NSTX-U

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Energy transport analysis of NSTX plasmas with the TGLF turbulent and NEO neoclassical transport models

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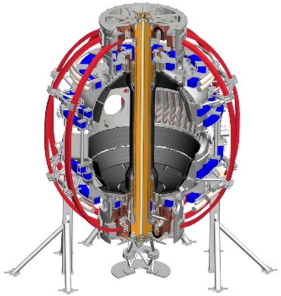
PPPL



Outline

- Motivation
- Experimental data details
- **Workflow of the data analysis**
- Profiles prediction with TGYRO (TGLF+NEO) solver
- Comparison of profiles prediction with experimental data
- **Variation of input parameters**
- Linear stability analysis
- Results

Motivation: Reduced models are more advantageous in terms of computational cost

- Comprehensive numerical transport models are typically not feasible for real-scale full-device modeling

⇓

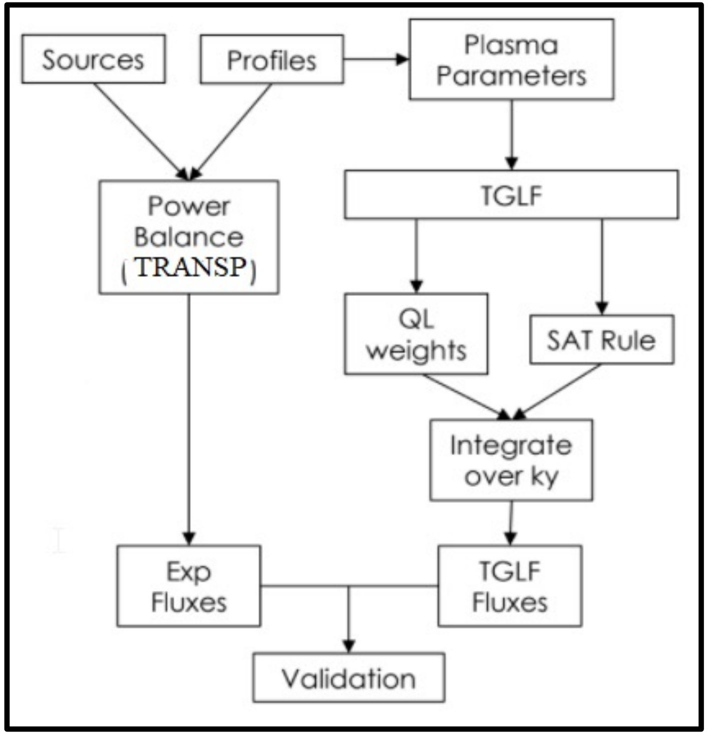
- **Fast reduced turbulent numerical models**

- Identifying the regimes of validity of such models increases the fidelity of predictive modeling

- The design of the next generation fusion machines requires **validation of transport models over a range of aspect ratio** to determine the optimal parameters

Trapped-gyro-Landau-fluid (TGLF) model is a reduced turbulent model

- TGLF[1] predicts a transport driven by drift-wave instabilities (TEMs, ITGs, ETGs)
- TGLF computes turbulent fluxes using the linear eigenmode solution and a model of the saturated intensity
- Versions of the saturation rule:
  SAT0[1], **SAT1[2]**, SAT2[3]
- *NEO*[4] is a drift kinetic neoclassical solver



1 [*Staebler G.M et. al., Physics of Plasmas 12, (2005)*]; 2 [*Staebler G.M et. al., Nuclear Fusion 57, (2017)*]; *3 [Staebler G. M. et al., Physics and Controlled Fusion 63, (2021)]; 4 [Belli E. et. al., Plasma Phys. and Controlled Fusion 50, (2008)]*

TGLF model validations on STs is still in its early stages

- TGLF has been **extensively utilized for transport modeling of conventional tokamaks** (ASDEX-U, JET, DIII-D)

- **Only a few studies** of validation of reduced transport models **at low aspect ratio plasmas** have been reported

  - first demonstration of TGLF on STs ⇒ limitations of the implementation of the collisional model and the saturation rule[1]

    1 *Staebler G.M et. al., 22nd IAEA Fusion Energy Conf., (2008)]*

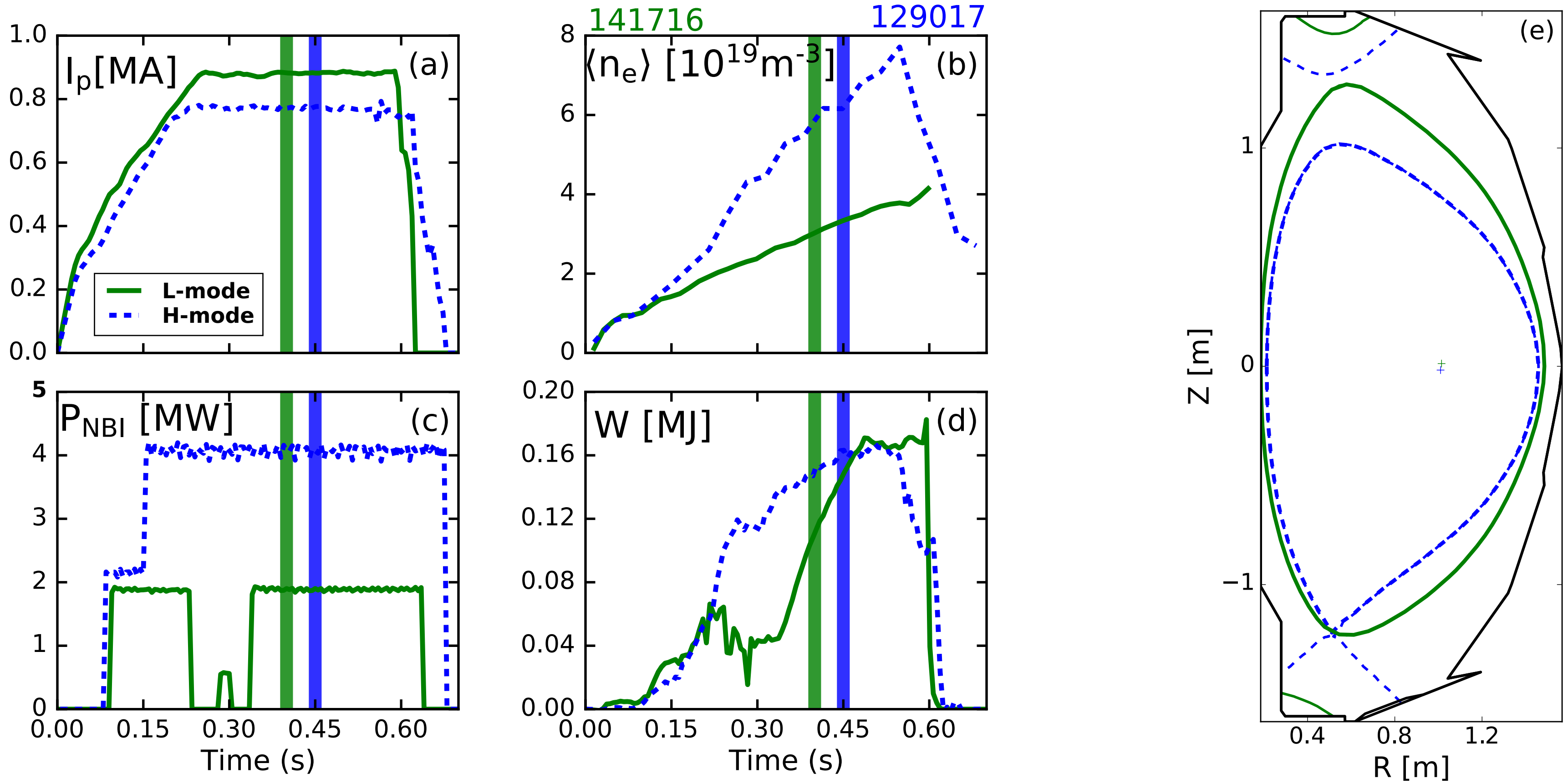
  - modeling of NSTX ⇒ better results with SAT1 model compared to simulations with the simplified SAT0 model [2]

    2 *S.M. Kaye et al., Nucl. Fusion 59 (2019)*

An extension of previous studies is conducted to verify TGLF and NEO models on the NSTX data

