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Electron thermal transport induced by magnetic turbulence in the HT-7 tokamak

W. Zhang *, G.S. Xu, B.N. Wan

Institute of Plasma Physics, Chinese Academy of Sciences, P.O. Box 1126, Hefei, Anhui 230031, People's Republic of China

Abstract

An inserted magnetic probe was used to simultaneously measure the poloidal and radial magnetic fluctuations from (normalized minor radius) $\rho = 1.1$ to $\rho = 0.8$ in the HT-7 tokamak. It is found that when the magnetic probe was gradually moved inward the magnetic fluctuation levels continually increased and did not show saturation tendency. The electron thermal transport induced by magnetic turbulence is quite small in the HT-7 tokamak. By calculating the propagation velocity along the poloidal direction, it was found that this velocity is very close to the electrostatic turbulence phase velocity at the plasma edge. So it leads us to consider that the magnetic fluctuations may be coupled with the electrostatic drift waves. This experimental finding implies that the magnetic turbulence is possibly not an independent mode, instead it seems to be more an intrinsic component of the basic underlying micro-instability.

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Keywords: HT-7 tokamak; Cross-field transport; Fluctuations and turbulence

1. Introduction

As we know, the cross-field electron thermal transport is highly anomalous. The underlying physical mechanism responsible for the high energy losses in the electron channel still cannot be fully understood. Generally speaking, the anomalous transport is driven by low frequency plasma turbulence [1]. Due to the small mass of electrons, they have very high motility along the magnetic field. So a localized small break-up of the nested magnetic field structure will result in rapid escape of electrons and the heat they carried.

The magnetic fluctuations driven anomalous transport has been investigated in many fusion devices [2–4,8,9]. Some theories have also been developed to calculate the electron thermal conductivity [5,6]. An upper limit estimated for the magnetic fluctuation induced energy flux has developed [7], and equipments to simultaneously measure the energy flux and the magnetic fluctuations have been used in some experiments in different devices [4,8,9]. It was found that the magnetic fluctuations cannot account for the observed thermal transport at the edge of the tokamak.

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* Corresponding author. Fax: +86 551 5591310.
E-mail address: zhangwei@ipp.ac.cn (W. Zhang).

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The tokamak-plasma turbulence is well-known electrostatic dominated; due to the strong toroidal magnetic field, there is a magnetic fluctuation component coupled with the electrostatic drift wave. For the drift waves, since they have finite $k_{\|}$, electrons can freely flow along magnetic field lines to establish their thermodynamic equilibrium. So every turbulence eddy has a fluctuating parallel electron current acting as the response of potential fluctuation associated with the drift wave. This parallel electron current produces the magnetic fluctuation component. As a result, the magnetic fluctuation may be an intrinsic component of the drift-wave turbulences, although they are electrostatic dominated. The fluctuating parallel electron current in every turbulence cell can destroy the local nested flux surface and generate ergodic magnetic fields or tiny magnetic islands. This allows electrons and energy to flow along magnetic field lines which themselves follow stochastic trajectories. So the generated tiny magnetic islands are coupled with the turbulence eddies and therefore they have the similar spatial and temporal scales. The dynamic of electron thermal transport induced by magnetic turbulence is still unclear, partially due to the absence of a good model to describe the behavior of electrons in response of magnetic fluctuations. So the experiments dedicated to this topic are required, especially in small devises where utilizing the inserted magnetic probe is possible.

2. Experimental setup

The HT-7 is a superconducting tokamak, whose major radius is 1.22 m and minor radius is 0.27 m.

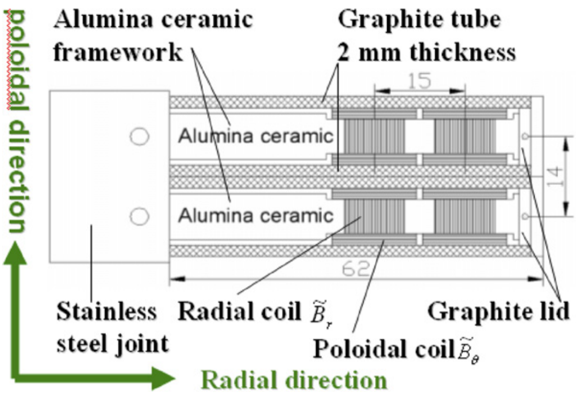

Fig. 1. Schematic view of the double-tube magnetic probe.

There are two probe systems in HT-7 tokamak: a reciprocating Langmuir probe system and a hand operated probe system. The two probe systems are both mounted on the top of the tokamak along the central line. The reciprocating probe system is driven by pneumatic cylinder; it can be remotely controlled by a trigger signal and stroked into the edge of plasma and back between 120 ms.

