Statistical validation of predictive TRANSP simulations of JET baseline discharges

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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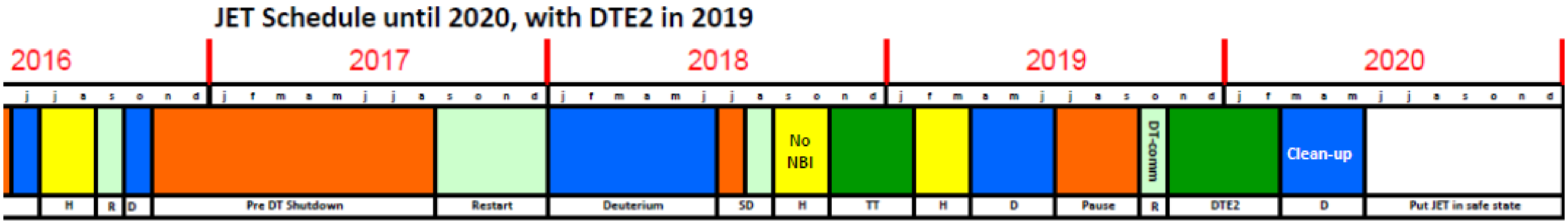
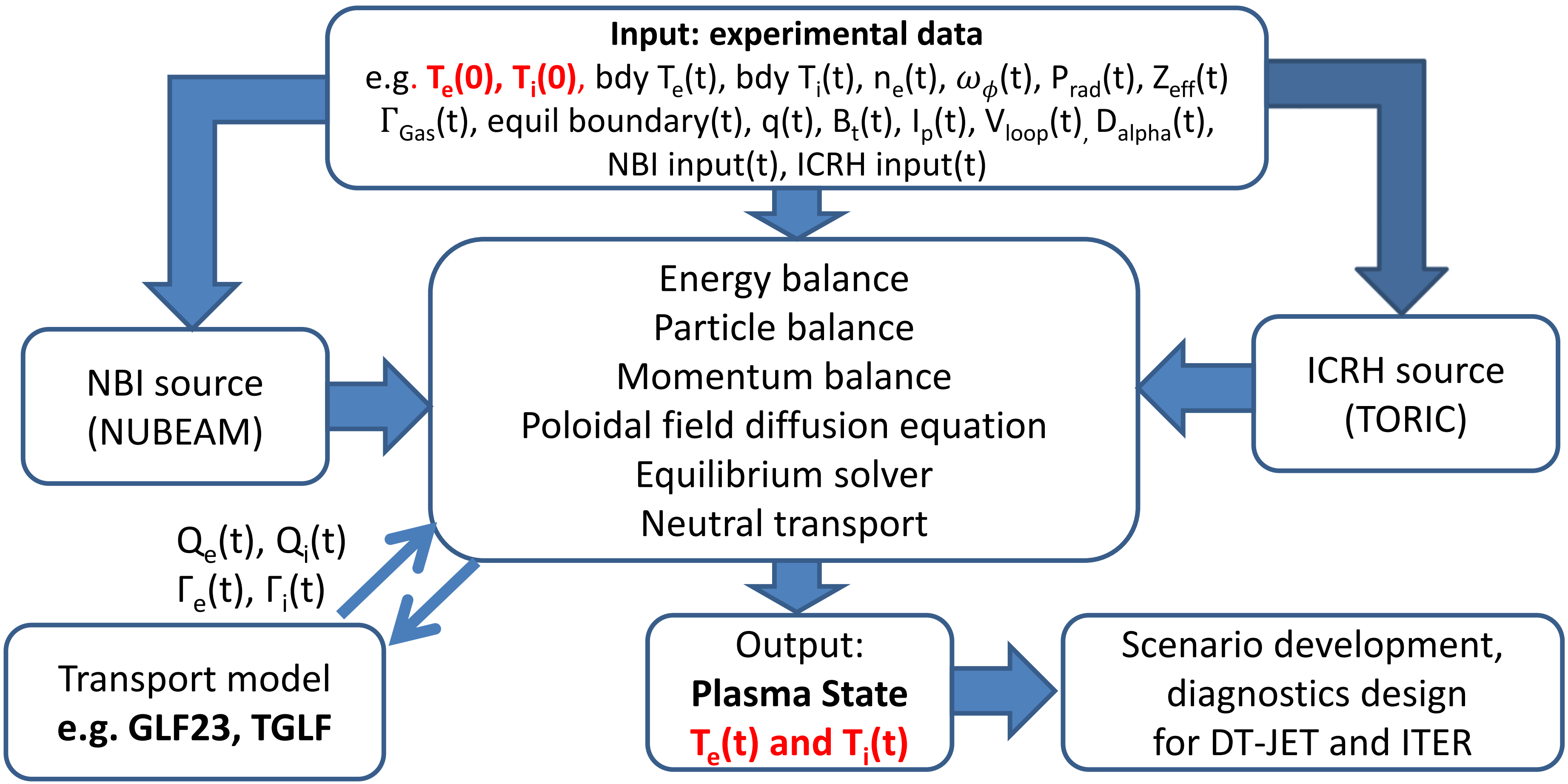
Background



- D-T campaigns in 2019 on JET with ILW have scientific objectives, which require JET operation of 10-15MW fusion power for at least 5 seconds.
- Reliable predictive simulations are needed as it is unprecedented operational scenario.
- The current capability to predict plasma temperature evolution and the resultant fusion power is still limited, due to the incompleteness of turbulent transport models and the uncertainties of input data.
- In addition, D-T mixture might add further uncertainty.
- In order to predict future discharges, it is necessary to quantify the impact of the foreseen uncertainties on reproducing the present discharges and to assess the current prediction capability.

