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Complex Scrape-Off Layer Analysis of KT-1 Edge Plasmas

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For the first time, the overall profiles of the KT-1 tokamak edge plasma parameters, including transport coefficients, are measured using single and triple electric probes, and the results are analyzed using simple fluid approximations. The cross-field particle diffusion coefficient ($D_\perp$) in the boundary plasma is calculated from the measured density scrape-off length (λ_n). The particle density and the electron temperature fall exponentially in the radial direction with an e-folding length of $\lambda_n = 0.17$ cm and a temperature scrape-off length of $\lambda_e = 0.45$ cm. Based upon a simple scrape-off layer (SOL) model, the experimental values of the scrape-off length ($\lambda_{n,e}$) are used to calculate the cross-field diffusion coefficient ($D_\perp = 1.0 \times 10^3$ cm^2/s); roughly corresponding to one third of the Bohm value. An SOL model, including the contribution from recombination, is constructed to evaluate Bohm diffusion in the KT-1 edge plasmas. From these deduced values, the cross-field heat conductivity in the SOL is calculated to be $\sim 3.0 D_\perp$.

I. INTRODUCTION

The importance of tokamak edge plasmas is now widely recognized and has been analyzed from the experimental and theoretical study of scrape-off layer (SOL) physics. Edge conditions are important, for they influence the plasma characteristics, especially in the divertor region [1,2]. Many of the current issues, such as detached plasmas [3,4], the existence of flow reversal [5], and a strong heat-flux limit [6,7], are interrelated with momentum transport in the SOL. The nature of a tokamak boundary plasmas is complex due to particle transport in the helical magnetic field, as well as to the atomic processes therein. In addition, a complete analysis of a boundary plasma inherently requires a 3-D problem. Although sophisticated 2-D numerical models of a boundary plasma have been developed [8], complete and self-consistent models of the particle transport processes in the boundary layer are not yet available.

In diverted tokamaks, especially in the private region of the divertor, atomic processes become very important not only for understanding the particle transport between the core and the edge plasmas but also for designing the edge structures. A physical picture of the main processes in SOL plasmas can be constructed by separately analyzing the particle transports along the magnetic field and across the field and the parameters inside and outside the last-closed magnetic flux surface (LCFS) [1,9]. Outside the LCFS, the ions flow along the magnetic field lines into the limiter and/or divertor surface, and this region is generally identified as the scrape-off layer. Inside the LCFS, the plasma density and temperature are thought to be uniform on each of the nested flux surfaces, at least to first order. Thus, the simplest model of the main process of particle transport along the magnetic fields in the SOL is the steady-state, isothermal, 1-D, fluid model [10]. This has been modified by considering the shear viscosity in fluid [11,12] and kinetic models [13,14]. Meanwhile, since cross-field transport is not the only particle source in the SOL, especially for edge plasmas with a high neutral background, the contribution from a possible volume source should be considered. This is not a simple task, however, because there are complex source effects, such as ionization, recombination, and charge exchange due to the collision processes among electrons, ions, and neutrals. In addition, these atomic processes depend upon the local plasma density and temperature.

In order to obtain information on the transport parameters, diagnostics, such as single, triple, Mach, and Visco-Mach probes, have been used to measure the plasma den-

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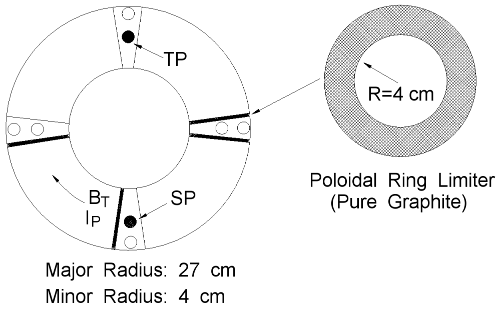

Fig. 1. The positions of the single probe (SP) and the tripe probe (TP) on the KT-1 tokamak with the upper view of the torus and the cross-sectional view of the graphite limiter. B_T and I_p are the toroidal magnetic field and the plasma current, respectively.

sity, temperature, and flow velocity in the flux tube of the boundary layer [15–21]. For most tokamaks, the edge plasma parameters have been documented as the reference data for tokamak operation or for the study of improved confinement and have been compiled in JET [1], Alcator-C Mod [3], and TEXT [21] tokamaks for various diagnostics, including single, triple, and/or Mach probes.