In this experiment, we use a double-tube magnetic probe (see Fig. 1) to simultaneously measure the poloidal and radial magnetic fluctuation. The double-tube probe was mounted on the hand operated probe system. The double-tube magnetic probe consists of two single magnetic probes; they are arrayed along the poloidal magnetic field and 14 mm away from the centre. Each probe has two pairs of coils which are 15 mm apart in radial direction consisting of a radial coil and a poloidal coil, and can simultaneously measure the radial and

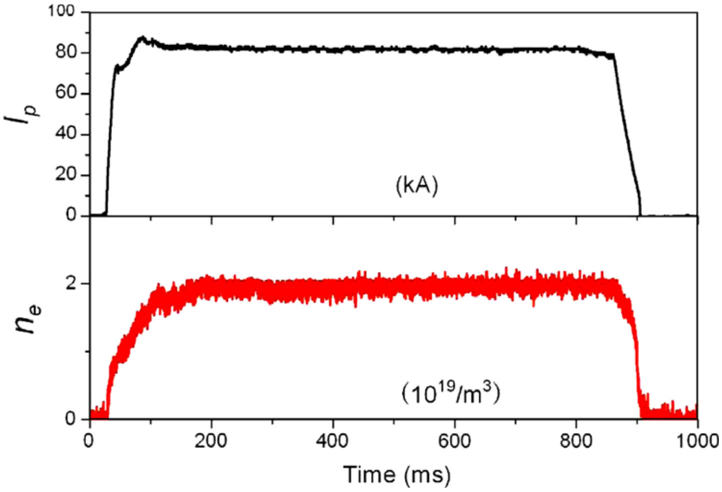

Fig. 2. A typical discharge signal of plasma current and plasma density.

poloidal magnetic fluctuations. The poloidal coil has 80 turns and the radial coil has 400 turns, both with a 0.008 m^2 effective induction area. The coil is protected by a 14 mm diameter graphite shield. The reciprocating Langmuir probe with a triple tip array is used to measure the plasma boundary profile of plasma density and temperature.

The experiment was conducted in toroidal magnetic field $B_\phi \cong 2$ T, plasma current $I_p \cong 80$–145 kA, $n_e \cong 2.0 \times 10^{19}$ m^{-3}. The magnetic fluctuations were measured at normalized minor radius $\rho = 0.8$–1.1 region. The plasma current and density are quite smooth in the duration of discharges (Fig. 2), and the discharge is repeatable in the experiment. The duration of discharge time is about 1 s.

3. Experimental results

The plasma density profile (Fig. 3) and plasma temperature (Fig. 4) profile in the plasma edge is measured by reciprocating Langmuir probe with a triple probe.

By analyzing the power spectra of the magnetic coil signal, it was found that, the magnetic turbulence concentrates on the low frequency region (Figs. 5 and 6). There is a very strong MHD in the low frequency area. For example 5 kHz MHD was found in the SOL and LCFS in the condition of plasma current $I_p = 80$ kA. The broadband magnetic turbulence is overlapped with the MHD (Fig. 5). In most conditions, the MHD fluctuation levels are much stronger than the broadband magnetic fluctuations levels, MHD is hard to avoid in the discharge duration in HT-7 tokamak. The broadband magnetic turbulence in $\Delta r = -4$ cm point is separated from the MHD; the peak of the broadband turbulence is about 30 kHz (Fig. 6). This frequency is higher than the more outward point. So we can imply that the broadband magnetic turbulence is of very low frequency in the SOL, it is close to the MHD frequency.

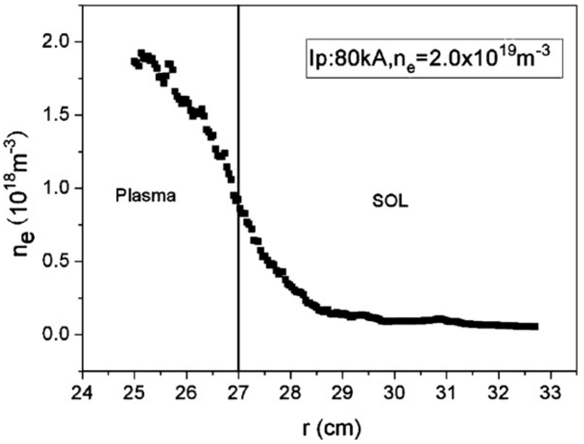

Fig. 3. The radial profile of plasma density, which is measured by reciprocating Langmuir probe.