→ Statistical validation over a large number of discharges.

Predictive TRANSP simulation



Uncertainties of the predicted $T_e(t)$ and $T_i(t)$ arise mainly due to the transport model and/or input data!

Database

The database consist of 80 baseline H-mode discharges with ILW which are

- 46 discharges from ITPA database low q95(=2.7 ~ 3.3) experiments for 2012-2014, selected by G. Sips
  - Stationary state for 5 confinement times (τ_E) in baseline H-mode (i.e. β_N>0.85 $\beta_{N,max}$)
  - high n_e and rotation profile available
  - I_p (=2~3.5MA), B_t(=1.9~3.2T), P_{heat}(=10.8~27.7MW), T_{e0}(=2.2~6keV), $\langle n_e \rangle$(=4~10.2m^{-3}), β_N(=1~2)
- 22 discharges from the database for dimensionless parameter scanning, provided by L. Frassenstti.
  - nu_e^*=0.04 – 0.15 at (rho=0.4), rho*=0.003~0.005
- 10 discharges from the database for comparative confinement study (Hyun-Tae Kim et al PPCF, 57 2015 065502)
  - I_p (=2.5MA), B_t(=2.7T), P_{heat}(=14~17MW), $\langle n_e \rangle$(=7.1~10.2m^{-3})
- 2 discharges from T15-01 i.e. 87215 and 87412

Input and assumption

The following input and the assumptions (i.e. reference setting) are used for all predicted simulations

- Core T_e and T_i predicted for rho=0 ~ 0.9
- Pedestal T_e prescribed by HRTS at rho=0.9
- Pedestal T_i = T_e
- Whole profile of n_e prescribed by HRTS
- Turbulent transport is computed by GLF23
- Neoclassical transport is computed by NCLASS
- Uniform radiation profile prescribed by BOLO/TOBU
- Uniform Zeff profile prescribed by KS3/ZEFV assuming Be is the only impurity.
- Rotation profile prescribed by CX
- Heating and particle source terms calculated consistently by NUBEAM and TORIC

Input and assumption

The following input and the assumptions (i.e. reference setting) are used for all predicted simulations

- Core T_e and T_i predicted for rho=0 ~ 0.9
- Pedestal T_e prescribed by HRTS at rho=0.9 → **rho=0.8**
- Pedestal T_i = T_e
- Whole profile of n_e prescribed by HRTS
- Turbulent transport is computed by GLF23 → **TGLF-SAT0** → **TGLF-SAT1**
- Neoclassical transport is computed by NCLASS
- Uniform radiation profile prescribed by BOLO/TOBU → **Radiation profile**
- Uniform Zeff profile prescribed by KS3/ZEFV assuming Be is the only impurity.
- Rotation profile prescribed by CX → **Predicted rotation**
- Heating and particle source terms calculated consistently by NUBEAM and TORIC

The impact of the input and the assumptions on predicting Te and Ti profiles is investigated by modifying one input or assumption in the reference setting.

Turbulent transport models in TRANSP

- Gyrokinetic simulations of turbulent transport is extremely expensive to routinely perform simulations for a large radial window (i.e. rho=0~ pedestal top) with consistent source calculations.
- **Gyro-Landau Fluid (GLF)** eqns are **velocity moment** eqns of the **gyro**-averaged kinetic eqns that are closed retaining **Landau** damping and FLR effects.
- **GLF23** is the original **simple (but fast)** GLF model to model gyrokinetic drift-wave instabilities (i.e. TEM, ETG, ITG, and KBM) and ExB velocity shear stabilisation.
    - For low-k modes, 4 eqns for passing ions (no trapped ions), 2 eqns for passing electrons, 2 eqns for trapped electrons
    - For high-k modes, 4 eqns of passing electrons assuming ions are adiabatic.
    - 4 moments equations with 2 species + 1 poloidal basis function → 8x8 matrix eigenvalue problem
    - Shifted circular geometry
- **'Trapped' GLF (TGLF)** is **more complete (but slow)** GLF model with better accuracy than GLF23.
    - Unification of trapped and passing particles in a single set of GLF equations, and this enables the equations working for the whole range of drift-wave wave number i.e. low-k ITG ~ high-k ETG
    - 15 moments (12 for passing ptls and 3 for trapped ptls) with 2 species + 4 poloidal basis functions → 120x120 matrix eigenvalue problem!
    - Shaped Miller geometry
- **Trapped particles are modelled in a more complete way in TGLF than GLF23**

G. M. Staebler, Phys. Plasmas 14 055909 2007

Turbulent energy and particle fluxes from GLF23/TGLF

- Linear eigenmodes for gyrokinetic drift-wave instabilities (i.e. TEM, ETG, ITG, and KBM) is found by solving GLF equations.
- Turbulent energy and particle fluxes are computed by a quasilinear saturation rule.
- Intensity of the saturated turbulence level is determined by adjusting C1, C2, C3, and C_{norm} to match the energy flux from nonlinear gyrokinetic/GLF turbulence simulations.