- **Two discharges** with a transport predominantly driven by the electrostatic drift-wave instabilities have been selected:
    - **L-mode** (# 141716) at low-$\boldsymbol{\beta}$ and density **with conditions close to the conventional tokamaks** where both low-*k* ($k_{\theta}\rho_s \leqslant 1$) ion scale and high-*k* ($k_{\theta}\rho_s > 1$) electron scale turbulence are present
    - **H-mode** (# 129017) which is **typical for STs**, where ion transport is neoclassical
- A **sensitivity study of predicted results** is performed by variations of input plasma profiles
- Results of a linear stability analysis are analyzed to determine if a picture of mechanisms driving the transport is captured correctly by TGLF and NEO models

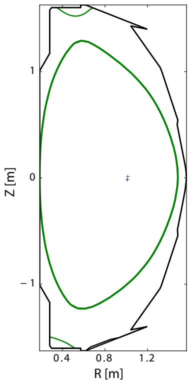
Experimental data is analyzed over a time window of 40 ms



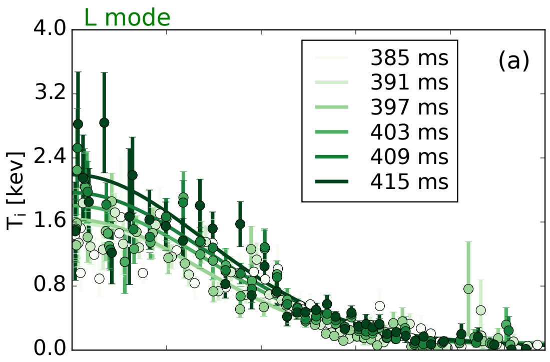
Equilibrium reconstruction is obtained through EFIT-TRANSP integrated workflow using OMFIT

Initial equilibrium → Mapping of profiles to flux coordinates → Transport code computes a current density profile and a total plasma pressure

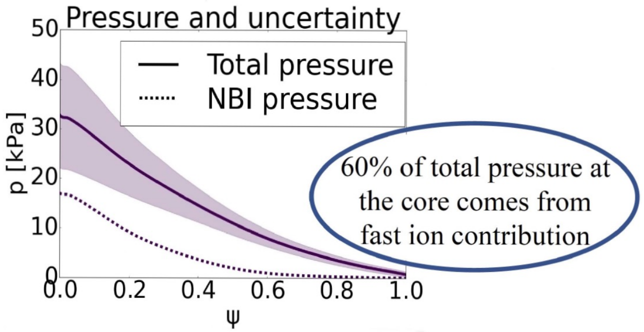
EFIT with magnetics, MSE, isothermal constraints



OMFITprofiles: fetching, mapping, slicing, fitting, averaging



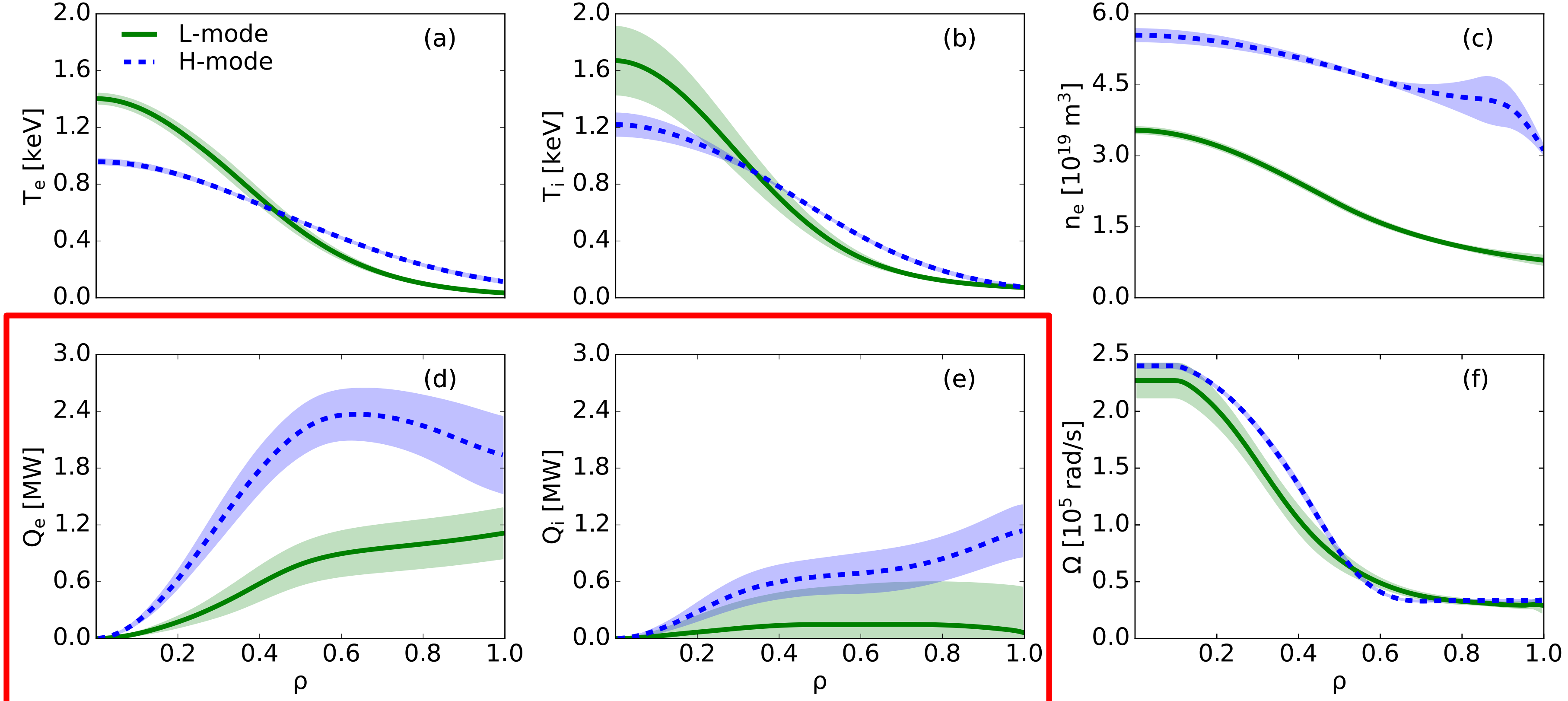
TRANSP + NUBEAM



Apply these constraints on the next iteration of the equilibrium reconstruction

The self-consistent solution is usually obtained after 3 - 4 iterations

The power deposition is determined through the power balance analysis with TRANSP+NUBEAM



TGYRO (TGLF +NEO) flux-matching solution predicts profiles based on known plasma sources

- TGYRO solver reconstructs plasma profiles based on gradients, which satisfy the steady state transport equation

$$\frac{1}{V'}\frac{\partial}{\partial r}[V'(r)\boxed{Q(r)}] = \boxed{S}$$

Q – energy flux predicted based on the plasma gradients

$$Q_{model} = Q_{turbulent}^{TGLF} + Q_{neoclassical}^{NEO}$$

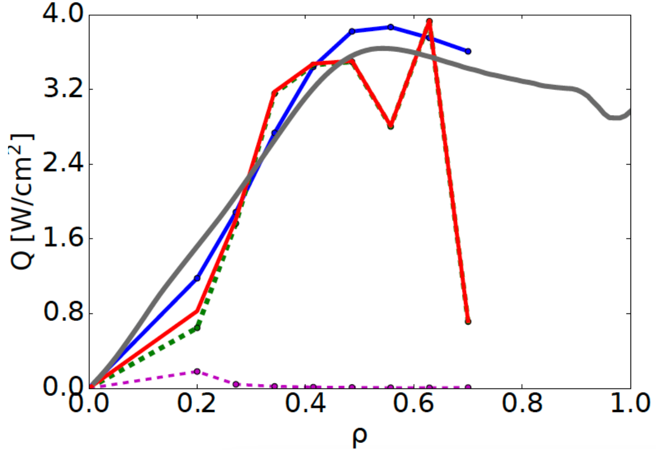
S – integrated source (power/volume), obtained from the power balance analysis
*auxiliary NBI heating, radiation losses, **collisional e-i heat exchange** minus energy gain*

$$Q_{target} \approx S$$

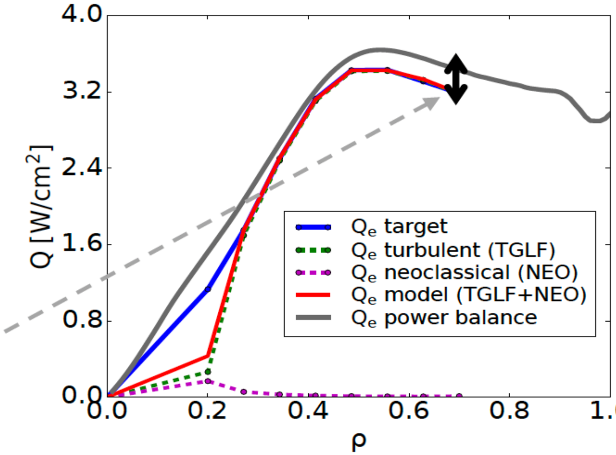
TGYRO flux-matching solution predicts profiles based on known plasma sources

