Extension of the high-ion-temperature regime in the Large Helical Device


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High-ion-temperature (exceeding 5 keV) hydrogen plasmas have been successfully produced in the Large Helical Device [Iiyoshi et al., Nucl. Fusion 39, 1245 (1999); Motojima et al., Nucl. Fusion 47, S668 (2007)] with the ion heat confinement improvement in the core region. The experimental ion heat diffusivity at the core region is found to be almost independent of the ion temperature, \( T_i \) (even decreasing as \( T_i \) increases). The neoclassical (NC) ripple transport is suppressed by the ambipolar radial electric field, \( E_r \) (<0) predicted by NC transport fluxes. The temperature ratio, \( T_i/T_e \), is one of the key parameters to reduce the NC ambipolar particle and heat fluxes. Thus, it is suggested that the selective ion heating (making \( T_i/T_e \) larger) is a plausible approach to further increase \( T_i \). Spontaneous rotation is evaluated in these high-\( T_i \) plasmas, in which a co-directed component is recognized at the radial location with a large \( T_i \) gradient, in addition to the tokamak-like counter-directed component expected for \( E_r < 0 \). © 2008 American Institute of Physics. [DOI: 10.1063/1.2890755]

I. INTRODUCTION

The Large Helical Device (LHD) is the world’s largest superconducting helical device, which has significantly extended the high-performance regime of magnetic confinement research in helical systems, and also has demonstrated long-pulse capability, which is an inherent advantage provided by the helical magnetic configuration. The capability of high-ion-temperature plasma confinement is also one of the key issues to be demonstrated.

It has been known that the temperature ratio \( (T_i/T_e) \) is one of the important parameters to determine the plasma confinement properties. Here, \( T_e \) and \( T_i \) denote the electron and ion temperatures, respectively. For example, particle and heat transport improve as \( T_i/T_e \) is increased, as recognized in DIII-D. The damping rate of the zonal flow is predicted to depend on the radial electric field \( E_r \) in helical plasmas, where \( E_r \) is strongly affected by the temperature ratio, through the ambipolarity condition based on neoclassical (NC) particle fluxes.

LHD plasmas typically have had a higher \( T_e \) than \( T_i \) due to the electron-predominant heating from the high-energy neutral beam injection (NBI) heating. The NC ambipolar \( E_r \) in such \( T_i/T_e > 1 \) plasmas tends to be positive (electron root), and the impact of the positive \( E_r \) on confinement properties and improvement have been extensively studied in LHD and also in other helical devices.

On the other hand, helical plasmas with \( T_i > T_e \) are predicted to have a negative ambipolar \( E_r \), as systematically evaluated in Ref. 5. In this regard, the ion heating experiments in LHD are significant not only to demonstrate the high-\( T_i \) plasma confinement capability, but also to extend the plasma parameter regime to \( T_i > T_e \) so that the impact of the negative \( E_r \) on helical plasma confinement can be widely studied, and also to comprehensively understand the impact of temperature ratio on helical plasmas.

To demonstrate high-\( T_i \) plasma confinement capability in LHD, high-Z (such as Ne and Ar) plasmas with low ion density (in the range of \( 10^{18} \) m\(^{-3} \)) were used as targets during the period when only tangential NBIs were operating, to effectively increase the absorption power per ion. \( T_i \) of about 13.5 keV was successfully demonstrated by this approach. More importantly, it was found that the scaling between the achieved \( T_i \) and the absorbed power normalized by the ion density is almost similar regardless of the ion species. This successful proof-of-principle ion heating experiment has encouraged the installation and power increase (up to 6–7 MW) of a low-energy (40 keV) perpendicular NBI to increase the direct ion-heating power. As a result, \( T_i \) has now exceeded 5 keV in a hydrogen plasma, which extends the high-\( T_i \) regime in helical system research. The core of the high-\( T_i \) plasma is characterized by \( T_i/T_e > 1 \), which provides a new parameter regime for LHD plasmas. It should also be mentioned that this low-energy NBI is perpendicularly injected, enabling the charge exchange spectroscopy (CXS) measurement with a toroidal line of sight for measuring radial profiles of \( T_i \) and toroidal rotation \( (V_t) \) even in cases with a hollow impurity density profile (carbon is utilized for the measurement). The observation of \( T_i \) and \( V_t \) profiles has enhanced the physics understandings of ion confinement in helical plasmas.