J.E. Kinsey et al, Phys. Plasmas 15, 055905 2008

$$Q = \frac{3}{2}\sum_{\hat{k}_y} p c_s \left(\frac{\mathrm{Re}[i\hat{k}_y \tilde{\Phi}^* \tilde{p}_T]}{\sum_a \tilde{V}_a^* \tilde{V}_a}\right)\bar{V}^2$$

$$\Gamma = \sum_{\hat{k}_y} n c_s \left(\frac{\mathrm{Re}[i\hat{k}_y \tilde{\Phi}^* \tilde{n}]}{\sum_a \tilde{V}_a^* \tilde{V}_a}\right)\bar{V}^2$$

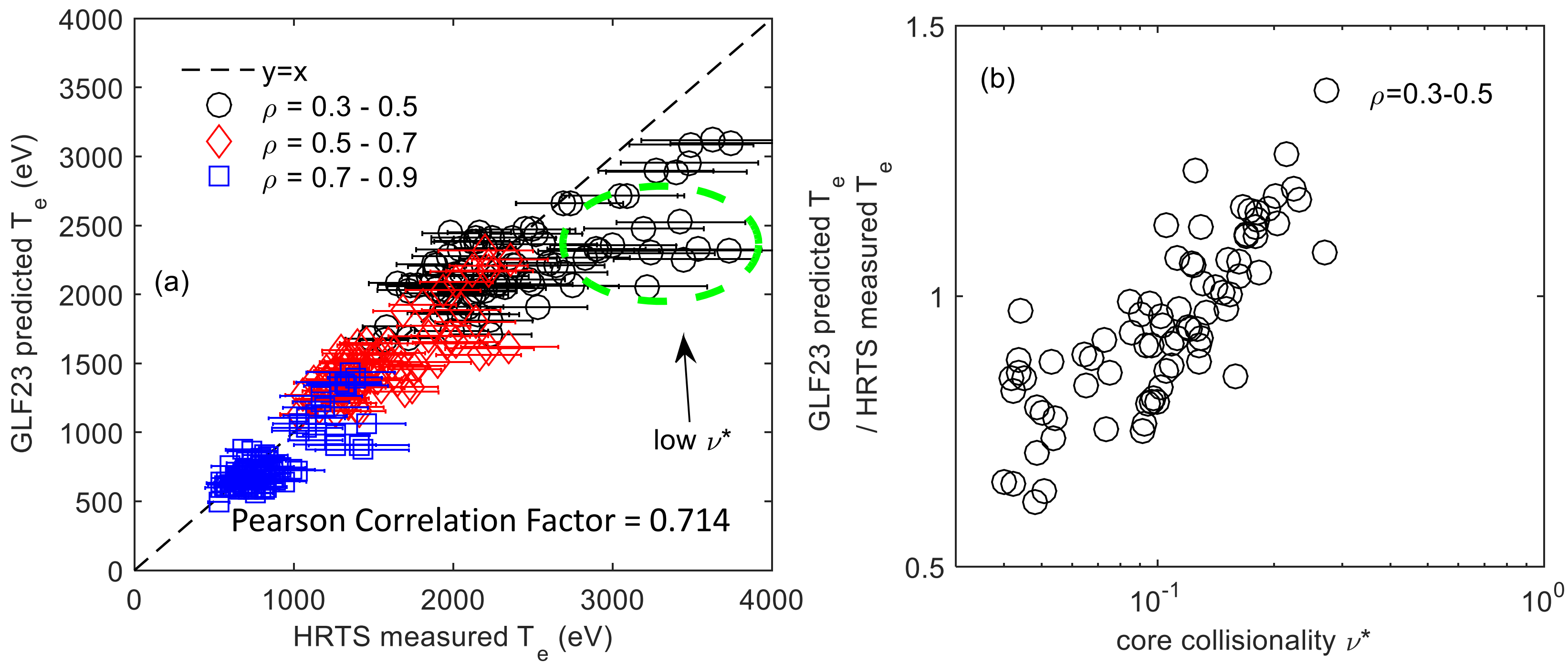
where

$$\tilde{\Phi} \equiv \frac{e\tilde{\phi}}{T_e}$$

$\tilde{V}_a \equiv$ total eigenvector of the GLF moment equations

$$\bar{V}^2 = C_{norm}\left(\frac{\rho_s \hat{\omega}_{d0}}{a\hat{k}_y}\right)^2 \left(1+\frac{T_e}{T_i}\right)^2 \left(\bar{\gamma}_{net}^{C1} + C2\bar{\gamma}_{net}\right)\frac{1}{\hat{k}_y^{C3}} \quad \text{where } \bar{\gamma}_{net} = Max\left(\frac{\hat{\gamma}-\alpha_E \hat{\gamma}_{ExB}}{\hat{\omega}_{d0}}, 0\right)$$

