Survey of diagnostic systems for the study of gyrocenter shifts on National Spherical Torus Experiment

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(Received 8 May 2006; presented on 11 May 2006; accepted 29 May 2006; published online 22 September 2006)

The formation of the radial electric field at the boundary of high temperature plasmas can be induced by the radial "gyrocenter shift" during the charge exchange process with neutrals. The model of the gyrocenter shift to be discussed here is different from the conventional gyrocenter drift. Specifically, in this model, the induced electric field is a strong function of neutral density and its gradient in addition to the conventional $E\times B$ and diamagnetic terms. The preliminary calculation of the gyrocenter shift of the *H*-mode plasma on the National Spherical Torus Experiment (NSTX) demonstrates the sensitive dependence of the radial electric field on the neutral density profile. An assessment of diagnostics on NSTX is carried out for the measurement of neutral density. The required spatial and time resolutions for the measurements are 2 mm and a few kilohertz, respectively. In this article, the predicted profile of the edge electric field on NSTX based on the gyrocenter shift model is discussed in conjunction with the in and out asymmetry of diverter *D*-alpha camera data and the measurement of the edge electron density by the far infrared tangential interferometer/polarimeter system.
[DOI: 10.1063/1.2220079]

I. INTRODUCTION

The origin of the sudden increase in the radial electric field strength at the high confinement mode (*H*-mode) transition on the boundary of fusion devices has been regarded as one of the incompletely understood phenomena in fusion research for decades.[1] Recently, a theoretical work concerning the gyrocenter shift was carried out in which the fundamental mechanism of radial electric field formation in conjunction with the plasma-neutral interaction is explained.[2] It is important to apply the effect of the gyrocenter shift to the experimental study in different time bases from the same plasma shot such as before and after the *H*-mode transition or on a shot to shot basis since this was not available in the previous theoretical work. The National Spherical Torus Experiment (NSTX) provides an opportunity for comparing the theory with the experimental result because NSTX operates over a broad parameter region including *H* mode.[3–5] The theoretical background and example calculations of the radial electric field due to the gyrocenter shift are introduced in Sec. II. The assessment of the required diagnostics for the neutral density measurement and radial electric field measurement with preliminary diagnostic results related to the gyrocenter shift are described in Sec. III which is followed by the conclusion.

II. RADIAL ELECTRIC FIELD CALCULATION OF THE *H*-MODE PLASMA BY GYROCENTER SHIFT ON NSTX

One of the important aspects in the theory of the gyrocenter shift is that the radial electric field and the radial current density are strong functions of the neutral density gradient. This was driven by the poloidal momentum change during the charge exchange reaction of the plasma ions with the boundary neutrals. The ion momentum loss occurs due to the random direction of the new ions after the exchange with the neutral atoms. The main poloidal velocity component of the incident ion at the reaction consists of three parts: $E\times B$ drift, diamagnetic drift, and the contribution by the neutral density gradient which is described by the gyrocenter shift. These three components are expressed in the following formula for the radial current density:[2]

$$J_r(r) = \frac{m_i n_i n_n}{B}\langle \sigma v_i\rangle\left(\frac{E}{B} - \frac{1}{q_i n_i B}\frac{\partial p_i}{\partial r} + \frac{T_i}{q_i n_n B}\frac{\partial n_n}{\partial r}\right). \quad (1)$$

Here, the ion mass m_i and ion charge q_i are constants while all other parameters (toroidal magnetic field B, radial electric field E, ion density n_i, neutral density n_n, reaction coefficient $\langle\sigma v_i\rangle$, ion pressure p_i, and ion temperature T_i) are functions of radial location. The plasma parameters for the calculation of radial electric field profile are indicated in Fig. 1; most parameters are taken from the measured data as done in Ref. 2 except for the neutral density. Since neutral density mea-

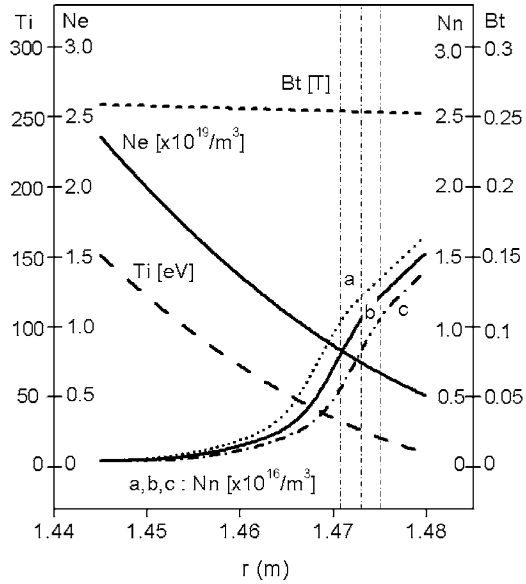

FIG. 1. Input data profiles of NSTX plasma parameters for the numerical calculation (No. 110077, t=0.24 s, H mode).

