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Experimental Simulation of High Temperature Plasma Transport Using Almost Dimensionally Similar Cold Plasmas in the Compact Helical System

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Abstract

In the Compact Helical System (CHS), experimental simulation of high temperature plasma transport is attempted by using cold plasma having similar dimensionless parameters such as electron-ion collision frequency normalized by bounce frequency ν^*_{ei}, averaged toroidal beta value β_t and the normalized gyro radius ρ^*_s. The cold plasma is produced by 2.45 GHz electron cyclotron waves at very low toroidal field less than 0.1 T, and has ν^*_{ei} ~ 0.05–1, β_t < 0.02 % and ρ^*_s ~ 0.02–0.05. The radial profiles of fluctuation amplitude have similarity to those in a high temperature plasma. In the cold plasma with low ν^*_{ei} < 0.1, internal transport barrier is clearly formed in electron density and temperature profiles when the radial electric field rapidly evolves to positive value.

Keywords:

plasma transport, dimensionally similar plasma, helical systems, radial electric field, turbulent fluctuations, internal transport barrier

1. Introduction

Energy and particle transport in a toroidal plasma is a very important and challenging issue in magnetic confinement fusion research. In a tokamak or helical plasma where the plasma transport is controlled by electrostatic fluctuations, the turbulent particle and electron heat fluxes are respectively expressed as $\Gamma_{turb} = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B_t$ and $Q_{eturb} = 3/2\ (T_e \langle \tilde{n}_e \tilde{E}_\theta \rangle + n_e \langle \tilde{T}_e \tilde{E}_\theta \rangle / B_t$, where $\tilde{n}_e, \tilde{T}_e$ and $\tilde{E}_\theta$ are fluctuations of electron density, electron temperature and poloidal electric field, and B_t is the toroidal magnetic field strength. Therefore, correlation measurement among plasma fluctuations is crucial to clarify underlying physics mechanisms in turbulent particle and heat transport of a toroidal plasma. However, the correlation measurement is extremely difficult in a high temperature plasma, except for the measurements with Langmuir probes (LPs) in the plasma edge region. If the transport behaviors of high temperature plasma are simulated by cold and low density plasma, detailed studies of turbulent transport are possible by LPs and may provide a powerful knob to clarify unknown transport mechanisms. When relevant dimensionless plasma parameters such as ν^*_{ei} (electron-ion collision frequency normalized by bounce frequency), B_t (averaged toroidal beta), relative scale lengths of density and temperature profiles and so on are the same in two kinds of plasmas except for one parameter ρ^*_s (ion gyro-radius estimated with Te normalized with the plasma minor radius a), these two plasmas are "dimensionally similar" each other and their plasma transport is expected to be similar [1,2]. Based on this hypothesis, an initial simulation experiment using cold and tenuous plasma obtained with 2.45 GHz electron cyclotron heating (ECH) at very low B_t < 0.1 T was carried out in CHS heliotron/torsatron [3]. Main objectives of the experimental simulation are as follows, (1) to compare fluctuation characteristics of both plasmas, (2) to obtain improved confinement regimes achieved in high temperature plasmas and clarify physics mechanisms of turbulence suppression, and (3) to establish realistic transport model in a toroidal plasma through detailed comparison between experimental data and numerical simulations.

2. Main dimensionless plasma parameters achieved

This simulation experiment has been carried out in CHS using 2.45 GHZ ECH with much higher power (~ 20 kW).

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The microwave power is launched as perpendicularly and/or tangentially against the toroidal field line. The toroidal magnetic field at the magnetic axis is varied from 0.105 T to 0.06 T in order to study various ECH scenarios. The magnetic axis position is adjusted to inward-shifted (R_{ax} = 92.1 cm) or outward shifted (R_{ax} = 97.4 cm) configuration. Plasma parameters are measured with a triple Langmuir probe, 2 mm microwave interferometer, bolometer and visible spectrometer. The line averaged electron density is in the range of about 10^{17} m^{-3} for hydrogen plasma and the central electron temperature is 5–20 eV. Ion temperature is expected to be very low (<< 1 eV) if charge exchange loss is dominant. Two important dimensionless parameters ν^*_{ei} and ρ^*_s achieved in these cold and tenuous plasmas are plotted on Fig.1, together with β_t. The effective collision frequency ν^*_{ei} has reached to fairly low value (ν^*= 0.05–1) that is comparable to that of high temperature plasmas in LHD and CHS at higher field. The averaged toroidal beta is considerably low β_t (< 0.02 %). The normalized gyro-radius ρ^*_s is by a factor of 2–4 larger than that in CHS plasma at high B_t.