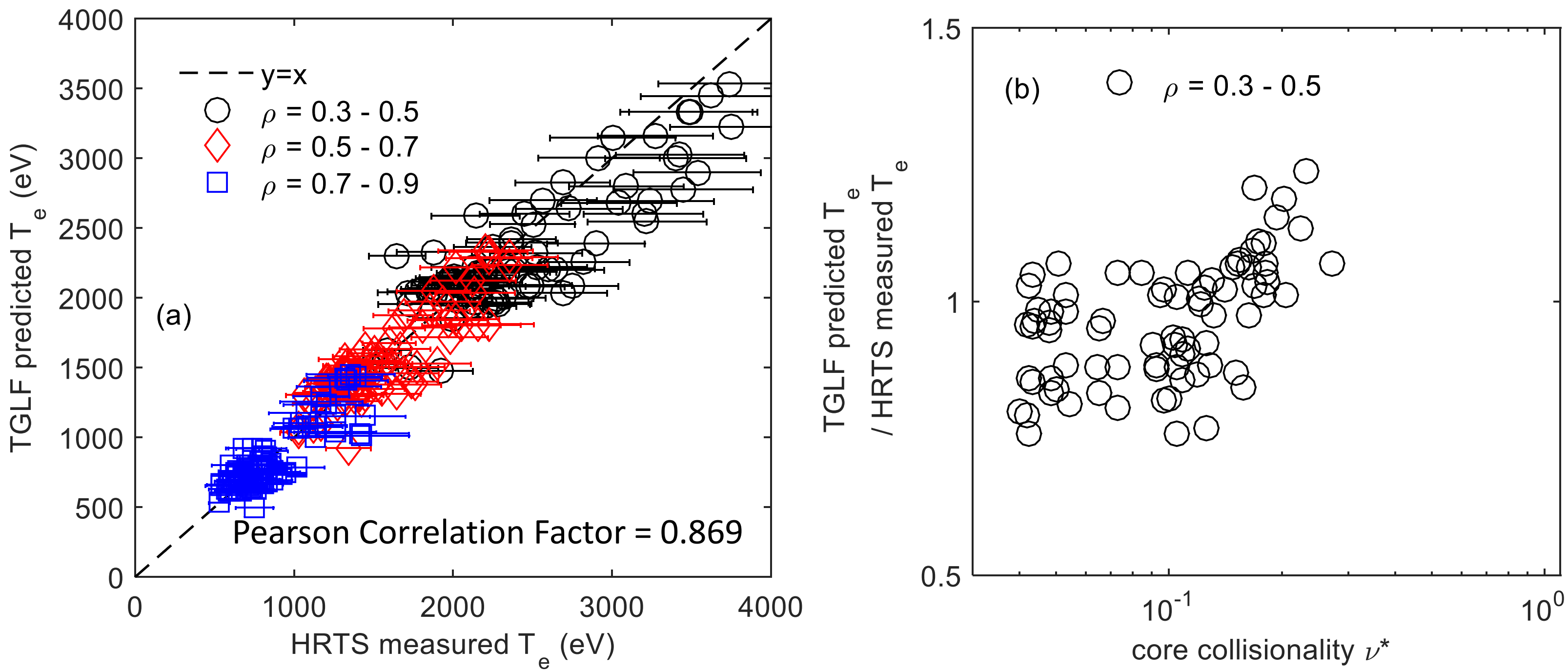
T_e prediction with GLF23



- T_e reproducibility is subject to the ν^* regime i.e. under-prediction at low ν^* and over-prediction at high ν^*
- This implies that turbulent electron energy fluxes are over-calculated at low ν^* and under-calculated at high ν^*. This is probably due to the over-simplified trapped electron model in GLF23.

