EX/P5-21

Influence of electron cyclotron resonance heating on ion heat conductivivty in T-10 plasma

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1. Experimental setup

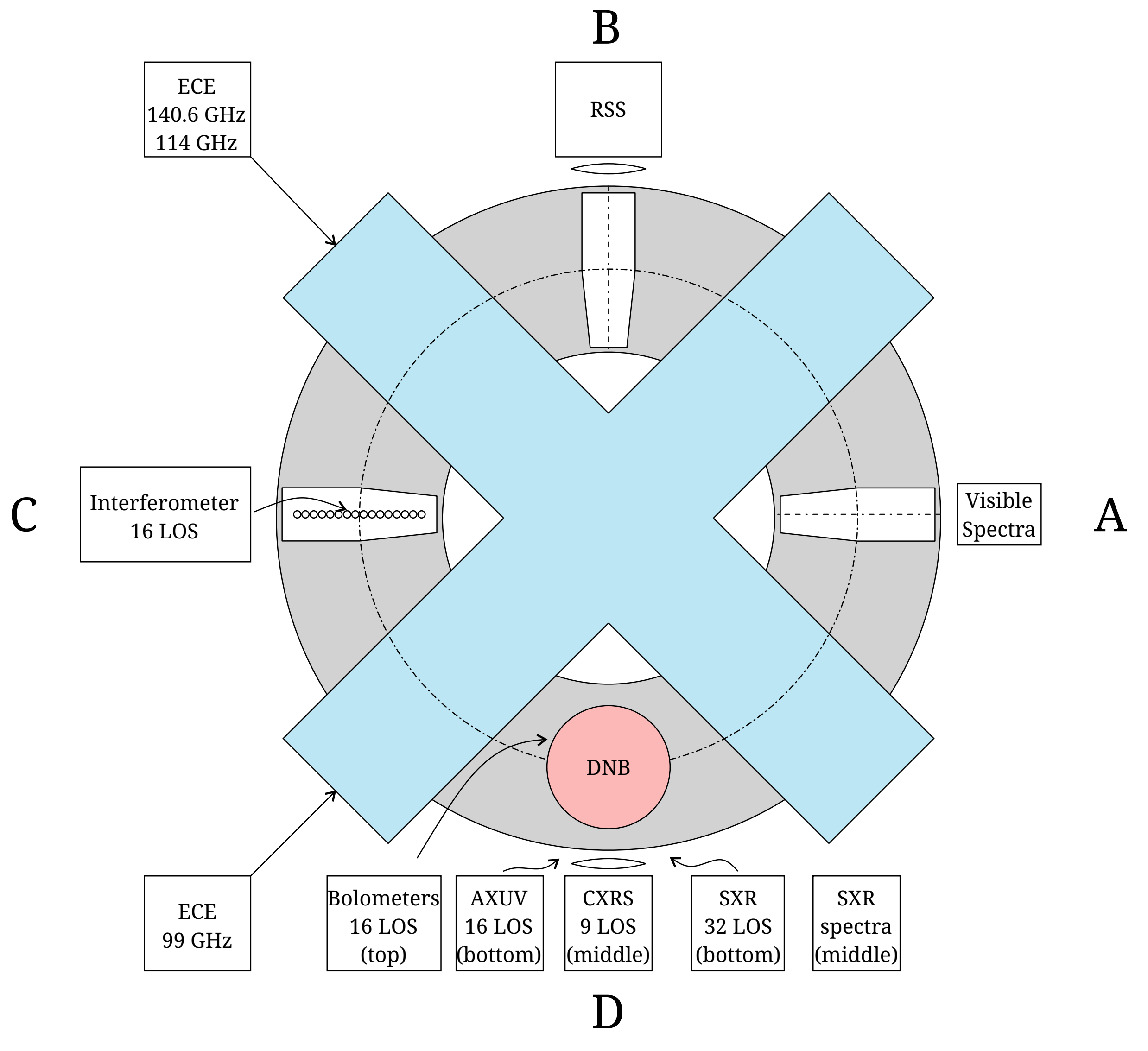
The T-10 tokamak is a limiter machine with circular cross-section (R=1.5 m, a_L=0.3 m). Main parameters are $I_{pl} \leq 300$ kA, $B_{t0} \leq 2.5$ T, $\bar{n}_e \leq 6.5 \cdot 10^{19}$ m^{-3}.

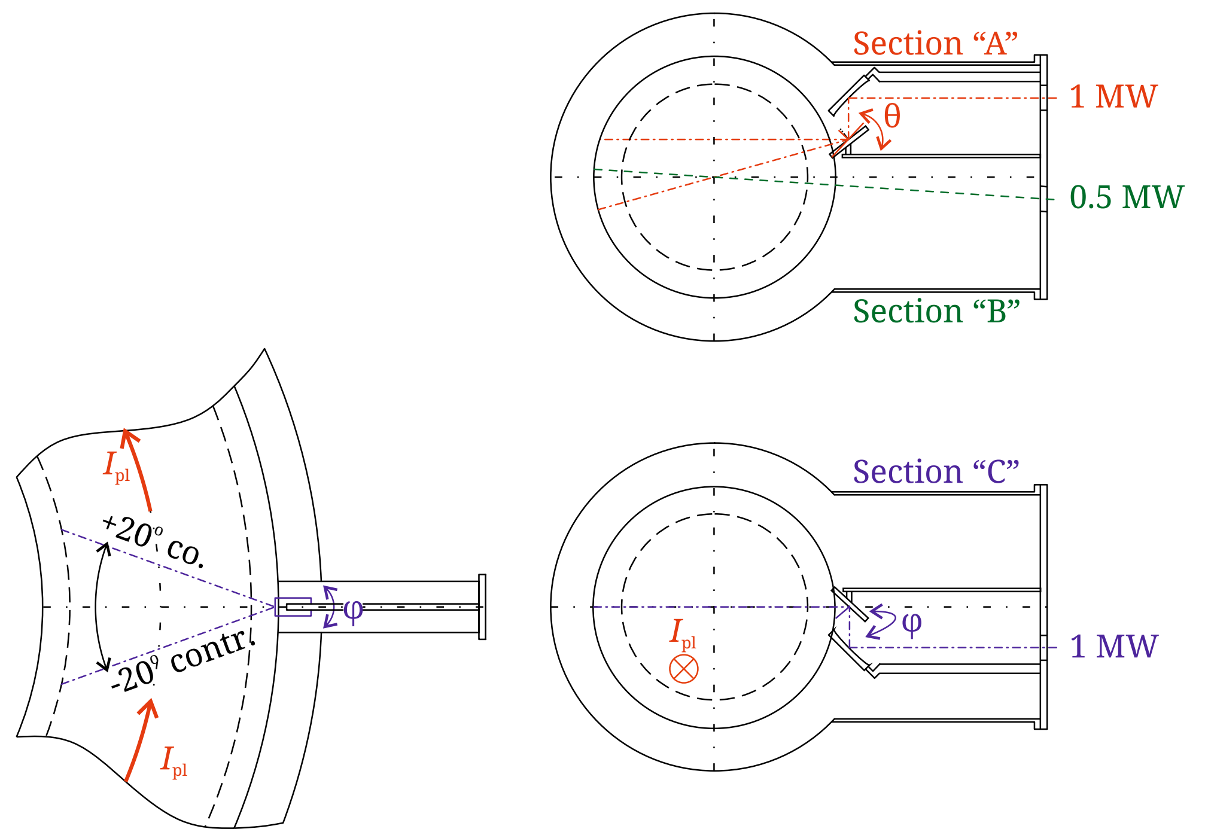
The following diagnostics are available:

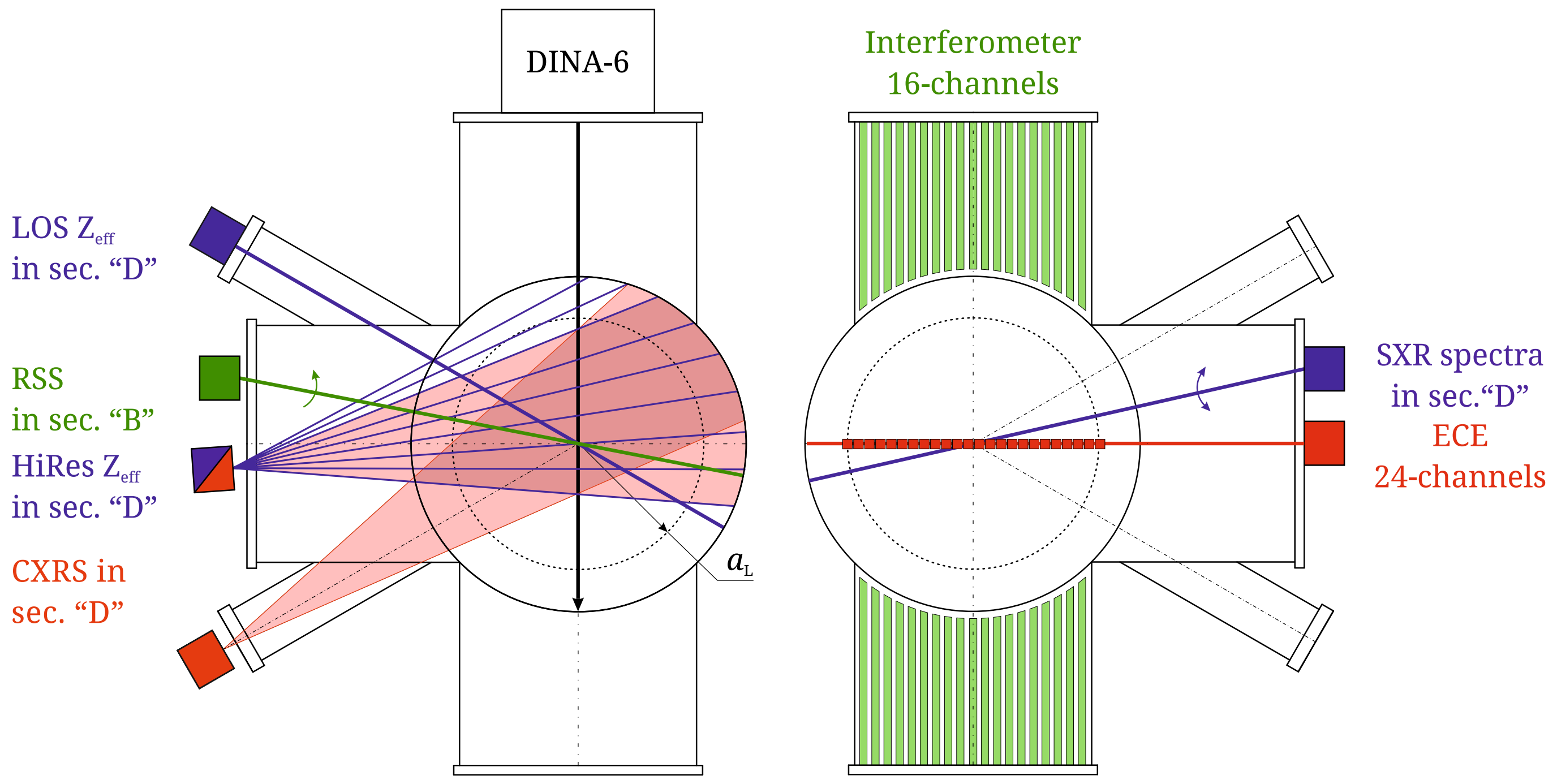
- CXRS - $T_i(r)$ and $n_Z(r)$
- ECE - $T_e(r)$
- SXR spectra - $T_e(0)$
- interferometers - $n_e(r)$
- visible spectroscopy - $Z_{eff}(r)$ and $I_Z(r)$
- bolometers and AXUV - $P_{rad}(r)$
- SXR diagnostics

Three gyrotrons with total power of 2.5 MW are used:

- "A": $P_A \leq 1$ MW, f_A=140 GHz, 200 ms length, poloidal rotation, co-ECCD;
- "B": $P_B \leq 0.5$ MW, f_B=129 GHz, 400 ms length, injection perpendicular to electron current direction;
- "C": $P_C \leq 1$ MW, frequency f_C=140 GHz, 200 ms length, toroidal rotation, co/counter-ECCD.