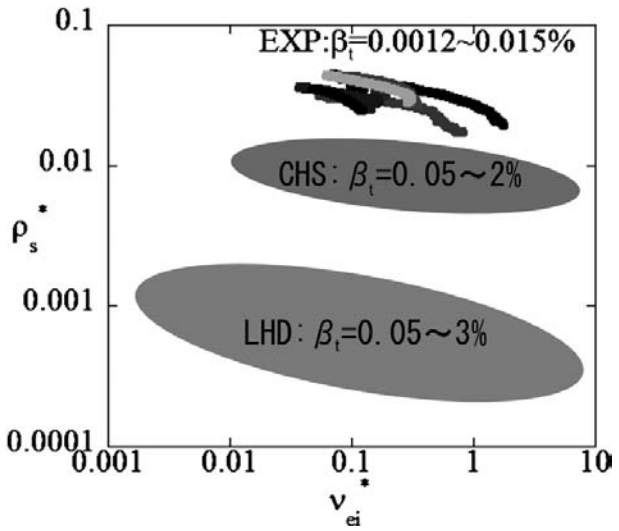


Fig. 1 Comparison of ν^*_{ei} and ρ^*_s in 2.45 GHz ECH plasmas shown in the upper part of this figure with those in CHS and LHD plasmas obtained at high B_t.

3. Characteristics of electrostatic fluctuations

In this cold and tenuous plasma, fluctuations can be measured even in the plasma core region with LP, as shown in Fig.2(a). All relative amplitudes of fluctuations $\tilde{n}_e/n_e$, $\tilde{T}_e/T_e$ and $\tilde{V}_s/T_e$ increase rapidly from ρ ~ 0.8 toward the last closed flux surface (LCFS), of which features are similar to those in high temperature plasmas and their edge [4-6]. In the core region of $\rho \leq 0.8$, they stay almost a constant level that is considerably enhanced for that in 2.45 GHz ECH plasma of 0.4 kW [3]. Spectral power of ne-fluctuations in the plasma edge (ρ ~ 1.0) extends up to 100 kHz, and that in the core region is concentrated in lower frequency less than 10 kHz (Fig.2(b)). On the other hand, the spectra of T_e and V_s fluctuations extend to relatively high frequency range more than 100 kHz in the core region as well as the edge. Turbulent particle flux is concentrated within the core region of $\rho \leq$ 0.8, while the flux is localized in the plasma edge on the very low power case [3].

4. Transport barrier formation in outward-shifted plasma with low collisionality

As mentioned above, cold plasma with low ν^*_{ei} has already been obtained using 2.45 GHz ECH, although B_t is very low and ρ^*_s is fairly large. In this plasma, internal transport barrier is clearly formed in electron density and temperature profiles (ρ < 0.6), where the barrier formation starts from t ~ 150 ms in Fig.3(a). On the other hand, the