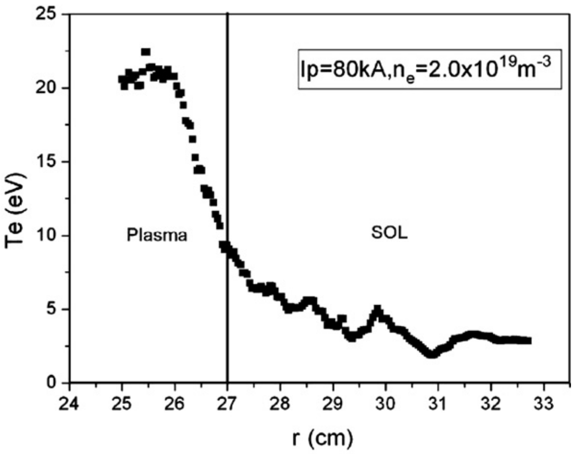

Fig. 4. The radial profile of plasma temperature, which is measured by reciprocating Langmuir probe.

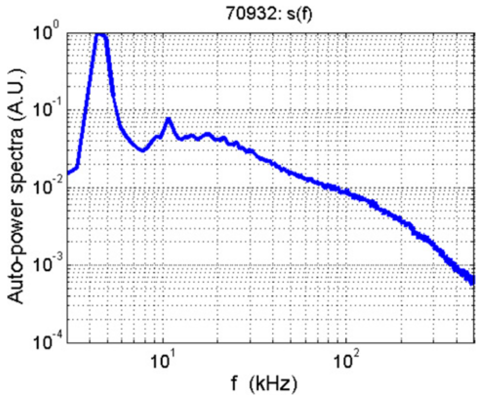

Fig. 5. The power spectra of poloidal coil signal at $\Delta r = 0.5$ cm.

We integrate the coil signals and times with the effective induction area to get magnetic fluctuations. In order to get more precise results of the broadband magnetic turbulence fluctuations level, an order 2 high-pass digital Butterworth filter with normalized cutoff frequency 10 kHz was used to filter the low frequency MHD from the magnetic fluctuations. The filter is hard to avoid filtering some turbulence fluctuations signal in the overlapping case. The radial profiles of the relative fluctuation

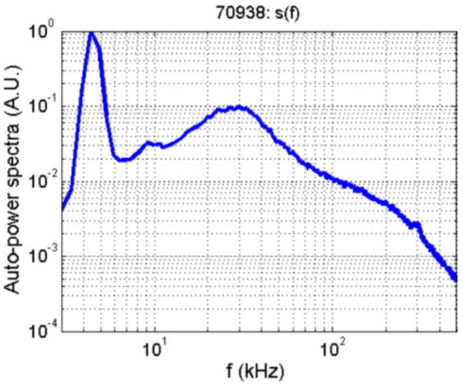

Fig. 6. The power spectra of poloidal coil signal at $\Delta r = -4$ cm.

levels of radial and poloidal magnetic fluctuations are shown in Fig. 7. It is found that when the magnetic probe was gradually moved inward the magnetic fluctuation levels continually increased and did not show saturation tendency. Similar results have been found in other devices [2,3]. The electron thermal conductivity caused by magnetic fluctuations was calculated by a quasi-linear estimate which is developed by Rechester and Rosenbluth [5].

$$\chi_e = qR_0V_{Te}\tilde{b}_r^2.$$

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 the radial magnetic fluctuations. The calculated electron thermal conductivity $\chi_e < 10^{-2}$ m^2 is much smaller than that estimated from power balance analysis at the plasma edge, which is larger than 5 m^2 in such discharges [10]. But it was increased greatly inward (Fig. 8).

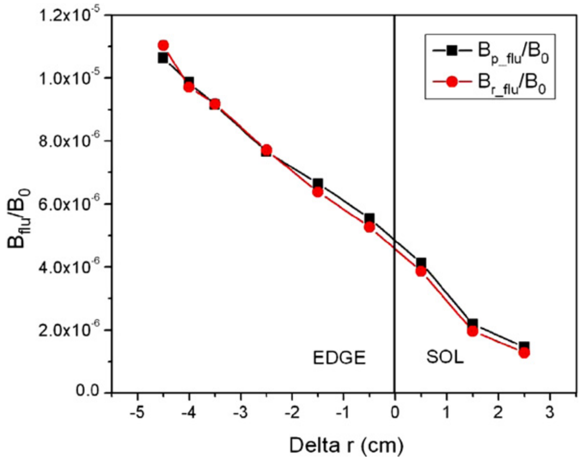

Fig. 7. The poloidal and radial relative magnetic fluctuation levels, at the $I_p = 80$ kA condition.

