ with $l_\mathrm{C} = 120$mm and (b) the ratio of the path integral coefficients $\overline{\Phi'}/\overline{\Phi}$

5 Summary

The path integral effect on the density fluctuation measurement by use of MeV-range HIBP system is estimated. When net electron and proton fluctuations are in in-phase, the equation of the measured fluctuation is the same formula as a few keV-range HIBP system. And, the path integral effect of MeV-range HIBP system is much larger due to the proton ionization. If the net electron and proton fluctuations are in anti-phase, the fluctuation can be measure more locally.

[1] A. Fujisawa, H. Iguchi, S. Lee, and Y. Hamada, Rev. Sci. Instrum. **68**, 3393 (1997).

[2] A. Shimizu, A. Fujisawa, S. Ohshima, and H. Nakano, Rev. Sci. Instrum. **76**, 043504 (2005).

[3] H. Nakano, *et al*, Rev. Sci. Instrum. **78**, 063502 (2007).

[4] T. Ido, *et al*, Rev. Sci. Instrum. **77**, 10F523 (2006).

[5] M. Nishiura, *et al*, J. Plasma Fusion Research (2007) *in press*.