This paper is organized as follows. In Sec. II, heating equipment for ion heating experiments in LHD is explained. Plasmas with \( T_i > 5 \) keV are described in Sec. III including the ion heat confinement properties in such plasmas.
utilization of ambipolar $E$, for higher-$T_i$ plasma production (toward the reactor relevant regime) is also suggested based on the current understanding of the obtained high-$T_i$ plasmas in LHD. Spontaneous rotation is also briefly mentioned. Finally, a summary and discussion will be given in Sec. IV.

II. SETUP FOR ION HEATING EXPERIMENTS IN LHD

The LHD is equipped with three tangential negative-ion-based and one recently installed perpendicular positive-ion-based NBI, in which the nominal injection energy of the hydrogen beam is as high as 180 keV (for the tangential beams) and 40 keV (for the perpendicular beam). The tangential NBIs were designed to achieve a high fusion triple product and the injection energy was determined for target densities of $(3−5) \times 10^{19}$ m$^{-3}$. For lower-density hydrogen plasmas, however, most of the beam power goes to electrons due to the high injection energy. The total injection power of the three tangential NBIs has reached about 14 MW. One injector (No. 2) has the opposite injection direction to the other two injectors (Nos. 1 and 3). A low-energy NBI (No. 4) began operation in 2005, and 7 MW injection was achieved in the last experimental campaign (2006–2007).

Ion cyclotron range of frequency heating (ICH) can also be utilized since the target plasmas for ion heating experiments in LHD recently has been the low-Z species, like hydrogen and/or helium. A total power of about 2 MW (38.47 MHz) was injected through four antennas with the minority heating mode. The resonance layer of the minority heating mode is located near the core region for a case with $R_{ax}=3.60$ m and $B=2.75$ T. Here, $R_{ax}$ denotes the magnetic axis position and $B$ is the magnetic field strength.

The electron cyclotron range of frequency heating (ECH) has also been recognized to be effective to improve ion confinement at the core region through the appearance of the electron root $E$, with a large positive value. This effect was clearly recognized at the electron density of about $0.3 \times 10^{19}$ m$^{-3}$ in high-Z plasmas. The target density for ion heating experiments described in this paper is above $1 \times 10^{19}$ m$^{-3}$. In such a density regime, clear effects of ECH on ion confinement have not yet been observed, although the increase of the $T_e$ gradient ($T_e$ is in the range of 1 keV) at the core region associated with a co-toroidal rotation enhancement was observed.

III. HIGH-ION-TEMPERATURE HYDROGEN PLASMAS IN LHD

A. High-$T_i$ hydrogen plasma production in LHD

High-$T_i$ hydrogen plasmas with $T_i>5$ keV were successfully produced. Figure 1 shows the results of a 5.2 keV discharge at a density of about $1.2 \times 10^{19}$ m$^{-3}$, where the following results are shown: (a) $T_i$ (CXS), (b) $T_e$ (Thomson scattering), (c) $V_e$ (CXS) profiles, and (d) the heating scenario. The magnetic configuration is characterized by $R_{ax}=3.575$ m with $B=−2.769$ T (reversed magnetic field direction), which makes two tangential beams (Nos. 1 and 3) co-injection and No. 2 counter-injection. The low-energy beam (No. 4) consists of four ion sources with the two independently operatable power supply systems (4A and 4B). This flexibility is utilized to modulate one of power supplies (in this case, 4B) to modulate the injection with 100 ms interval to obtain the background signals of CXS measurement, as seen at the bottom of Fig. 1(d).