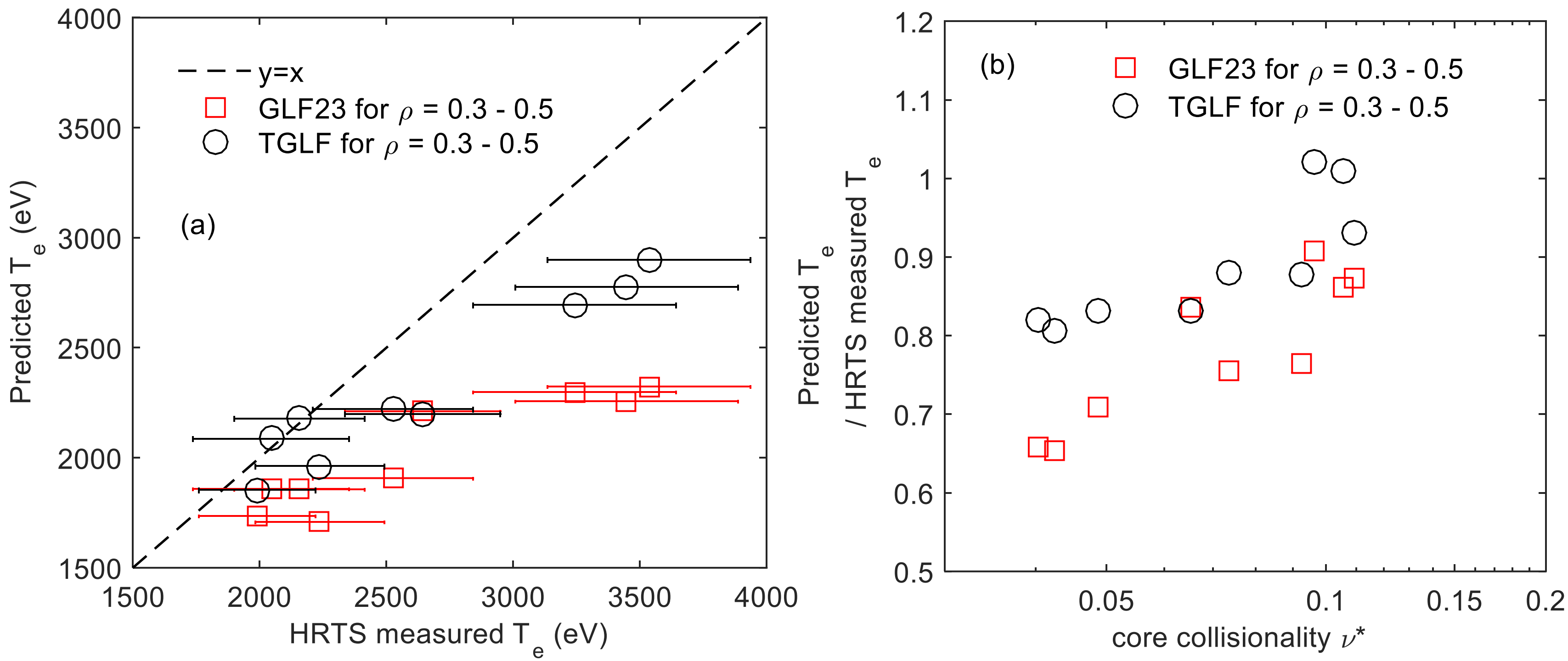
$$\nu_e^* \equiv \frac{\nu_e}{\text{freq of the bounce orbit}} = \frac{\nu_e R q}{(R/q)^{3/2}(kT_e/m_e)^{0.5}} \quad \text{where } \nu_e = \frac{2.91e-12 \times n_e \ln\Lambda}{T_e^{3/2}[eV]}$$

T_e prediction with TGLF



- No T_e under-predictions at low ν^* is observed in TGLF results.
- Note, one of the main improvements in TGLF compared to GLF23 is to model trapped particles in a more complete way i.e. two moment equations for trapped particles in GLF23 , but six moment equations in TGLF.

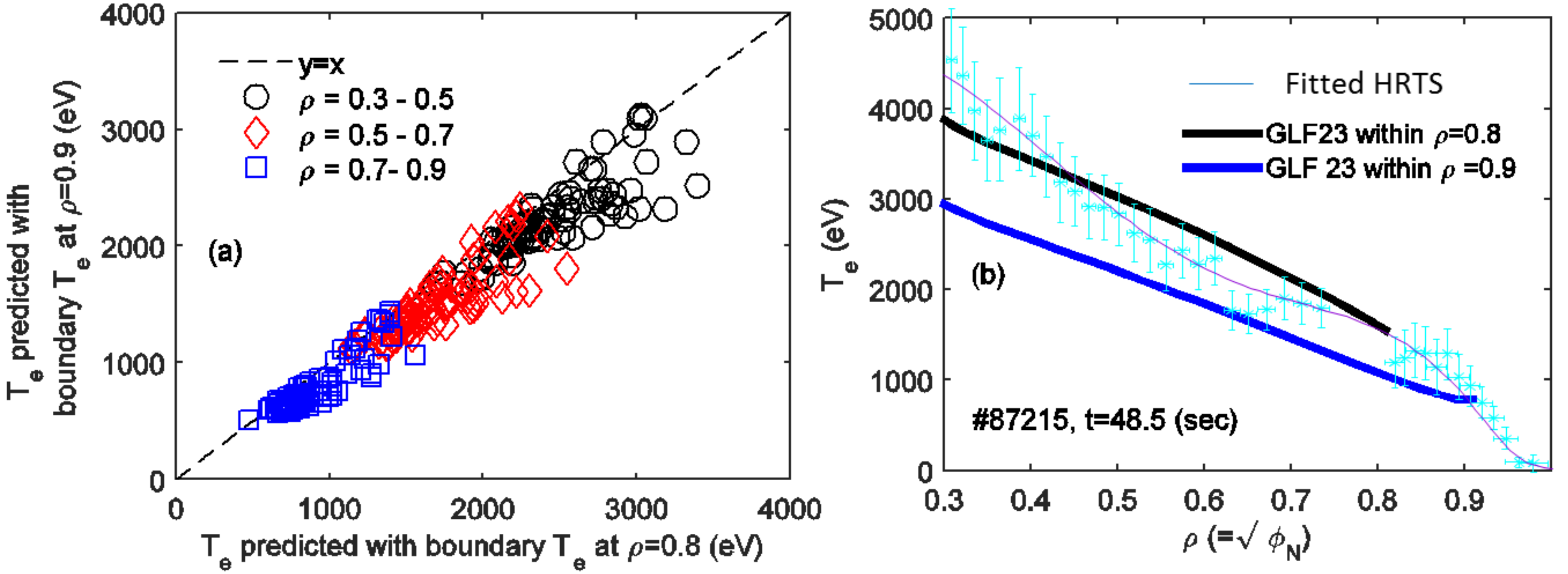
T_e predictions in ν^* scan database



- Under-prediction of T_e at low ν^* is more clearly seen in ν^* scan discharges where other dimensionless parameters are maintained, and it is clearly less significant in TGLF runs.

