First Measurement of the Magnetic Turbulence Induced Reynolds Stress in a Tokamak *

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(Received 1 July 2003)

Reynolds stress component due to magnetic turbulence was first measured in the plasma edge region of the HT-7 superconducting tokamak using an insertable magnetic probe. A radial gradient of magnetic Reynolds stress was observed to be close to the velocity shear layer location; however, in this experiment its contribution to driving the poloidal flows is small compared to the electrostatic component. The electron heat transport driven by magnetic turbulence is quite small and cannot account for the total energy transport at the plasma edge.

PACS: 52. 55. Fa, 52. 25. Fi, 52. 35. Ra

Sheared flows have been found to play a major role in explaining the transition to a variety of enhanced confinement regimes in magnetically confined fusion plasmas.[1] Finding the generation mechanism of sheared flows is crucial to understand the confinement transition and helpful for developing techniques to suppress turbulence and reduce transport. Recent progress in understanding the formation of transport barrier in fusion plasmas reemphasized the importance of turbulence-driven flows via Reynolds stress.[2] In neutral fluids the Reynolds stress not only leads to turbulence viscosities, but also generates a number of geophysical flows such as the quasi-biennial oscillation.[3,4] The importance of the Reynolds stress as a flow generation mechanism in neutral fluids suggests that it should not be ignored in plasma turbulence. Since sheared flows suppress turbulence through the shear decorrelation mechanism,[5] a feedback loop between turbulence and sheared flows will be closed, if flows could be driven by fluctuations. This feedback loop makes turbulence exist in a self-regulated state, which might be able to explain self-consistently the spontaneous confinement mode transition when auxiliary heating power exceeds a certain threshold.[6] Both the nonlinear gyrokinetic global simulations of plasma turbulence in confinement region [7] and the nonlinear gyrofluid simulations of boundary turbulence [8] gave prominence to the mechanism of flows generated by turbulence through the action of Reynolds stress in a steady state. In their simulations, the pressure gradient profile is input parameter and a static velocity shear always accompanies a steep pressure profile. It is interesting that the ion orbit loss mechanism for flow generation, which is caused by the interaction with the limiter,[9] is not included in the above-mentioned simulations. As a result, nonlinear turbulence simulations support the understanding that in a steady state, turbulence dominates the flows driving process. The measurement of Reynolds stress in fusion plasmas is not easy to perform in view of apparent difficulties but is crucial to a detailed understanding of transport barrier physics. Thus, there is considerable interest in the quantitative investigating the contribution of Reynolds stress in the process of sheared flow generation. Experiments that have addressed this problem to date have only studied the electrostatic component of Reynolds stress.[10−12] The role of magnetic fluctuations in the flow driving is an unresolved question. Although many experiments have demonstrated that magnetic turbulence is not important to explaining the total energy transport at plasma edge,[13,14] the contribution of magnetic Reynolds stress to poloidal flow is unclear. In this Letter, we present the first measurement of magnetic Reynolds stress in the tokamak edge plasmas.

HT-7 is a superconducting tokamak [15] with two circular poloidal limiters separated in the toroidal direction by 180 and a high-field-side belt limiter. This experiment was conducted in ohmically heated deuterium plasmas with $R_0 = 122\,\mathrm{cm}$, $a = 27\,\mathrm{cm}$, $B_\phi \cong 1.98\,\mathrm{T}$, $I_p \cong 120\,\mathrm{kA}$, $\bar{n}_e \cong 1.5\times10^{19}\,\mathrm{m}^3$, $T_{e0} \cong 0.7\,\mathrm{keV}$ and loop voltage $V_l \sim 1.3\,\mathrm{V}$. The discharge duration was typically 1 s. The edge safety factor was $q_a \sim 4.9$ and there was very weak sawtooth and Mirnov activity. Because of the circular cross-section, the poloidal β is not as high as $\beta_p \sim 0.4$ that is measured by magnetic diagnostics. A naturally occurring velocity shear layer [16−19] existed at the plasma edge ($\Delta r = 2.5$–$0\,\mathrm{cm}$), which resulted in a steeper pressure profile; however, the confinement is still low and falls into the ALCATOR scaling. The boundary profiles of electron density and temperature are plotted in Figs. 1(a) and 1(b).