The No. 4 beam was injected for 1 s from $t=0.5$ s (just after the ECH turn-off), with the superposition of Nos. 1–3 beams from $t=0.9$ s. At the timing of No. 4 only ($t=0.75$ s), $T_i$ reaches about 1.6 keV with comparable $T_e$. The density profile at this timing is peaked with the particle fueling from No. 4 beam. The $V_e$ is rather small (less than 10 km/s) at $t=0.75$ s. Once the Nos. 1–3 beams are injected in addition to the beam No. 4, $T_i$ increases and reaches 5.2 keV at the core region with the apparent change of the gradient around $R=4.2$ m. In this high-$T_i$ phase, $T_e$ exceeds $T_i$ [$3.5$ keV at the core region as seen in Fig. 1(b)]. The density profile tends to become flat to hollow at this timing, which is a typical trend for tangential beam injection in LHD. The $V_e$ is also largely enhanced in the co-direction in accordance with the predominance of co-injected beams. The $V_e$ at the very core region is difficult to measure due to the lack of the line intensity for the measurement. However, at least as much as 50 km/s of $V_e$ (about 7% of the thermal velocity of the hydrogen ion with 5.2 keV) is observed.

There is another example of a high-$T_i$ discharge with ICH at a higher density of about $1.6 \times 10^{19}$ m$^{-3}$, as shown in Fig. 2: (a) $T_i$ and (b) $V_e$ profiles, and (c) the heating scenario. In this case, the ICH ($\sim 2$ MW) is superimposed on the No. 4 beam just after ECH turn-off and followed by the further superposition of the Nos. 1–3 beams from 1.1 s. The magnetic configuration is $R_{ax}=3.6$ m with $B=2.85$ T (normal direction), making counter-injection dominant (Nos. 1 and 3 are counter-injection). The $T_i$ reaches above 2 keV (at the density range of about $1.6 \times 10^{19}$ m$^{-3}$) during the phase of...
No. 4 beam injection and ICRH and further increases up to about 5 keV 200–300 ms after the Nos. 1–3 beam injections. The $V_i$ is also enhanced in the counter-direction at the timing of the maximum $T_i$. It is also noted that the core $T_i$ changes from about 2 to 3.5 and then 3 keV at $t=0.95$, 1.35, and 1.75 s, respectively. Thus, $T_i> T_p$ is again the case at the timing of the maximum $T_i$.

The density scan experiments were also performed as summarized in Fig. 3, where the core $T_i$ and $T_p$ are plotted as a function of the electron density deduced from the FIR measurement. It is clearly recognized that $T_i> T_p$ at the lower density regime and then $T_i$ tends to become comparable to $T_p$ (due to the energy equipartition) as the density is increased. $T_i$ reaches 3 keV even at $n_e>3 \times 10^{19}$ m$^{-3}$.

B. Ion heat confinement properties

The ion heat confinement properties of high-$T_i$ plasmas are described to clarify the confinement characteristics of these high-$T_i$ plasmas.

First, ion thermal diffusivity ($\chi_i$) is described from the viewpoint of both the experimental and NC one. For the experimental ion thermal diffusivity ($\chi_i$,exp) analysis, an NBI deposition calculation is performed using the FIT code, which can analyze the NBI heating profiles in a 3D magnetic configuration assuming a quasi-steady-state plasma. It is a reduced-version of the GNET code.\(^{1,18}\) The GNET code can evaluate the accurate deposition profile and distribution in the velocity space of injected beam particles based on the Monte Carlo approach in 5D phase space. For the purpose of the application of this time-consuming GNET code to the experimental analysis, it has been reduced to the FIT code by considering that the full-orbit effect during the slowing-down process on the deposition profile evaluation is not necessary, and that the prompt orbit loss effect is a sufficient approximation for such a purpose.

Here, the effective $Z$ of the background plasma is assumed to be 2. It has been confirmed that changing $Z$ from 2 to 3 gives only a slight change in the deposited power and therefore the estimation of $\chi_i$,exp.