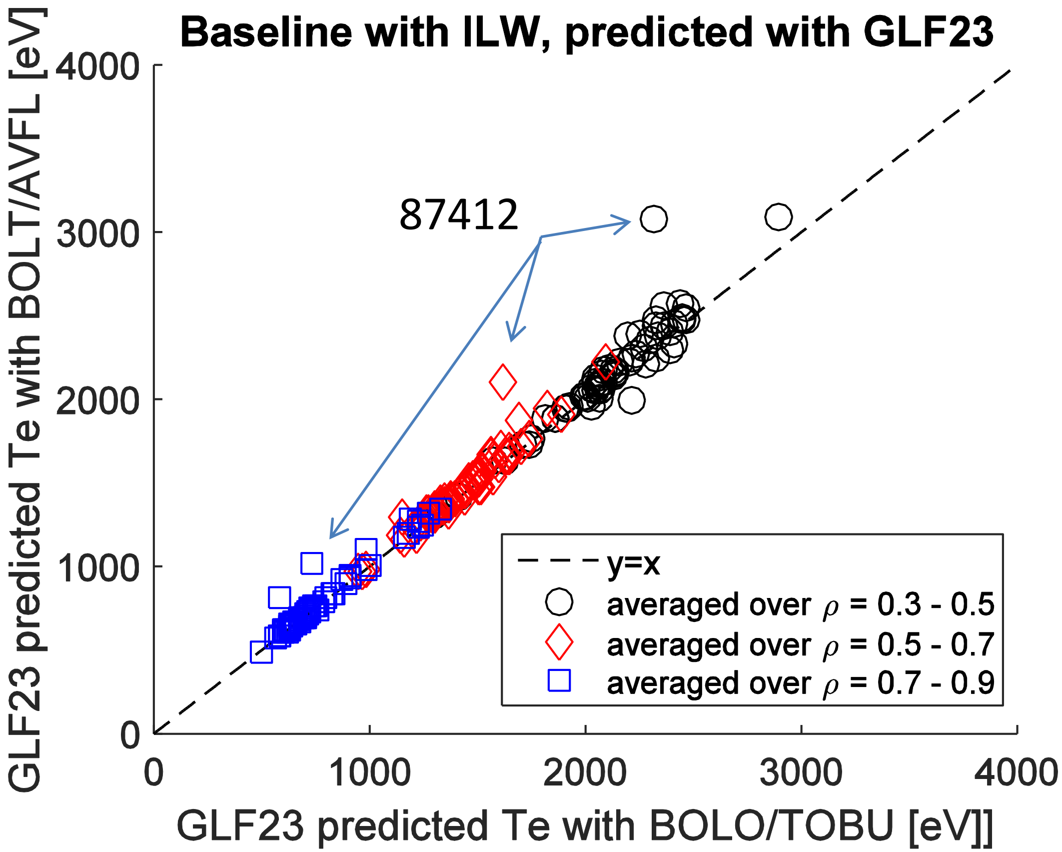
ν^* scan discharges are from L. Frassinetti et al EPS 2015

Impact of the boundary position of T_e on predictions with GLF23 or TGLF



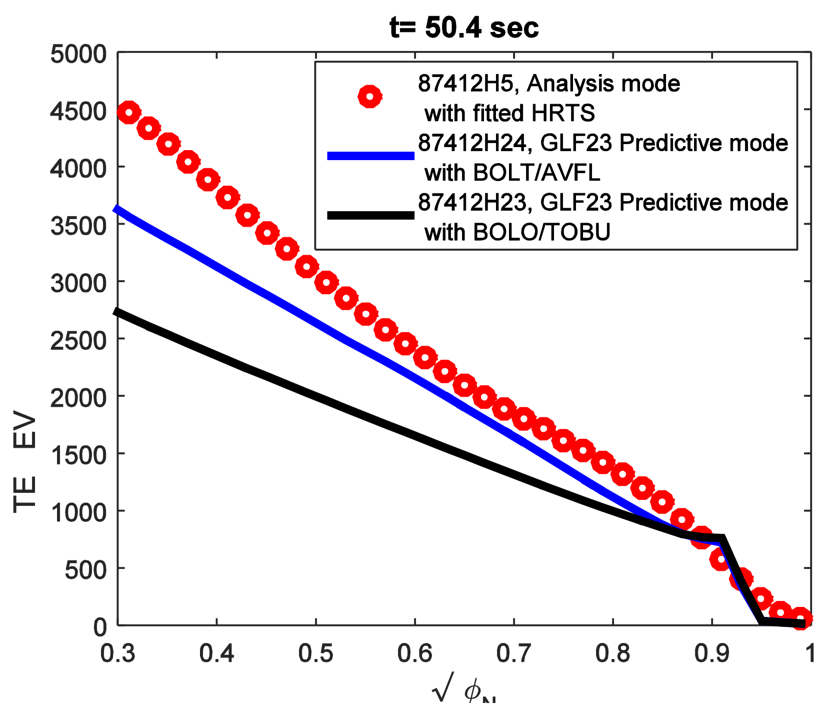
- Neither GLF23 nor TGLF can model the transport in the ETB region.
- If the radial position of boundary T_e is not inner enough to exclude the Edge Transport Barrier (ETB) region, the pedestal T_e is underestimated, thereby decreasing the predicted core T_e.
- However, the normalized gradient is not modified.

