The neoclassical plasma viscosity analyses relevant to high-ion-temperature plasmas in the Large Helical Device (LHD)

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High ion-temperature (T_i) hydrogen plasmas, about 5 keV at the density range of 1.2-1.6x10^{19}m^{-3}, have been successfully realized in the LHD. The toroidal-view charge exchange recombination spectroscopy (CXRS) has observed the fast toroidal rotation velocity (V_t) with a several 10 km/s at the core region in these high-T_i hydrogen plasmas. Previously, high-T_i (more than 10 keV) plasmas have also been obtained in high-Z (like Ar, Ne) plasmas in LHD, in which several 10 km/s of toroidal rotation at the core region was also observed. Although, the impact of fats toroidal rotation on confinement improvement of ions is still unclear, consideration how the toroidal viscosity can be lowered at the core region in the LHD to maintain the faster toroidal rotation would be an important research issue. For this purpose, neoclassical transport code, DKES, has been begun to be applied to high-T_i LHD discharges. The present status of this application and a possible future direction is reported.

Keywords: LHD, high-T_i plasmas, toroidal rotation, neoclassical viscosity and flow, DKES

1. Introduction

The high-energy (~150-180 keV) neutral beam injection (NBI) with mainly electron heating has realized high ion temperature (T_i) as much as 13.5 keV in low-density (in the range of several 10^{18}m^{-3}) high-Z (Ar) plasmas as a proof-of-principle experiment [1] by effectively increasing the ion heating power (per an ion). Recent installation and the power increase (~6 MW) of lower-energy (~40 keV) NBI increases the ion heating, which has resulted in the recent achievement of more than 5 keV in hydrogen plasmas (with a line average density of about 1.2×10^{19}m^{-3}) in LHD as shown in Fig. 1 [2]. This perpendicular injected beam is also utilized for the T_i-profile measurement with the charge exchange recombination spectroscopy (CXRS) with the toroidal line of sight. This toroidal line of sight enhances the measurement capability for the central region (even for the case of a hollow profile of carbon content used for measurement) compared to that with a poloidal line of sight [2].

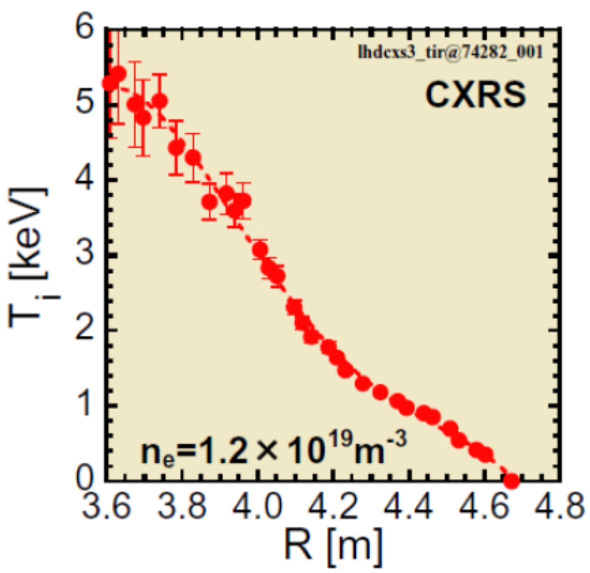

Fig.1 Ti profile in a high-Ti discharge measured by CXRS with a toroidal line of sight.

2. Toroidal rotation in high-T_i plasmas in LHD

The CXRS measurement has revealed that the toroidal rotation velocity (V_t) increases at the core region accompanied by the increase of T_i there as shown in Fig. 2(a) [the same shot and timing as that of Fig.1]. Since this plasma is heated by the 2-Co and 1-Counter (Ctr) NBI (in a configuration with the magnetic field reversed) with a perpendicular injection, the toroidal rotation direct in the Co-direction (positive value in Fig. 2(a)). We have also performed experiments in a configuration with the magnetic field un-reversed. In such a case, 3 parallel beam lines provide 1-Co and 2-Ctr. About 5 keV-T_i was