Figure 4(a) shows $\chi_i$,exp (normalized by a Gyro-Bohm factor, $T_i^{1.5}$) at a radial location from near the center to $R \sim 0.6$ for the lower- and higher-$T_i$ cases shown in Fig. 1(a). The reduction of $\chi_i$,exp is recognized, especially about a two orders of magnitude (in $\chi_i$,exp/$T_i^{1.5}$) reduction occurs at the core region. This clearly indicates that the ion heat confinement is largely improved at the core of a higher-$T_i$ plasma.

A change of the $T_i$ gradient (“foot-point”) can be observed at $R \sim 4.2$ m (corresponding to $t \sim 0.7$). Since a global $T_i$ fitting (from $\rho=0$ to $\rho=1$) may miss this local structure, a closer look at the $T_i$ gradient is performed in the radial location of $R \sim 4.0–4.4$ m, as shown in Fig. 4(b). It is clearly seen that there is a discontinuity in the $T_i$ gradient, indicating that the ion heat confinement property is qualitatively different between the outer and inner region separated by a foot-point. It can be even quantitatively shown by evaluating the $\chi_i$,exp utilizing the locally evaluated $T_i$ gradient. Such an estimate is shown in Fig. 4(c), where the spatial jump and the change of the slope of $\chi_i$,exp are recognized for the higher-$T_i$ case. Based on these facts, it can be concluded that a high-$T_i$ plasma is obtained as a result of the improved conformation mode, not just a result of the gradual increase of $T_i$.
formed for the case shown in Fig. 1 by using the GSRAKE code. The NC diffusion coefficients are evaluated by utilizing the experimentally obtained density and temperature profiles to obtain the electron and ion particle fluxes (\( \Gamma_e \) and \( \Gamma_i \)). The ambipolar condition, \( \Gamma_e = \Gamma_i \), provides the ambipolar \( E_r \). Unfortunately, due to the hollow carbon impurity profiles, \( E_r \) has not yet been measured at the core region of such high-\( T_i \) plasmas. Thus, the NC ambipolar \( E_r \) is the only available information on \( E_r \). However, it is fair to think that the NC ambipolar \( E_r \) gives a rather good indication for the experimentally observed \( E_r \) in LHD as demonstrated in previous papers.

The estimated ambipolar \( E_r \) at \( t=0.75 \) s \([T_i(0) \sim 1.6 \text{ keV}] \) and \( 1.15 \) s \( (\sim 5.2 \text{ keV}) \) are shown in Fig. 5(a). A negative \( E_r \) is anticipated all the way from the core to the edge for both cases, with a slight enhancement in the core region for the higher-\( T_i \) case. The positive \( E_r \) is also predicted in an isolated narrow peripheral region for the higher-\( T_i \) case, which is not shown in Fig. 5(b) [so as in Fig. 9(b)]. Figure 5(b) shows the NC ion heat diffusivity \( (\chi_{i,NC}) \) with the ambipolar \( E_r \) \((<0)\) taken into account. The \( \chi_{i,NC} \) shows little change in the core region between the two cases even with an almost tripled \( T_i \) in the higher-\( T_i \) case compared to that of the lower-\( T_i \) case. It should be also noted that \( \chi_{i,NC} \) is predicted to be about three orders of magnitude larger (up to \( \sim 10^3 \text{ m}^2/\text{s} \)) in the higher-\( T_i \) case if \( E_r \) is assumed to be zero ("pure" ripple transport). The ambipolar \( E_r \) plays a significant role in preventing the theoretically predicted ripple transport level to appear. Figure 6 shows NC ion and electron fluxes as a function of \( E_r \) at \( \rho=0.2 \) for the (a) lower- and (b) higher-\( T_i \) cases. A significantly larger \( \Gamma_i \) is predicted to appear at \( E_r=0 \) in the higher-\( T_i \) case compared to that in the lower-\( T_i \) case. However, the NC ambipolarity assures a negative \( E_r \) so that the realizable level of the NC particle flux remains comparable to that obtained in (a). In this regard, it can be said that the ripple transport can be well suppressed by the presence of ambipolar \( E_r \) even in this high-\( T_i \) plasma.

