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Maximizing the ion temperature in an electron heated plasma: from WEST towards larger devices

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Abstract

In electron heated plasmas, as the power increases, it is experimentally reported that the ion temperature (T_i) saturates while the electron temperature (T_e) increases [1]. As on AUG [2], W7X [3] and elsewhere, T_i saturates around 1.5 keV in WEST L-mode electron heated plasmas while T_e reaches 4 keV [4,5]. Simulations within the integrated model METIS [6] have been compared against a whole WEST campaign consisting mostly of L-mode plasmas with Lower Hybrid heating ranging from 1 to 5.5 MW. In METIS, the collisional equipartition is modelled as well as the turbulent heat transport using the neural network regression of the quasilinear gyrokinetic code QuaLiKiz [7]. The observed T_i saturation is well captured by the modelling framework. The saturation correlates with a high ratio of the volume averaged electron-ion collisional heat exchange time (τ_{ei}) to the energy confinement time (τ_E) to [8,9]. It is then shown that T_i saturation in electron heated plasma is due to an equipartition time larger than the energy confinement time. In larger devices, no T_i saturation is expected nor predicted by physics based integrated modelling used in this work, thanks to equipartition times sufficiently shorter compared to the energy confinement time [10-14].

WEST Experiments: T_i saturation

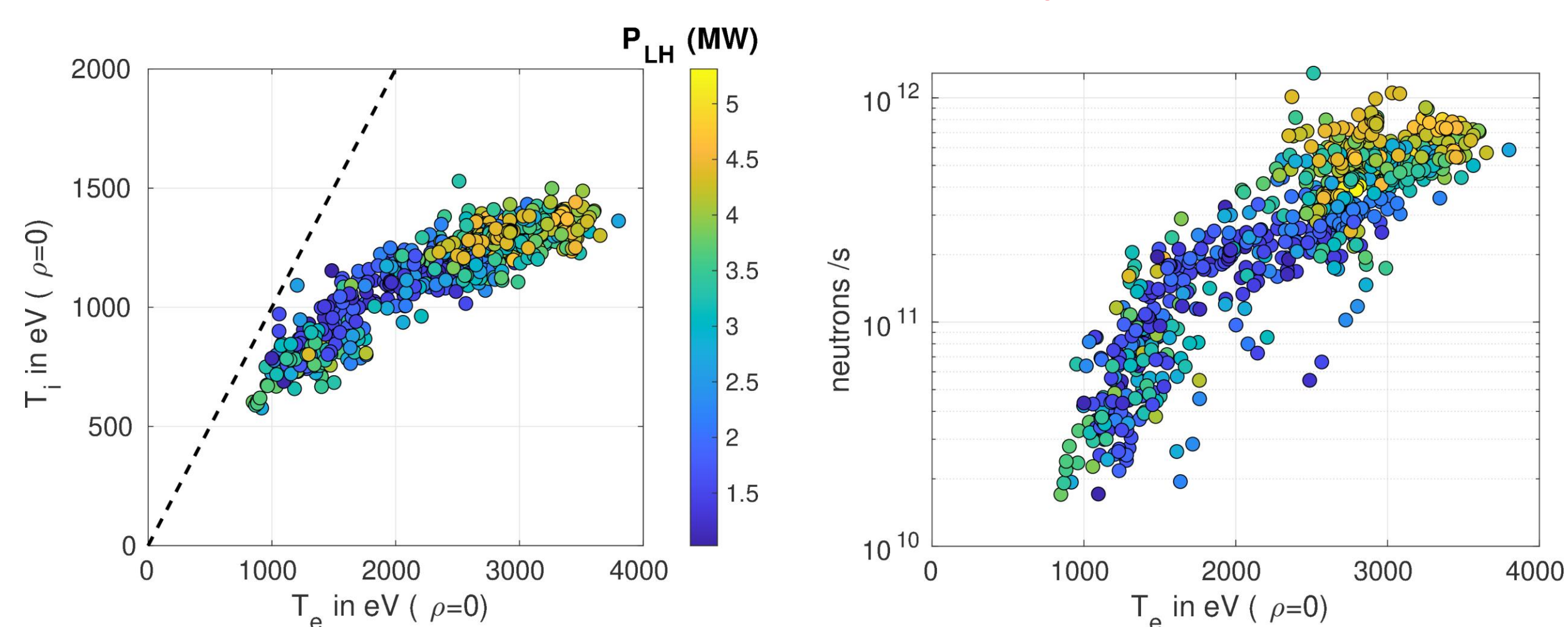


Fig 1: (left) Measured D-D neutron rate against central electron temperature from ECE. The database corresponds to the C4 and C5 WEST campaigns altogether with injected power above 1 MW (LHCD heating only) and for a plasma current of 0.5 MA, a magnetic field of 3.7 T and D only plasmas. (right) Corresponding central ion temperature inferred from the D-D neutron rate.