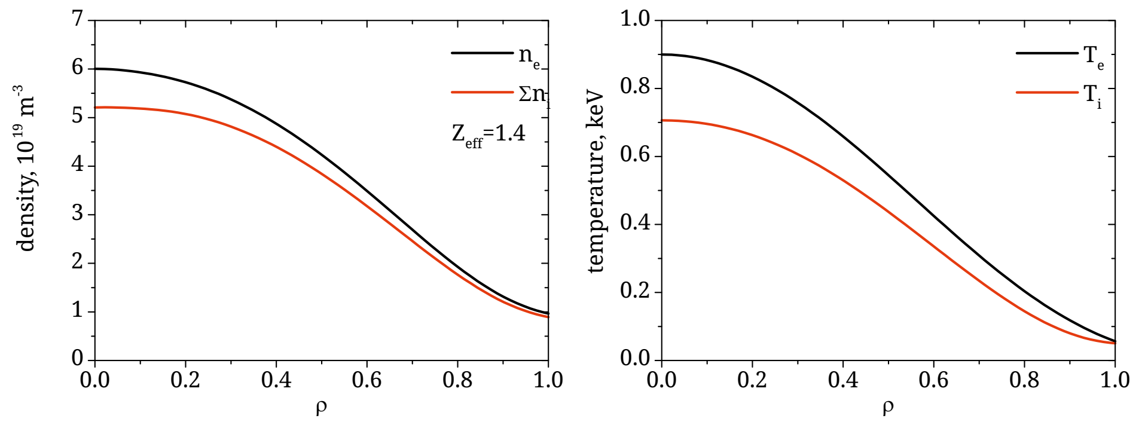




2. Ion heat transport in T-10 plasma with ohmic heating

Determination of ion heat conductivity χ_i^{eff} by means of power balance equation:

$$\mathrm{div}\left(-\chi_i^{eff} n_i \nabla T_i + \frac{5}{2} T_i \Gamma_i\right) = P_{ei} - P_{CX}$$



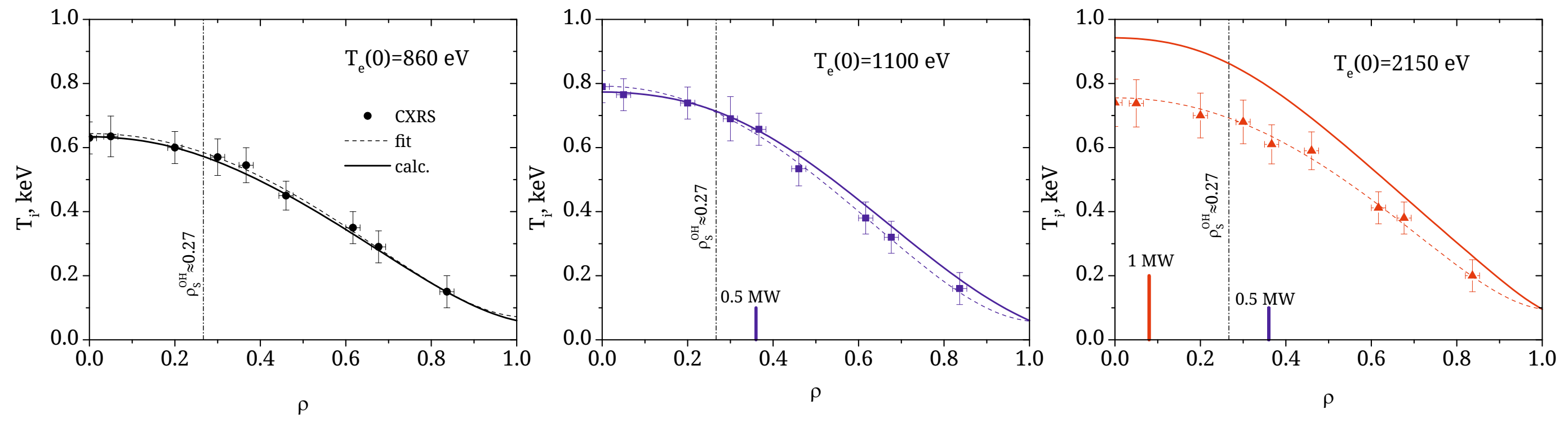
4. Calculations of $T_i(r)$ in ECRH plasma using OH scaling of χ_i^{an}

Direct calculation is performed using OH-scaling:

$$\chi_i^{eff}(\rho) = \chi_i^{neo}(\rho) + \chi_{i,scaling}^{an,OH}(\rho)$$

If calculated and measured profiles are coincidence, then anomalous heat conductivities in OH and ECRH plasma have similar values. If not, then χ_i^{an} are different.

Discharge #71864 with off-axis and combined ECRH
$\bar{n}_e$=4·10^{19} m^{-3}, Z_{eff}=1.6, I_{pl}=220 kA, B_{t0}=2.48 T