Since each tokamak has its own character, it is worthwhile to see the characteristics of edge plasmas in the KT-1, one of the leading tokamaks being operated in Korea. For the first time, the overall profiles of the edge plasma parameters are measured with single and triple electric probes installed in the boundary region of the KT-1 tokamak [22], and the results are analyzed by using simple fluid approximations. From the radial profile of the plasma density, the density scrape-off length is obtained by assuming an exponential decay of the density in the radial direction; in addition, the cross-field diffusion coefficient is calculated by balancing the flux due to the cross-field transport with the flux flowing into the limiter. Although it is not well established whether cross-field transport is convective or diffusive [15,23,24], we assume a diffusive cross-field particle transport in the SOL throughout this analysis.

Since the measured values of cross-field diffusivity in the edge plasmas of most tokamaks are of the same order as the Bohm values ($D_\perp = 1 \sim 10D_b$) [1], one make a similar assumption for the KT-1 tokamak, *i.e.*, $D_\perp = D_b$. This assumption is necessary to find a plausible model for the KT-1 edge plasma other than the simple model with no volume source along the SOL, which gives a value too small to explain the KT-1 edge plasma as a conventional limiter tokamak. Although it would be desirable to independently obtain the cross-field diffusivity instead of obtaining it from a density measurement, and to then compare it with various SOL models to see which model is suitable for the analysis of the SOL of the KT-1, here we developed an SOL model which includes ionization, recombination, and charge exchange effects, along with cross-field transport, in the plasma source term. If this model turns out to be successful, it will give us important clues about the role of atomic processes along the SOL. Based upon anomalous diffusivity, we can choose an additional contribution among the above atomic processes. From these procedures, we deduce the cross-field diffusion coefficient, the recombination rate, and the cross-field conductivity. Section II introduces the experimental setup, and the analyses and results are given in the Sections III and IV. Finally, Section V summarizes the present work.

II. EXPERIMENTAL SETUP

The KT-1 tokamak is a small device (major radius: 27 cm, minor radius: 4 cm, and inner radius of torus surface: 5 cm) with a large aspect ratio and perfect circular geometry. The toroidal magnetic field is 1 Tesla, and two iron cores with a position difference of toroidal span π are used for the ohmic discharge of the KT-1 tokamak. Four graphite poloidal ring-limiters are installed at an inner radius of 4 cm at different toroidal positions of $\sim$ 90 degrees, $\sim$ 180 dgrees, and $\sim$ 270 degrees (two limiters) from a triple probe, as shown in Fig. 1. The plasma current and the current flat-top time are 5 kA and about 16 ms, respectively. The KT-1 tokamak is operated with a feedback control system, which controls the ohmic heating (OH) coil, as well as the vertical and the horizontal magnetic fields, by using the signals from a Rogowski coil and from two saddle loop coils located poloidally outside the vacuum vessel at both 0-180 degree and 90–270 degree [22].

A triple probe is made of 0.25-mm-diameter and 2.0-mm-long tungsten wire. A single probe is made of 1.0-mm-diameter and 2.5-mm-long molybdenum wire for comparing the radial density profile with that obtained from the triple probe. The positions of the single and the triple probes on the KT-1 tokamak are also shown in Fig. 1. Typical passive probe circuits are used for obtaining the probe data. Data from these probe circuits are received and analyzed by a personal computer (PC) through a VXI (VMEbus eXtensions for Instrumentation) digitizer (maximum 20 Ms/s). The probe data in the flat-top period are used to measure the edge parameters and to calculate the density and the temperature scrape-off length. The radial profile of the ion saturation current from the single probe is shown in Fig. 2, which is used as a reference for the triple probe in deducing the decay lengths of the density and the electron temperature. This gives us more information on the density variations of the core plasma near the LCFS, and there is no steep density gradient near the LCFS. The density and the temperature profiles in the SOL of the KT-1 boundary layer obtained from a triple probe are fitted exponentially by using a least-squares curve-fitting method.

