§40. The Measurement of Magnetic Field Fluctuation with Heavy Ion Beam Probe on LHD

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In the measurement with Heavy Ion beam probe (HIBP), the information of magnetic field fluctuation in the core plasma can be obtained by observing the shift of beam in the horizontal (toroidal) direction. From measured beam shift, the toroidal component of vector potential of magnetic field can be estimated. However, this is not a pure local measurement, because that the temporal change of magnetic field on the beam path makes an effect on this measurement. This effect is so called "path integral effect". Here, the amount of path integral effect in the magnetic field fluctuation measurement with HIBP in LHD is estimated and reported.

By using the axisymmetric approximation, the fluctuation of toroidal shift of probing beam at detector is expressed as follows,

$$R_D\tilde{\phi}_D = \alpha R_S \tilde{A}_{\phi S}\int_{\ell_S}^{\ell_D}\frac{1}{R^2}d\ell - \alpha\int_0^{\ell_S}\frac{\tilde{A}_\phi}{R}d\ell - 2\alpha\int_{\ell_S}^{\ell_D}\frac{\tilde{A}_\phi}{R}d\ell \ . \quad (1)$$

Here, ℓ are the beam path length, and $\alpha \equiv qR_D/mv$. R, A_ϕ are the major radius, the toroidal component of vector potential. The tilde means the fluctuation of variable is taken. The subscript D (S) shows the quantity is at the detector (sample volume). The first term of right hand side (RHS) is the local term, which is proportional to the fluctuation at the sample volume. The second (third) term is the integral of fluctuation over the primary (secondary) beam path. In the analysis of fluctuation, the ensemble average of square of Eq. 1 is taken, as follows,

$$\left\langle \left(R_D\tilde{\phi}_D\right)^2 \right\rangle = A_1 + B_1 + B_2 + C_{11} + C_{12} + C_{22} \ . \quad (2)$$

A_1 is the ensemble average of square of local term (first term in Eq. 1). B_1 (B_2) is the first order of path integral term, which is the ensemble average of product of the first and second (third) term in RHS of Eq. 1. C_{11}, C_{12}, C_{22} are the second order of the path integral terms. B_i and C_{ij} contain the path integral of correlation of fluctuation between two positions. In order to estimate the effect of path integral, we assume that these correlations are expressed as follows,

$$\left\langle \tilde{A}_\phi(\ell_i)\tilde{A}_\phi(\ell_j) \right\rangle = P_{ij}\gamma_{ij}\Psi_{ij} \ . \quad (3)$$

The P_{ij} is the product of the fluctuation amplitude, which is defined as $P_{ij} = P_i \cdot P_j$. For the profile of fluctuation amplitude, the Gaussian function is used,

$$P_i = \tilde{A}_{\phi\max}\exp\left[-\left(\rho_i-\rho_0\right)^2/\rho_w^{\ 2}\right]. \quad (4)$$

The $\tilde{A}_{\phi\max}$ is the maximum value of fluctuation amplitude. The γ_{ij}, Ψ_{ij} are the coherence and the phase, which are assumed as follows, $\gamma_{ij} = \exp(-|\mathbf{r}_i-\mathbf{r}_j|^2 / \ell_c^2)$, $\Psi_{ij} = \cos(m(\theta_i-\theta_j))\cos((\rho_i-\rho_j)/2\pi\lambda_\rho)$. ℓ_c, θ, m, λ_ρ are the coherence length, the poloidal angle, the poloidal mode number, the normalized radial wave length. In the calculation, the toroidal shift normalized by $\tilde{A}_{\phi\max}$ is calculated. In Fig.1, an example of calculation results to estimate the path integral effect in LHD is shown. For the fluctuation profile P_i, $\rho_0 = 0.25$, $\rho_w = 0.1$ are assumed. For the mode structure, $m = 2$, $\lambda_\rho = 10^4$ are assumed. In the figure, solid line shows the result in case that the path integral effect is neglected artificially. Other three dotted lines are results in case that $\ell_c = 0.01$, 0.1, 1 m. In the region close to the peak of fluctuation ($\rho \sim 0.25$), the path integral effect is small and the measured profile of fluctuation is very similar to the no path integral case. However, in the region far from the fluctuation peak, the phony signal appears which reaches to 10 % of the maximum of fluctuation amplitude.

The detectable level of magnetic field fluctuation in LHD is estimated. In this estimation, the experimental conditions are assumed as follows. The width of beam is 2 cm, the total secondary beam current is 200 pA, detectable level of secondary beam current variation is 1 pA. In this case, the detectable level is about 4.0×10^{-5} T. This is one order worse than that of Mirnov coil, however the fluctuation level in the plasma is larger than in the outside of plasma, so the measurement of magnetic field fluctuation with HIBP will be possible.

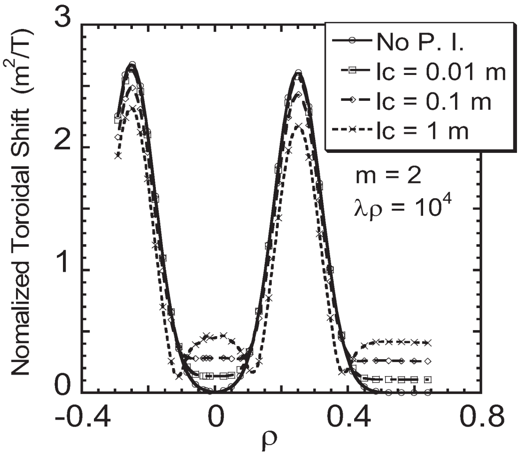

Fig.1. The normalized toroidal shift as a function of sample volume position is shown.