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Simulation of Path Integral Effects for the Magnetic Field Fluctuation Measurement by a Gold Neutral Beam Probe in the Tandem Mirror GAMMA 10

KOJIMA Atsushi, ISHII Kameo, TAKEMURA Yuichiro, HAGISAWA Kazuhisa, MIYATA Yoshiaki, ITAKURA Akiyosi, ICHIMURA Makoto and CHO Teruji

Plasma Research Center, University of Tsukuba, Ibaraki 305-8577, Japan

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Abstract

The path integral effects were simulated for the magnetic field fluctuation measurement using a gold neutral beam probe method. In this simulation, we considered separately the influence of the magnetic field fluctuation components (ΔB_r, ΔB_θ and ΔB_z) on the path integral effects. The deflection caused by the azimuthal fluctuation component ΔB_θ is 2 [mm] on the detector surface in case of the central passing beam, whereas the deflection caused by ΔB_r is about 0.2 [mm]. The beams are mainly influenced by ΔB_θ. It was found that use of the energy sweeping beam was effective to estimate the ΔB_θ. We obtained the criterion of the magnetic field fluctuation measurement using the gold neutral beam probe.

Keywords:

magnetic field fluctuation, fluctuation measurement, beam probe, path integral effect, mirror, GAMMA 10

1. Introduction

In the tandem mirror GAMMA 10, confinement potentials are generated by carrying out electron cyclotron resonance heating at both plug regions of the plasma. The generated potentials are measured with the gold neutral beam probes (GNBP) using gold neutral particle as the primary beam. We measured the radial and two-dimensional profiles of the potentials by the GNBPs installed in the central cell and the barrier cell [1,2], and also measured fluctuations with low and high frequencies [3]. However, the beam probe methods always contain the problem of the path-integrated signals as the path integral effects [4]. It is quite important to estimate the path integral effects in the beam probe methods. An improved electrostatic analyzer in the GNBP system was newly installed in the central cell as shown in Fig. 1. Two types of microchannel plate detectors are used in the analyzer, that is, one is used for the potential measurement, and the other is used for the magnetic field fluctuation measurement. Because of using the neutral particle as the primary beam, only the orbits of the singly charged secondary ion beam are influenced by the change of the magnetic field. This is an important point different from the Heavy Ion Beam Probe (HIBP) methods. Therefore, the path integral effects appear only on the orbits of the secondary beam in the measurement of the magnetic field fluctuation.

2. Principle of magnetic field fluctuation measurement using GNBP

The orbits of the secondary ion beam are influenced by the magnetic field fluctuation excited in the plasma. The shift of the detected position of the secondary beam on the detector includes the information of the path-integrated magnetic field fluctuation. As the axial velocity v_z of the secondary beam is much smaller than the radial velocity v_r and the azimuthal velocity v_θ, the fluctuation components of the Lorenz force caused by the fluctuation components $\Delta B_{r,\ \theta,\ z}$ of the magnetic field are described approximately as follows,

$$\begin{pmatrix} \Delta F_r \\ \Delta F_\theta \\ \Delta F_z \end{pmatrix} = q \begin{pmatrix} v_\theta \Delta B_z - v_z \Delta B_\theta \\ v_z \Delta B_r - v_r \Delta B_z \\ v_r \Delta B_\theta - v_\theta \Delta B_r \end{pmatrix} \approx \begin{pmatrix} v_\theta \Delta B_z \\ -v_r \Delta B_z \\ v_r \Delta B_\theta - v_\theta \Delta B_r \end{pmatrix}.$$

The component ΔF_z moves the secondary beam along the z-axis, though the radial component ΔF_r and the azimuthal component ΔF_θ change the injection angle of the secondary beam into the analyzer. We pay attention to the component ΔF_z and estimate the path-integrated value of the magnetic field fluctuation, because ΔF_z does not have any influences on the potential measurement.

Corresponding author's e-mail: kojima@prc.tsukuba.ac.jp

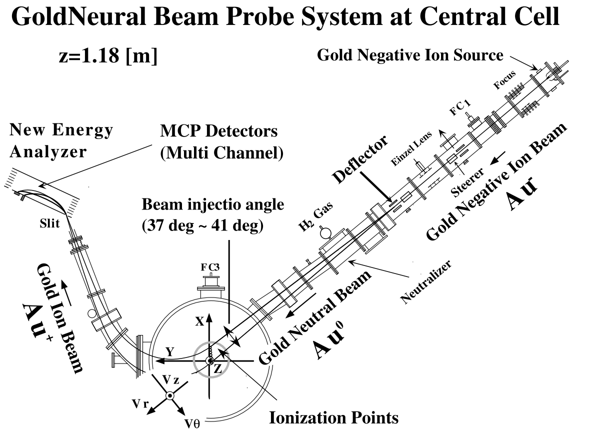

Fig. 1 The schematic GNBP system in the central cell. Coordinates are as shown in figure. An improved analyzer was newly installed. The primary beam of gold neutral particle is ionized in the plasma region, and the secondary ion beam enters the analyzer.