- TGYRO applies an iterative scheme varying the local gradients to minimize $|Q_{model} - Q_{target}|$

Iteration 20



Iteration 60



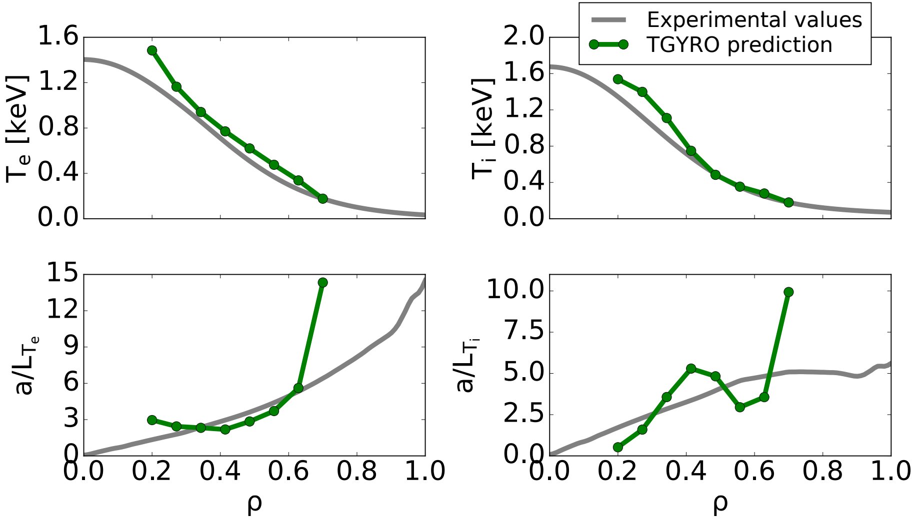
Due to dynamic exchange term $\propto T_e/T_i$

- Plasma profiles are obtained by the integral of the local gradients

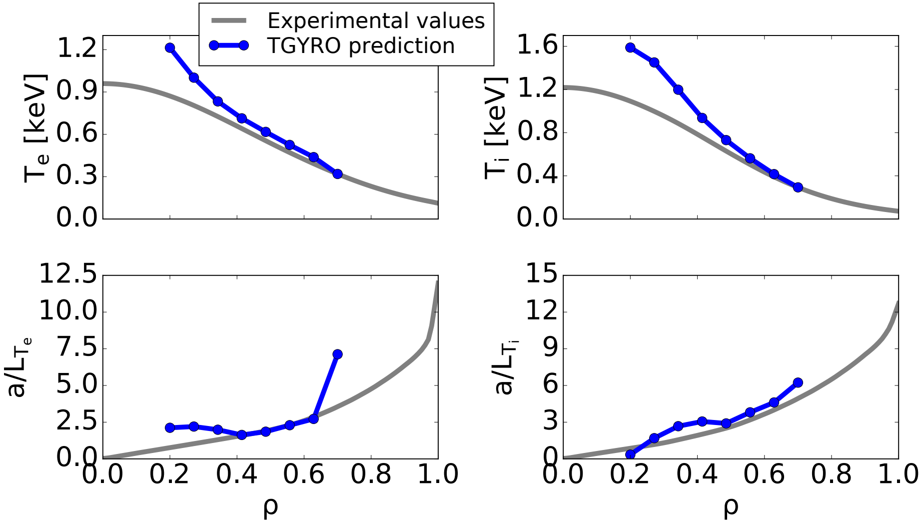
$$T(r) = T^* exp\left(-\int_r^{r^*} \frac{1}{T}\frac{\partial T}{\partial r}\, dr\right)$$

Predicted plasma profiles and inverse gradients are then compared with experimental data

L-mode



H-mode



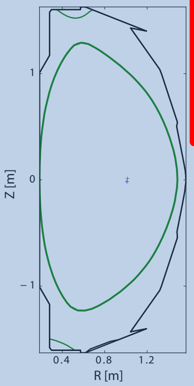
Variation of input parameters

Equilibrium reconstruction is obtained through EFIT-TRANSP integrated workflow using OMFIT

Initial equilibrium → Mapping of profiles to flux coordinates → Transport code computes a current density profile and a total plasma pressure

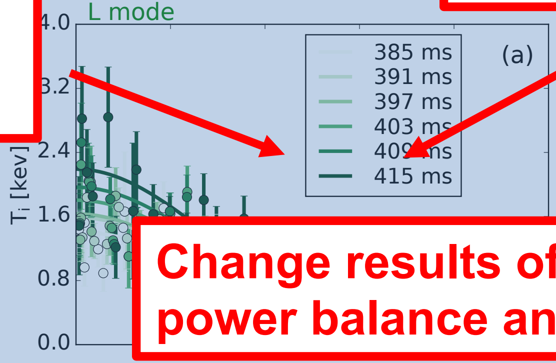
EFIT with magnetics, MSE, isothermal c

A) Change number of constraints



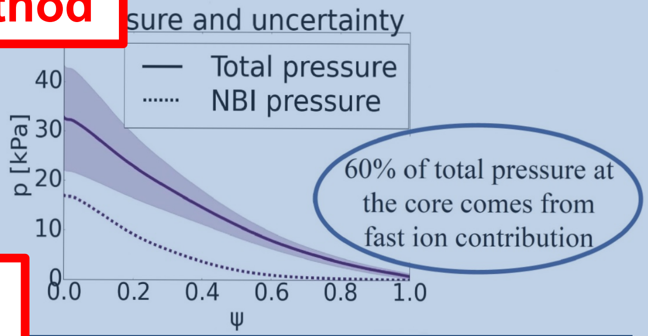
OMFITprofiles: fetching, mapping, slicing, fitting, a