The magnetic component of Reynolds stress tenser is $\dfrac{\langle \tilde{B}_r \tilde{B}_\theta \rangle}{\rho_m \mu_0}$,[20] where $\tilde{B}_r$ and $\tilde{B}_\theta$ is the radial and poloidal magnetic field fluctuations dominated by small-scale magnetic turbulence and ρ_m is the mass

* Supported by the National Natural Science Foundation of China under Grant No 10175069.
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density. An insertable magnetic probe with two perpendicular coils was mounted on the top of the tokamak along the central line. The two coils were used to achieve local measurements of radial and poloidal magnetic field fluctuations. The effective area are $S_r = 0.0038\,\mathrm{m}^2$ for radial coil and $S_\theta = 0.0036\,\mathrm{m}^2$ for poloidal coil. The inductances are $L_r \cong 1 \times 10^4\,\mathrm{H}$ and $L_\theta \cong 2 \times 10^5\,\mathrm{H}$. Thus the response frequency can be estimated as 750 kHz and 3.7 MHz, respectively. Graphite shield allowed the reliable measurement 3 cm inside the last closed flux surface (LCFS). The profiles were presented with a shot-by-shot scan and the data were sampled at 1 MHz with 12-bit resolution using a multi-channel digitizer. The boundary profiles of plasma parameters were measured with a fast reciprocating Langmuir probe [21] using a standard triple tip array.

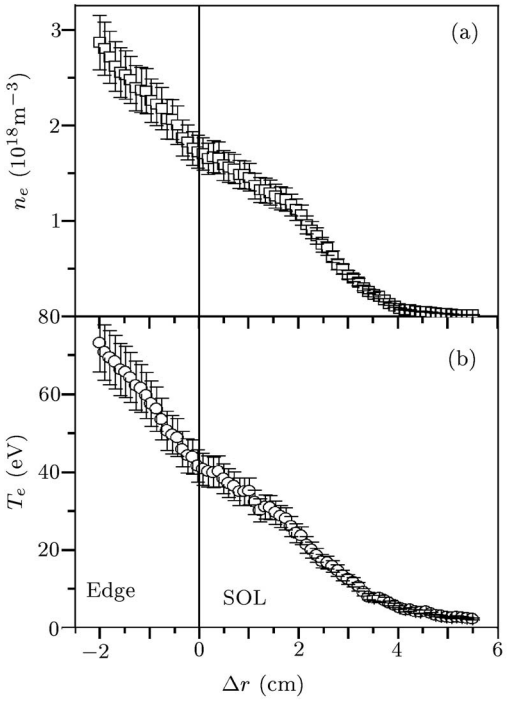

Fig. 1. Boundary profiles of (a) electron density and (b) electron temperature.

Magnetic field fluctuations were calculated from the integral of magnetic coil signals with mean value removed. Figure 2 shows the time history of a discharge (shot 60703). The radial and poloidal magnetic coil signals measured at the plasma edge $\Delta r = 2.5$ cm $\left(\dot{B}_r = \dfrac{\partial B_r}{\partial t}\right.$ and $\left.\dot{B}_\theta = \dfrac{\partial B_\theta}{\partial t}\right)$ are illustrated in Figs. 2(e) and 2(f), respectively. From these two plots, one can see that the magnetic fluctuation levels in the time range of 100–450 ms are higher than those in the time range of 500–800 ms. To find the correlation between the magnetic fluctuation levels and plasma parameters, we plot the central line averaged plasma density (Fig. 2(a)), plasma temperature at $r = -3$ cm measured by electron cyclotron emission (ECE) diagnostics (Fig. 2(b)), H emission signal (Fig. 2(c)) and central line soft x-ray signal (Fig. 2(d)). Comparing the time evolutions of these signals, we found the magnetic fluctuation levels correlated with radiation signal. The data available in this experiment all support this correlation. Since radiation is proportional to $Z_{\mathrm{eff}} n_e^2 \sqrt{T_e}$, where Z_{eff} is the effective charge number, radiation is strongly correlated with density. For the temperature, temperature gradient or recycling, there seems to be no obvious correlation. In addition, the impurity content and as a result, Z_{eff} was low in the time range of 10–450 ms. Thus, the correlation with radiation mainly reflects the influence of density on the magnetic fluctuation levels. As shown in Figs. 3(a) and 3(b), the auto power spectra of radial and poloidal relative magnetic fluctuations exhibit the typical broad band (1–200 kHz) feature. They peak at around 50 kHz and decays in both low-frequency and high-frequency regions. The decay index of auto power spectra in the high-frequency region is about -2, which is close to that of electrostatic fluctuations as measured by the Langmuir probe. The shape of spectra at plasma edge is similar to that in the scrape off layer (SOL) and the fluctuation levels increase

