Ion heat transport in ohmic plasmas of the T-10 tokamak

L A Klyuchnikov¹, V A Krupin, M R Nurgaliev, A R Nemets, I A Zemtsov, D V Ryjakov and D V Sarychev
National Research Centre “Kurchatov Institute”, 1, Akademika Kurchatova pl., Moscow, 123182, Russia

¹ E-mail: lklyuchnikov@list.ru

Abstract. Results of the investigation of ion heat transport processes in the T-10 tokamak are presented. Experiments are carried out in a wide range of ohmic plasma parameters ($n_e$, $I_p$, and $Z_{eff}$). Variation of the effective ionic charge from 3.5–4 to 1 is performed by inserting a lithium limiter. Measurements of the ion and electron temperature and density profiles are presented. The power balance approach is used for the determination of the ion heat conductivity. Modeling is performed using the ASTRA transport code. It is shown that in ohmic plasmas in the region of $r/a \sim 0.5$, ion heat conductivity is close to the neoclassical values, which are calculated using the NCLASS code.

1. Introduction
The necessity of achieving high efficiency plasma heating in future tokamak reactors makes it important to investigate heat transport processes. To solve this issue, energy confinement processes should be well understood. Therefore, the study of heat transport coefficients in plasmas with ohmic and auxiliary heating is performed.

On the T-10 tokamak (major radius $R = 1.5$ m, minor radius $a = 0.3$ m, toroidal filed $B_t \leq 3$ T), the study of heat transport can be performed in a wide range of ohmic parameters and with auxiliary electron-cyclotron resonance heating (ECRH) with a power up to 3 MW. Herewith, the control of light impurity (C and O) inflow using a movable lithium limiter allows us to vary the plasma effective ionic charge $Z_{eff}$ in the range of 1 to 4.

To carry out the abovementioned investigations of heat transport, reliable measurements of ion and electron temperature and density profiles are required. On T-10, the electron temperature $T_e$ profiles are obtained via the SXR spectra [1] and ECE diagnostics [2]. The SXR spectra measurements provide an absolute value of $T_e$ in a particular spatial point in one tokamak discharge, while ECE diagnostics give the full profile. Electron density profiles $n_e$ are measured using a 16-channel interferometer. Ion densities $n_i$ and temperature $T_i$ are measured via charge exchange recombination spectroscopy (CXRS) [3, 4].

All mentioned profiles are necessary to perform the power balance approach, which is described below. The ASTRA transport code [5] is used to determine ion heat conductivity, and the NCLASS code [6] is used for calculating neoclassical heat conductivity.

2. Power balance
The ion power balance equation in a steady state phase of discharge with ohmic heating (OH) can be written as following:
\[ \text{div} \left( -\chi_{i}^{\text{eff}} \frac{\partial T_{i}}{\partial r} \sum_{i} n_{i} \right) = P_{e} - P_{\text{CX}} - P_{\text{conv}}, \]

where, \( \chi_{i}^{\text{eff}} \) is the effective ion heat conductivity; \( P_{e} = \sum_{i} \frac{T_{e} - T_{i}}{\tau_{ei}} n_{e} \frac{3m_{i}}{m_{e}} \) is the heat transfer from electrons to all ions, \( \tau_{ei} \) is the electron-ion collision time; \( P_{\text{CX}} = \frac{3}{2} (T_{i} - T_{0}) n_{d} n_{0} \langle \sigma v \rangle_{\text{CX}} \) are the heat losses due to charge exchange of deuterons \( n_{d} \) on deuterium atoms \( n_{0} \) with temperature \( T_{0} \), \( \langle \sigma v \rangle_{\text{CX}} \) is the charge exchange rate coefficient; \( P_{\text{conv}} = \frac{5}{2r} \frac{\partial}{\partial r} (r \cdot T_{i} \cdot \Gamma_{i}) \) are the heat losses due to ion transport, and \( \Gamma_{i} \) is the ion flux. Thus, the effective coefficient of ion heat conductivity can be determined from (1):

\[ \chi_{i}^{\text{eff}} = \frac{\int_{0}^{r} (P_{e} - P_{\text{CX}} - P_{\text{conv}}) r dr}{r \cdot \nabla T_{i} \cdot \sum n_{i}} \]  

Charge exchange and convective losses can be significant at the plasma periphery, while in the central plasma region \( (\rho < 0.8) \), they can be ignored. To determine \( \chi_{i}^{\text{eff}} \), the radial profiles of \( T_{e}, T_{i}, n_{e}, \) and \( n_{i} \) need to be carefully measured.

