

Simultaneous measurements of density and potential fluctuation with heavy ion beam probe in the Compact Helical System

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Density and potential fluctuations are simultaneously measured, using a heavy ion beam probe, in electron cyclotron resonance heated plasmas of the Compact Helical System. The spectra of density and potential fluctuations are presented with radial profiles of these fluctuation amplitudes. Local density fluctuations are evaluated by removing the path integral effect under the simplest assumption that the correlation length of the fluctuations is infinitesimally short. © 2004 American Institute of Physics. [DOI: 10.1063/1.1784513]

I. INTRODUCTION

A heavy ion beam probe (HIBP)¹ is a powerful tool to investigate the plasma fluctuations and fluctuation-driven transport since the diagnostic can measure simultaneously density and potential fluctuations, even in the plasma core of high temperature. Measurements of density fluctuations using a HIBP have been reported in many devices, e.g., Impurity Study Experiment Tokamak-B (ISX-B),² Torus Experiment for Technology (TEXT),³ Advanced Toroidal Facility (ATF),⁴ Compact Helical System (CHS),⁵ Japanese Institute of Plasma Physics Torus-II Upgrade (JIPP-TIIU),⁶ and JAERI Fusion Torus-2 Modified (JFT-2M),⁷ while potential fluctuation measurements have not been successfully achieved in so many cases; the experiments of ISX-B and TEXT tokamaks^{2,3} are examples of simultaneous measurements of density and potential fluctuations.

In CHS, the HIBP has been used to measure mainly the potential profile and its dynamics and density fluctuations with a high temporal ($\sim \mu\text{s}$) and spatial resolution ($\sim \text{mm}$). These observations contribute to understanding the bifurcation physics including transport barrier formation in toroidal plasmas. In order to obtain further understanding of plasma transport, we have developed an intense ion source to fully utilize the capabilities of the HIBP, that is, simultaneous measurements of density and potential fluctuations. In this article, we present the initial results of simultaneous measurements of density and potential fluctuations in CHS plasma with electron cyclotron resonance (ECR) heating, and discuss the path integral effect on density fluctuations.

II. EXPERIMENTAL SETUP

CHS⁸ is a helical device whose major radius is $R=1.0$ m and averaged minor radius is $\langle a \rangle=0.2$ m. The

HIBP of CHS consists of a 200 keV accelerator and a 30° parallel plate energy analyzer. A feature of this system is that the beam trajectories are controlled using a secondary beam sweep system, in addition to the standard primary beam system. This method gives a wider observation range covering almost the whole plasma.

The secondary beam is detected with a split plate detector in an energy analyzer. The detected beam current I_d is expressed as the product of local birth rate of the secondary beam and attenuation of beam orbits, explicitly written as⁹

$$I_d = I_0 \left(n_e \frac{\langle \sigma_{12} v_e \rangle}{v_b} \right) w_s \exp \left(- \int n_e \frac{\langle \sigma_1 v_e \rangle}{v_b} d\ell_1 - \int n_e \frac{\langle \sigma_2 v_e \rangle}{v_b} d\ell_2 \right), \quad (1)$$

where I_d , v_e , v_b , w_s , n_e , σ_{12} , σ_1 and σ_2 represent injected beam current, electron thermal velocity, beam velocity, sample volume length, electron density, ionization rate at the sample volume, the ionization cross section from the first to the other ionized states and that from the second to the others, respectively. The detected beam current fluctuations can reflect the local density fluctuations if the fluctuations on the beam orbits (or attenuation contribution) are negligible.

The energy difference between the primary and secondary beam current corresponds to the potential at the ionization point.¹ Hence, the detected beam energy fluctuations reflect the potential fluctuations. The beam energy is measured from the beam displacement on the split plate detector in the energy analyzer. The potential change (or beam energy change) $\delta\phi$ is related to the current difference between the upper and bottom plates in the detector, I_d . The minimum potential fluctuation is expressed as $\delta\phi \sim D_\phi (\delta I_{d,\min}/I_d)$ with D_ϕ and $\delta I_{d,\min}$ being the dynamic range of measured potential and the minimum of the detectable current difference, respectively.