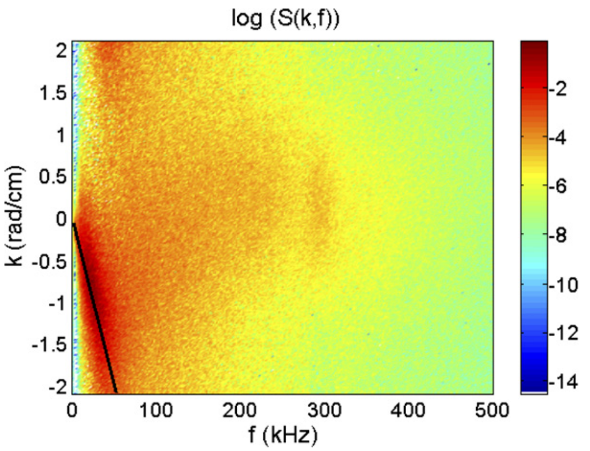

Fig. 8. The electron thermal conductivity caused by the magnetic fluctuation.

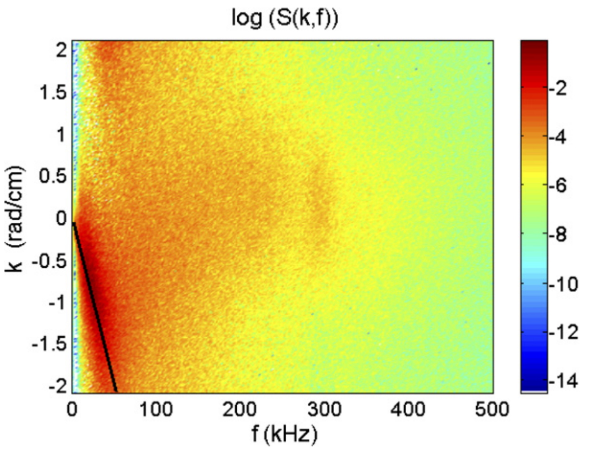

Fig. 9. The magnetic turbulence propagation spectrum, for the condition $I_p = 80$ kA.

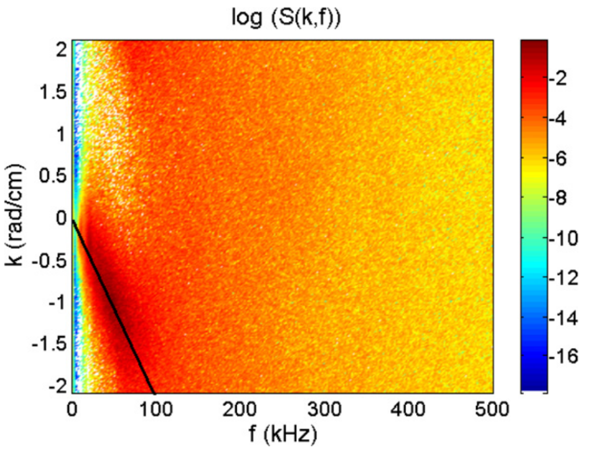

Fig. 10. The magnetic turbulence propagation spectrum, in the condition of $I_p = 115$ kA.

By using the double-tube magnetic probe, we can calculate the magnetic turbulence propagation velocity of the poloidal direction. Under plasma current $I_p = 80$ kA condition, the magnetic turbulence propagates in the electron diamagnetic direction with phase velocity $V_{ph} \sim -1.7$ km/s in the HT-7 tokamak edge (Fig. 9). When plasma current $I_p = 115$ kA, the magnetic phase velocity $V_{ph} \sim -1.8$ km/s (Fig. 10). This is very close to the electrostatic turbulence phase velocity at the plasma edge, which is about -2.0 km/s in the HT-7 tokamak edge.

4. Conclusion

In this experiment, we found that when the magnetic probe was gradually moved inward the magnetic fluctuation levels continually increased and did not show a saturation tendency. The thermal transport in electron channel was analyzed and compared with available result. By filtering the low frequency high level MHD from the magnetic fluctuation, the calculated electron thermal conductivity $\chi_e < 10^{-2}$ m^2 is much smaller than that estimated from power balance analysis at the plasma edge. This cannot account for the heat lost in the plasma edge. By calculating the propagation velocity of the poloidal direction, which is very close to the electrostatic turbulence phase velocity in the plasma edge. Thus it leads us to consider that the magnetic fluctuations are essentially coupled with the electrostatic drift waves, this experimental finding implies that the magnetic turbulence is possibly not an independent mode, instead it seems to be more an intrinsic component of the basic underlying micro-instability. So from the implications of our experimental results it is proposed that extending the electrostatic instability models as well as related simulations to their comprehensive electromagnetic versions is required to help better understand the contribution of magnetic fluctuation to the anomalous electron thermal transport.

Acknowledgement

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