The comparison of ion and electron anomalous heat conductivities in T-10 plasma

M.R. Nurgaliev[1], V.A. Krupin[1], L.A. Klyuchnikov[1], A.R. Nemets[1], I.A. Zemtsov[1,2], A.Yu. Dnestrovskiy[1],A.A. Borschegovskiy[1], A.Ya. Kislov[1], D.V. Sarychev[1], N.A. Solovev[1], V.M. Trukhin[1], I.S. Pimenov[1], D.S. Sergeev[1], T.B. Myalton[1], S.N. Tugarinov[1], N.N. Naumenko[3]

[1] *National Research Center "Kurchatov Institute", Moscow, Russian Federation*

[2] *Bauman Moscow State Technical University, Moscow, Russian Federation*

[3] *B.I. Stepanov Institute of Physics NASB, Minsk, Republic of Belarus*

The aim of this work is the determination of phenomenological dependencies of anomalous ion and electron heat conductivities on parameters of ohmically (OH) and electron cyclotron (ECRH) heated plasmas on the T-10 tokamak. In order to do this, verified experimental data base of plasma parameters, heat fluxes, and transport coefficients is made. Two transport characteristics are considered: local heat conductivities assuming a quasilinear form of heat flux and anomalous volume integrated times.

Heat conductivities are determined from steady state heat flux continuity equation for ions and electrons:

$$\operatorname{div}\left(-\chi_{e,i} n_{e,i} \nabla T_{e,i} + \frac{5}{2} T_{e,i} \vec{\Gamma}_{e,i}\right) = P_{e,i}, \tag{1}$$

where $\chi_{e,i}$ – heat conductivity of electrons or ions, $n_{e,i}$ - electron or ion density, $T_{e,i}$ - electron or ion temperature, $\Gamma_{e,i}$ - particle flux of electrons or ions, $P_{e,i}$ - heat sources and sinks. The required distribution of the absorbed ECR-power profile $P_{EC}(r)$ is calculated using the OGRAY code [1]. The analysis is performed for anomalous heat conductivities $\chi_e^{an} = \chi_e - \chi_e^{neo} \approx \chi_e$ and $\chi_i^{an} = \chi_i - \chi_i^{neo}$

Integral characteristics $\nu_{e,i}^{an}$ is inverse to transport times $\nu_{e,i}^{an} = (\tau_{e,i}^{an})^{-1}$ and determined as a ratio of total anomalous flux to stored energy inside current magnetic surface:

$$\nu_{e,i}^{an} = \left(\tau_{e,i}^{an}\right)^{-1} = \frac{\int_S \left(Q_{e,i} - Q_{e,i}^{neo}\right) dS}{\int_V \left(\frac{3}{2} n_{e,i} T_{e,i}\right) dV} \quad \left[\mathrm{s}^{-1}\right], \tag{2}$$

where $Q_{e,i} = \frac{1}{r}\int_0^r P_{e,i} x dx - \frac{5}{2} T_{e,i}\Gamma_{e,i}$ – electron or ion heat flux, $Q_{e,i}^{neo}$ – neoclassical heat flux of electrons or ions.

Let us proceed to analysis of these transport characteristics in OH plasma. First parameter is averaged density $\bar{n}_e$. The growth of $\bar{n}_e$ results in decrease of χ_e^{an} (common result that was shown

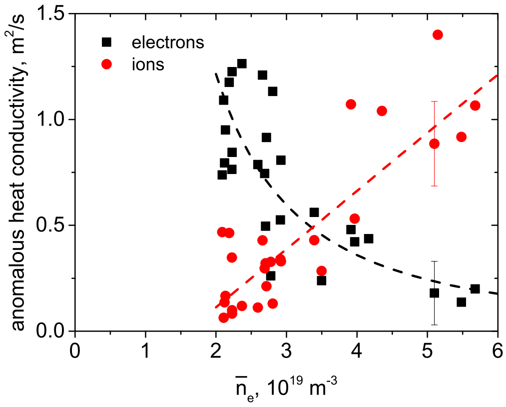

Figure 1: *Dependence of local anomalous heat conductivities on $\bar{n}_e$ at $\rho = 0.8$*