Off-axis ECR heating

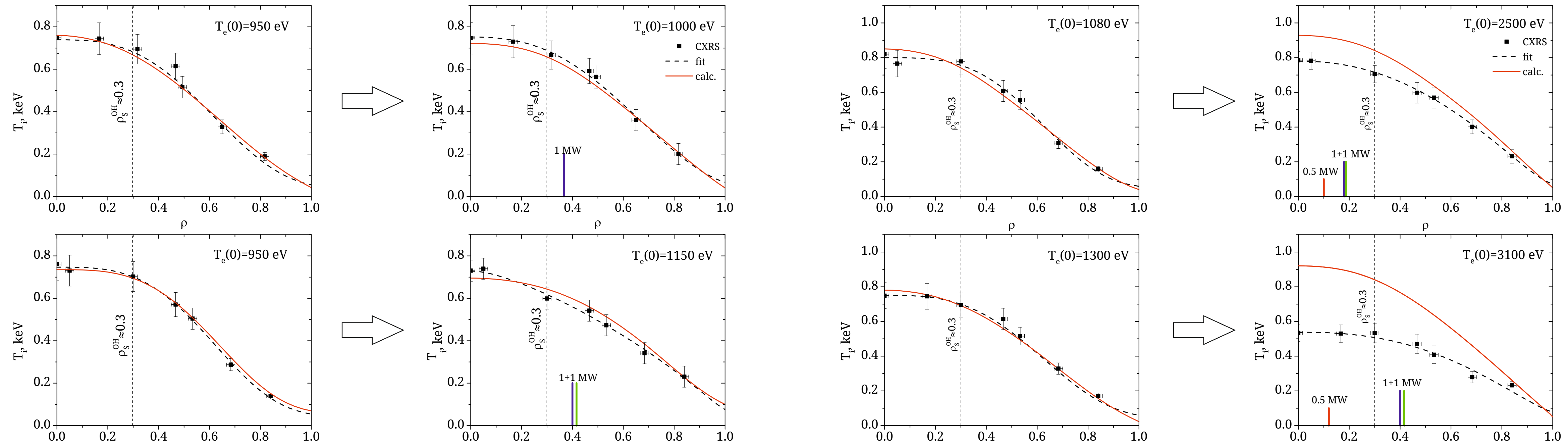
OH stage

ECRH stage

On-axis ECR heating

OH stage

ECRH stage



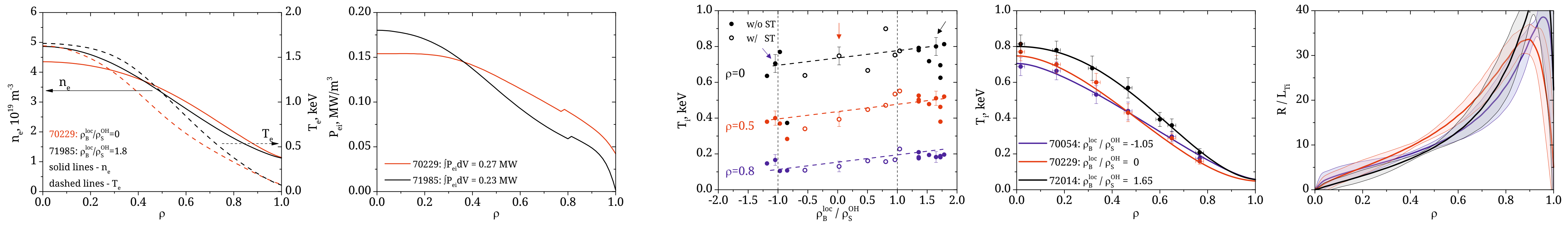
Only on-axis ECRH can significantly icrease the anomalous ion heat conductivity

5. Influence of ECRH localization

The gyrotron "B" is used to perform a scan ECRH over localization radius. The increase of toroidal magnetic field B_{t0} results in the resonance radius shift from High Filed Side (HFS) to Low Filed Side (LFS).

On-axis and off-axis ECRH influence on plasma parameters differently, as it is shown in the table.

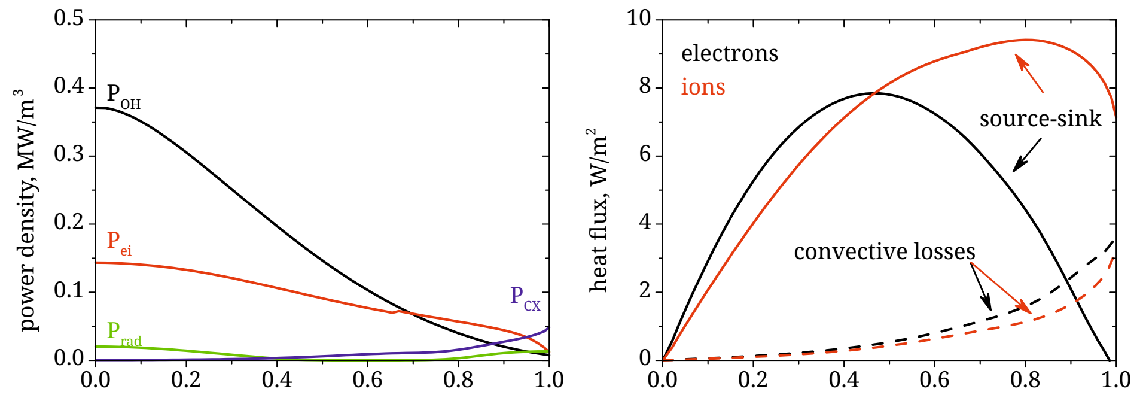
	on-axis	off-axis
$n_e(r)$	flattening	peaking
$T_e(r)$	peaking	flattening
$T_i(r)$	slightly peaking ?	no change
$P_{ei}(r)$	flattening	peaking



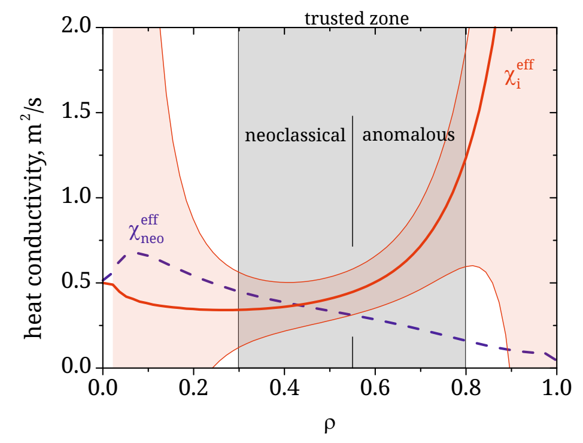
where n_i – total ion density, Γ_i – total flux of ion particles, P_{ei} – heat transfer from electron to ions through Coulomb collisions, P_{CX} – charge exchange losses on main gas atoms:

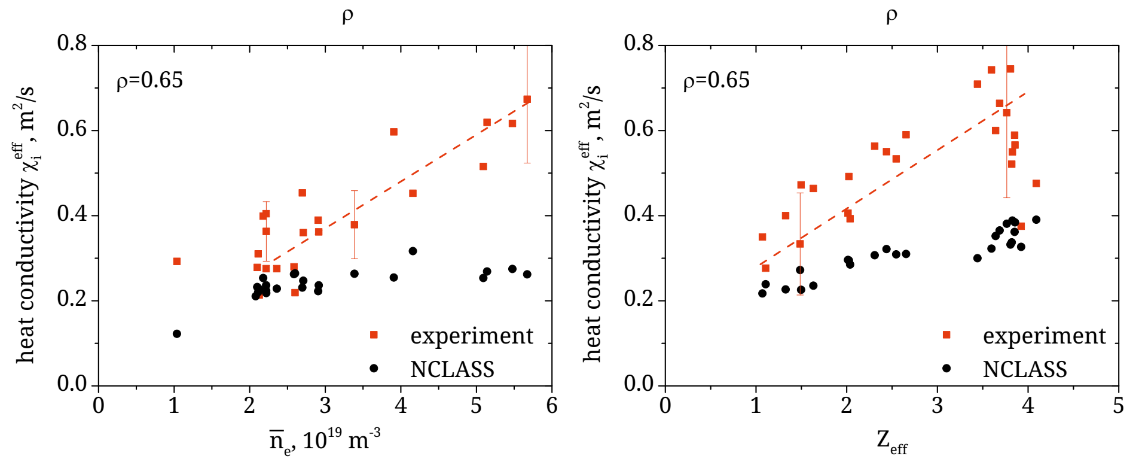
$$P_{ei} = 3m_e\left(T_e - T_i\right)n_e\sum_k\left(\nu_{ek}/m_k\right) \propto \left(T_e - T_i\right)n_e^2 / T_e^{3/2}$$

$$P_{CX} = \frac{3}{2}\left(T_i - T_0\right)n_d n_0\left\langle\sigma\upsilon\right\rangle_{CX}$$