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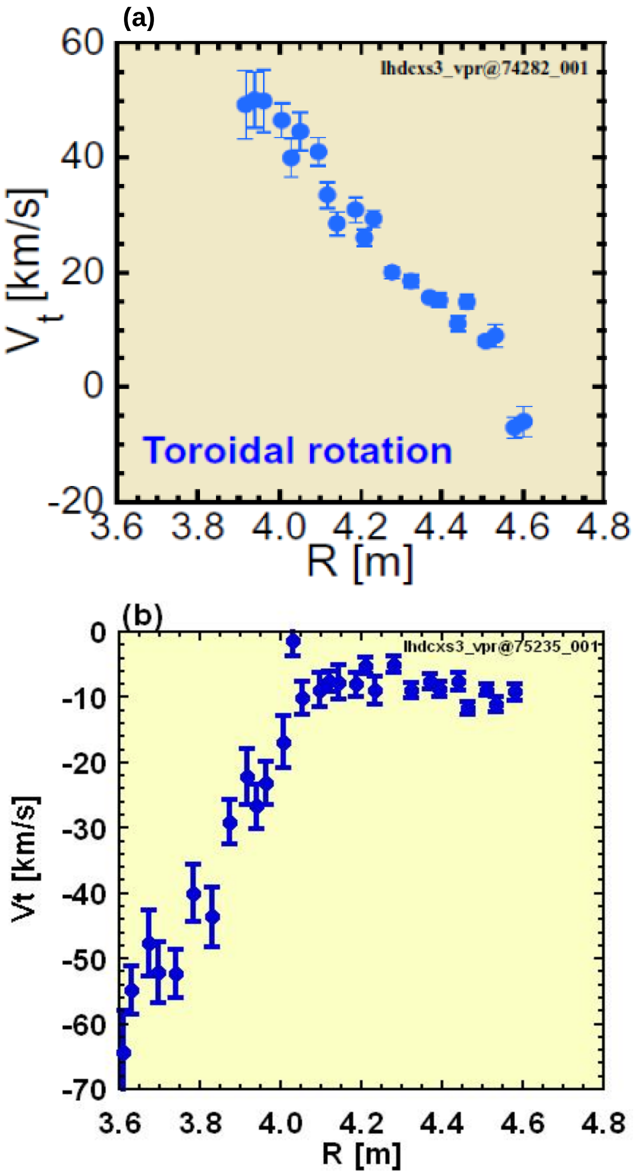

Fig.2 Toroidal rotation velocity profile in a high-Ti discharge measured by CXRS with a toroidal line of sight.

also obtained in such an experiment, where V_t directs in the Ctr-direction as shown in Fig. 2(b). These V_t are in the range of several tens of km/s at the core region. It should be also noted here that such a fast toroidal rotation at the core region was also observed in high-Z high-T_i discharges, which was measured by the Doppler shift of the X-ray line as in Ref. [4,5].

The impact of fast toroidal rotation on realizing high-T_i plasmas is uncertain. However, it is the experimental observation that these high-T_i discharges (regardless the ion species) in the LHD have been realized accompanied by such a fast toroidal rotation at the core region. Of course, large (mainly toroidal) momentum input exists from 3 parallel beam lines for these plasmas, which is the source of a fast toroidal rotation. Thus, it is meaningful to consider how the toroidal viscosity can be lowered at the core region in the LHD, to maintain the fast toroidal rotation with less damping.

2. Application of DKES code for high-T_i discharges in LHD

The neoclassical transport coefficients can be evaluated from the solution of the drift kinetic equation. The Drift Kinetic Equation Solver (DKES) [6] can solve the linearized DKE and provide mono-energy neoclassical transport coefficients in 3D magnetic configurations, without approximations connecting collisionality regimes. The mono-energy transport coefficients can be evaluated at given ν/v and E_r/v, where ν is the energy-dependent collision frequency, E_r is the radial electric field and v the thermal velocity. Since the evaluation of the ambipolar E_r is a key element of the analysis, the module interpolating the mono-energy transport coefficients on parameters ν/v and E_r/v has been added to the DKES code [7], so that ambipolar radial electric field can be determined by balancing the electron and ion particle fluxes depending on E_r.