B) Change fitting method



Change results of the power balance analysis

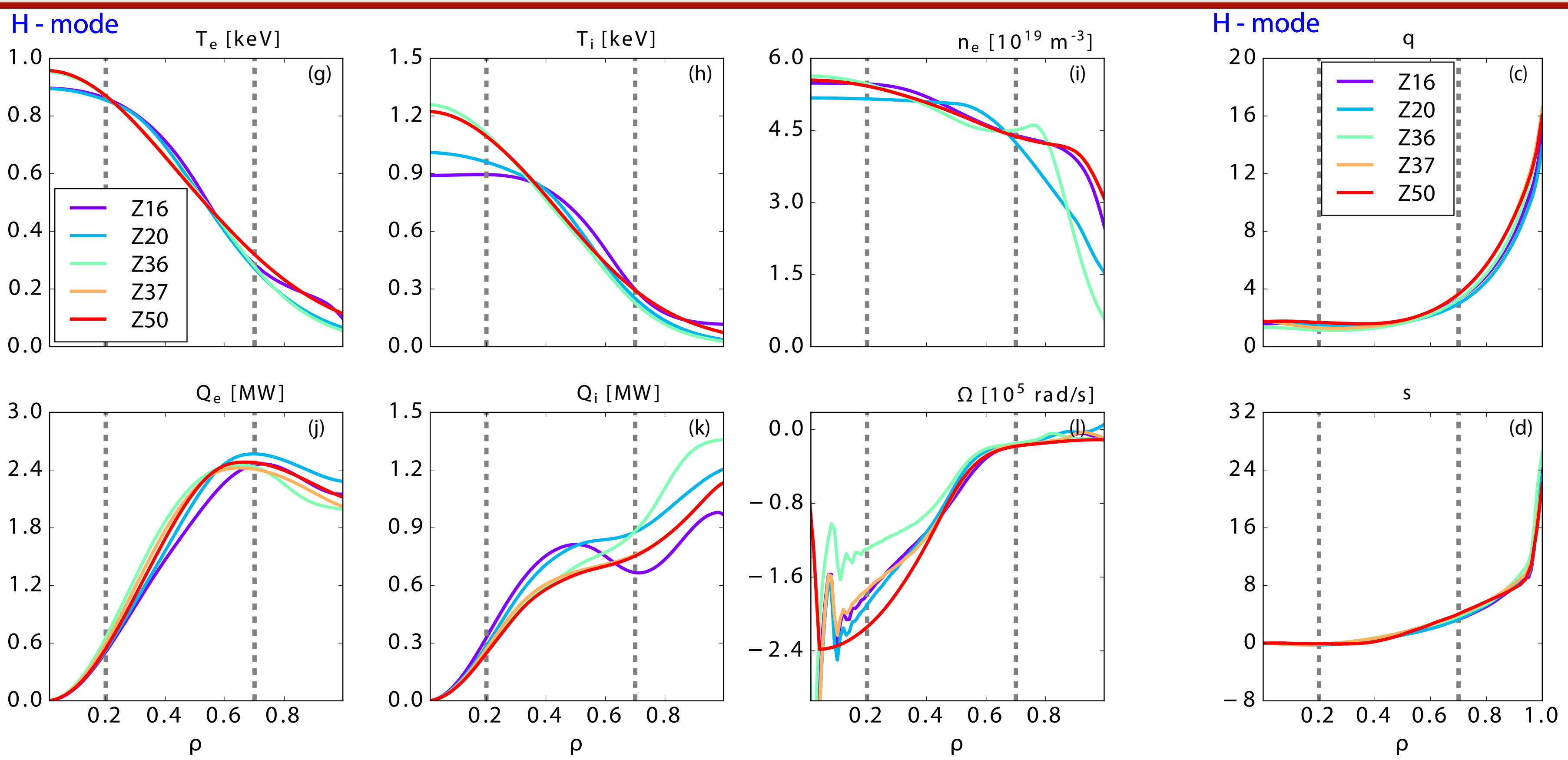
TRANSP + NUBEAM



Apply these constraints on the next iteration of the equilibrium reconstruction

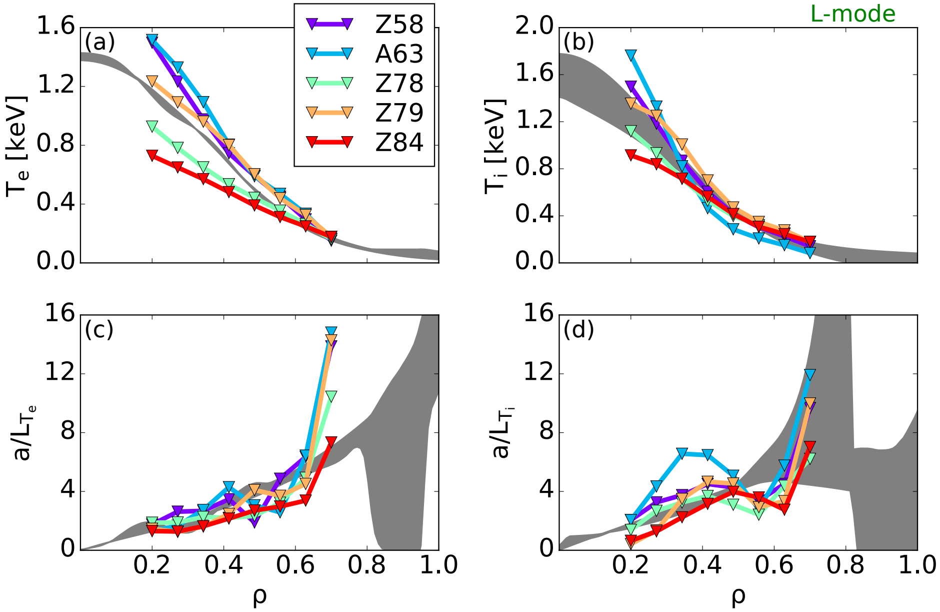
The self-consistent solution is usually obtained after 3-4 iterations