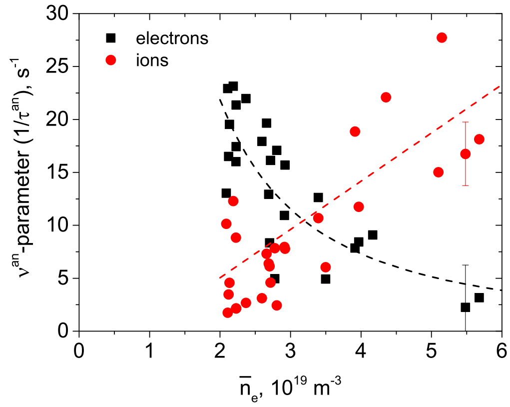

Figure 2: *Dependence of integral parameter $\nu^{an}_{e,i}$ on $\bar{n}_e$ at $\rho = 0.8$*

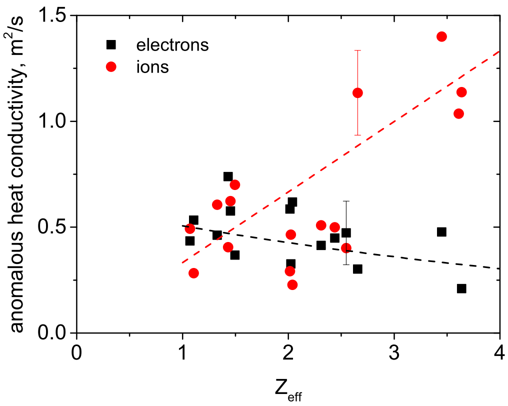

Figure 3: *Dependence of local anomalous heat conductivities on Z_{eff} at $\rho = 0.8$*

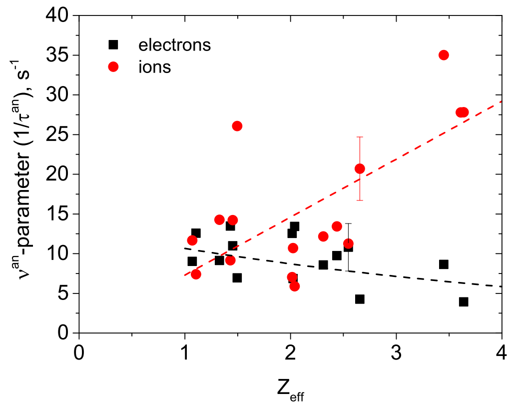

Figure 4: *Dependence of integral parameter $\nu^{an}_{e,i}$ on Z_{eff} at $\rho = 0.8$*

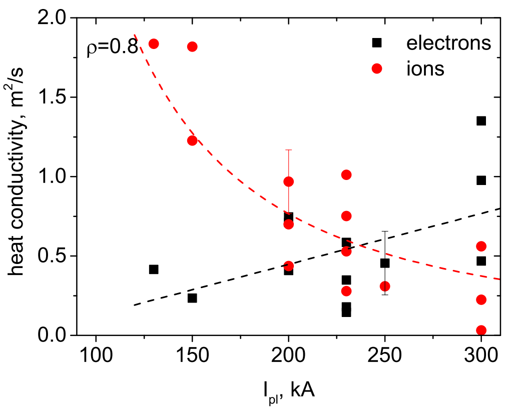

Figure 5: *Dependence of local anomalous heat conductivities on I_{pl} at $\rho = 0.8$*

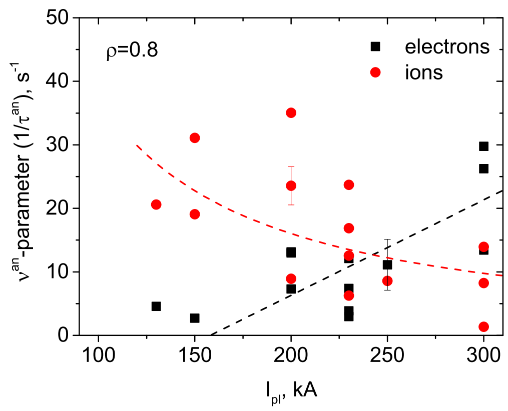

Figure 6: *Dependence of integral parameter $\nu^{an}_{e,i}$ on I_{pl} at $\rho = 0.8$*