DKES code, Sugama-Nishimura's method [8] included, has been applied to analyze high-T_i discharges in LHD such as shown in Fig. 1. Before injecting 3 parallel NBI, core T_i is about 1.5 keV at the same discharge. Calculations for these two cases (one is a case of $T_i(0)$~1.5 keV and the other is one with $T_i(0)$~5.2 keV) have been performed, and the evaluated ambipolar E_r is compared with those by GSRAKE code [9], as shown in Fig. 3. The parameters used for DKES calculations are as follows; (mpol, ntor, mpolb, ntorb, lalpha)=(16,12,6,2,100), where notations indicate poloidal and toroidal mode numbers for perturbed distributions function and magnetic field expression and Legendre polynomials, in order. For a case of lower $T_i(0)$, DKES and GSRAKE results are fairly close each other. The convergence of DKES calculations with the mini-max variational principle employed is rather well satisfied. On the other hand, for a case of higher $T_i(0)$, the difference between two codes becomes apparent especially toward the core region with higher T_i. It is also noted that the range of mini-max variation shown by "error bars" becomes larger there, indicating that the convergence becomes poorer at lower collisionality.

To examine the convergence properties, above mentioned parameters for DKES calculations are varied for the calculation at ρ~0.37 of "74282-1.15s". Figure 4 shows the parameter dependence of evaluated ambipolar E_r for several conditions with varied parameters written in the figure. It is noted that "the condition 1" corresponds to the result shown in Fig. 3. It seems that

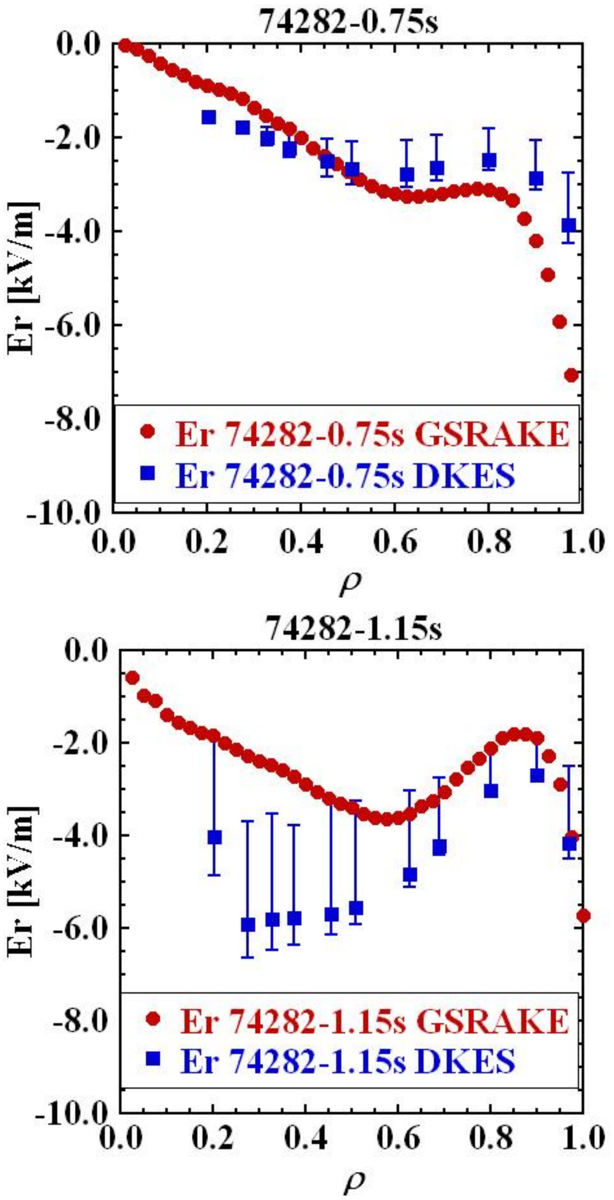

Fig. 3 Ambipolar E_r evaluated by DKES (blue) and GSRAKE (red) for cases with Ti(0)~1.5 keV (upper) and 5.2 keV (lower). (see the parameters used for DKES calculations in the text).

