Collective scattering system for transport study on NSTX

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Abstract. The problem of degraded energy confinement due to excessive transport across the magnetic field remains one of the critical issues for magnetically confined plasma. Radial transport of ion energy is relatively well understood, but that of the electrons has remained as anomalous, greatly exceeding the neoclassical prediction. It has been suggested that the anomalous electron thermal transport is explained by an electron gyro-scale turbulence driven by the electron temperature gradient (ETG) instability. A 280-GHz collective Thomson scattering system has been employed to address the electron gyro-scale fluctuations in National Spherical Torus Experiment (NSTX) plasmas. The spatial resolution of the targeting wavenumber is greatly affected by the configuration of the magnetic field since the radial fluctuation is perpendicular to the local magnetic field line. The effect of the toroidal field curvature and magnetic shear on the spatial resolution of the scattering system is investigated numerically. An absolute power calibration was performed to determine the power response of the heterodyne detection system. These spatial resolution studies and absolute power calibration were applied to estimate the normalized density fluctuations from the measured scattering signals in NSTX plasmas.

1. Introduction

A sufficient energy confinement time is critical to achieve a burning plasma in magnetically confined devices and the confinement time primarily depends on radial transport of the particle and energy. Although the ion thermal and particle transports can be suppressed to the neoclassical level, the electron thermal transport has always been anomalous in the tokamak plasmas. Recent studies have suggested the electron gyroscale turbulence driven by the electron temperature gradient (ETG) instability serves as the underlying mechanism for the electron thermal transport. Experimental studies in various devices have been performed to investigate the electron thermal transport driven by the electron temperature gradient (ETG) instability [1, 2, 3, 4]. Experiments on NSTX are significantly extending the studies [5, 6, 7]. The NSTX plasma, which has a large electron gyro-radius, is well suited for electron thermal transport studies.

The five-channel, 1 mm wavelength (280 GHz) collective scattering system has been installed on NSTX to measure the electron gyroscale fluctuations [8]. The five-channel detection system was designed to simultaneously measure the frequency spectra of density fluctuations at five
discrete wavenumbers. The range of wavenumbers extends up to 20 cm\(^{-1}\) which corresponds to \(k_{\perp} r_{e} \leq 0.7\), where \(k_{\perp}\) is the perpendicular component of the fluctuations with respect to the local magnetic field and \(r_{e}\) is the electron gyroradius. Probe and scattered beams are nearly on the midplane, so that the detected fluctuations are primarily radial or perpendicular to the magnetic surface. Steerable launching and receiving optics have been used to position the scattering volume ranging from the magnetic axis to the outer edge of the plasma.

Plasma density fluctuation levels were estimated from the scattering signals measured in \(H\)-mode and high electron temperature \(L\)-mode NSTX plasmas. The estimation of the scattered power (or fluctuation level) was carried out based on absolute power calibration of the detection system and numerical calculation of the scattering length of each channel.

2. Basic principle of the collective scattering experiment

The scattering process is based on the three-wave coupling among the incident and scattered electromagnetic waves and a plasma density fluctuation wave. In the scattering process, energy and the momentum have to be conserved as 

\[
\mathbf{q}_{i} + \mathbf{q}_{s} = \mathbf{q}_{f}
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where \(\mathbf{q}_{i}\) and \(\mathbf{q}_{s}\) refer to the incident and scattered wave, respectively. Since the frequencies of the wave source of a known output power together with calibrated attenuators \([10]\). Raw data of the calibration are shown in Fig. 1. The power responses of the five-channel detection system

the measured scattered power in Eq. 3 as the time-averaged density fluctuation in the frequency range

\[\delta n^{2}(\mathbf{k},\omega) \equiv \frac{d\omega}{2\pi} \frac{|\bar{n}_{e}(\mathbf{k},\omega)|^{2}}{V^{2}} \sim 10^{25} \times \frac{P_{s}(\mathbf{R},\omega)d\omega}{L_{v}^{2}} \text{[mW]}.\]
were 26, 36, 30, 33, and 30 dB, respectively. The minimum detectable power (or noise level) is $\sim -75$ dBm (or $\sim 3 \times 10^{-8}$ mW), which corresponds to the normalized density fluctuation level, $\delta n_e/n_e$, of $\sim 6 \times 10^{-6}$ in the assumption of $n_e \sim 10^{13} /\text{cm}^3$ and $L_v \sim 10$ cm. In the Fourier space with 4096 sample points, the noise level is $\sim -110$ dBm (or $\sim 10^{-11}$ mW) and the minimum detectable $\delta n_e/n_e$ is $\sim 1 \times 10^{-7}$ in the same assumption.

4. Scattering length on the detected scattered power
As shown in Eq. 4, it is essential to properly take into account the scattering length in the estimation of the fluctuation levels. The scattering length decreases as the scattering angle increases since the scattering volume is basically an overlap region of the probe beam and scattered beam. The exact scattering length is determined by the magnetic field configuration since the plasma turbulence is anisotropic in general with $k_\perp \gg k_\parallel$ where the subscripts $\perp$ and $\parallel$ represent the perpendicular and the parallel components to the magnetic field, respectively. The variation of the magnetic field direction within the scattering volume can modify the detecting efficiency of the receiver due to the varying momentum matching condition shown in Eq. 1. The scattering length in nonuniform magnetic fields was numerically calculated in references [11, 12, 10]. The scattering lengths were found to be primarily affected by the toroidal curvature. Figure 2 shows the calculated scattering lengths for fluctuation wavenumbers ($k_\perp = 4, 8, 12, 16, \text{and } 20 \text{ cm}^{-1}$) at several toroidal toroidal curvature radii ($R = 110, 120, 130, \text{and } 140 \text{ cm}$). The scattering length decreases as the fluctuation wavenumber increases and toroidal curvature radius decreases.
Figure 2. Scattering lengths for several fluctuation wavenumbers. The scattering length decreases as the wavenumber increases and the toroidal curvature radius decreases.