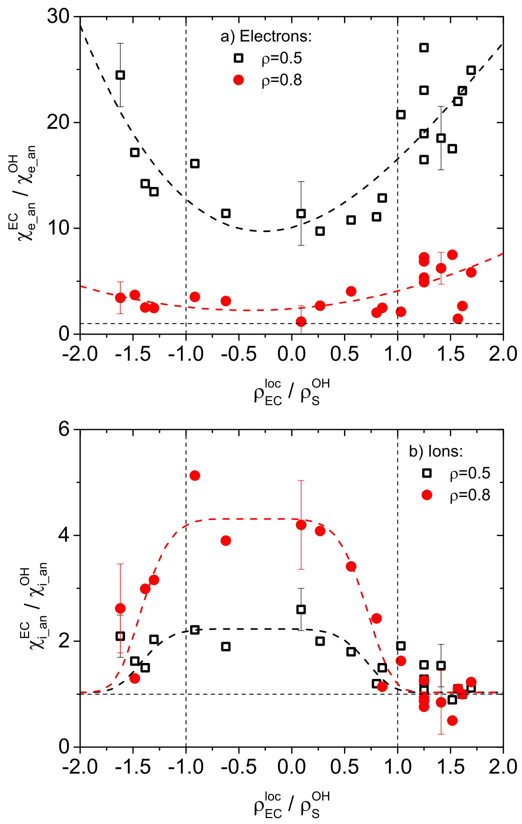

Figure 7: *Change of anomalous heat conductivity in comparison with OH regime as a function of localization radii of ECRH ($P_{EC} = 0.4 - 0.42$ MW)*

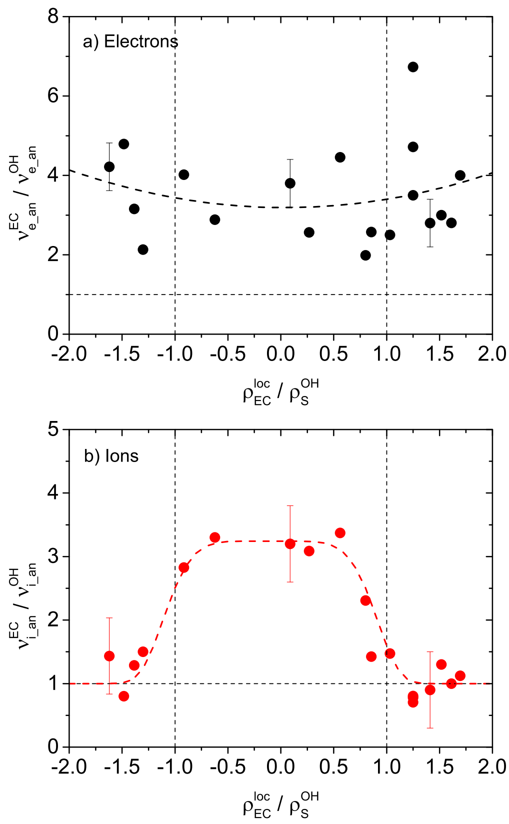

Figure 8: *Change of $v^{an}_{e,i}$ inside $\rho = 0.8$ in comparison with OH regime as a function of localization radii of ECRH ($P_{EC} = 0.4 - 0.42$ MW)*

many times) and increase of χ_i^{an} as it is shown in Fig. 1. One can see in Fig. 2, that integral characteristics v_e^{an} and v_i^{an} sustain local transport characteristics. The region $\bar{n}_e < 2 \cdot 10^{19}$ m^{-3} at $\rho \geq 0.8$ is unsuitable for power balance analysis due to the large uncertainty in charge exchange and convective losses. The growth of effective charge Z_{eff} also leads to the increase of χ_i^{an} and v_i^{an} as it is shown in Fig. 3-4. Electron anomalous transport slightly decreases with Z_{eff} rise. It is also obtained that the increase of plasma current (magnetic field preserved) leads to the increase of anomalous electron transport and the decrease of anomalous ion transport (see Fig. 5-6).