A comparison between \( \chi_{exp} \) and \( \chi_{exp} \) is shown as a function of \( T_i \) (at the core region with \( \rho=0.4 \)) taking the obtained high-\( T_i \) discharges as examples, which is shown in Fig. 7(a). Additional cases of comparison should be made, but the trend can be already seen from this figure. The experimental \( \chi_i \) is greater than the NC one (by about an order of magnitude) in the lower-\( T_i \) case. The experimental \( \chi_i \) remains almost unchanged (even decreasing a bit) as \( T_i \) increases, indicating that high-\( T_i \) plasmas do not follow a Gyro-Bohm scaling \((\sim T_i^{1.5})\), thus showing an improvement of the ion heat confinement. The \( \chi_{i,NC} \) is increasing as \( T_i^{1.7} \), whose power law is much smaller than the \( T_i^{1.5} \) predicted theoretically in a "pure" ripple transport. The \( \chi_{exp} \) and \( \chi_{i,NC} \) become comparable at \( T_i \approx 4 \text{ keV} \) in these examples. However, \( \chi_{i,NC} \) can be further reduced by enhancing the ion-root \( E_r \), for example, by increasing the \( T_j/T_i \) ratio. Figure 7(b) shows \( \Gamma_i \) and \( \Gamma_e \) at \( \rho=0.2 \) for the higher-\( T_i \) case shown in Fig. 1(a). It clearly shows that \( \Gamma_i \) is reduced to the level of \( \Gamma_e \). The \( T_j/T_i \) is about 1.4 in this case, where the ripple transport enhancement (at \( E_r=0 \) of \( T_i \)) begins to appear. If \( T_e \) is lowered artificially to make the ratio \( T_j/T_e \approx 4 \), such an enhancement does not appear, and \( \Gamma_e \) is further decreased to
calculations for reduction of 10 keV is possible with more than one order of magnitude increase of $T_{e}$, which suggests that the selective ion heating should be an effective approach for the further increase of $T_{e}$. However, in the higher density regimes such as those relevant to a reactor, decoupling the ions and electrons is unrealistic. In such a case, i.e., for the case of comparable $T_{e}/T_{i}$, $\Gamma_{e}$ enhancement due to the appearance of the electron’s ripple transport can be utilized to make the electron root possible. Such an estimate has been carried out in Ref. 21, where it is reported that the electron-root scenario for the reactor-relevant density regime with $T_{e} \sim T_{i}$ in the range of 10 keV is possible with more than one order of magnitude reduction of $\chi_{NC}$ compared to that for the ion-root case.

C. Spontaneous rotation

Transport in the plasma is considered to be sensitive to the profile of the flow velocity. The mechanism for driving the spontaneous toroidal flow is of great interest in the area of momentum transport physics and has been investigated experimentally and theoretically.\textsuperscript{22-27} Besides the toroidal flow driven by the external momentum input of the tangential NBI, there is the spontaneous toroidal flow driven by the coupling of the $E \times B$ force and the viscosity tensor. The stress tensor redirects some fraction of the diamagnetic and $E \times B$ flows into parallel flows.

In the following, the observed toroidal flow is described together with an estimate of the spontaneous rotation in high-$T_{i}$ plasmas in LHD.