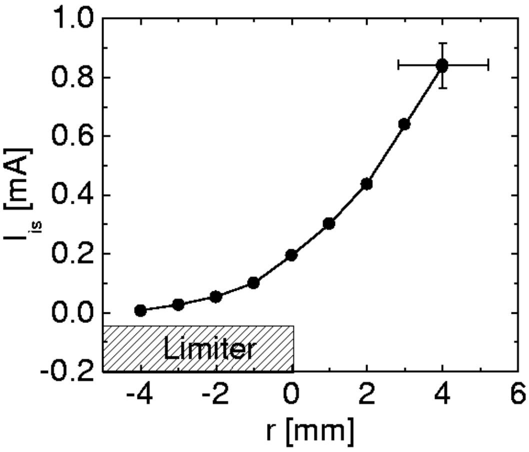

Fig. 2. The radial profile of the ion saturation current from the directional single probe. ($r = 0$ is the radial position of the limiter surface. $r < 0$ is the SOL area, and $r > 0$ refers to positions past the limiter into the core plasma).

III. ANALYSES

In order to deduce the transport coefficients from measurements of the electron temperature and the plasma density in the SOL, we assume the following: (i) The cross-field diffusion is one-dimensional with toroidal uniformity, because the toroidal field is so strong (about 1 Tesla) that any perturbation due to a small object becomes a very long, thin structure; (ii) the particle flux falls off exponentially in the radial direction as $\exp(-r/\lambda_n)$; (iii) radial and toroidal variations of the ion acoustic speed (c_s) are negligible; and (iv) $T_i = T_e$. While a simple SOL model includes no volume source in the SOL, our SOL model includes atomic processes, such as ionization and/or recombination.

Without any prior knowledge of the SOL, we shall first start with a simple SOL model, where the cross-field particle transport is the only source term and the limiter is the only terminal sink. The radial scale lengths in the SOL are so short that the heat flux to the edge structures is highly concentrated. If the particle flux falls off exponentially in the radial direction as $\exp(-r/\lambda_n)$, provided the wall is located just a few scrape-off lengths (λ_n) behind the leading edge of the limiter, the wall will receive a negligible plasma flux. One can then balance the particle loss along the magnetic field lines in the SOL with the net particle flow from inside the LCFS (core plasma) across the magnetic field into the outside of the LCFS (SOL plasma). If the connection length L_c of the SOL and the poloidal depth w are considered, the total cross-field particle flux into the SOL is then approximated as

$$D_\perp \frac{dn}{dr}\Big|_{LCFS} L_c w \approx D_\perp \frac{n_0}{\lambda_n} L_c w. \tag{1}$$

The particle flux reaching the limiter is also calculated as

$$w\int_{LCFS}^{wall} n_e(r)c_s(r)dr \approx 0.5 n_0 c_s w \lambda_n, \tag{2}$$

where λ_n is the density scrape-off length and n_0 is the density on the LCFS far from the limiter [25–27]. Thus, $D_\perp$ can be deduced by equating Eq. (1) with Eq. (2) as

$$D_\perp \simeq \frac{c_s}{2L_c}\lambda_n^2, \tag{3}$$

where $c_s \equiv \sqrt{2T_e/m_i}$ with $T_i = T_e$ in the SOL. The measurement of the e-folding length λ_n from the radial profile of the plasma density and the local measurement of T_e are performed by using electric probes in the SOL, provided the impurity content is very small. In most limiter/divertor tokamaks, the measured cross-field diffusivity is of the same order as the Bohm diffusivity, *i.e.*, $D_\perp \simeq 1 \sim 10 D_b$ [1,15,21], where the Bohm diffusivity is given by D_b [cm^{2}s^{-1}] $= 600\, T$ [eV]$/B$ [T] [28]. Therefore, if Eq. (3) does not produce a value similar to the Bohm value, one has to think of a different SOL model, *i.e.*, a complex SOL [1], where there are other particle sources, such as ionization, charge exchange, and recombination. Although each atomic process has its own temperature and density regions for the most probable cases, one can choose any one of them as a possible additional volume source in the SOL with the source from cross-field transport. Since we have no idea about the profile of the reaction rate for each process, we shall assume that the additional volume source is proportional to the cross-field transport, *i.e.*,

$$\begin{aligned} &< \sigma v >_{ion} n_e n_n ; < \sigma v >_{rec} n_e n_i ; < \sigma v >_{cx} n_i n_n \\ &\approx K D_\perp \frac{dn}{dr}\Big|_{LCFS} L_c w, \end{aligned} \tag{4}$$

where σ is the microscopic cross-section, K is a rate constant, and n_n is the neutral density. Combining Eqs. (1), (2), and (4) leads to

$$D_\perp \simeq \frac{c_s}{2(1+K)L_c}\lambda_n^2, \tag{5}$$

where K is positive if the volume source is ionization (*ion*), negative if it is recombination (*rec*), and almost zero if it is charge exchange (*cx*).