These different TRANSP runs are results of a self-consistent integrated solution

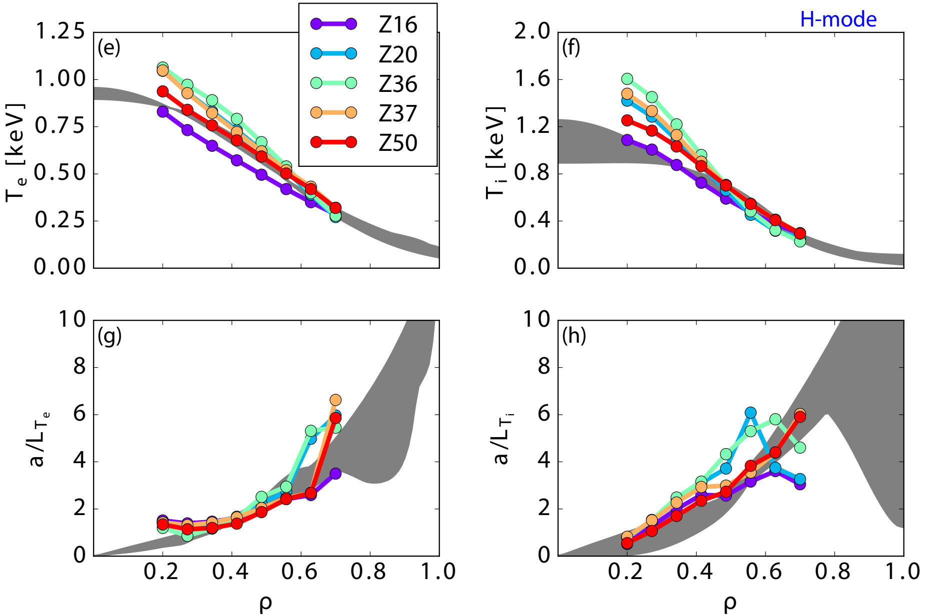


No trend of under- or over- prediction is observed

L-mode

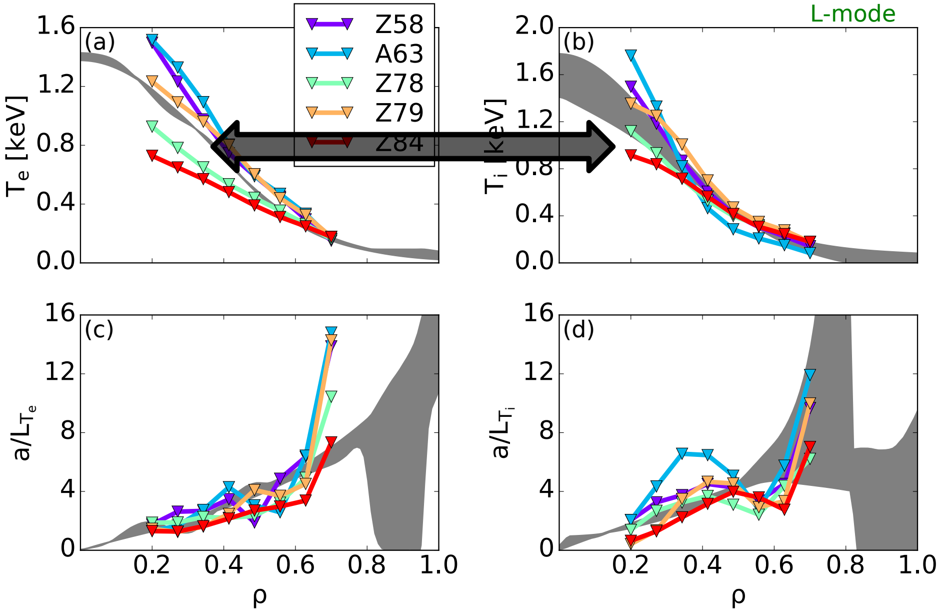


H-mode

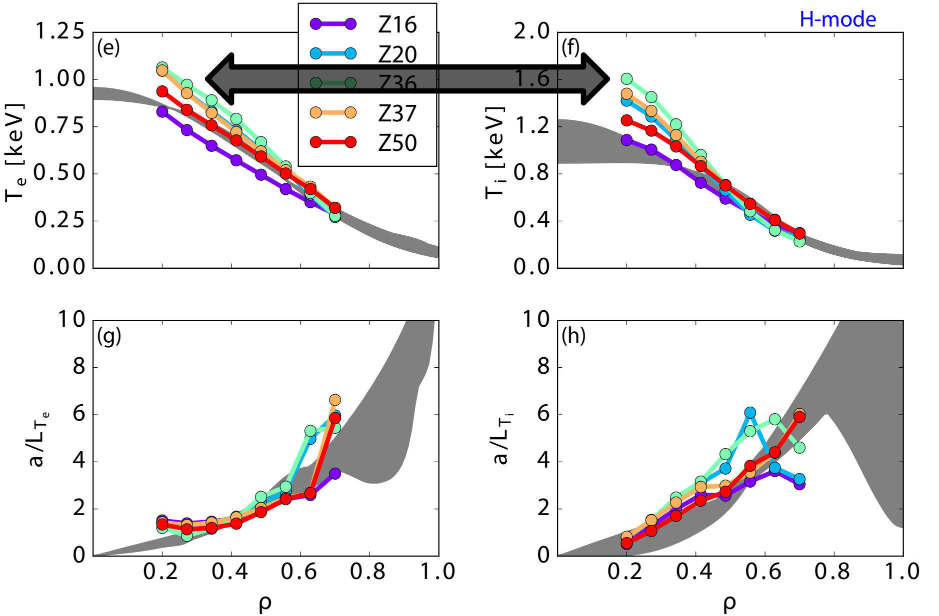


No trend of under- or over- prediction is observed

L-mode



H-mode

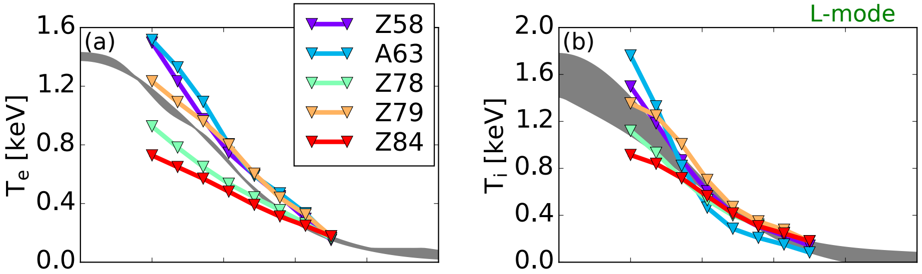


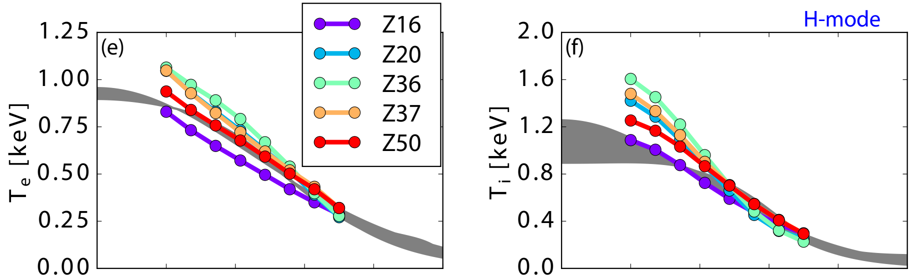
But there is a correlation in under- and over- prediction between T_e and T_i

Prediction of each temperature separately gives a more uniform set of solutions

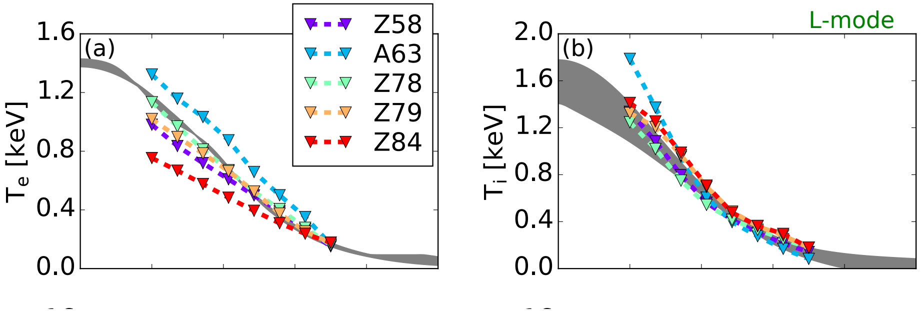
L-mode

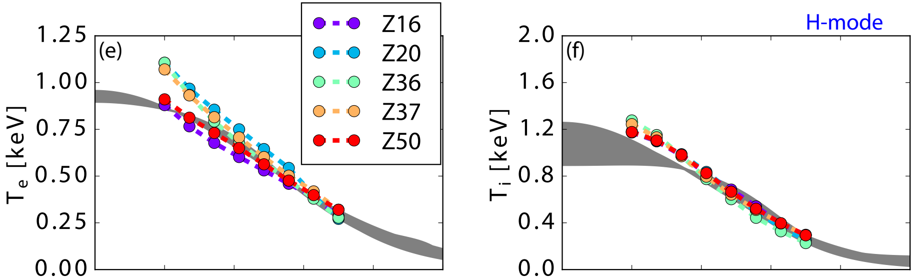
H-mode





Prediction of each temperature separately



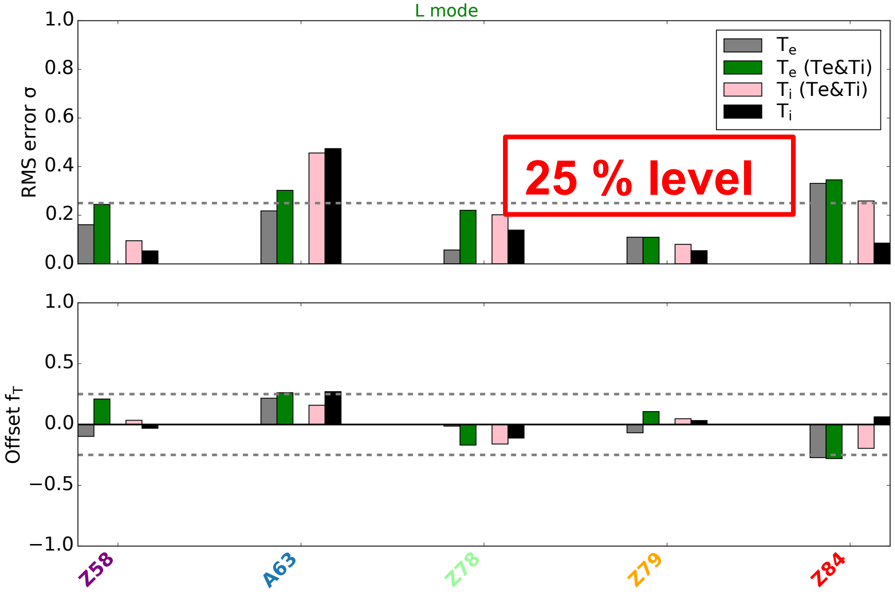


The predicted plasma profiles are consistent with experimental data on average

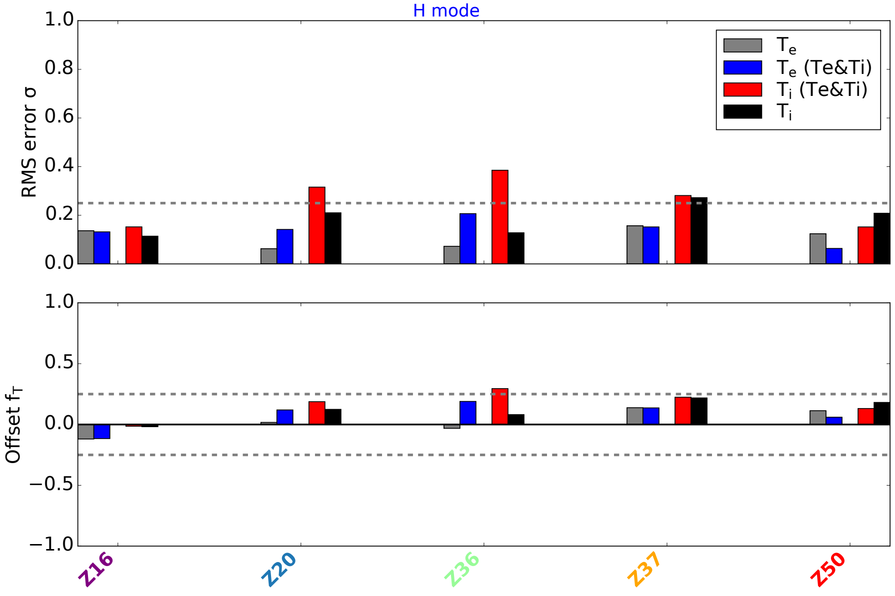
RMS error $\sigma_T = \sqrt{\frac{1}{N}\sum_j {\epsilon_j}^2} \Big/ \sqrt{\frac{1}{N}\sum_j T_{x,j}^2}$

$f_T = \frac{1}{N}\sum_{j=N}^{N} \epsilon_j \Big/ \sqrt{\frac{1}{N}\sum_j T_{x,j}^2},$ *Offset*