Analytical model → main players

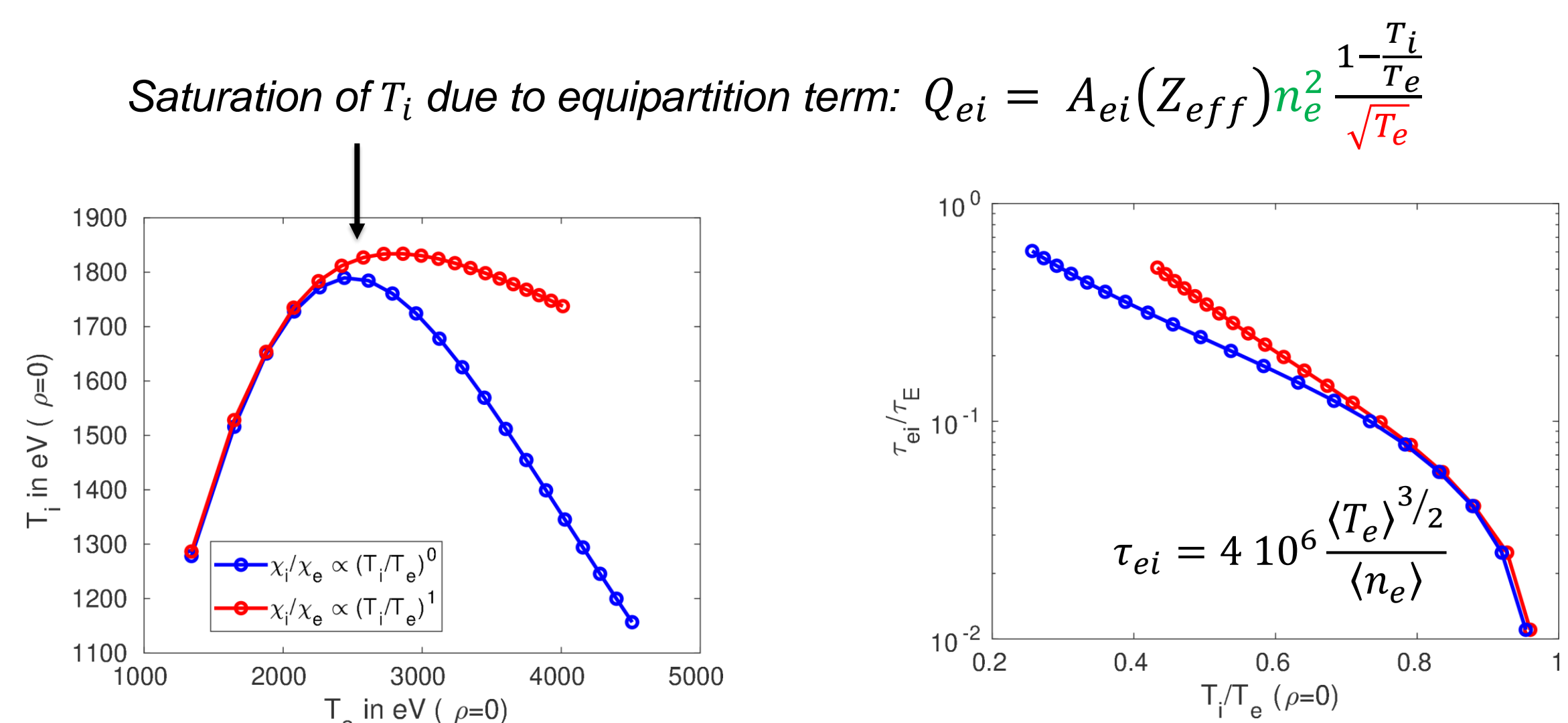
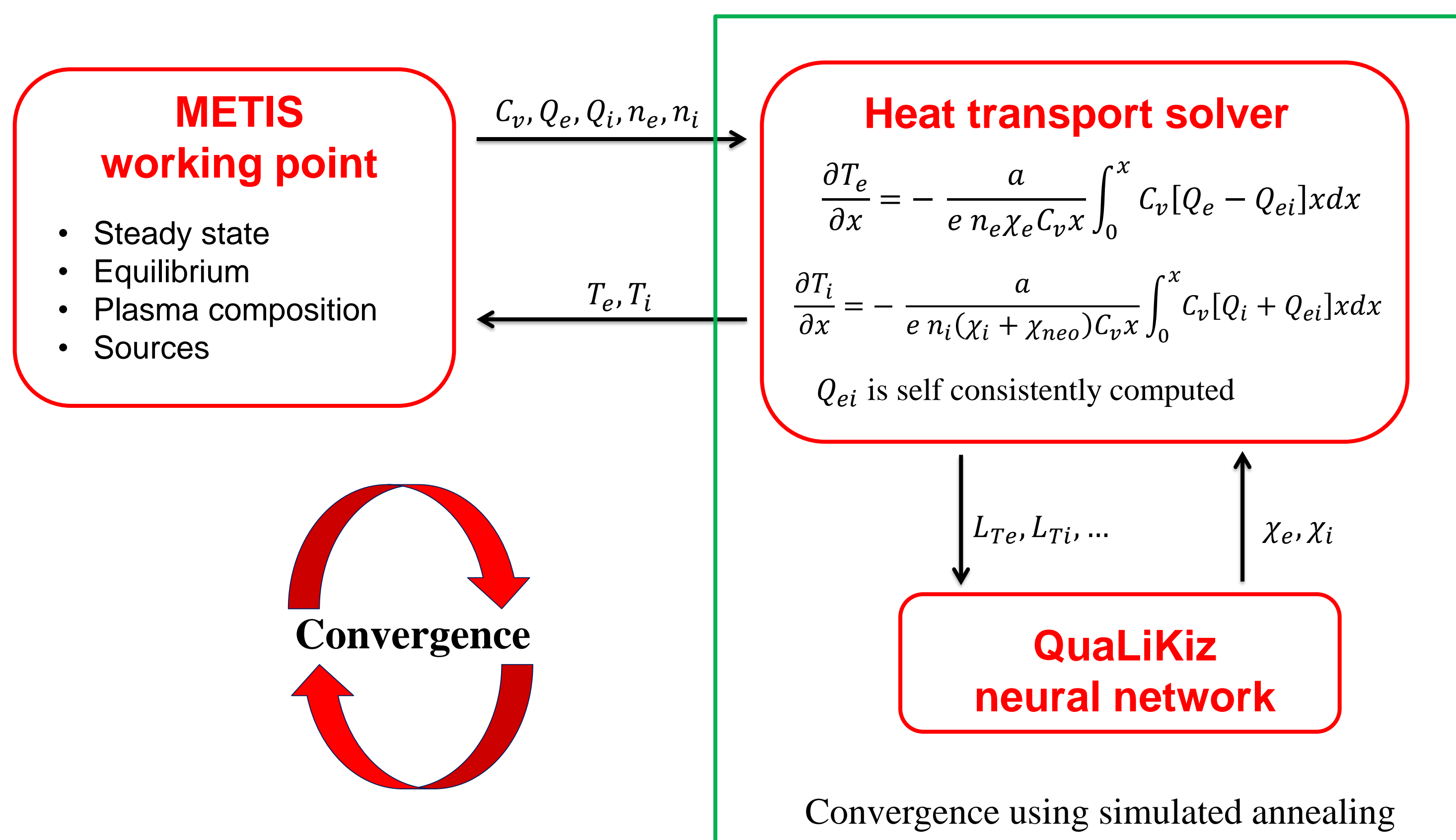


Fig 2: (left) Results from the analytical model for WEST parameters. Here a scan in the external input power on the electrons has been performed from 0 to 7 MW for a given line averaged density of $4 \cdot 10^{19} \text{ m}^{-3}$. (right) The ratio of the electron-ion heat exchange time (τ_{ei}) over the energy confinement time (τ_E) is shown for two different dependences of the ratio of the ion to electron heat diffusivities for the same power scan.