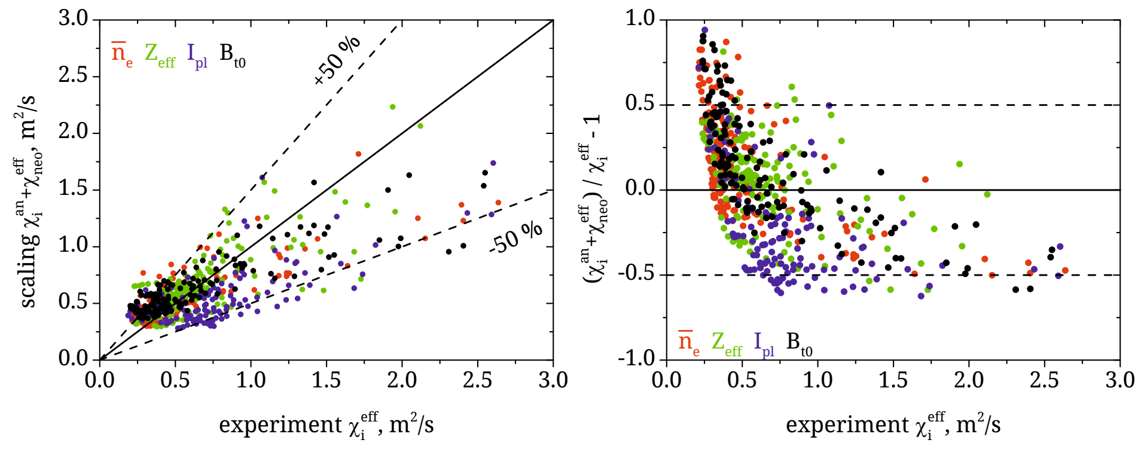
Ion heat conductivity exceeds neoclassical values up to 5-10 times in zone of $\rho = r/a_L > 0.5\text{-}0.6$.



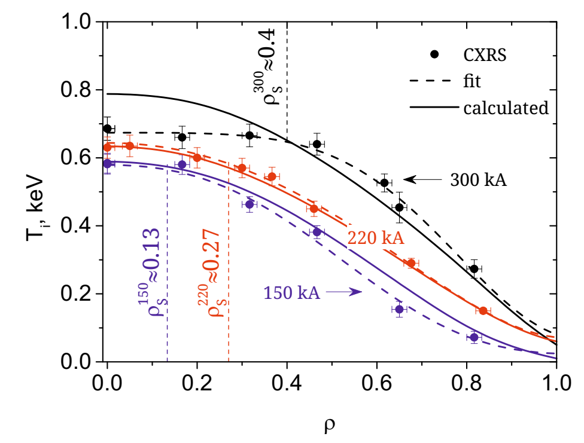


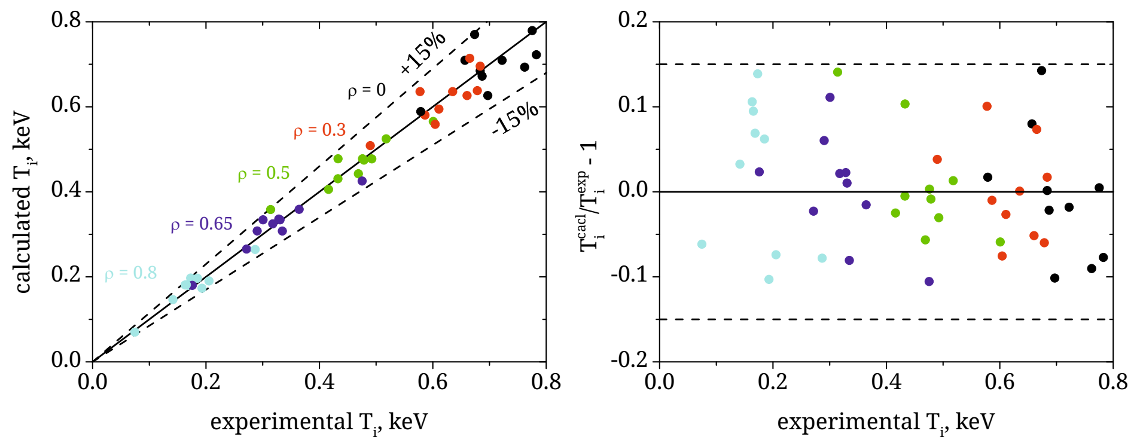
Linear regression model is used to generalize the large set of experimental data. The following scaling of OH anomalous ion heat conductivity is obtained:

$$\chi_{i,scaling}^{an,OH}(\rho) = 0.05\cdot\bar{n}_e\cdot Z_{eff}\cdot\left(\frac{I_{pl}}{220}\right)^{-0.5}\cdot\frac{\rho^2}{n_e(\rho)/n_e(0)}$$



