Investigation of the toroidal flow damping in edge plasma of J-TEXT tokamak with an electrode biasing

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1. Introduction

In a magnetically confined fusion device, the plasma flow makes a significant effect on determining the plasma stability, due to its stabilizing effect on the magnetohydrodynamic (MHD) instabilities, such as the tearing modes [1, 2] and the resistive wall modes [3]. However, the plasma flows are inevitably damped due to some damping mechanisms, e.g. the neo-classical toroidal viscosity (NTV) [4] and the neutral particle damping (NPD) [5].

The NTV is currently the focus of extensive attention of the plasma flow damping in annular magnetically confined devices [4]. It is caused by the interaction of the plasma with magnetic field components which break the toroidal symmetry of the magnetic confinement field. The NPD, caused by the charge exchange between bulk ions and cold neutral atoms, is another widespread flow damping process, which is found to considerably affect the flow in both stellarators and tokamaks [5].

In this paper, the responses of edge flow to the bias are analyzed firstly. Then, the torque densities driven by the bias current, the momentum transport and the NTV effect are calculated. The remnant damping torque densities, mainly contributed by the neutral particle damping, are also obtained from the angular momentum balance equation. In addition, the neutral particle density (n_{H}) in the edge plasma of J-TEXT has been estimated from the NPD torque density.

2. Experimental set-up

The experiments are carried out in Ohmic hydrogen discharges on the J-TEXT with a limiter configuration [6]. The electrode biasing (EB) system [7] (shown in figure 1(a)), is applied to drive the plasma flow. The EB source region is $-30 < \Delta r < 0$ mm, here Δr is the distance relative to the last close flux surface (LCFS). A reciprocating probe system [8], equipped with a Langmuir–Mach probe (LMP) array, is utilized to measure the plasma parameters in the region of $-20 < \Delta r < 30$ mm (shown in figure 1(b)). The schematic of the LMP array is presented in figure 1(c). More detailed descriptions about the experiments can be found in [9].

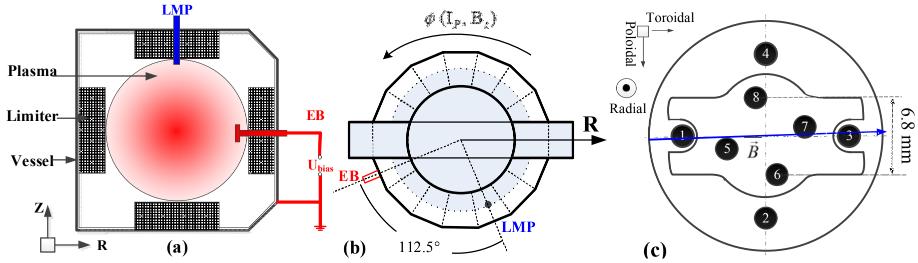

Figure 1. (a) Poloidal cross-section and (b) top view of the layouts of Langmuir–Mach probe (LMP) array and electrode biasing (EB) system. (c) Schematic of the LMP array used in the experiments.

3. Experimental results

The response of the flow to the bias is depicted in figure 2. It is clear that after the bias fast turning on, the toroidal flow reach to a new steady state in 8 ms (figure 2(c)) and recovers in about 2.5 ms after the bias turning off (figure 2(d)). The classical recovering time is about 140 ms for the typical discharge parameters, which is much longer than the measured recovering time τ_{off} ~2.5 ms, suggesting that the toroidal flow damping in J-TEXT is anomalous.

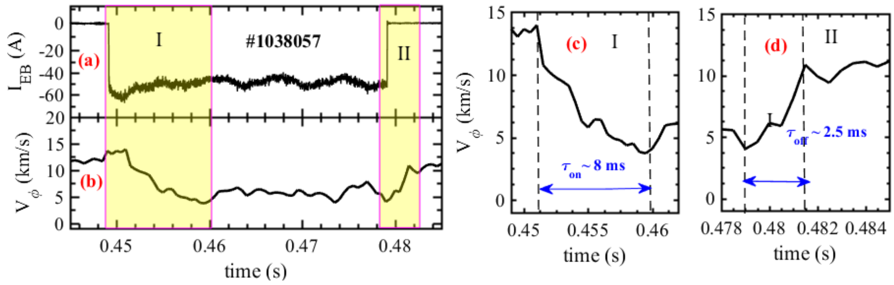

Figure 2. Response of toroidal flow to the electrode current: (a) and (b) are the electrode current and toroidal flow. (c) and (d) are the enlarged drawings of the fragments near the bias turning on / off.

What causes the anomalous flow damping? To investigate it, the local angular momentum equation (in the EB source region) is considered, which is expressed as:

$$R_0 m_i \frac{\partial(n_e V_\phi)}{\partial t} = -R_0 m_i \frac{d\Gamma_\phi}{dr} + j_r R_0 B_\theta + \eta_{NTV} - \mu_\phi R_0 m_i n_e V_\phi, \qquad (1)$$

here, $R_0 m_i n_i V_\phi$ is the angular momentum, with R_0 as the major radius, n_i/m_i as the ion density/mass. Γ_ϕ is the toroidal momentum flux. B_θ is the poloidal magnetic field. μ_ϕ is the effective damping coefficient. $j_r = I_{EB} / (4\pi^2 r R_0)$ is the radial current density yielded from the EB. The four items in the right side of equation (1) are the deposit torque density of the momentum transport, $\eta_{trans} = -R_0 m_i \, d\Gamma_\phi / dr$, the driving torque density of the EB, $\eta_{EB} = j_r B_\theta R_0$, the torque density caused by the NTV effect, η_{NTV} and the remnant momentum damping torque density, $\eta_{damp} = \mu_\phi R_0 m_i n_e V_\phi$, respectively. The deposit torque density of the momentum transport, η_{trans}, can be computed from the radial profiles of Γ_ϕ, as well as the sum of η_{trans}

and η_{EB}, which are depicted in figures 3(a) and (b).