L-mode

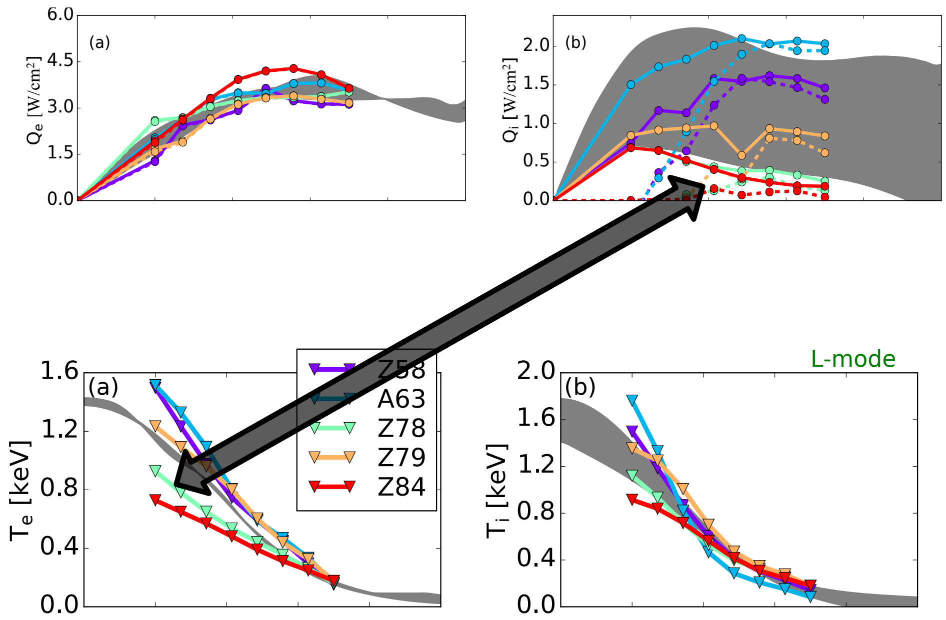


H-mode

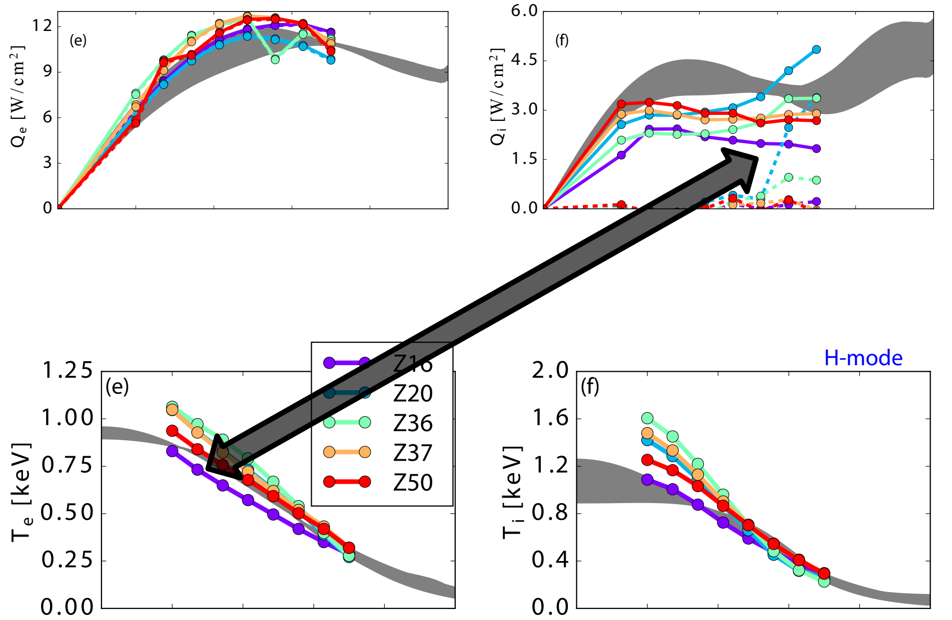


TGYRO solution is predominantly affected by the accuracy of the sources (including Q_{ei})

L-mode

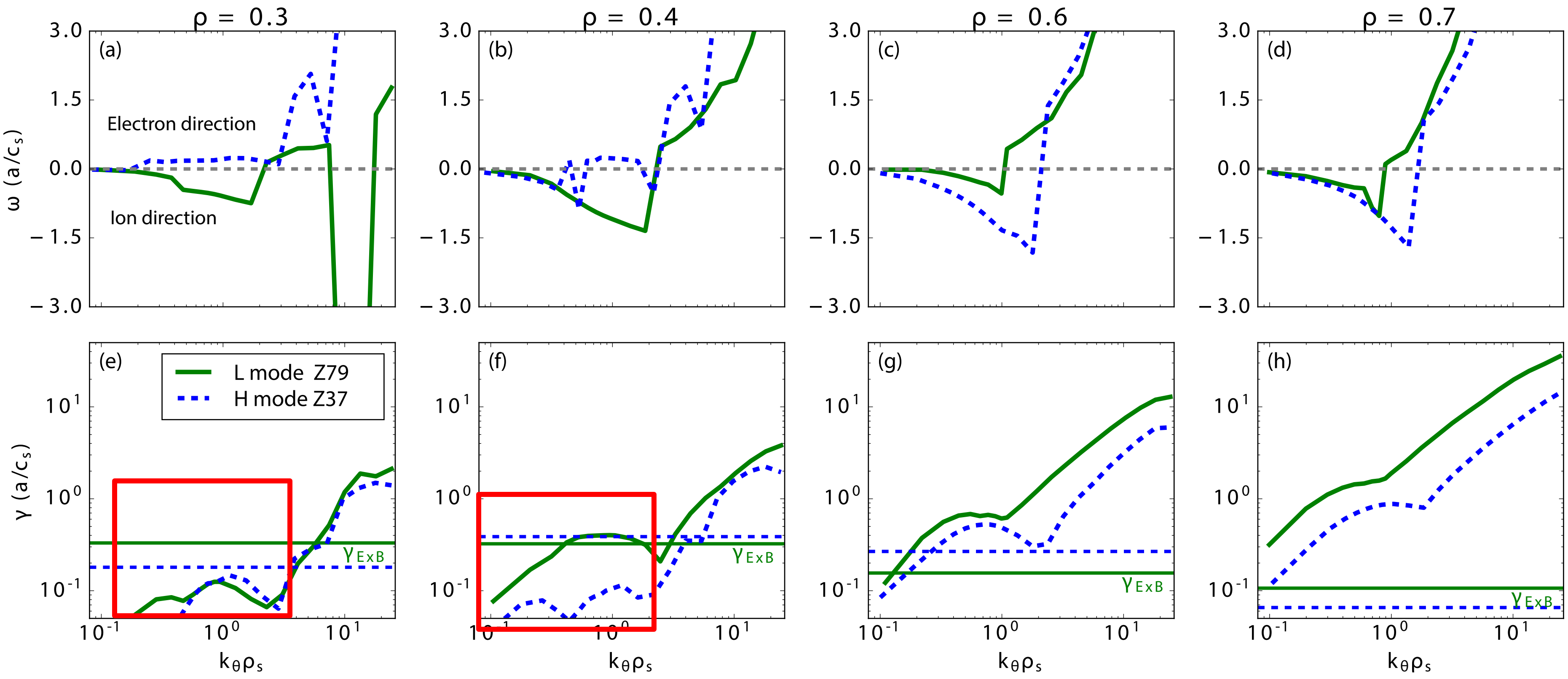


H-mode



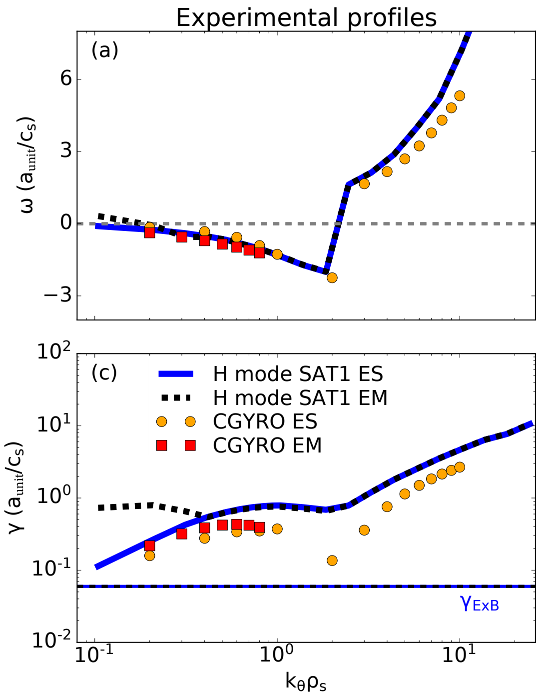
Linear stability analysis to identify unstable modes

Growth rates of low-*k* modes ($k_\theta \rho_s$<1) are below ExB shearing rate at deep core locations