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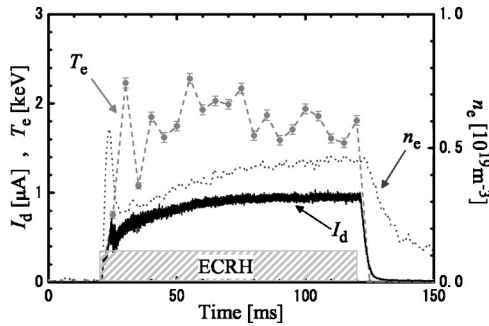


FIG. 1. Time evolutions of a typical ECRH plasma. The dotted and solid lines represent the line average density measured with an interferometer, and the detected beam current of the HIBP. The closed circles show central electron temperature measured with Thomson scattering.

By employing the Boltzmann relation, $e\delta\phi/T_e \sim \delta n_e/n_e$, the condition for the necessary beam current is written as $I_d > \delta I_{d,\min}(eD_\phi/T_e)(n_e/\delta n_e)$. The dynamic range and the minimum detectable current in CHS HIBP are $D_\phi = 630$ V and $I_{d,\min} \sim 1$ nA, respectively. By assuming that density fluctuations are $\sim 1\%$ with $T_e \sim 100$ eV (i.e., potential fluctuation of ~ 1 V), the formula gives the necessary beam current of $I_d \sim 630$ nA. On the other hand, the necessary beam current for $\sim 1\%$ density fluctuation is only ~ 100 nA. Therefore, larger current should be necessary for potential fluctuations. Recent modification of the ion source increases the beam current from a few dozens μA to $\sim\text{mA}$. The increase in the beam current enables us to obtain potential fluctuations in addition to density fluctuation.

III. EXPERIMENTAL RESULTS

The measurements of density and potential fluctuations with HIBP were performed in the magnetic configuration with field strength of 0.88 T at the center of the vacuum chamber. In the present experiments, a 53 GHz gyrotron was used to sustain the hydrogen plasma. Figure 1(a) shows a set of typical wave forms of discharges; central electron temperature T_e measured with Thomson scattering, line average density n_e measured with an interferometer, and detected beam current I_d . The fluctuations are measured under steady state conditions, e.g., 90 m–100 ms in Fig. 1(a).

Figure 2 shows examples of fluctuation power spectra of density and potential at $\rho \sim 0.68$. The potential fluctuation is normalized with the electron temperature ($T_e \sim 170$ eV) measured with the Thomson scattering measurement. The HIBP data are acquired with a sampling time of 2 μs ; hence, the corresponding Nyquist frequency is 250 kHz. Here, a fluctuation spectrum is calculated using the fast Fourier transform method for data of ~ 1 ms (that is 512 data points). The spectra shown in the figures are the average of the ones obtained from ten sequential periods. The gain of the current–voltage converter used for our HIBP is 10^7 V/A, and the voltage of the noise corresponds to $I_{d,\min} \sim 1$ nA. The noise levels (gray lines) are estimated from the noise of the current–voltage converter.

Both spectra show broadband (or turbulence) characteristics. The power density decreases monotonically in the higher frequency range from ~ 70 kHz, and becomes close to