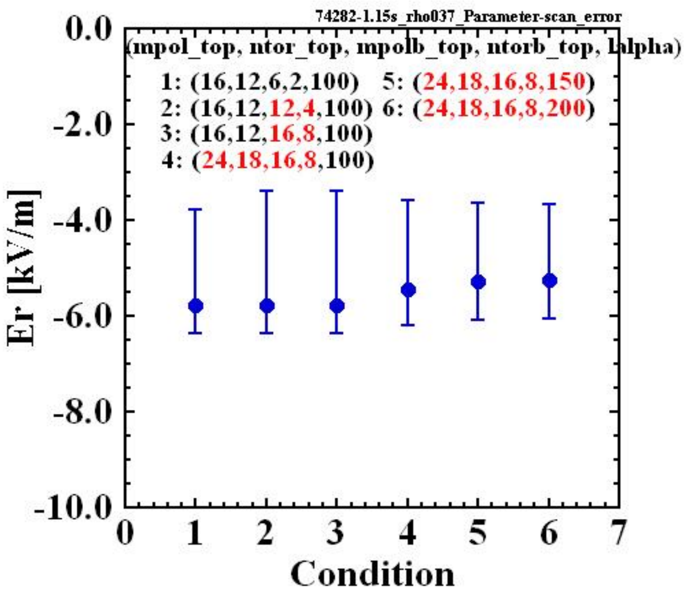

Fig. 4 Ambipolar Er evaluated at ρ~0.37 for "74282-1.15s" with varied parameters used for DKES calculations. The parameters are listed in figure according to the condition number.

the averaged values (circles) tend to become gradually less negative according to the increase of mode numbers for perturbed distribution function (condition 3 to 4) with reduction of mini-max variation. The increase of mode numbers for magnetic field seems to increase the min-max variation (condition 1 to 2 and 3) with fixed mode numbers for perturbed distribution function, which indicates that the further increase of mode numbers of perturbed distribution function is required for larger mode numbers for magnetic field.

The difference of evaluated ambipolar E_r between DKES and GSRAKE are still large even for the largest parameters used for DKES calculations (condition 6). Detailed comparison between results from both codes and additional information provided by other neoclassical transport code (such as DCOM [10]) will be performed soon. It would be necessary to further increase the mode numbers used for DKES calculations when we consider the application to low collisional plasmas like high-T_i discharges in LHD. It has been already confirmed that DKES and GSRAKE predict almost similar values of ambipolar E_r each other [8] in collisional plasma like IDB/SDC (Internal Diffusion Barrier/Super Dense Core) in LHD [11].

The further investigation will be extensively performed so that DKES can be properly and practically applied for neoclassical transport analyses of high-T_i discharges in LHD. This will allow us to apply DKES code for analyses of further high-T_i and even reactor-relevant situations.

4. Conclusion and discussion

The fast toroidal rotation has been commonly observed in high-T_i (high Z and low Z (hydrogen), regardless the ion species) plasmas in LHD in circumstances of high power NBI heating.

DKES code has been attempted to apply for the viscosity and flow analyses for such plasmas. However, unfortunately, the difficulty for treating low collisional regime (high-T_i region) has been encountered so far so that relevant analyses have yet been performed. Extensive investigation how to resolve this difficulty will be performed so that DKES can be practically and properly applied for neoclassical transport analyses of high-T_i discharges in LHD.

At last, an “intuitive” consideration for plasma rotation is drawn. It is experimentally confirmed that the toroidal rotation is enhanced towards the core region in high-T_i discharges. It has been predicted by ambipolar E_r analysis and also experimentally demonstrated (as measured by CXRS with poloidal line of sight [12]) that the poloidal rotation is usually enhanced towards the plasma edge (either in ion-root and electron-root regime) [13]. This combination of radial variations of toroidal and poloidal rotation can provide a macroscopic shear of plasma rotation, which may be helpful to reduce radial transport. This feature is unique in L=2 (where L is the poloidal polarity of helical coils) heliotron–type configuration where the helicity of magnetic field increase towards the edge and the toroidicity becomes larger than helicity at the very core region. We will perform the analyses to make this “hypothesis” more evident.

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