surement is not available on NSTX, the example neutral density profiles in Fig. 1 are estimated assuming that the neutral density profile has the same tendency with respect to the ion plasma density profile as was reported in Doublet III-D (DIII-D) experiments.[6] Due to the uncertainty of the location of the separatrix, three different examples of neutral density profiles are included in the calculation. Each profile in the three examples has a different location for the separatrix with a spacing of 2 mm between them. The result of the calculation is shown in Fig. 2. Although there are many factors not included in the calculation such as poloidal nonaxisymmetry, the calculation result in Fig. 2 is comparable with experimental measurement.[7] The calculation was performed for the same shot of the measurement in Ref. 7 at the middle of the H-mode period (0.24 s). The measured value of the radial electric field during the H-mode in Ref. 7 is approximately 5 ± 1 kV/m at the radius of 1.46–1.47 m.

III. REQUIREMENT OF DIAGNOSTICS FOR THE STUDY OF GYROCENTER SHIFT ON NSTX

The theory of the gyrocenter shift provides a mechanism of radial electric field formation that can be analyzed by the plasma parameters including neutral density profile. Therefore, neutral density measurement is essential for the study of the gyrocenter shift. One of the major diagnostic methods for the neutral density measurement employs calibrated D-alpha emission data. Since the emission intensity is a combined function of neutral density, plasma density, and plasma temperature, if the other parameters are measured the neutral density can be calculated. NSTX has high resolution D-alpha emission diagnostics[8] including divertor cameras. The plasma temperature and plasma density measurements in the area of the x point are required for the neutral density profile measurement in that region. The divertor probes and divertor Thomson scattering diagnostics can be used for this purpose. On the other hand, neutral measurement on the outboard midplane requires a calibrated D-alpha camera, since the existing Thomson scattering diagnostics provides electron density and temperature. The impurity concentration measurement at the boundary is also important because the major contribution to the gyrocenter shift is carried out by the main ions and their density is different from the electron density due to the impurity population (the calculation indicated in Fig. 2 includes impurities by setting the effective atomic number as 3.5). Neutral transport code simulation such as DEGAS-2 (Ref. 9) is required for the confirmation of neutral density measurement. Diagnostics for the radial electric field measurement are also required for the comparison of the theoretical calculation with the experimental result. Edge rotational diagnostic is already implemented on NSTX, and motional Stark effect diagnostic with boundary channels is required for the direct measurement of the radial electric field. There are many other measurements that can possibly provide evidence of the effect of gyrocenter shift. Figures 4 and 5 show examples of NSTX measurement related with the gyrocenter shift. Equation (1) contains three components of poloidal drift that provide the source of momentum loss. Among them, the diamagnetic drift is effective without interaction with neutrals. However, the diamagnetic drift is fictitious since there is not an actual physical gyrocenter drift. The contribution from the neutral density gradient in Eq. (1) is also fictitious in terms of poloidal drift since it exists only by taking the average over the circular motion on the interaction with neutrals. Consequently, there is no actual physical poloidal movement in this activity either. According to this analysis from the gyrocenter shift, the only real cross-

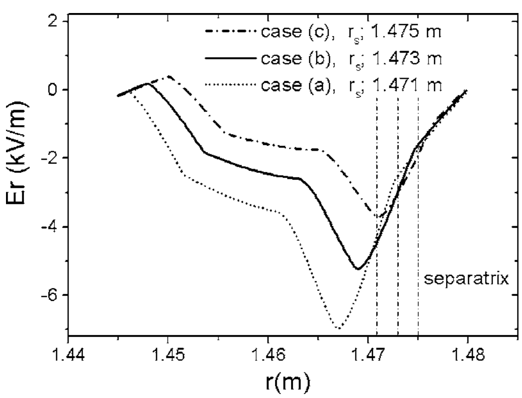

FIG. 2. Radial electric field profile calculated by the gyrocenter shift for the NSTX plasma (No. 110077, t=0.24 s, H mode).

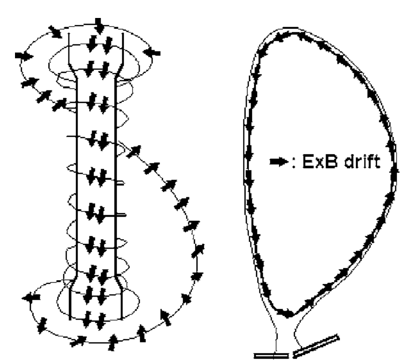

FIG. 3. $E\times B$ flow directions of the NSTX plasma in the vicinity of separatrix at the H-mode transition.