ECRH power injection results in the change in the values of transport coefficients. Thus, off-axis ECRH (localization of P_{EC} outside saw-teeth inverse radius ρ_S^{OH}) increases χ_e^{an} in 15-30 times at $\rho = 0.5$ and in 2-8 times at $\rho = 0.8$ in comparison with OH regime (see Fig. 7 a)). At the same time, χ_i^{an} stays at OH level as it is shown in Fig. 7 b). In case of on-axis ECRH (inside ρ_S^{OH}) the change of χ_e^{an} is lower and the change of χ_i^{an} on the contrary large. Corresponding changes of $v_{e,i}^{an}$ are shown in Fig. 8 a)-b).

The increase of on-axis ECRH power results in significant rise of both local and integral elec-

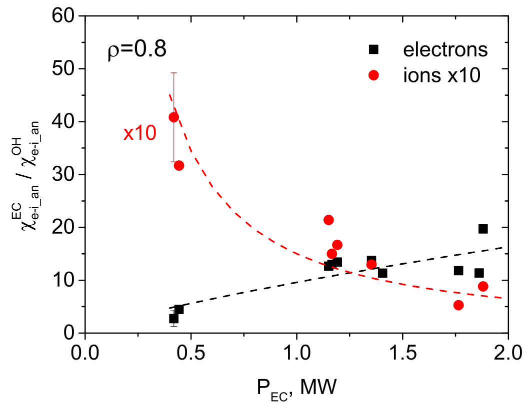

Figure 9: *Change of anomalous heat conductivity in comparison with OH regime as a function on-axis ECRH power*

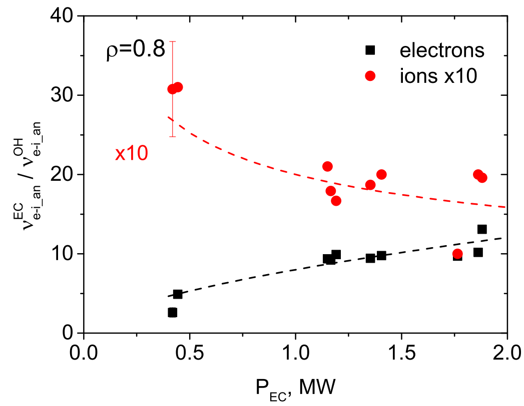

Figure 10: *Change of* $\nu_{e,i}^{an}$ *inside* $\rho = 0.8$ *in comparison with OH regime as a function on-axis ECRH power*

tron heat transport characteristics. The increase of P_{EC} form 0.4 MW to 1.9 MW leads to 5-15 times growth of χ_e^{an} and ν_e^{an} as it is shown in Fig. 9-10. In contrast, ion transport characteristics decrease with increasing heating power. This fact is related to the reduction of electron to ion heat transfer due to an intense growth of electron temperature: $P_{ei} \propto (T_e - T_i)/T_e^{3/2} \cdot n_e^2$

Demonstrated dependencies of χ_e^{an} and χ_i^{an} on plasma parameters in OH and ECRH discharges of T-10 correlate with the behavior of electric plasma potential measured by HIBP diagnostics [2]. According to [2], the value of electric potential is more positive in regimes with high χ_e^{an}/χ_i^{an}. These are low density discharges with $Z_{eff} = 1$ and high heating power.

Conclusion

Anomalous transport characteristics of electrons and ions demonstrates strictly opposite dependencies on the all considered parameters of OH ($\bar{n}_e$, Z_{eff}, and I_{pl}) and ECRH (localization and value of P_{EC}) T-10 plasmas. These statements are supported by local and integral transport approaches. The created database is ready to be used for testing predictive transport models.

Acknowledgment

Authors are thankful to Dr. A.Yu. Kuyanov and Dr. N.A. Kirneva for providing the OGRAY code and for advices on its usage. Study of electron component is carried out by RSF Project No. 19-12-00312. Study of ion component is carried out by RFBR Project No. 18-32-00100. Experimental data are obtained under ROSATOM contract.

References

[1] Zvonkov, A.V. et.al. (1998). Plasma Physics Reports, 24(5), 389-400

[2] Melnikov A et.al. (2013) Nucl. Fusion 53 093019