Growth rates predicted by TGLF are higher than CGYRO simulations

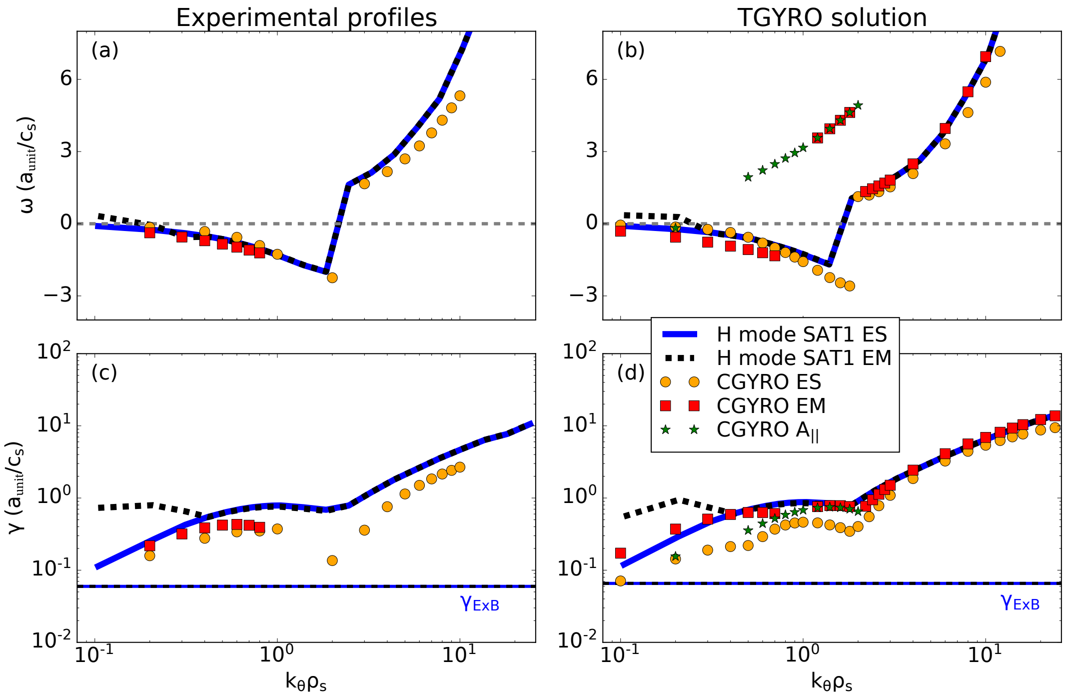
H-mode ρ = 0.7



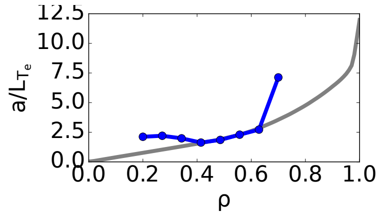
- Good agreement between real frequencies
- No electromagnetic modes are unstable in simulations with experimental profiles

Growth rates predicted by TGLF are higher than CGYRO simulations

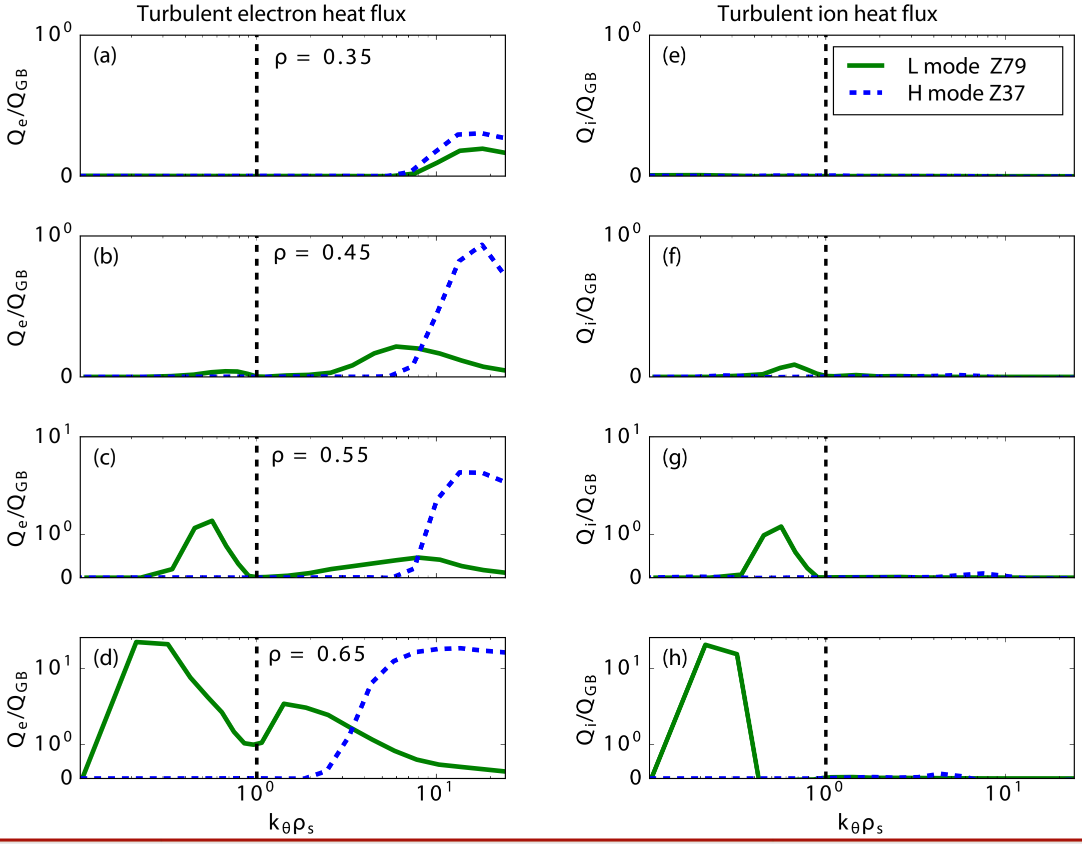
H-mode $\rho = 0.7$



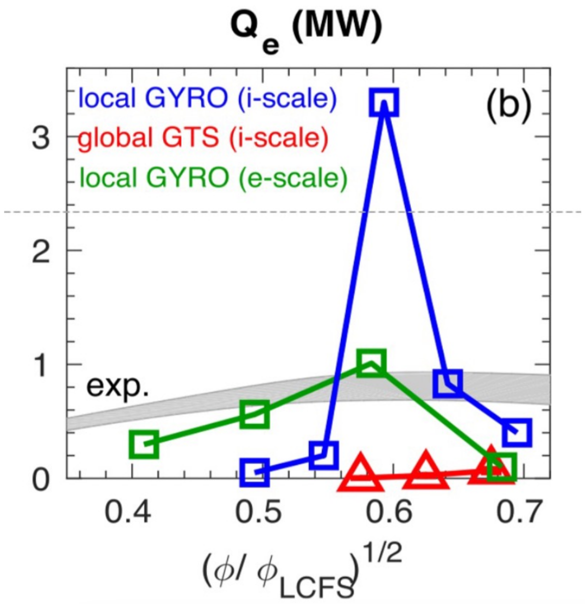
- Good agreement between real frequencies
- No electromagnetic modes are unstable in simulations with experimental profiles
- TGYRO solution profiles have higher temperature gradients, which destabilize electromagnetic instabilities



The contribution of low-k and high-k modes into the total turbulent flux is consistent with previous results