3. Beam simulation in the plasma with the magnetic field fluctuation

3.1 Simulation parameters

It is necessary to estimate the beam deflection caused by the magnetic field fluctuation. In this simulation, we examined the trajectories of the secondary gold ion beams moving in the magnetic field of the GAMMA 10. The magnetic field fluctuation $\widetilde{B}_1$ is independently assumed to be described as follows,

$$\widetilde{B}_1(r,\theta,z) = \begin{pmatrix} B_1\cos(\omega t+\phi)\cdot\hat{r} \ (r \le 0.2[\mathrm{m}]),\ 0 \ \ (r > 0.2[\mathrm{m}]) \\ B_1\cos(\omega t+\phi)\cdot\hat{\theta} \ (r \le 0.2[\mathrm{m}]),\ 0 \ \ (r > 0.2[\mathrm{m}]) \\ B_1\cos(\omega t+\phi)\cdot\hat{z} \ (r \le 0.2[\mathrm{m}]),\ 0 \ \ (r > 0.2[\mathrm{m}]) \end{pmatrix},$$

where B_1 is the magnitude of the fluctuated magnetic field, ω is the angular frequency of the fluctuation, ϕ is the initial phase at the ionization point of the secondary beam, and $\hat{r}$, $\hat{\theta}$, $\hat{z}$ are the radial, azimuthal, axial unit vectors, respectively. We consider the phase dependency by changing from 0 to