High-$T_{i}$ plasmas have been obtained in LHD in configurations either in the normal or in the reversed magnetic field direction, as shown in Figs. 1 and 2. As described there, toroidal rotation is enhanced in the direction of the dominant tangential NBI. Here, two almost identical (from the viewpoint of $T_{i}$ values and profiles, plasma density and injection power, etc.) high-$T_{i}$ discharges are considered. One is the discharge shown in Fig. 2 (counter-dominant NBI) and the other is shown in Fig. 8 [(a) $T_{i}$ and (b) $V_{i}$ profiles] for co-dominant NBI. To estimate the spontaneous rotation contribution on these measured $V_{i}$, the average of these two discharges is performed (both in higher- and lower-$T_{i}$ cases) so that the toroidal flow driven by the external momentum input from tangential NBIs can be canceled out. Such an averaging has resulted in profiles as shown in Fig. 8(c). For the lower-$T_{i}$ case, the spontaneous toroidal flow is in the counter-direction. It is noted that the predicted $E_{r}$ is negative in these cases [as shown in Fig. 5(a)]. The core region of the LHD magnetic configuration is dominantly governed by toroidicity rather than helicity due to their $\rho$ dependences such as $\sim \rho$ and $\sim \rho^2$, respectively, from which it can be very roughly considered that the magnetic configuration of the core region of LHD is similar to that of tokamaks. Spontaneous rotation in tokamaks in the case of negative $E_{r}$ is directed in the
counter-direction.25 Thus, the counter-rotation estimated in the lower-$T_i$ cases shown in Fig. 8(c) can be understood as a property similar to that in tokamaks. On the other hand, for higher-$T_i$ cases, the contribution toward the co-direction is recognized by considering the difference between higher- and lower-$T_i$ cases in Fig. 8(c). This contribution is pronounced at the radial region where the $T_i$ gradient becomes large [cf. Figs. 2(a) and 8(a)]. Since the $E_r$ is predicted to be negative also in these high-$T_i$ cases, this co-direction contribution should be based on a mechanism other than $E_r$, and it might be related to the $T_i$ gradient (then pressure gradient). The mechanism for this observation has not yet been understood, and remains an open issue.

IV. SUMMARY AND DISCUSSIONS

High-ion-temperature (exceeding 5 keV) hydrogen plasmas have been successfully produced in LHD. Such high-$T_i$ plasmas are obtained by the improvement of ion heat confinement associated with a change of the $T_i$ gradient. It is also revealed that the neoclassical ripple transport is well suppressed by the ambipolar $E_r(<0)$. It is found, from the comparison between experimental and NC ion heat diffusivities, that the NC level is approaching the experimental one as $T_i$ increases in analyzed high-$T_i$ plasmas. The temperature ratio, $T_i/T_e$, is one of the key parameters to reduce the NC ambipolar particle and heat fluxes. It is suggested that selective ion heating (making $T_i/T_e$ larger) is a plausible approach to further increase $T_i$ by making the ion root $E_r$ larger (in absolute value) with the current LHD heating equipment (ion-root scenario). Of course, for a reactor relevant situation with $T_i\sim T_e$, this approach does not work. For such a case, the electron-root scenario (by utilizing the appearance of the electron’s ripple transport) is demonstrated.21

Spontaneous rotation is also evaluated in these high-$T_i$ plasmas, in which the co-directed component is recognized at the radial location with a large $T_i$ gradient, in addition to the tokamak-like counter-directed component expected for $E_r<0$. Systematic analyses for spontaneous rotation in high-$T_i$ plasmas are ongoing tasks.

The NC analyses beyond the radial transport, such as plasma flows and their relationships with parallel/ perpendicular viscosities, have been initiated as described in the Appendix. Such analyses will increase the understanding of plasma flow issues in helical plasmas and their impacts on confinement properties along with experimental verifications in LHD.