→ Transport coefficients should be predicted from first principle model for reliable prediction

Modelling tool



Modelling validation

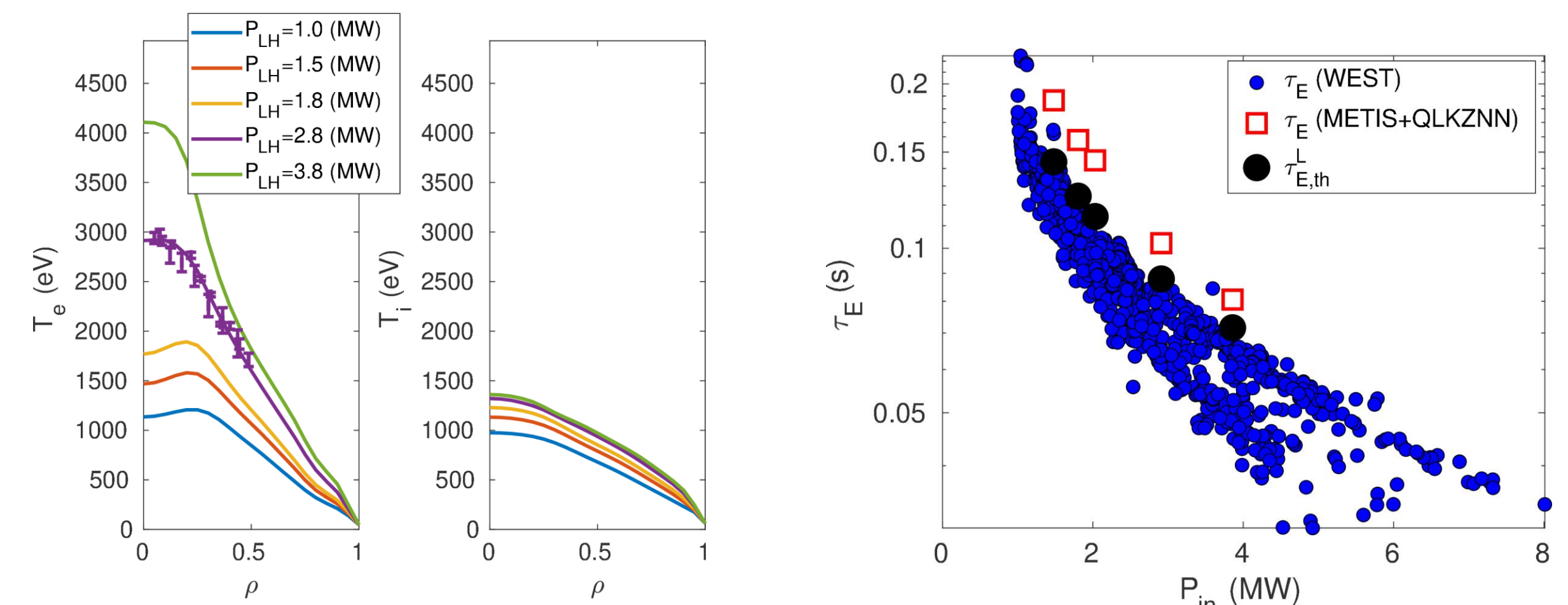


Fig 3: (left) LHCD power scan based on discharge 55025 at 8.5 s. Electron and ion temperature profiles obtained at steady state using METIS and QLKZNN-10D. The measured electron temperature profile from ECE is shown up to $\rho = 0.5$ due to pollution from fast electrons in more peripheral channels. (right) Energy confinement time degradation with injected power computed from METIS with QLKZNN-10D compared to the L-mode scaling law and the WEST database.