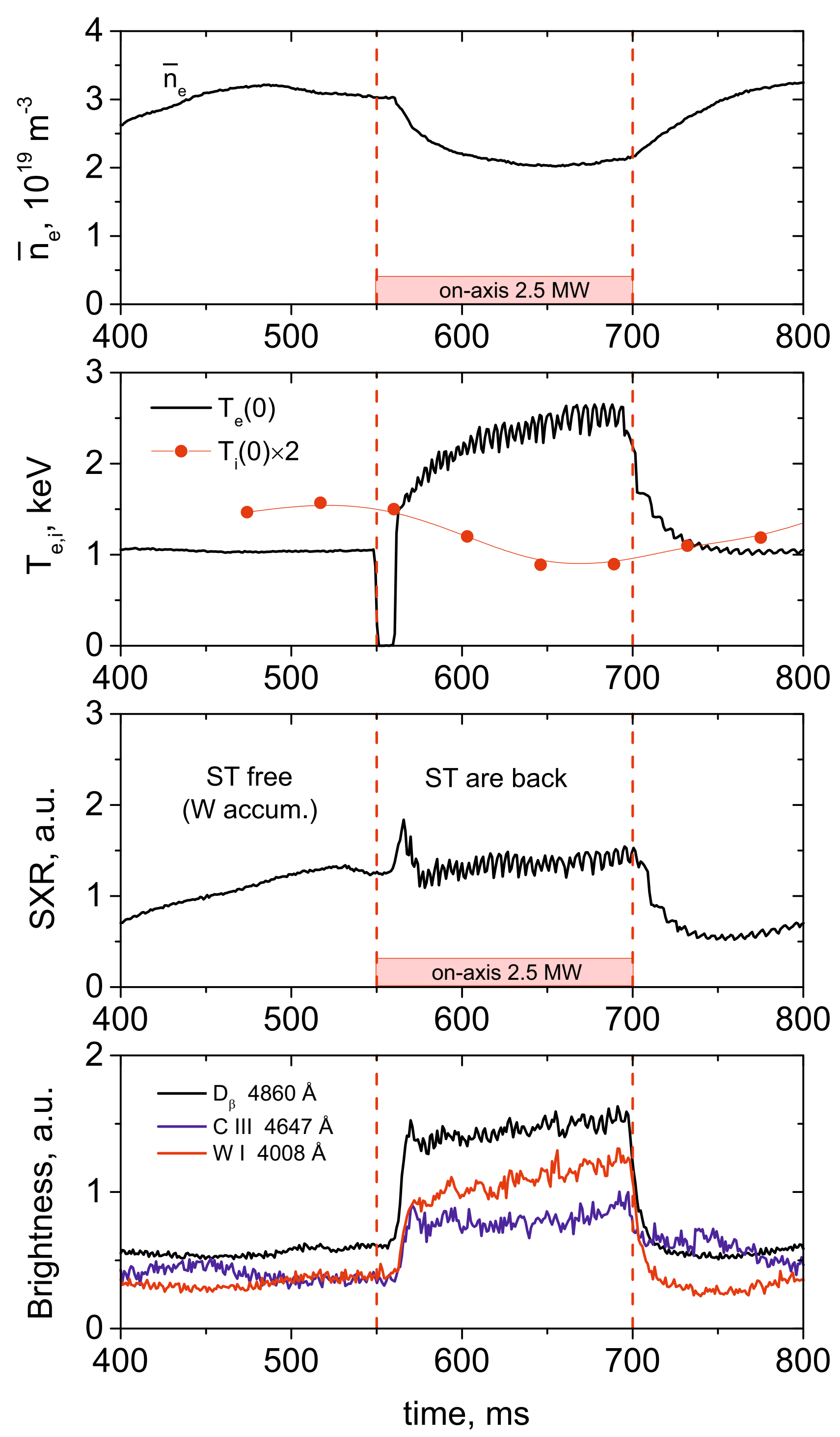
It is verified in range of plasma parameters $\bar{n}_e$=2-5.5·10^{19} m^{-3}, Z_{eff}=1-4, I_{pl}=150-300 kA, B_{t0}=1.9-2.49 T by describing experimental profiles of ion temperature. No dependence of B_{t0} was obtained.