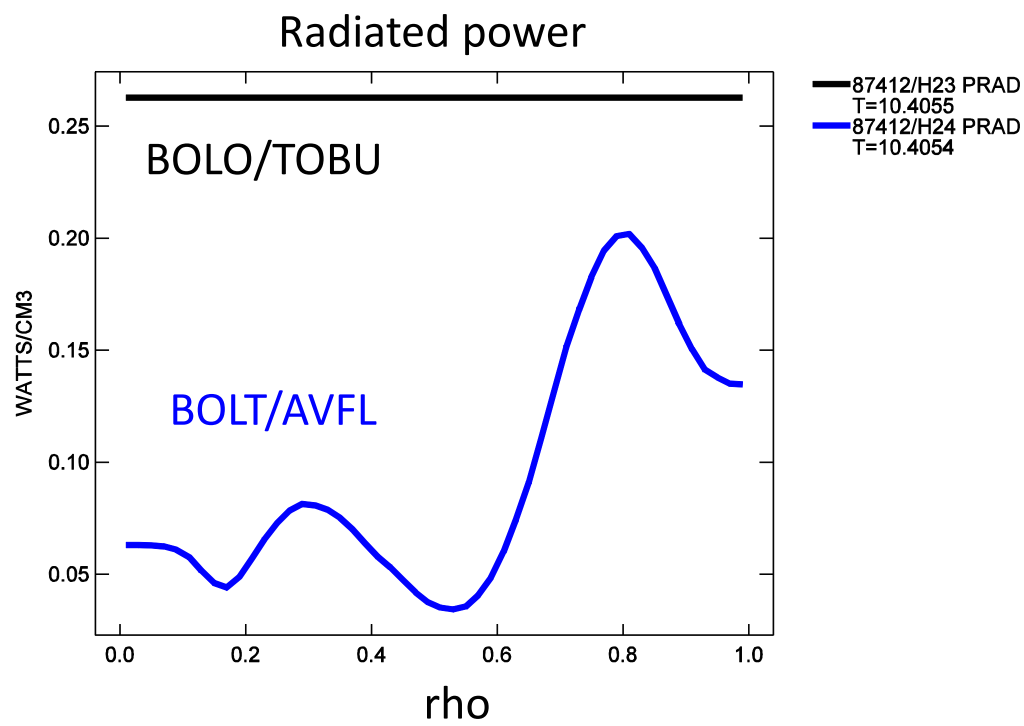
Impact of radiation input data i.e. BOLT/AVFL and BOLO/TOBU



- BOLO/TOBU from Chain 1 is good enough for T_e prediction with GLF23, except 87412 which has unusual BOLO/TOBU data. (See next slide)

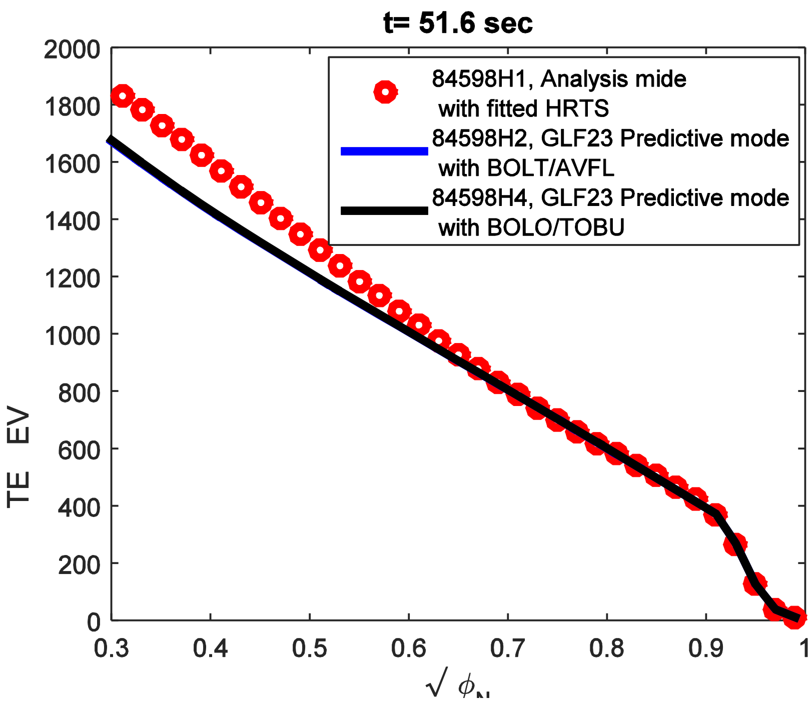
Impact of radiation input data i.e. BOLT/AVFL and BOLO/TOBU