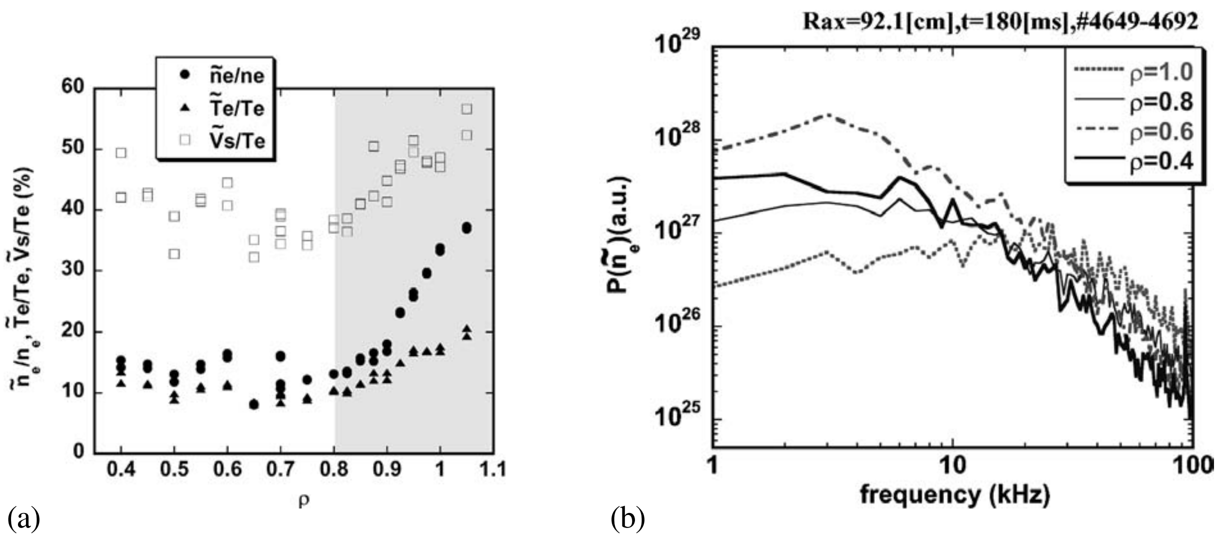
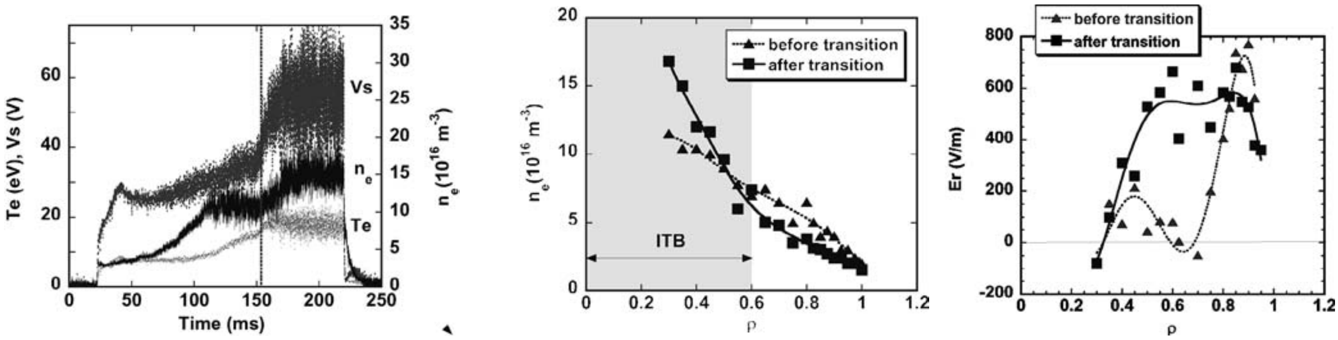


Fig. 2 (a) Radial profiles of relative fluctuation amplitude of electron density, electron temperature and plasma potential, where B_t = 0.079 T and R_{ax} = 0.92 m. (b) Frequency spectra of electron density fluctuations at various radial locations.



(a) (b)

Fig. 3 (a) Temporal evolution of electron density n_e, electron temperature T_e and plasma potential V_s measured at ρ = 0.35, where B_t = 0.061 T and R_{ax} = 0.97 m. (b) Radial profiles of electron density and radial electric field just before (t = 150 ms) and after the transition (t = 180 ms).

electron density and temperature outside the barrier region start to decrease at the transition. It should be noted that the fluctuation amplitude even increases after the transition. As shown in Fig.3(b), radial electric field E_r evolves from ~ 0 to the positive value of ~ 0.6 kV/m in the core region after the transition, which corresponds to the high poloidal velocity of ~ 10 km/s because of very low B_t. However, the poloidal velocity shear seems to be marginal to suppress micro turbulence (~ 1×10^5 s^{-1}). Formation mechanism of this internal transport barrier (ITB) is under investigation. A possible candidate mechanism is the reduction of neoclassical transport by the electron root regime [7,8]. However, energy and particle transport in this plasma is dominated by anomalous transport. Detailed study of E_r profile is necessary to clarify the ITB formation. In this discharge condition, the layer of fundamental electron cyclotron resonance is located just outside LCFS, and the second harmonic cyclotron layer is in ρ ~ 0.6. Moreover, the electron density exceeds the cutoff density (~ 7×10^{16} m^{-3}). This suggests electron heating by electron Bernstein waves mode-converted from launched X-mode.

5. Summary

Experimental simulation of high temperature plasma transport using almost dimensionally similar cold plasma produced by 2.45 GHz ECH at low toroidal field has been successfully carried out in CHS. The plasma fluctuations seem to behave similarly to those in high temperature plasmas. One significant example is to achieve the formation of ITB in this cold plasma. This new experimental project would contribute to clarifying important transport mechanisms in high temperature toroidal plasmas.

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