The electron temperature scrape-off length λ_e in the SOL of the KT-1 tokamak is also obtained by using a function $\sim \exp(-r/\lambda_e)$ and an exponential fitting method as shown in the density e-folding length. If the three conservation equations, mass, electron energy, and ion energy, and the relation of λ_e to λ_n are used, the following equatoin for the cross-filed heat conductivity can be obtained [1]:

$$\chi_{\perp 0} = D_{\perp 0}\Big(\frac{\gamma}{\alpha(1+\alpha)} - \frac{2.5}{\alpha}\Big), \tag{6}$$

where $\alpha = \lambda_n/\lambda_e$, γ is the sheath electron heat transmission coefficient, and $D_{\perp 0}$, and $\chi_{\perp 0}$ are the values

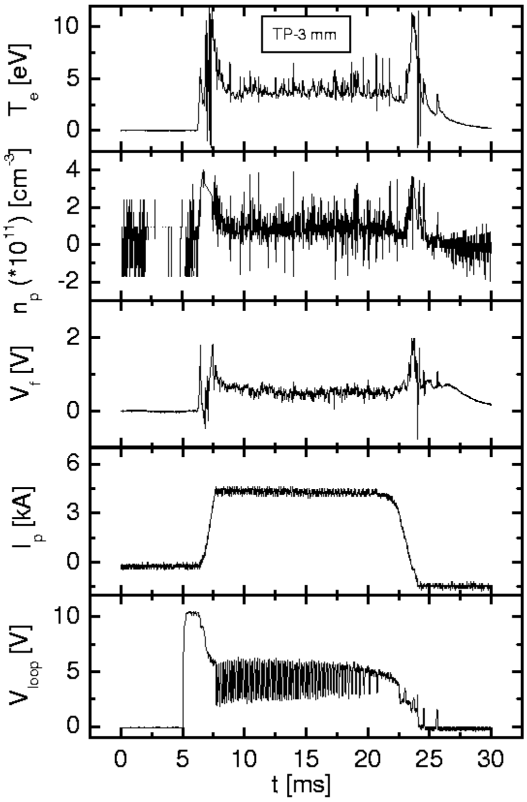

Fig. 3. Time history of a typical KT-1 discharge showing the plasma current (I_p), the loop voltage V_{loop}), the electron temperature (T_e), the plasma density (n_p), and the floating potential (V_f) from a triple probe at a position of r = –3 mm.

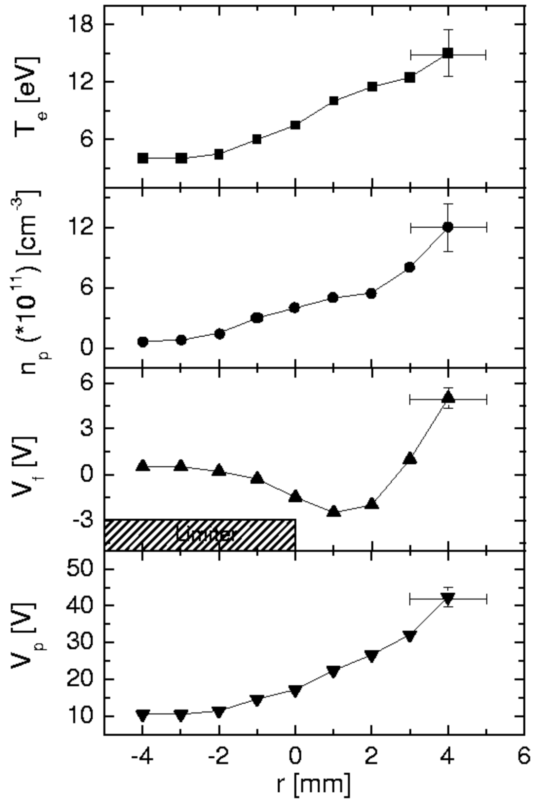

Fig. 4. The radial profiles for the electron temperature (T_e), the plasma density (n_p), the floating potential (V_f), and the plasma potential (V_p) from a triple probe ($r < 0$ is the SOL region, and $r > 0$ is the region past the limiter into the core plasma).

