§16. Reconstruction Method of Local Density Fluctuation Spectrum with a Heavy Ion Beam Probe

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A heavy ion beam probe (HIBP) can measure density fluctuation from the detected beam fluctuation, although the measured fluctuation contains so-called path integral effects. This report describes a method to reconstruct the normalized local density fluctuation, $\xi = \mathrm{d}n_e/n_e$, from the normalized detected beam fluctuation, $\eta = \mathrm{d}I_d/I_d$, and presents the obtained spectrum of local density fluctuation in CHS. The relation between these two quantities ξ and η are written in the following integral equation for each frequency,

$$\begin{aligned}\langle\eta^2(\rho_*)\rangle &= \langle\xi^2(\rho_*)\rangle \\ &- 2\int\langle\xi(\rho_*)\xi(\rho_1)\rangle S_1(\rho_1)\mathrm{d}l_1 \\ &- 2\int\langle\xi(\rho_*)\xi(\rho_2)\rangle S_2(\rho_2)\mathrm{d}l_2 \\ &+ \iint\langle\xi(\rho_1)\xi(\rho_1')\rangle S_1(\rho_1)S_1(\rho_1')\mathrm{d}l_1\mathrm{d}l_1' \\ &+ \iint\langle\xi(\rho_2)\xi(\rho_2')\rangle S_2(\rho_2)S_2(\rho_2')\mathrm{d}l_2\mathrm{d}l_2' \\ &+ 2\iint\langle\xi(\rho_1)\xi(\rho_2')\rangle S_1(\rho_1)S_2(\rho_2')\mathrm{d}l_1\mathrm{d}l_2'\end{aligned} \quad (1)$$

where S_i and $\mathrm{d}l_i$ represent ionization ratio which describe electron density, n_e, and temperature, T_e, and line element of beam orbit, respectively. Subscripts *, 1 and 2 indicate ionize point, primary and secondary beam orbits, respectively. A bracket, $\langle\rangle$, means ensemble average. If $\langle\xi(\rho_i)\xi(\rho_j)\rangle$ can replace $|\xi(\rho_i)||\xi(\rho_j)|\exp(-\Delta_{ij}^2/l_c^2)$, a correlation length, l_c, can be defined, where Δ_{ij} is a distance between ρ_i and ρ_j.

In Eq. (1), the ionization position and the distance are known from trajectory calculation, η is measured with HIBP, and n_e and T_e are also measured with other diagnostics. Hence, the normalized density fluctuation ξ can be obtained by solving Eq. (1) with an iteration method if the correlation length l_c is given.

The CHS-HIBP measures simultaneously neighboring three positions, where distance is a few centimeter, and l_c can evaluate approximately from coherence of detected beam fluctuations. Using this approximation, the iteration process to solve Eq. (1) succeeds in finding solutions in a higher frequency range above 50 kHz, while it fails in lower frequency.

This is caused by the fact that the correlation length appears to become longer than the actual value because of path integral effect on the correlation length. The fluctuations of local three channels are strongly affected by the fluctuations in the outer plasma regions, where the density fluctuation is large. The correlation between detected beam fluctuations at two neighboring points is related to that between the corresponding local density fluctuations, as

$$\langle\eta^*(\rho_a)\eta(\rho_b)\rangle = \langle\xi^*(\rho_a)\xi(\rho_b)\rangle + \beta^2(\xi^*(\rho_a),\xi(\rho_b)), \quad (2)$$

where superscript * indicates complex conjugate, and β^2 is path integral term which has eight integral terms. The term β^2 should be necessary to be estimated to obtain the local power density in the low frequency regime, where the iteration process fails. As the first order approximation, we evaluate the correlation length by substituting η instead of ξ into the term, $\beta^2(\xi^*(\rho_a),\xi(\rho_b))$, of Eq. (2).

Figure 1 show correlation length as a function of radius before and after this correction at 10 kHz for the plasma maintained by ECRH with parameters, $n_e \sim 0.5\times10^{19}\ \mathrm{m}^{-3}$ and $T_e(0) \sim 1.5\ \mathrm{keV}$ in CHS. Before correction, gray line in Fig. 1, correlation length has a maximum around $r/a = 0.85$ and gradually decreases toward the center. After correction, black line in Fig. 1, the correlation length takes a maximum at the same radius, but the length become much shorter inside $r/a < 0.7$. Hence, the path integral effect on the correlation length is quite large in this region.

We succeed in estimating the power spectra of local density fluctuation by using corrected correlation length. Figure 2 shows an example of the reconstructed power spectrum of local density fluctuation, whose position is $r/a = 0.26$ in $n_e = 1.0\times10^{19}\ \mathrm{m}^{-3}$ and $T_e(0) \sim 1.0\ \mathrm{keV}$ maintained by ECRH. The result shows that the path integral effect is larger in low frequency than in high frequency. The proposed method expands the applicability of HIBP to higher density regime where the path integral effect largely deviates the detected beam fluctuation from the local density fluctuation. It helps understanding physics of high-density plasma, for example, NBI plasma, density collapse, etc.

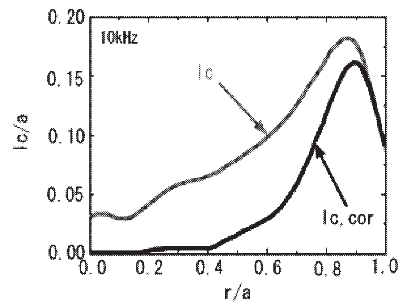

Fig.1. Correlation lengths before (gray line) and after (black line) the correction at 10 kHz.

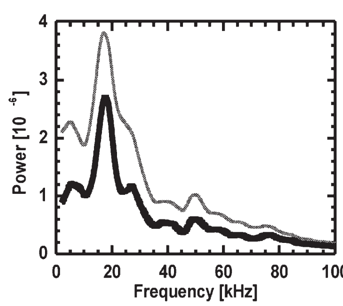

Fig. 2. Detected beam (gray line) and local density fluctuation (black line) spectrum.