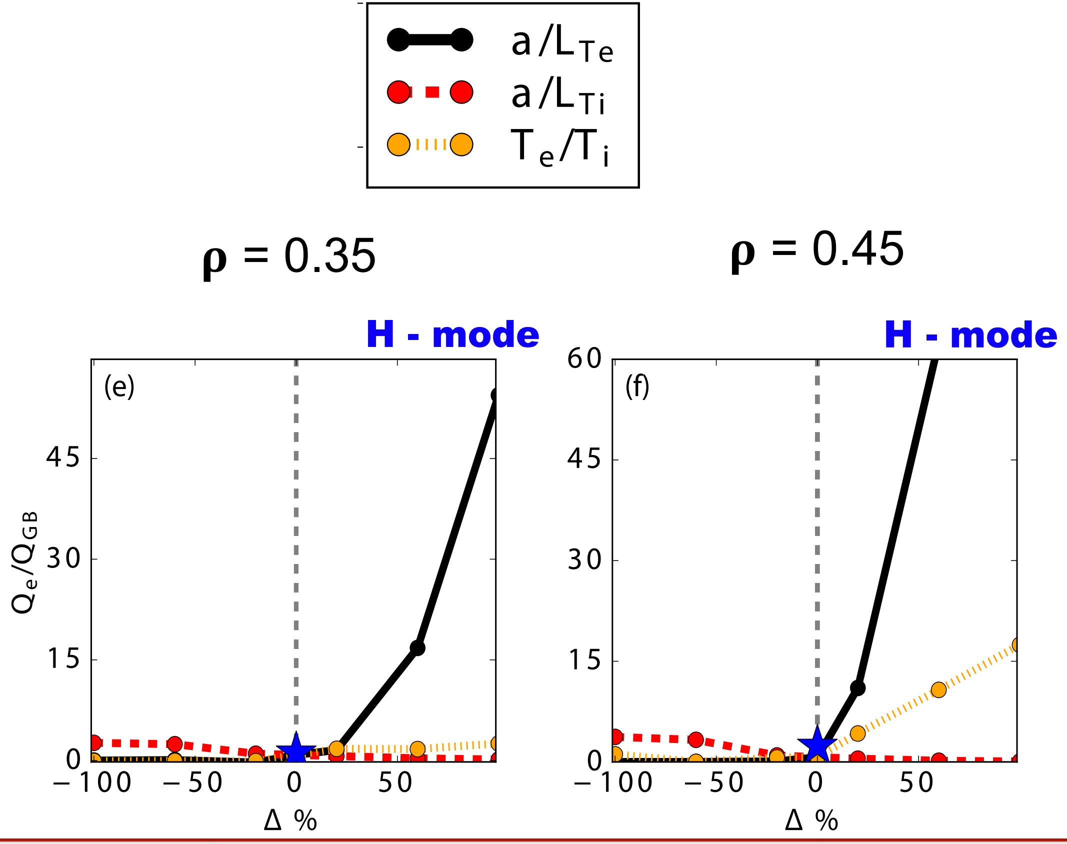


L-mode



- S.M. Kaye et al., Nucl. Fusion 59 (2019)
- Y. Ren et al., Nucl. Fusion, 53 (2013)

Scans of plasma parameters demonstrates how close the plasma conditions to the stability threshold



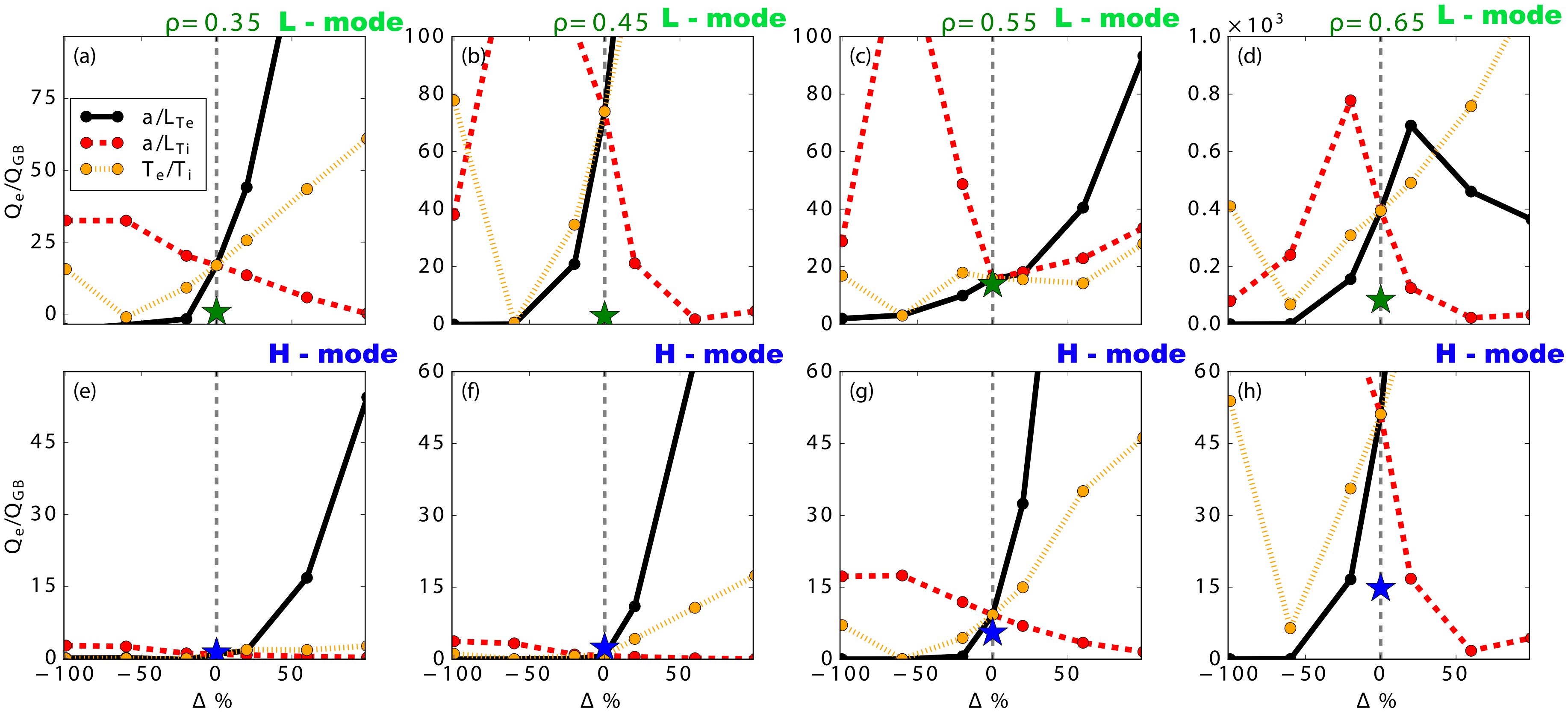
ρ = 0.35

- Plasma conditions are below the critical threshold
- Instabilities driven by a/L_{Te} are destabilized only at gradients above 25% of experimental level

ρ = 0.45

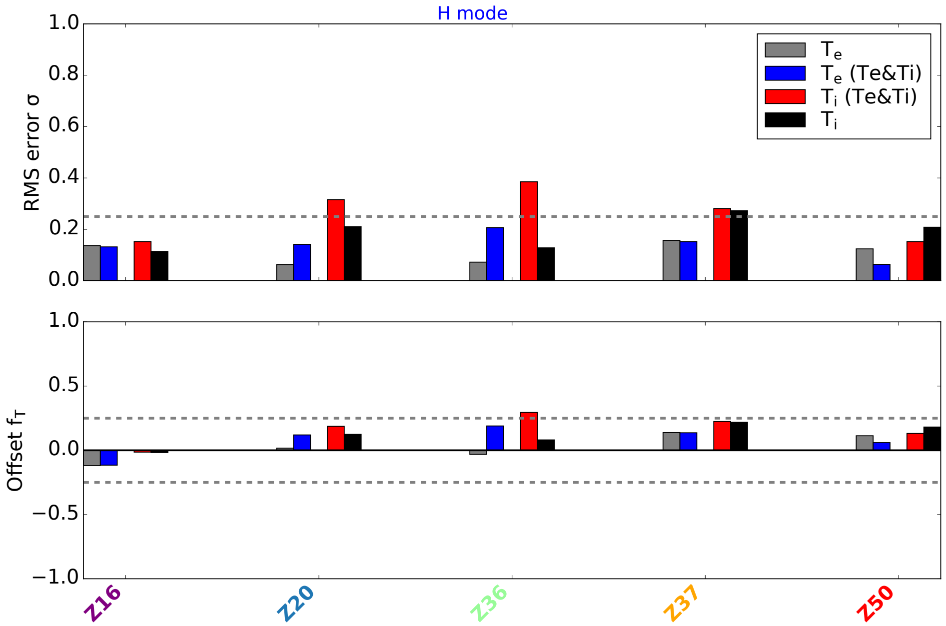
- A flux dependency from a/L_{Te} and T_e/T_i indicates unstable modes

Overall the scans demonstrate the complicated dependency of turbulent flux on the plasma parameters



Summary of results

- Overall, the predicted plasma profiles are consistent with experimental data on average
- The shortcomings of the TGYRO simulations are amplified when both temperature profiles are modeled instead of a single temperature profile
- A presence of multi-scale turbulence and ion-scale driven zonal flow mixing effects are observed



Paths toward reliable predictive modeling of STs with TGLF should include

- More accurate power balance analyses, which determines the target fluxes of the flux-matching solution

- More systematic calibrations of the saturation model on non-linear gyrokinetic simulations to verify the applicability of the saturation rule models for STs plasmas

- Models with comprehensive physics of electromagnetic instabilities would be required for a high plasma- β with increased influence of electromagnetic effects