3. Measurements of electron and ion temperatures
Ion temperature profiles on T-10 are measured via the CXRS diagnostics, which is described in [3, 4]. Measurements are performed via Doppler broadening of the \( \text{C}^{5+} 5291 \text{ Å} \) CXRS-line.

Examples of measured profiles in discharges with a different plasma current are shown in fig. 1. The CXRS diagnostics allow to investigate the \( T_{i} \) values and shape changes in a wide range of plasma parameters.

![Figure 1](image1.png)  
**Figure 1.** Ion temperature profiles measured via CXRS on T-10 in discharges with ohmic heating

![Figure 2](image2.png)  
**Figure 2.** Ion temperature profiles measured in plasmas with different \( Z_{\text{eff}} \) values
The ion temperature profiles, which are shown in fig. 2, are measured in discharges with high $Z_{\text{eff}} \approx 3.5$ and low $Z_{\text{eff}} \approx 1$, which are achieved after vacuum vessel lithization. In high $Z_{\text{eff}}$ OH plasmas contaminated by light impurities, the obtained values of $T_i$ are higher than in the low $Z_{\text{eff}}$ plasma case. However, the shape of $T_i(r)$ changes insignificantly.

To determine heat transport coefficients, reliable measurements of $T_i(r)$ and accurate measurements of $T_e(r)$ are required because ions are heated via electron-ion collisions. When comparing $T_i(r)$ that is measured in discharges with high and low $Z_{\text{eff}}$ using SXR spectra and ECE diagnostics, one can observe that the electron temperature profiles, which are measured using both diagnostics, match well. The values of $T_e$ in the central region are significantly higher in discharges that are contaminated by light impurities than in plasma with $Z_{\text{eff}} = 1.5$. It is necessary to note that the experimental $T_i(r)$ profiles together with the measured $Z_{\text{eff}}$ can be used to describe the loop voltage and saw-tooth inverse radius in the ASTRA code.

4. Experimental results
Experiments with wall lithization are performed on the T-10 tokamak to vary the content of light impurities. In the discharge with a plasma current $I_p = 220$ kA and line-averaged electron density $\bar{n}_e = 2.5 \cdot 10^{19}$ m$^{-3}$, the values of $Z_{\text{eff}}$ are changed in the range of 3.5–4 to 1.

Ion heat conductivity coefficients, which are determined via the power balance approach in discharges with high and low $Z_{\text{eff}}$, are presented in fig. 4. It is shown that with an increase of the $Z_{\text{eff}}$ value, the increase of the experimental and neoclassical transport coefficients is observed. Herewith, the values of experimental heat conductivity are close to the neoclassical value in the central area $\rho \leq 0.5$. However, at the plasma periphery, $\chi_i^{\text{eff}}$ increases drastically, while the neoclassical value decreases. This can be an evidence of the existence of anomalous part of the ion heat flux, which is dominant at the plasma edge.

As shown above, the increase of $Z_{\text{eff}}$ from 1 to ~4 leads to the insignificant increase of $T_i$ to 10–15% together with a strong decrease of the total ion density $\sum n_i$ up to 50% due to dilution of the main gas by light impurities (C and O). Thus, the total energy of plasma ions decreases with an increase of the $Z_{\text{eff}}$ value. In turn, the heat transfer from electron to all ions changes slightly despite the growth of $T_e$ because of the $\sum n_i$ decrease.
Wall lithization allows to achieve the values of $Z_{\text{eff}} \sim 1$–1.3 as well as high values of line-averaged electron density (up to $5.6 \cdot 10^{19}$ m$^{-3}$) in ohmic discharges with $I_{pl} = 220$ kA. In fig. 5, the dependence of effective ion heat conductivity at $\rho = 0.5$ on electron density is shown. The presented experimental transport coefficients are in good agreement with neoclassical ones, which are calculated using the NCLASS code in the entire range of $\tilde{n}_e$.

5. Conclusion
The electron, ion temperature and density diagnostics of the T-10 tokamak provides data that is necessary for the ion heat transport analysis. Measurements are performed in discharges with various values of electron density and effective ionic charge.

The ion heat conductivity values, which are determined via the power balance approach, are similar to neoclassical values in the range of $\rho \leq 0.5$. The experimental and neoclassical heat conductivities increase with an increase in $Z_{\text{eff}}$. However, the experimental profile of $\chi_i^{\text{eff}}(r)$ increases at the plasma periphery where it exceeds the neoclassical coefficient. Therefore, it can be concluded that anomalous heat transport dominates neoclassical transport at the plasma edge.

Analysis of the electron heat transport will be performed in future works. Moreover, regimes with auxiliary ECR heating will be also investigated. It is important to consider the data of plasma density fluctuations [7] and plasma potential fluctuations [8] and compare them with our results to study the relations of turbulent processes and plasma transport.

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