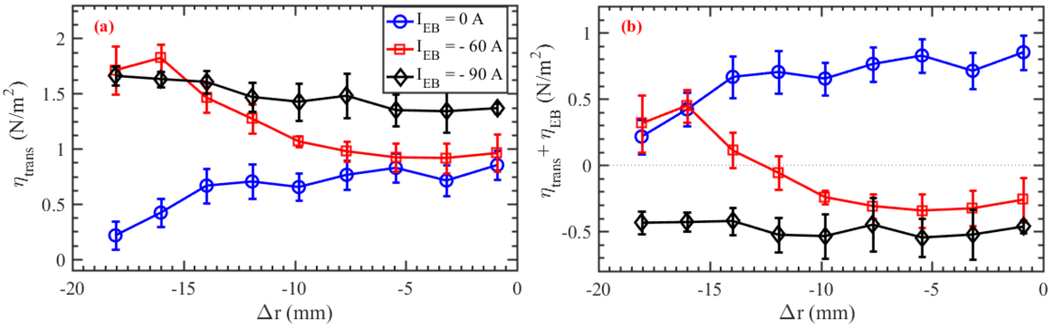

Figure 3. Radial profiles of (a) the deposit torque densities of momentum transport (η_{trans}) and (b) the sum of η_{trans} and η_{EB} under three bias cases (I_{EB}=0, -60 and -90 A) in EB source region.

With regard to the torque density induced by the NTV, it is mainly contributed by the toroidal field ripple in the present experiments, due to a significant large ripple and sufficiently small error fields at the edge of J-TEXT [10]. Based on a simply calculation, we find the plasmas in our experiment are located in the 1/*ν*-regime. According to Ref. [11], the NTV torque density in the 1/*ν*-regime can be expressed as: $\eta_{NTV} \approx 0.87 n_i m_i v_{ti}^2 \frac{\varepsilon^{3/2}}{\nu_{ii}} I_{1/\upsilon}[V_\phi - q(V_\theta + 2.367\frac{1}{erB_0}\frac{dT_i}{dr})]$.

Here, v_{ti} is the ion thermal speed, $V_\theta \sim (1.17/eB_0)dT_i/dr$) is the poloidal rotation velocity. The parameter $I_{1/\nu}$ is related to the toroidal field ripple and the pitch angle of the particle velocity relative to the field line (see detailed expression in Ref. [12]).The results of the torque densities (η_{NTV}) are presented in figure 4(a). In comparison with figure 3(b), one can see that, the torque densities driven by NTV are comparable with that induced by the momentum transport and EB.

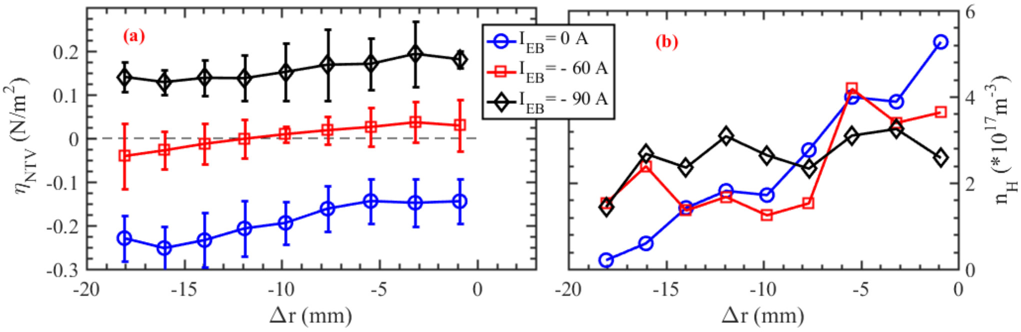

Figure 4. Radial profiles of (a) the NTV torque densities due to toroidal field ripple in the 1/ν-regime and (b) the estimated neutral particle density n_H for three bias cases (I_{EB}=0, -60 and -90 A).

In the equilibrium state suggested by equation (1), the sum of η_{trans}, η_{EB}, η_{NTV} and η_{damp} should be zero. Based on this relation, the remnant momentum damping torque density (η_{damp}) can be easily gotten. Besides, the η_{damp} in equation (1) is considered to be mainly contributed by the neutral particle damping (η_{NPD}), which gives $\eta_{damp} \approx \eta_{NPD} = n_H R m_i n_i V_\phi \langle\sigma v_i\rangle_{CX}$, where,

n_H is the neutral particle density. $<\sigma v_i>_{cx}$ is the charge-exchange rate between the hydrogen atoms and hydrogen ions, which is portrayed in [13]. Hence, the neutral particle densities can be computed, as shown in figure 4(b). It is found that, in the EB source region, the neutral particle densities are about in the range of 1 ~ 4 ($\times 10^{17}$ m^{-3}) and display a decreasing trend from the LCFS to inner, agreement with the previous result [14], which suggests that our way to estimate the neutral density is reliable.

4. Summary

The toroidal flow damping in the edge plasma of J-TEXT tokamak has been investigated using an electrode biasing. It is found that the flow damping is anomalous and the torque densities of the NTV effect due to the toroidal ripple are found to be comparable with that induced by the bias/momentum transport. The remnant damping torque densities which are mainly contributed by the neutral particle damping effect, are also obtained based on the angular momentum balance equation. Furthermore, the investigation of flow damping provides a method to estimate the neutral particle density in experiments, which gives the neutral particle densities at the edge plasma of J-TEXT in the range of 1 ~ 4 ($\times 10^{17}$ m^{-3}).

Acknowledgments

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