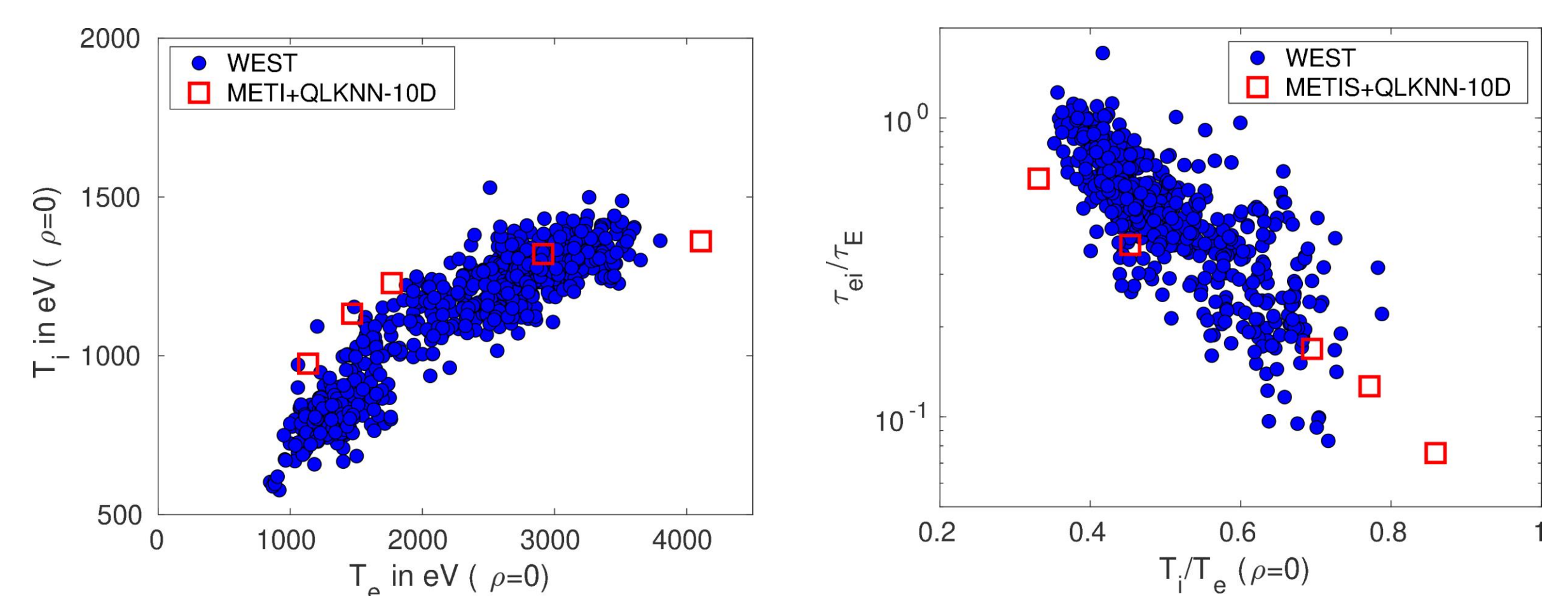


Fig 4: (left) Inferred central ion temperature against measured central electron temperature from the WEST database. Results from METIS+QLKNN-10D simulations are also shown for the LHCD power scan. (right) Ratio of the electron-ion heat exchange time over the energy confinement time for the WEST database and METIS+QLKNN-10D modelling.