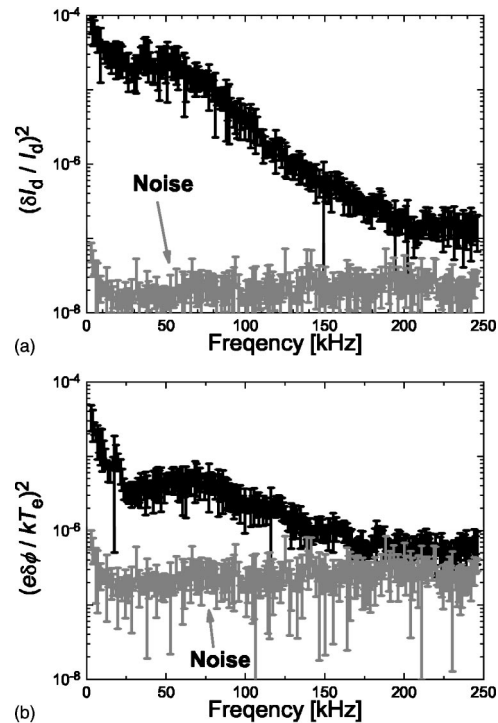


FIG. 2. Examples of density and potential spectra at $\rho = 0.68$. (a) The density fluctuation spectrum (black line) and the noise spectra (gray line). (b) The normalized potential fluctuation spectrum (black line) and the noise spectrum (gray line).

the noise level above ~ 200 kHz. The power of density fluctuation appears larger than that of the normalized potential. The fluctuation levels of these examples are 4.1% and 2.7% for density and normalized potential, respectively. The level of fluctuation amplitude is evaluated by taking the square root of the power density integrated from 10 to 250 kHz without noise.

Fluctuation spectra for the density and the normalized potential have been obtained for quite a wide range of plasma radius with spatial resolution of 2.5 mm in the ECR-heated plasma that has a line-averaged density ranging from 4×10^{18} to 6×10^{18} m^{-3} . Figure 3 shows the radial profiles of fluctuation level for density and potential in the region of $\rho < \sim 0.95$. The fluctuation signals outside $\rho \sim 0.95$ are below the noise level in our measurements. The solid line in Fig. 3 is the fitting curve with the assumed form $\alpha + \exp[(\rho - \rho_0)/\beta]$. The plot includes experimental data for five different campaigns. Both fluctuation levels show a rapid increase in the plasma periphery of $\rho > \sim 0.85$.

For comparison, the normalized potential fluctuation level is shown in Fig. 3(c), where the electron temperature profile is assumed as $T_e = 54 + 1.8 \times 10^3 \exp[-(\rho/0.1417)^2]$ eV. The level of the normalized potential fluctuation suffers from uncertainty due to rather large error bars of the Thomson scattering measurements owing to the poor photon scattering in the low density discharges. This suggests that the fluctuation level is stationarily $\sim 0.8\%$ in the region of $\rho < \sim 0.85$ with a drastic rise in the periphery of $\rho > 0.85$, and that the Boltzmann relationship should be satisfied in this region; the levels of density fluctuation are $\sim 2.2\%$. Note that the fluctuation level outside $\rho > 0.9$ is not

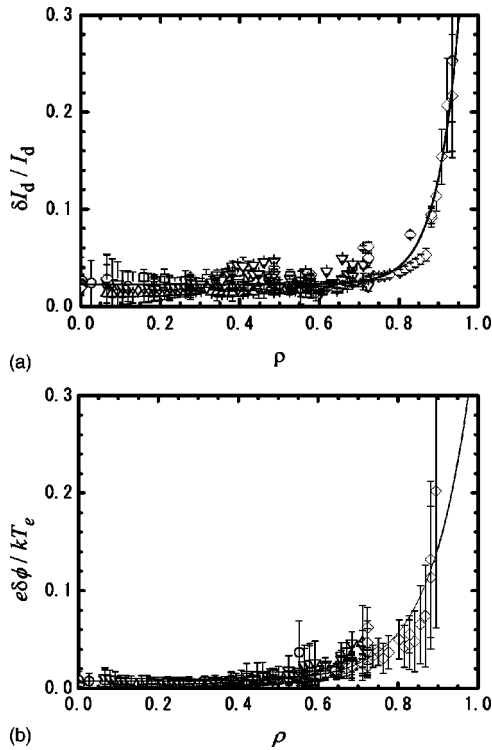


FIG. 3. (a) The radial profile of density fluctuation amplitudes (precisely the detected beam fluctuation amplitude). (b) The radial profile of potential fluctuations normalized by electron temperature. The solid line is a fitting curve to the data. Different symbols correspond to data taken from the different experimental sets performed on different days.

evaluated since both error bars of the potential fluctuation level and electron temperature are large. It is one of our future plans to investigate the validity of the Boltzmann relationship in the periphery.