Finally, the evaluation of the ambipolar $E_r$ is discussed. Previously in Wendelstein 7-A, it was demonstrated that the ion energy confinement was strongly improved by building up large negative $E_r$ through enhancing the fast ion loss by the perpendicular NBI.28,29 In this paper, the contribution from fast ion loss in the determination of the ambipolar $E_r$ was neglected. The characteristics supporting this assumption are the following. In LHD, ions are found to be heated up to the MeV range by ICH,30 which indicates that the fast ions are well confined without experiencing direct losses. The employed inward-shifted magnetic configurations for these experiments have been evaluated to provide enough power deposition (more than 70% of the injected power can be deposited) from perpendicular NBI. Another characteristic can be found in the electron channel. In LHD (as well as in other helical devices), the energy confinement of core electrons is significantly improved by the appearance of a large positive $E_r$ (electron root) in the core region as is systematically summarized in Ref. 31. In such discharges in LHD, the ambipolar $E_r$ predicted only from neoclassical fluxes (driven by thermal ions and electrons) agrees rather well with the experimentally measured $E_r$.32 This finding (although for the electron channel) also supports the estimate of the ambipolar $E_r$ only from the thermal fluxes in this paper. However, even with these supporting features, it is important to check the validity of this assumption by measuring $E_r$ in high-$T_i$ plasmas. The efforts for increasing the measurement capability have been made, such as bundling fiber arrays of the CXS system to increase the background signals even for hollow impurity profiles. It will provide a chance to measure and compare $E_r$ with the estimated ambipolar $E_r$.

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APPENDIX: APPLICATION OF DKES CODE FOR HIGH-$T_i$ PLASMAS IN LHD

The Drift Kinetic Equation Solver (DKES)33 can solve the linearized DKE and provide mono-energy NC transport coefficients in 3D magnetic configurations, without approximations such as connecting formulas in different collisionality regimes. The mono-energetic transport coefficients can be evaluated at given $v/v$ and $\nu$, where $\nu$ is the energy-dependent collision frequency and $v$ is the thermal velocity. Since the evaluation of the ambipolar $E_r$ is a key element of the analysis, the module interpolating the mono-energetic transport coefficients on parameters $v/v$ and $E_r$ has been added to the DKES code, so that the ambipolar $E_r$ can be determined by balancing the electron and ion particle fluxes.

The DKES code, with the method of Sugama-Nishimura34 included, has been applied to analyze high-$T_i$ plasmas in LHD. Calculations for lower- and higher-$T_i$ cases shown in Fig. 1 have been performed, and the evaluated ambipolar $E_r$ is compared with those by GSRAKE (cf. Fig. 5(a), as shown in Fig. 9. The parameters used
for DKES calculations are as follows: (mpol, ntor, mpolb, ntorb, alphal)=\((16, 12, 6, 2, 100)\), where the notations indicate the poloidal and toroidal mode numbers for perturbed distribution functions and the magnetic field expression and Legendre polynomials, in that order. For a case of lower-\(T_e\), DKES and GSRAKE results are fairly close to each other, indicating that particle fluxes themselves are also in good agreement. The convergence of DKES calculations with the min-max variational principle employed is rather well satisfied. On the other hand, for a higher-\(T_e\) case, the difference between the two codes becomes apparent especially toward the core region with higher \(T_e\). It is also noted that the range of min-max variation shown by the “error bars” becomes larger there, indicating that the convergence becomes rather poor at lower collisionality.

To examine the convergence properties, the above-mentioned parameters for DKES calculations are varied for the calculation at \(\rho \approx 0.37\) of a higher-\(T_e\) case shown in Fig. 1(a). Figure 10 shows the parameter dependence of the evaluated ambipolar \(E_a\) for several conditions with varied parameters written in the figure. It is noted that “condition 1” corresponds to the result shown in Fig. 9. It seems that the min-max averaged values (circles) tend to become gradually less negative with the increase of mode numbers for the perturbed distribution function (condition 3 to 4) with reduction of the min-max variation. The increase of mode numbers for the magnetic field seems to increase the min-max variation (condition 1 to 2 and 3) with fixed mode numbers for the perturbed distribution function, which indicates that the further increase of mode numbers of the perturbed distribution function is required for larger mode numbers for the magnetic field.

The difference in the evaluated ambipolar \(E_a\) between DKES and GSRAKE is 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 NC transport codes (such as DCOM\(^{35}\)) 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-\(T_e\) plasmas in LHD.

Further investigation will be extensively performed so that DKES can be properly and practically applied for NC transport analyses of high-\(T_e\) plasmas in LHD.