Impact of the ion turbulent transport

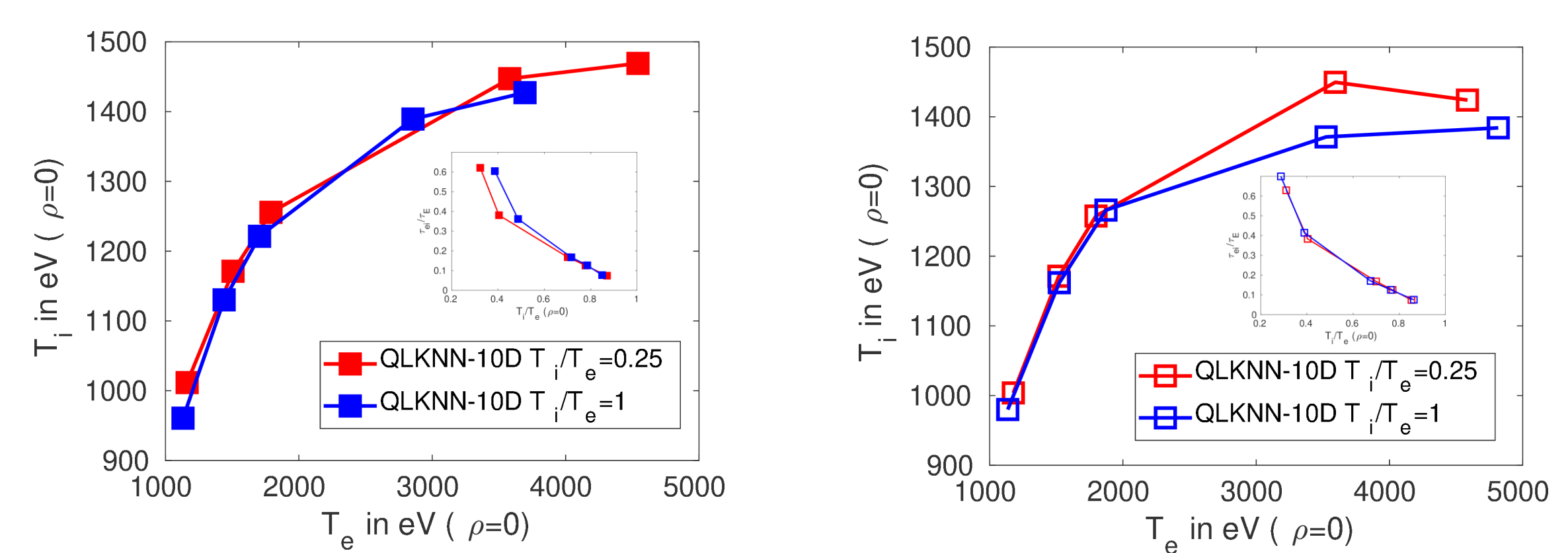


Fig 5: (left) Central ion temperature versus central electron temperature obtained from METIS+QLKNN-10D steady state simulations with constrained electron to ion temperature ratios in QLKNN-10D (inlay: corresponding ratios of the electron-ion heat exchange time over the energy confinement time against the electron to ion temperature ratio). (right) Same figure as the left one but without ETG contribution to the electron heat.