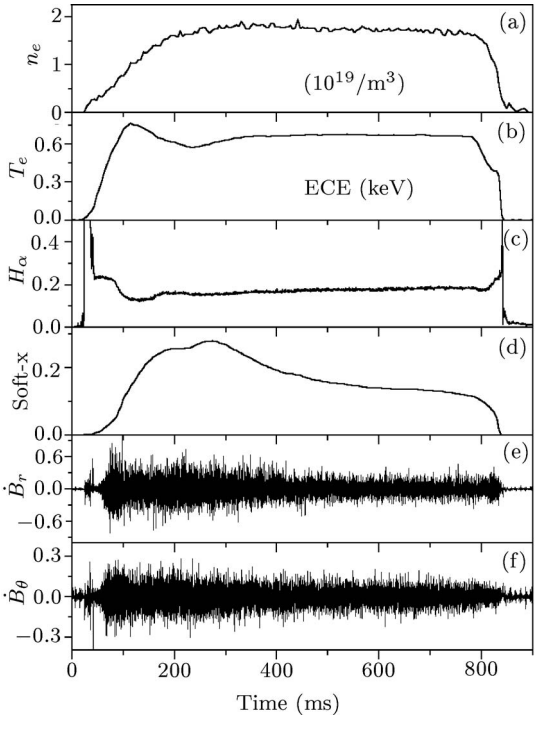

Fig. 2. Time evolution of a discharge (shot 60703): (a) central line averaged plasma density, (b) plasma temperature at $r = 3$ cm measured by electron cyclotron emission (ECE) diagnostics, (c) H emission signal, (d) central line of soft x-ray signal, (e) radial and (f) poloidal magnetic coil signals measured at the plasma edge $r = 2.5$ cm $\left(\dot{B}_r = \dfrac{\partial B_r}{\partial t}\right.$ and $\left.\dot{B}_\theta = \dfrac{\partial B_\theta}{\partial t}\right)$.

monotonically inward [Fig. 4(a)]. Mirnov activity is

low as shown in Fig. 3, especially in the SOL. As a result of high q and low β_p, the fluctuation level is low, but increases monotonically inward. Several experiments [22–24] indicated that magnetic fluctuations are linked to electron confinement, since the energy confinement time decreases with the increasing magnetic fluctuation level. We calculated the electron thermal conductivity caused by magnetic fluctuations with the often-used quasilinear estimate [25] $\chi_e = qR_0V_{Te}\tilde{b}_r$, where q is the safety factor, V_{Te} is the electron thermal velocity and $\tilde{b}_r = \tilde{B}_r/B_\phi$ is the relative amplitude of radial magnetic fluctuations. As shown in Fig. 4(b), the calculated electron thermal conductivity $\chi_e < 0.5\,\mathrm{m^2s}$ is much smaller than that estimated from power balance analysis at plasma edge, which is larger than $5\,\mathrm{m^2s}$ in such discharges.[26] However, χ_e increases monotonically inward in the measurement region. If it can be extrapolated to the interior, considerable electron thermal transport due to magnetic turbulence can be expected.