at the limiter boundary. We also use the value $\gamma = \frac{2}{1-\delta} - \frac{e(V_f - V_p)}{kT_e} + 0.5$, where δ is the secondary electron emission coefficient, and V_f and V_p are the floating and the plasma potentials, respectively. Since the secondary electron emission is generally not significant for $T_e \leq 30$ eV, this effect should not be included for the edge plasma of the KT-1 tokamak. Although the experimental determination of $\chi_\perp$ by using λ_e and λ_n is not easy because there are uncertainties in γ, one can find the cross-field conductivity $\chi_\perp$ if γ is given.

IV. RESULTS

Figure 3 shows a temporal evolution of the plasma current, loop voltage, electron temperature, plasma density, and floating potential from the triple probe at a position 3 mm outside the LCFS. From this, one notices that the KT-1 plasma is a conventional limiter tokamak plasma with a larger resistance, indicating the existence of more impurities than in other tokamak plasmas. The radial profiles for the electron temperature, plasma density, floating potential, and plasma potential from a triple probe at one fixed time during the current flat-top period in the boundary layer of the KT-1 plasma are shown in Fig. 4.

To find the density scrape-off length λ_n, we fitted the measured radial profile of the plasma density in the edge region from a triple probe to $\exp(-r/\lambda_n)$, and the results are shown in Fig. 5. The best-fit density scrape-off length is found to be 0.17 cm. Using Eq. (3), *i.e.*, assuming a simple SOL, the deduced cross-field diffusion coefficient $D_\perp$ is about 1.0×10^3 cm^2/s, where an ion acoustic speed of $c_s = 9.79 \times 10^5 \sqrt{2T_e/\mu}$ cm/s $= 3.1 \times 10^6$ cm/s is used with $T_e = T_i = 5$ eV. Here, the characteristic connection length of the SOL is used as the distance (L_c = 42.4 cm) between the limiters, instead of using the conventional length, $L_c = \pi R q$ = 339 cm, because the limiters of the KT-1 are of a closed poloidal-ring type, which blocks the free motions of charged particles along the presheath ($L_c = \pi R q$) and because two limiters form a bounded presheath. The conventional diffusion coefficient of the limiter tokamak is given as the Bohm value: D_b [cm^2/s] = 600 T [eV]/B [T] = 3.0×10^3 cm^2/s = 0.3 m^{2}s^{-1} with B=1 Tesla and T_e=5 eV. Comparing the measured diffusivity ($D_\perp$) with Bohm's value (D_b), then $D_\perp \approx D_b/3$, assuming that there is no volume source in the SOL. Since the measured dif-

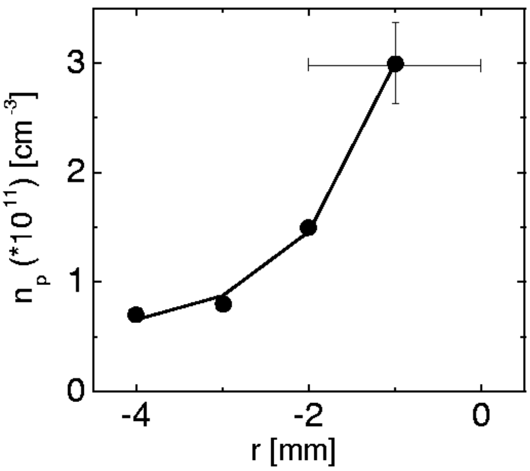

Fig. 5. Exponential fitting of the measured radial profile of the plasma density (n_p, solid circles) in the SOL with $\exp(-r/\lambda_n)$ (solid line).