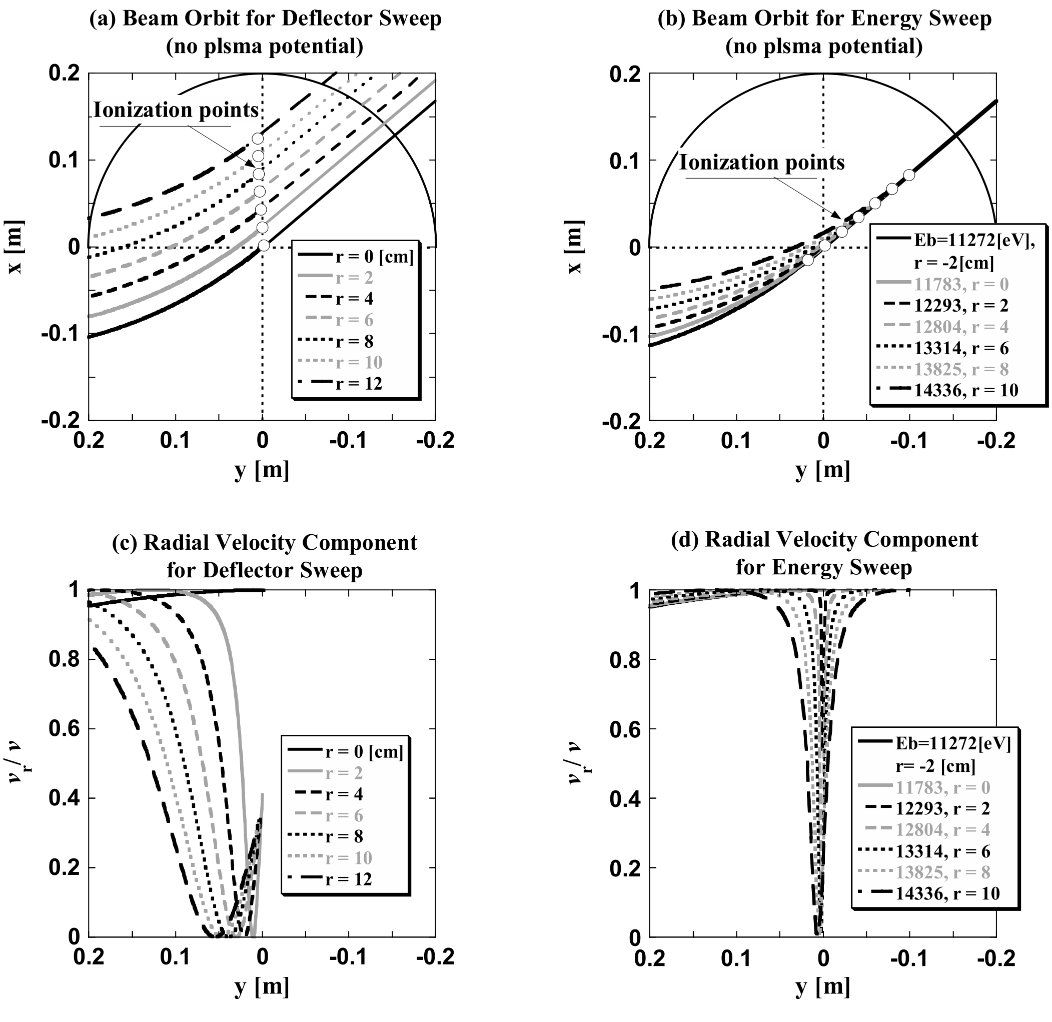

Fig. 2 Beam orbits and radial velocity components. The electrostatic potential was assumed to be zero. (a) Orbits for the vertical sweeping beams by changing the injection angle. The ionization points move to above along the x-axis. Each line shows the radial position of ionization points that can enter the analyzer. (b) Orbits for the energy sweeping beams. The ionization points move to backward along the beam path. (c) The ratio of radial velocity component to the beam velocity with the vertical sweeping beams. (d) The ratio of radial velocity component to the beam velocity with the energy sweeping beams.

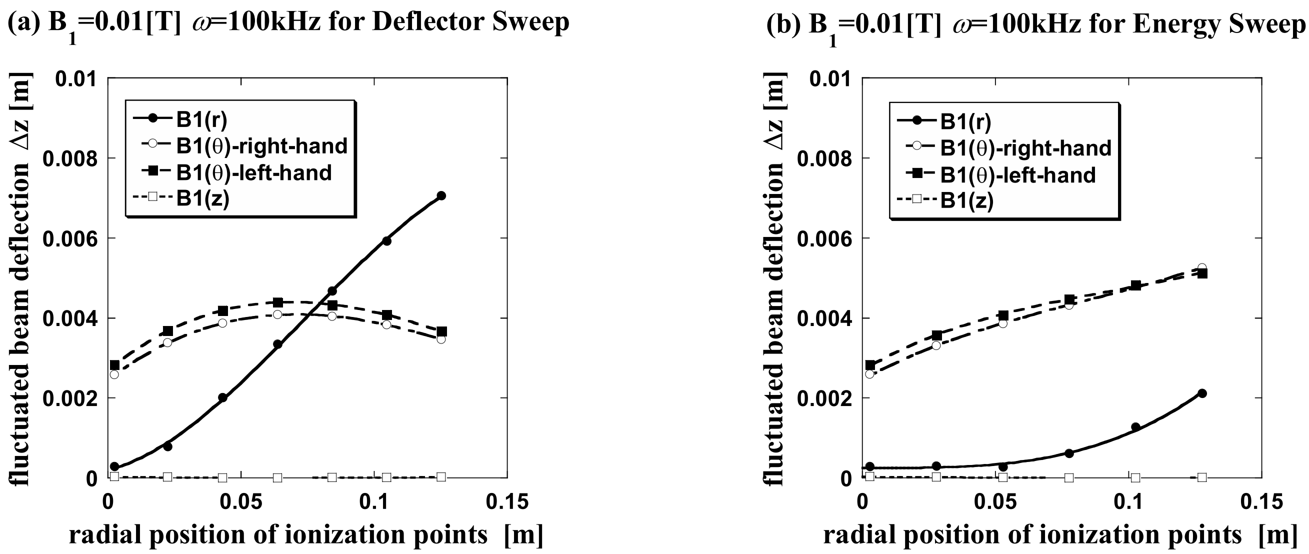

Fig. 3 Radial profiles of the beam deflection. The single component of $\tilde{B}_1$, B_1=0.01 [T], the frequency of 100 [kHz], were assumed. The vertical axis shows the fluctuated deflection amplitude Δz. The horizontal axis shows the radial position of ionization points. (a) In case of the vertical sweeping beam. (b) In case of the energy sweeping beam.

2π. In order to clear the path integral effects, we assume that $\tilde{B}_1$ has simple profile and only one component, that is, the radial component, or azimuthal component, or axial component. We estimated the detected position of the secondary beam shifted in the direction of the z-axis due to one component of $\tilde{B}_1$.

3.2 Velocity component of the secondary beam

At first, we estimated the influence of the velocity components (v_r, v_θ) on the injection angle of the secondary beam into the analyzer. In the GNBP method, the radial profile is measured by sweeping the beam energy or the injection angle of the primary beam into the plasma. The measurable points are moved along the path of the primary neutral beam by changing the beam energy, and also moved along the vertical axis by changing the injection angle, as shown in Fig. 2(a)(b). The paths of the secondary beam are almost the same in case of the energy sweeping, though the secondary beam has various paths in case of vertical sweeping.

Figure 2(c) and 2(d) show the ratio (v_r/v) of the radial velocity components to the total velocity, respectively. In case the primary beam is ionized near the center of the plasma, the ratios (v_r/v) are large in both sweeping, However, in case of ionizing near the plasma edge (r ~ 0.2 [m]), the ratio in the vertical sweeping is smaller than the ratio in the energy sweeping.