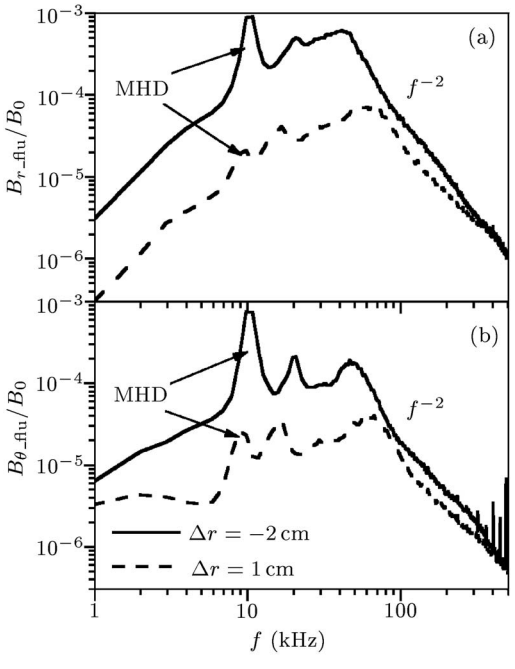

Fig. 3. Auto power spectra of (a) radial relative magnetic fluctuations and (b) poloidal relative magnetic fluctuations, in the plasma edge $r = 2\,\mathrm{cm}$ (shot 60699) and in the SOL $r = 1\,\mathrm{cm}$ (shot 60684).

The radial profile of magnetic turbulence-induced Reynolds stress $\dfrac{\langle\tilde{B}_r\tilde{B}_\theta\rangle}{\rho_m\mu_0}$ is illustrated in Fig. 5. It shows a radial gradient in the proximity of the velocity shear layer. However, the gradient ($\sim 3\times10^7\,\mathrm{ms^2}$) is small compared to the radial gradient ($\sim 2\times10^8\,\mathrm{ms^2}$) of the electrostatic Reynolds stress $\langle\tilde{V}_r\tilde{V}_\theta\rangle$. Therefore, the electrostatic component dominates the Reynolds stress tensor. The poloidal flows driven by magnetic Reynolds stress is so small to be negligible under these experimental condition. As in the case of low q and high β_p, the increased magnetic fluctuations may result in considerable magnetic Reynolds stress. The flow driven by magnetic turbulence especially should be examined in Reversed-field pinch, which normally exhibits large level of magnetic fluctuations.

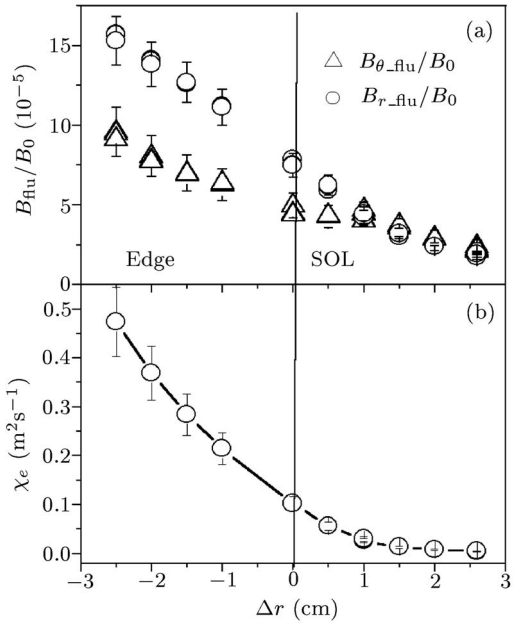

Fig. 4. Radial profiles of (a) the relative fluctuation levels of radial and poloidal magnetic fluctuations and (b) the electron thermal conductivity caused by magnetic fluctuations.

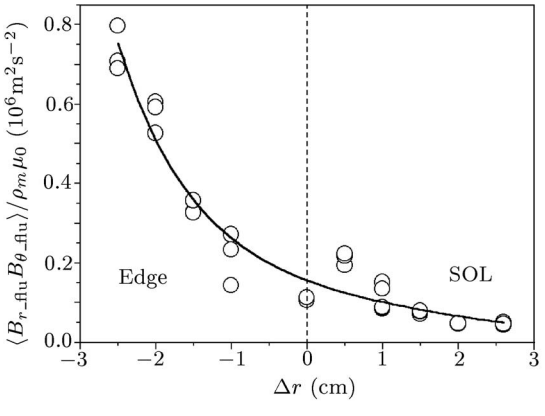

Fig. 5. Radial profile of magnetic Reynolds stress.

In conclusion, the Reynolds stress component due to magnetic turbulence has been first measured in the plasma edge region of the HT-7 superconducting tokamak using an insertable magnetic probe. A radial gradient of magnetic Reynolds stress has been observed in the vicinity of the velocity shear layer; however, its contribution to driving the poloidal flows is small compared to the electrostatic component. The electron heat transport driven by magnetic turbulence is

quite small and can not explain the total energy transport at plasma edge.

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