Main results

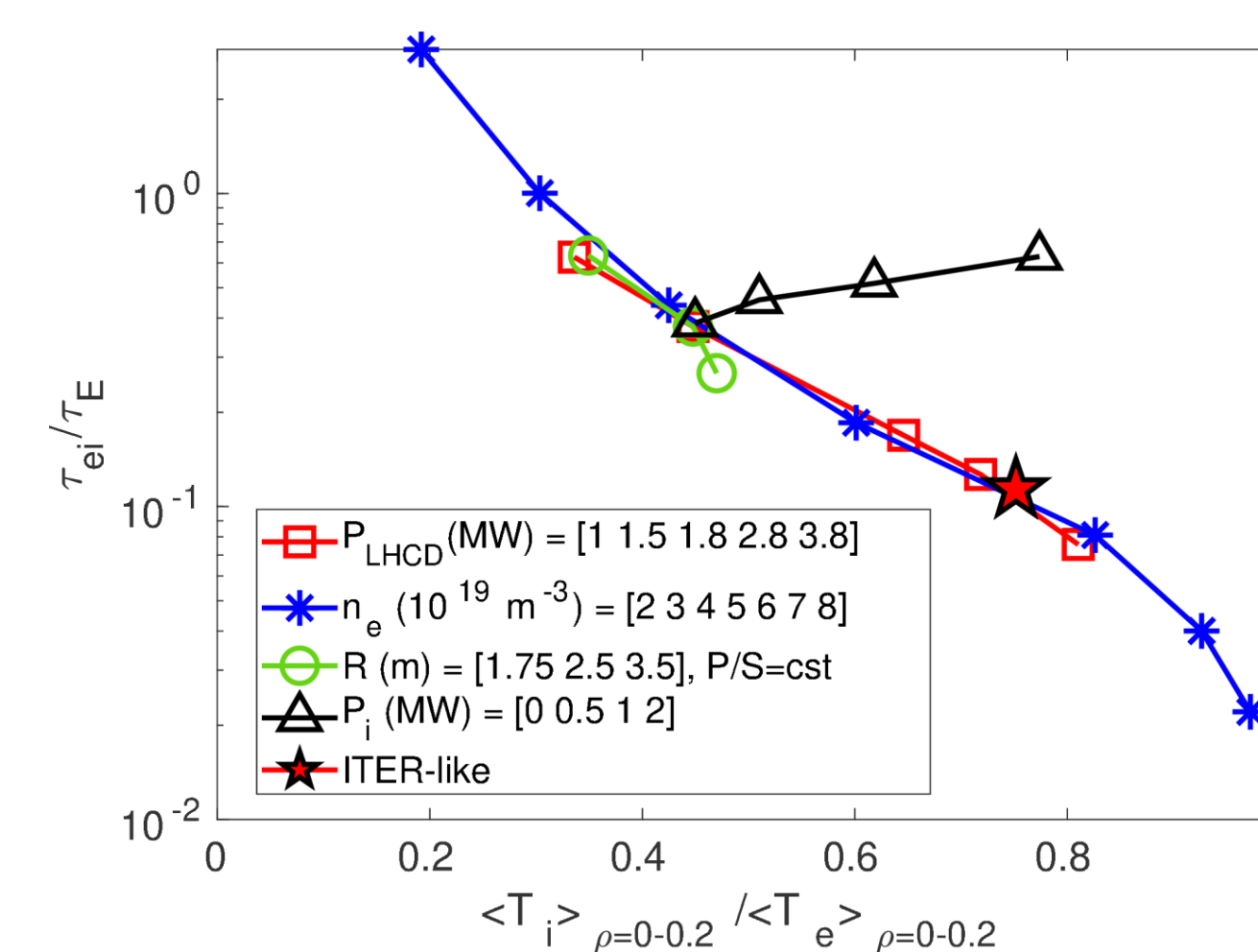


Fig 6: Ratios of the electron-ion heat exchange time over the energy confinement time against the electron to ion temperature ratio resulting from METIS+QLKNN-10D steady state simulations shown for various scans:
 • LHCD power scan (electron heating source)
 • Electron density scan @ $P_{LHCD} = 3.8 \text{ MW}$
 • Major radius scan @ $\epsilon = C^{st}$, $q_{95} = C^{st}$ & $\text{Additional Power} = C^{st}$ Plasma Surface
 • Direct ion heating + 2.8 MV of LHCD
 ★ ITER like scenario (15 MA scenario, 5.3 T, $Q \sim 8$, heating: 70% electron & 30% ion)

Conclusion

- T_i saturation with dominant electron heating (e.g. [2]) can be captured by modelling.
- T_i saturation on WEST, is, as on AUG and W7X due to the reduction of the equipartition term together with decreased confinement time (with increasing power).
- Modifying T_i/T_e dependence on the turbulent heat fluxes does not impact our results significantly in our case (unlike what is observed in W7X [3] and NBI+ECRH AUG plasmas [2]) as long as core ETG are not destabilized.
- T_i saturation is captured by the competition between the energy confinement time (τ_E) and the volume averaged electron-ion collisional heat exchange time (τ_{ei}).
- Projection for ITER and reactors: two effects are in favor of larger T_i/T_e :
 - ✓ larger volume at constant $\frac{P}{S}$ and $q_{95} = C^{st}$ allows to sufficiently improve τ_E compared to τ_{ei} , leading to higher T_i/T_e
 - ✓ alpha heating predominantly heat electron (80%) but it will also produce direct ion heating (20%) which is very efficient in increasing the T_i/T_e .
- No T_i saturation expected for ITER and DEMO [10-14]

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