Therefore the vertical sweeping beams were influenced by radial and azimuthal components of $\tilde{B}_1$ in the core plasma region (r < 0.2 [m]). It seems that the beam deflection parallel to the z-axis is caused by both radial and azimuthal components of $\tilde{B}_1$. When we measure the radial profile of the vertical sweeping, we can not separate the radial and azimuthal components of the path-integrated magnetic field fluctuation. But the energy sweeping beams are almost influenced by azimuthal component of $\tilde{B}_1$, because the beams have large ratio of v_r/v in the core plasma region. Then the beam deflection profile by the energy sweeping beams will be sensitive to the azimuthal component of the path-integrated magnetic field fluctuation.

3.3 Radial profile of the beam deflection

Figures 3(a) and 3(b) show the deflection of the secondary beams in cases of the vertical and energy sweeping, respectively. We assume that the magnitude B_1 of the fluctuated magnetic field is 0.01 [T] and the frequency is 100 [kHz]. In the profile with the vertical sweeping beams, the beam deflection caused by the azimuthal component is dominant in the small region (r < 0.05 [m]) and the beam ionized near the plasma edge is sensitive to the fluctuation of radial component. As the estimation of the velocity component, the vertical sweeping beams are influenced by the radial and azimuthal components of the magnetic field fluctuation. But in the profile with the energy sweeping beams, the beam deflection is mainly caused by the azimuthal component, because radial velocity component is dominant in the core plasma region. The beam passing plasma edge is slightly influenced by the radial $\tilde{B}_1$, because the radial velocity of the beam ionized near the plasma edge decreases when the secondary beam passes the center of the plasma. As a result, the deflection is mainly caused by the azimuthal $\tilde{B}_1$ excited within the radius of 0.1 [m].

4. Potential cross-talk effect

We estimated the "Potential Cross-Talk" effect in which the detected position of the secondary beam shifted along z-axis by both increasing the electrostatic potential and changing the magnetic field. Figure 4 shows the beam detected position calculated on the assumption that the plasma potential Φ was a Gaussian type described as following expression,

$$\Phi = \Phi_0 \times \exp\left(-\frac{r^2}{{r_0}^2}\right),$$

where Φ_0 is the electrostatic potential at the center and r_0 is the 1/e radius and assumed to be 0.1 [m]. The each sensitivity of the deflection parallel to the z-axis is -1.6×10^{-6} [m/V] for the electrostatic potential and 0.03 [m/T] for the non-fluctuated $\tilde{B}_1$. We adopt the strong magnetic field (B_1 = 0.01 [T]). Therefore, it is necessary for the magnetic field fluctuation measurement by GNBPs that the potential and the beam deflection are measured simultaneously.

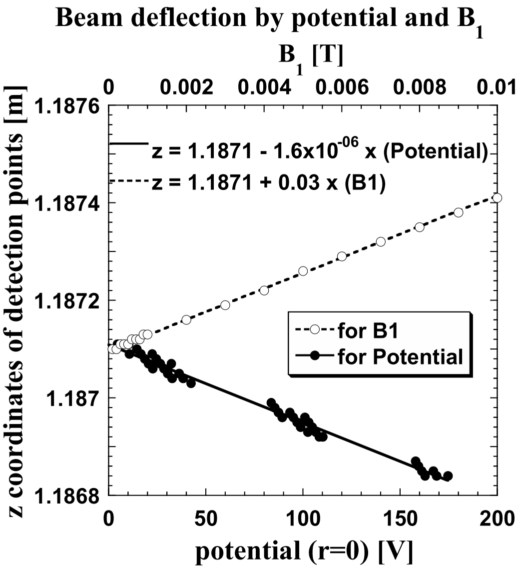

Fig. 4 Beam deflections caused by the electrostatic potential and non-fluctuated $\tilde{B}_1$ was estimated at various magnitude. The electrostatic potential was assumed to be a Gaussian profile with the 1/*e* radius 0.1 [m]. The initial z coordinate of the secondary beam is *z* = 1.186 [m]. The beam energy with the electrostatic potential increasing brings the beam deflection close to zero.

5. Summary

We simulated the beam deflection on the assumption that the radial, azimuthal or axial magnetic field fluctuations existed. We found that the beam deflection of the vertical sweeping beam was caused by both the radial and azimuthal components of the magnetic field fluctuation, but in case of the energy sweeping beam the deflection was mainly due to the azimuthal magnetic field fluctuation. In the magnetic field fluctuation measurement by GNBP methods, there was the “Potential Cross-Talk” effect. The each sensitivity of the deflection was -1.6×10^{-6} [m/V] for the electrostatic potential and 0.03 [m/T] for the non-fluctuated $\tilde{B}_1$.

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