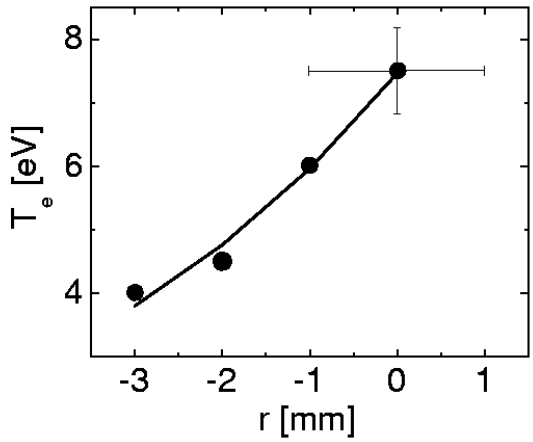

Fig. 6. Exponential fitting of the measured radial profile of the electron temperature (T_e, solid circles) in the SOL with $\exp(r/\lambda_e)$ (solid line).

fusivity is too small compared to the values for other conventional limiter tokamaks, which gives room to use Eq. (5), there is the possibility of an additional volume source in the SOL (a complex SOL). To find the probable source and the amount of contribution, we equate the cross-field diffusivity with Bohm's. Then, using Eq. (5), the rate constant (ratio of the recombination to the cross-field particle flux) is calculated as $K = -2/3$, indicating that there is a recombination in the SOL of the KT-1 tokamak and that it is about 67 percent of the flux due to cross-field transport. Since we know that the cross-field diffusivities of most tokamaks are $D_\perp \approx 1 \sim 10D_b$ [1,15,21], the deduced K is somewhat underestimated, so it should be approximately $-0.9 \leq K \leq -2/3$. Since the electron temperature in the SOL is about $4 \sim 8$ eV, one easily expects recombination of hydrogen ions with electrons rather than ionization (ionization energy = 13.6 eV). In fact, as for the energy $T_e = 4 \sim 8$ eV, the ratio of dissociative recombination to ionization of hydrogen is $3.7 \sim 55$ [1].

The electron temperature scrape-off length λ_e is found to be about 0.45 cm. The electron temperature e-folding length is about twice the density e-folding length, which is similar to the experimental values of other toroidal devices ($\lambda_e \geq \lambda_n$) [29]. The cross-field heat conductivity is also calculated as $\sim 3.0D_\perp$ from the values of λ_n and λ_e by using Eq. (6). The fitted result for λ_e is shown in Fig. 6.

V. CONCLUSIONS

We measured the radial profiles of the plasma density and the electron temperature in the boundary plasmas of the KT-1 tokamak by using triple and single electric probes. From these measurements, the density scrape-off length λ_n and the electron temperature scrape-off length λ_e are deduced as 0.17 cm and 0.45 cm, respectively, assuming an exponentially decaying density and temperature in the radial direction, $(\exp(-r/\lambda_{n,e}))$, these values are similar to the experimental results for other toroidal devices ($\lambda_e \geq \lambda_n$). The cross-field diffusion coefficient ($D_\perp = 1.0 \times 10^3$ cm^2/s) deduced from the measured density decay length is one third of the Bohm value if we use a simple SOL model. This value is too small when compared to the values for other conventional limiter tokamaks, thus warranting the introduction of an additional volume source in the SOL (a complex SOL). Based upon anomalous transport, we set up an equation for a complex SOL, which includes a general volume source, such as ionization and recombination, in addition to the cross-field transport along the SOL. From this, we find the contribution of recombination in the SOL of the KT-1 tokamak, and we calculate its rate in terms of the cross-field particle flux, *i.e.*, K (volume source/cross-field transport) = $-2/3$, by equating the cross-field diffusivity with the Bohm value. This indicates that there is recombination in the SOL of the KT-1 tokamak and that the ratio of this to the particle influx due to cross-field transport is about 0.67. In our model, the minus sign indicates that the recombination is a sink rather than a source. This result seems to be due to a colder electron temperature ($T_e(KT-1) \approx 4 \sim 8$ eV, $T_e(other) > 10 \sim 100$ eV) and a lower density ($n_e(KT-1) \approx 2 \sim 4 \times 10^{11}$ cm^3, $n_e(other) \approx 10^{12} \sim 10^{13}$ cm^{-3}) than in the other tokamaks. Since we know that the cross-field diffusivity of most tokamaks is $D_\perp \approx 1 \sim 10D_b$, the deduced K is underestimated, and it should be approximately $-0.9 \leq K \leq -2/3$. The cross-field heat conductivity is also calculated as $\sim 3.0D_\perp$ from measurements of λ_n and λ_e.

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