Figure 3. Peak normalized density fluctuations, \( \delta n_e(k, \omega)/n_e \), in (a) H-mode plasmas (\( B_t = 0.35 - 0.55 \) T, \( I_p = 0.7 \) MA, and \( P_{NB} = 4 \) MW) and (b) high-\( T_e \) L-mode plasmas (\( B_t = 0.55 \) T, \( I_p = 0.6 \) MA, and \( P_{RF} = 1.0 - 2.5 \) MW). Note that the \( \delta n_e(k, \omega)/n_e \) is a Fourier spectrum of \( \delta n_e(k, t)/n_e \).

5. Estimation of the fluctuation levels

The previous calibration result and scattering length calculation were applied to the NSTX plasmas to estimate fluctuation amplitudes from the measured scattering signals.

Figure 3 shows the peak value of the normalized density fluctuations, \( \delta n_e(k, \omega)/n_e \), measured in both (a) H-mode plasmas and (b) high-\( T_e \) L-mode plasmas. Note that the \( \delta n_e(k, \omega)/n_e \) is a Fourier spectrum of \( \delta n_e(k, t)/n_e \). The H-mode plasmas were heated by 4-MW NB power at a plasma current of 0.7 MA and three toroidal magnetic fields of 0.35, 0.45, and 0.55 T. The red points were measured at the plasma core of \( R \sim 113 \) cm (or \( r/a \sim 0.16 \)) and the blue points were measured at the intermediate region of \( R \sim 132 \) cm (or \( r/a \sim 0.6 \)). The L-mode plasmas were heated by high harmonic fast wave (HHFW) of power from 1.0 to 2.5 MW at a plasma current of 0.6 MA and toroidal magnetic field of 0.55 T. The HHFW power preferentially heats electrons rather than ions, so that the electron temperature of the plasmas can rise above 4 keV. All scattering measurements were performed in the plasma core region of \( R \sim 118 \) cm (or \( r/a \sim 0.3 \)). The normalized density fluctuations were \( 10^{-7} \sim 10^{-5} \) in H-mode plasmas and \( 10^{-7} \sim 10^{-4} \) in high-\( T_e \) L-mode plasmas. The normalized fluctuation levels tend to slightly decrease as the normalized wavenumber, \( k_\perp \rho_e \), increases since the scattering length is smaller at higher wavenumber.
Figure 4. Density fluctuation signal in $H$-mode plasma (left) and its normalized electron temperature gradient(right). Fluctuation appears when the normalized gradient near the critical value.

For exact interpretation of the scattered power, other factors must be considered such as the Faraday rotation of the linearly polarized probe and scattered beams. Specifically, a vertically polarized probe beam enters into the vacuum vessel and its polarization is changed by the magnetic field. The polarization of the scattered beam is also changed until it reaches the detector which is horizontally polarized. Here, it is simply assumed that a half of the scattered power enters to the detector considering the detector which has preference in polarization.

6. Effect of $T_e$ gradient on fluctuations
Recent studies [13, 14, 15, 16] have predicted that the electron gyro-scale fluctuations are associated with the electron temperature gradient (ETG) instabilities, and that is experimentally observed in NSTX plasmas [5]. Fluctuations appear when the electron temperature gradient is above or near a critical value which is calculated for the onset of ETG modes (see Fig 4). In addition, it is known that the electron gyro-scale fluctuations are suppressed in a strongly reversed (negative) magnetic shear [6, 16] and $E \times B$ flow shear [7]. In this paper, the effect of the electron temperature gradient on the fluctuations was investigated in the previous $H$-mode and high-$T_e$ $L$-mode plasmas. Here, the normalized electron temperature gradient, $R/L_{Te}$, is given as [15]

$$R/L_{Te} = -R/T_e(dT_e/dr)$$

where $R$ is the major radius.

Figure 5 shows the results. In $H$-mode plasmas, fluctuations weakly correlate with the normalized electron temperature gradient in the range of $2 \sim 8$. On the other hand, in high-$T_e$ $L$-mode plasmas, fluctuations strongly correlate with the electron temperature gradient in the range of $6 \sim 10$ for all wavenumbers. This result is additional evidence that the electron gyroscale density fluctuations in NSTX are induced by the ETG instabilities.

7. Conclusion
Electron gyro-scale density fluctuations were observed in NSTX plasmas by using the 1-mm wavelength scattering system. Fluctuations were measured at the core region $(r/a \sim 0.16 \sim 0.3)$ in both $H$-mode and $L$-mode plasmas and at the intermediate region $(r/a \sim 0.6)$ in $H$-mode plasmas. The fluctuations were in the normalized wavenumber, $k_{\perp}p_{Te}$, from 0.14 to 0.5, which is the wavenumber range of the ETG instability.

These fluctuation levels were estimated from the scattering signal based on the power calibration of the detection system and calculation of the scattering length. The peak normalized
Figure 5. Effect of normalized electron temperature gradient, $R/L_{T_e}$, on the density fluctuation in (a) $H$-mode and (b) high-$T_e$ $L$-mode plasmas. In high-$T_e$ $L$-mode plasma, fluctuations strongly correlate with the electron temperature gradient.

density fluctuations, $\delta n_e(k,\omega)/n_e$, were $10^{-7} \sim 10^{-5}$ in $H$-mode plasmas and $10^{-7} \sim 10^{-4}$ in high-$T_e$ $L$-mode plasmas. Fluctuations measured in high-$T_e$ $L$-mode plasmas strongly correlate with the electron temperature gradient.

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