IV. CONSIDERATION OF PATH INTEGRAL EFFECT

The density (or detected beam) fluctuation, which is contaminated with the density fluctuation along the beam orbits,⁹ cannot reflect purely local density fluctuations. From Eq. (1), the detected beam fluctuation is described as

$$\frac{\delta I_d}{I_d} = \frac{\delta n_e}{n_e} + \int \delta n_e \frac{\langle \sigma_1 v_e \rangle}{v_b} d\ell_1 + \int \delta n_e \frac{\langle \sigma_2 v_e \rangle}{v_b} d\ell_2, \quad (2)$$

if the electron temperature fluctuation, which may have a large contribution in the plasma edge, is neglected. The term on the left hand side corresponds to the measured detected beam fluctuation. The second and third terms on the right hand side represent the path integrated fluctuation along the primary and secondary beam orbits, respectively. By taking the square of the above equation, the fluctuation power is reduced into the following formula:

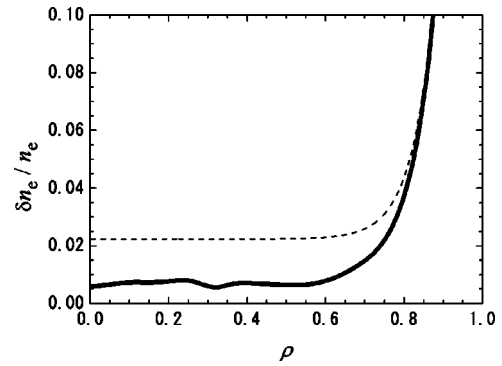


FIG. 4. The solid and dashed lines show the radial profiles of the estimated amplitude of local density fluctuation and measured amplitude of density (or detected beam) fluctuation (dashed line), respectively. The amplitude of detected beam fluctuation is the same as the fitting function in Fig. 3(a).

$$\begin{aligned} \left(\frac{\delta I_d}{I_d} \right)^2 &\sim \left(\frac{\delta n_e}{n_e} \right)^2 + \int \left(\frac{\delta n_e}{n_e} \right)^2 \left(n_e \frac{\langle \sigma_1 v_e \rangle}{v_b} \right)^2 d\ell_1 \\ &+ \int \left(\frac{\delta n_e}{n_e} \right)^2 \left(n_e \frac{\langle \sigma_2 v_e \rangle}{v_b} \right)^2 d\ell_2, \end{aligned} \quad (3)$$

under the simplest assumption that the correlation of density fluctuations is infinitesimally short. The power of local density fluctuations can be obtained by solving Eq. (3) as an integral equation, when the ionization cross sections on the orbits are known. The ionization cross-sections can be estimated using the Lotz's empirical formula.¹⁰ The solution can be found after iterations with the profile of detected beam intensity as the initial solution.

Figure 4 shows an estimated profile of density fluctuation levels together with the fitting curve of the beam fluctuation profile in Fig. 3. Here, we assumed that ionization rates are $\sigma_1 \sim \sigma_{12}^{\text{Lotz}}$ and $\sigma_2 \sim \sigma_{23}^{\text{Lotz}}$, and that density profile is $n_e = 5.0 \times 10^{18} [(1 - \rho^4)^2] \text{ m}^{-3}$. The same electron temperature profile used for the normalized potential fluctuation is assumed. The real beam trajectory of the CHS HIBP is used for this calculation. The result indicates that the profile can be significantly modified in the inner region of plasma, and that the level can be $\sim 0.5\%$.

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