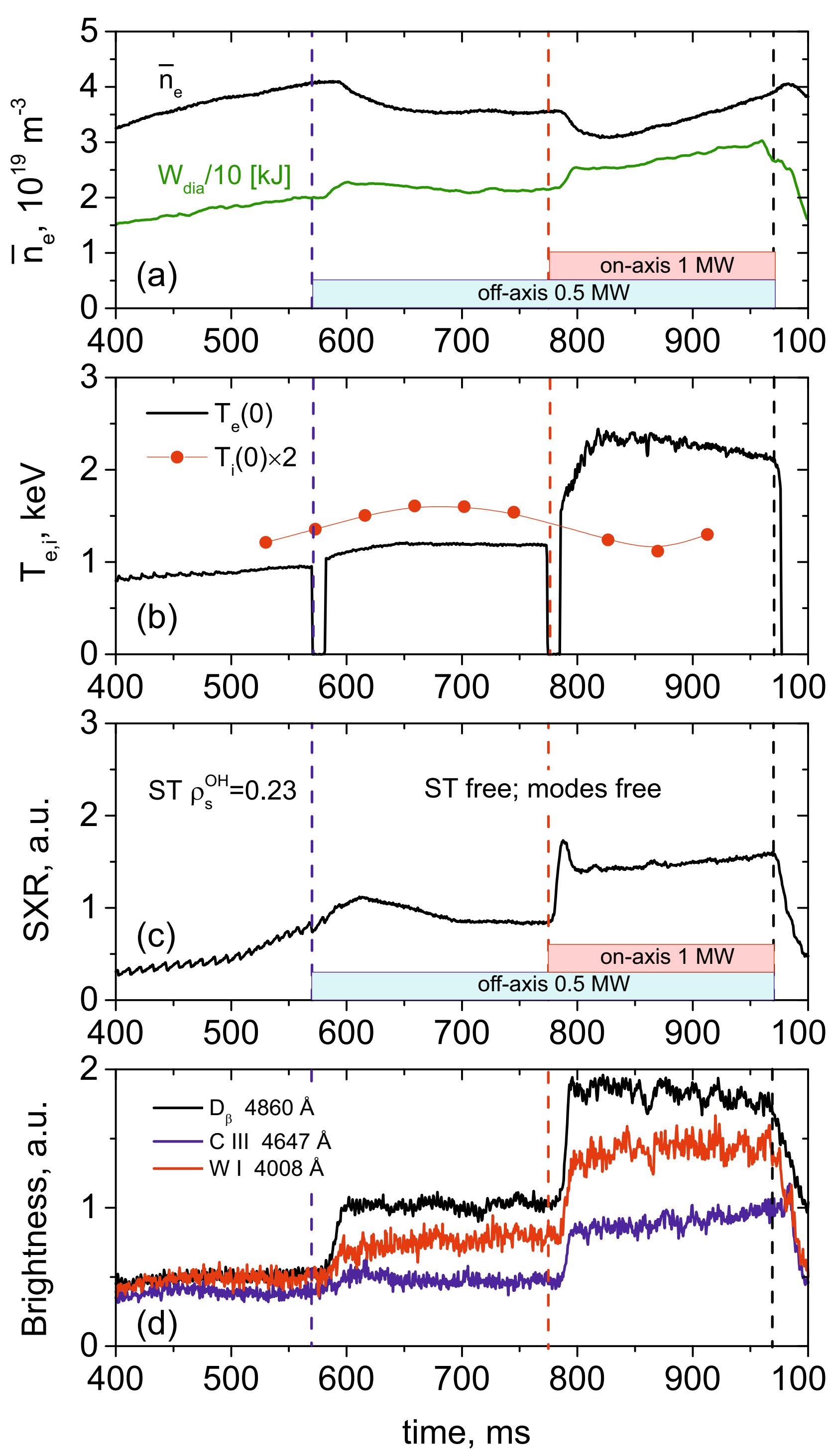


3. ECRH discharge scenarios

On-axis ECR heating
#72052: I_{pl} = 220 kA, B_{t0} = 2.4 T



Off-axis & Combined ECR heating
#71869: I_{pl} = 200 kA, B_{t0} = 2.48 T



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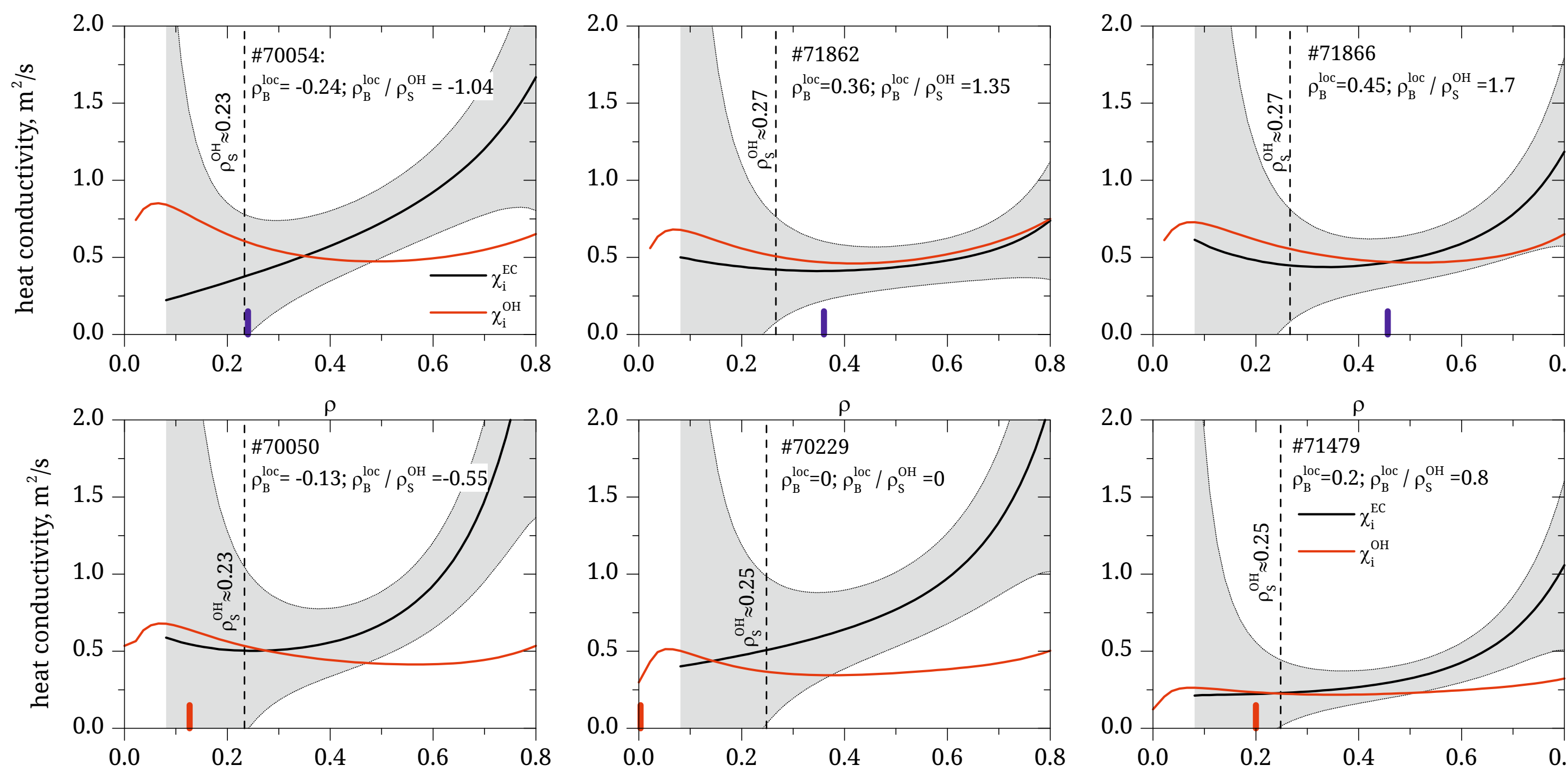
Power balance method gives higher ion heat conductivities χ_i^{EC} in discharges with on-axis ECRH.

The comparison of obtained χ_i^{eff} with ohmical values is performed by means of OH-scaling:

$$\chi_i^{OH}(\rho) = \chi_i^{neo}(\rho) + \chi_{i,scaling}^{an,OH}(\rho)$$

The closer to plasma center ECRH is applied, the more differences between χ_i^{EC} and χ_i^{OH}.



The data is gathered through 2017-2018 experimental campaigns in different plasma regimes, so normalizing is required.

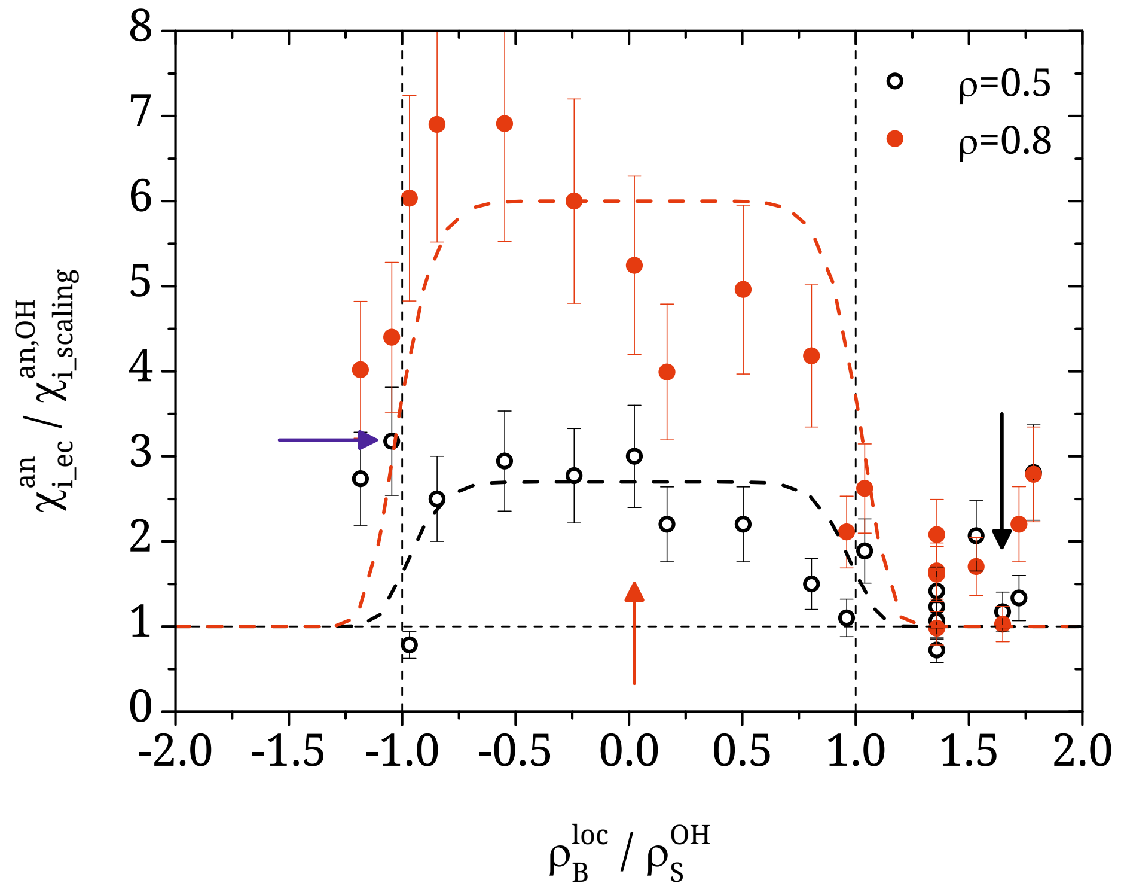
The change of anomalous ion heat conductivity is presented by the ratio:

$$\chi_{i\_EC}^{an} / \chi_{i,scaling}^{an,OH}$$

The normalizing of ECRH resonance radius by the saw-teeth inverse radius, ρ_S^{OH}, determined at the OH stage:

$$\rho_B^{loc} / \rho_S^{OH}$$

On-axis ECRH result in the growth of anomalous ion heat conductivity by 2-7 times



6. Influence of heating power with on-axis ECRH

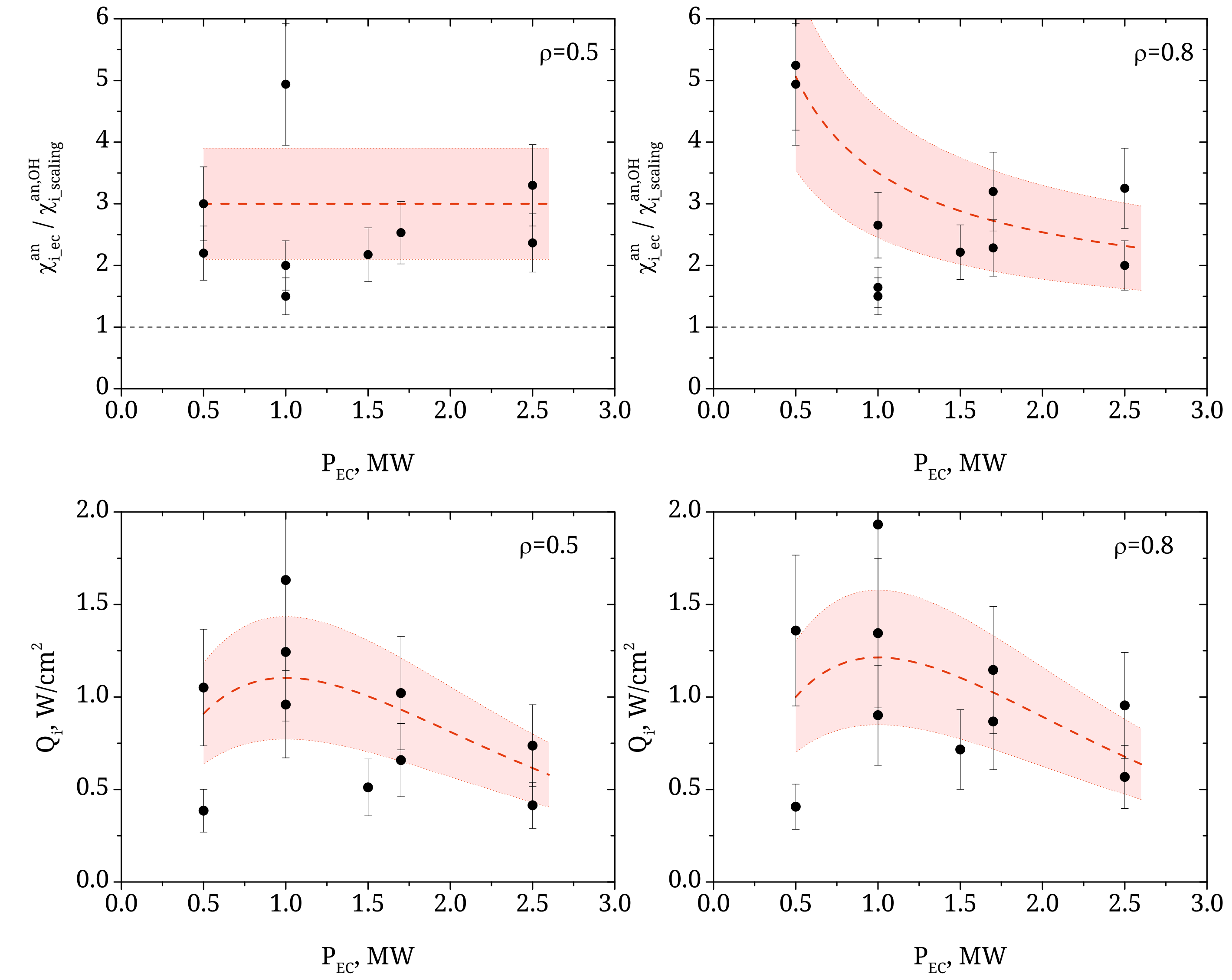
Five combinations of three gyrotrons are used to determine the dependence on ECRH power:

- "B": P_{EC} = 0.5 MW
- "C" (contr-ECCD): P_{EC} = 1 MW
- "B"+"C" (contr-ECCD): P_{EC} = 1.5 MW
- "A" (co-ECCD) + "C" (contr-ECCD): P_{EC} = 1.7 MW
- "A"+"B"+"C": P_{EC} = 2.5 MW

Localization radii of all cases are

$$0 < |\rho^{loc}/\rho_S^{OH}| < 0.5$$

in order to not take into account effects of ECRH localization



Within the variation of P_{EC} from 0.5 MW to 2.5 MW the change of anomalous ion heat conductivity $\chi_{i\_EC}^{an} / \chi_{i,scaling}^{an,OH}$ shows no change on ρ = 0.5 and slight decrease on ρ = 0.8.

This decrease related to the strong increase of electron temperature and corresponding decrease pf electron to ion heat transfer $P_{ei} \propto n_e^2(T_e - T_i)/T_e^{1.5}$. The latter leads to the decrease of ion heat flux, Q_i, with ECRH power increase.

On-axis ECRH increases the anomalous ion heat conductivity and deteriorate ion heat confinement in comparison with OH regime

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