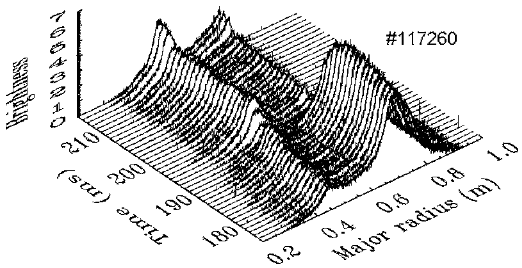

FIG. 4. *D*-alpha emission profile from lower diverter camera with in and out asymmetry. Unit of brightness is 10^{21} photons/s/m^2. Inboard divertor: r $=0.288-0.574$, outboard divertor: $r=0.620-0.968$ (*H*-mode transition at 0.194 s).

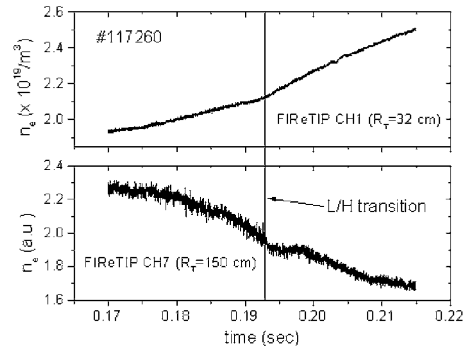

FIG. 5. Electron density measured by FIReTIP channels 1 and 7 at the *H*-mode transition on NSTX plasma.

field drift of plasma particles other than the radial gyrocenter shift during the *H*-mode transition is the $E\times B$ drift. The $E\times B$ drift direction of the plasma in the vicinity of the NSTX separatrix is indicated in the cartoon of Fig. 3. At the *H*-mode transition, the sudden increase of $E\times B$ flow makes plasma on the open field lines rotate from outboard to inboard while it suppresses the turbulent transport. The reversal of in and out asymmetry in *D*-alpha emission at the *H*-mode transition is shown in Fig. 4. The *D*-alpha emission is also a function of particle flow into the emission region so the result of Fig. 4 may reflect the change of particle flow into the divertor region induced by the $E\times B$ drift. The electron density variation during the same *H*-mode transition illustrated in Fig. 4 measured by the innermost and outmost channels of the far infrared tangential interferometer/polarimeter[10] (FIReTIP) is shown in Fig. 5. Channel 1 data in Fig. 5 indicate the density rise of inside ear structure due to the enhanced confinement of the *H* mode, but channel 7 reveals a sudden decrease due to the reduction of particle flow in the scrape off layer (SOL). These two contrasting trends in Fig. 5 show the prompt increase of electron density gradient in the vicinity of the separatrix at the *H*-mode transition. According to the *H*-mode scenario suggested by the theory of the gyrocenter shift, the increase of negative plasma density gradient induces an increase of positive neutral density gradient, which increases the radial current density to boost the *H*-mode transition. The measurement of the time evolution of the neutral density profile is critical for the verification of this scenario.

IV. DISCUSSION

The diagnostic requirements for the application of the gyrocenter shift theory to the experimental study on the NSTX are investigated. The sample calculation of the radial electric field on NSTX plasma revealed that the required spatial resolution of diagnostics in the vicinity of separatrix is approximately 2 mm. The required time resolution of neutral density profile measurement is a few kilohertz, since the preliminary measured SOL electron density reduction time is several hundred microseconds.

ACKNOWLEDGMENT

The authors thank the NSTX research team for the physics and engineering support.

[1] K. Itoh and S.-I. Itoh, Plasma Phys. Controlled Fusion **38**, 1 (1996).
[2] K. C. Lee, Phys. Plasmas **13**, 062505 (2006).
[3] S. M. Kaye *et al.*, Phys. Plasmas **8**, 1977 (2001).
[4] C. E. Bush *et al.*, Phys. Plasmas **10**, 1755 (2003).
[5] S. M. Kaye, C. E. Bush, E. Fredrickson, B. LeBlanc, R. Maingi, and S. A. Sabbagh, Phys. Plasmas **10**, 3953 (2003).
[6] B. A. Carreras, L. W. Owen, R. Maingi, P. K. Mioduszewski, T. N. Carlstrom, and R. J. Groebner, Phys. Plasmas **5**, 2623 (1998).
[7] T. M. Biewer, R. E. Bell, R. Feder, D. W. Johnson, and R. W. Palladino, Rev. Sci. Instrum. **75**, 650 (2004).
[8] V. A. Soukanovskii, A. L. Roquemore, C. H. Skinner, J. Menard, H. W. Kugel, R. Maingi, S. Sabbagh, and F. Paoletti, Rev. Sci. Instrum. **74**, 2094 (2003).
[9] D. P. Stotler and C. F. F. Karney, Contrib. Plasma Phys. **34**, 392 (1994).
[10] K. C. Lee, C. W. Domier, M. Johnson, N. C. Luhman, Jr., and H. Park, Rev. Sci. Instrum. **75**, 3433 (2004).