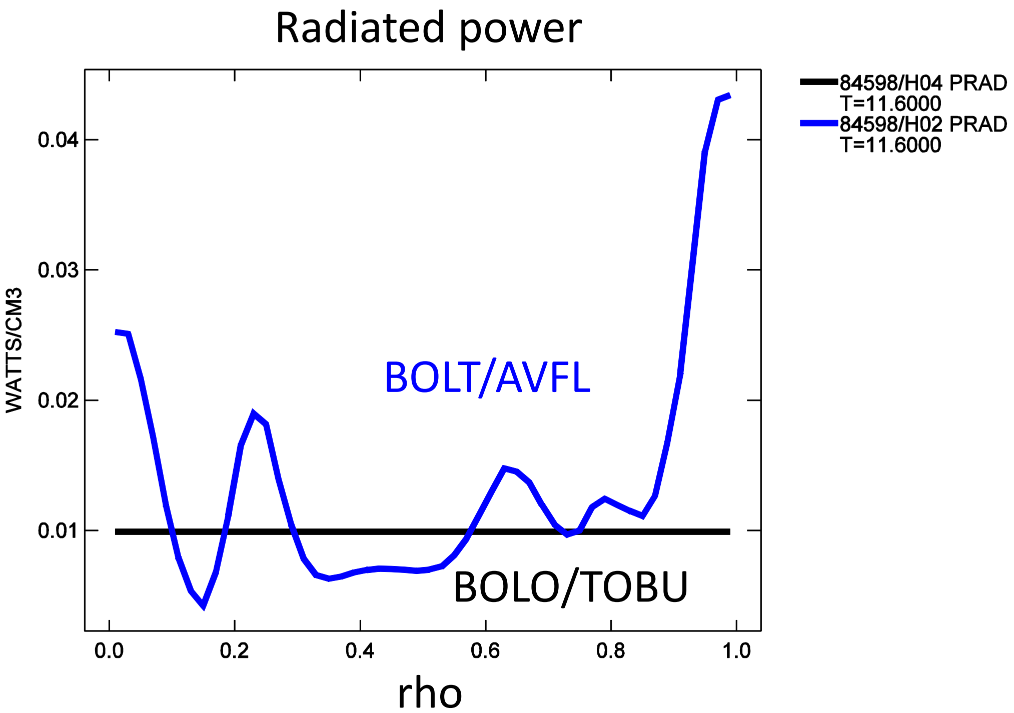




- The under-predicted Te is due to the fact that the BOLO/TOBU in 87412 is over-calculated. Note, this is just one discharge among 80 discharges!

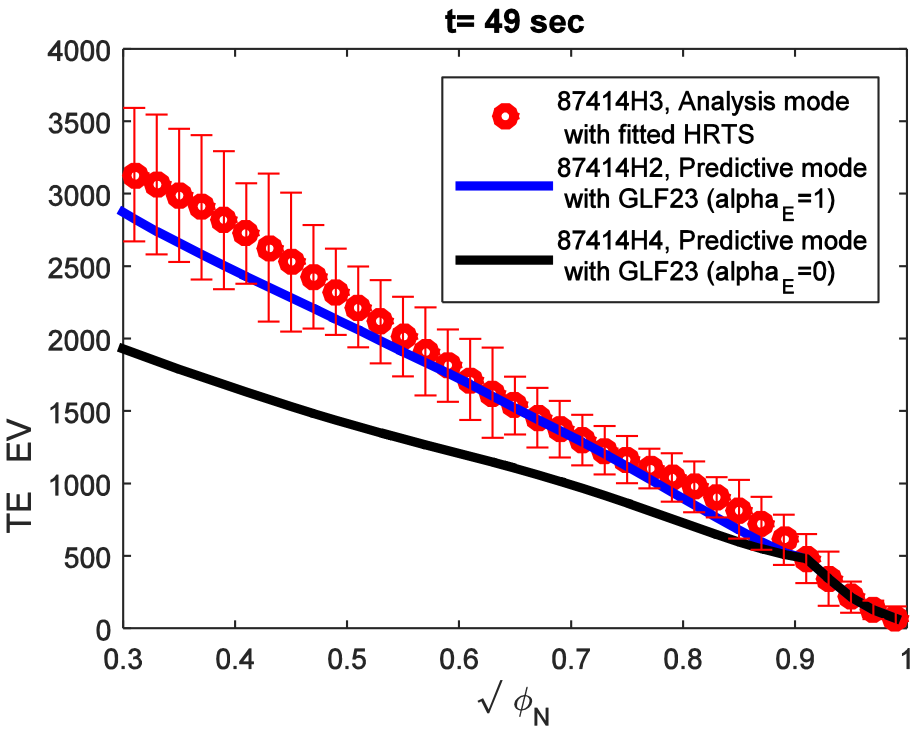
Impact of radiation input data i.e. BOLT/AVFL and BOLO/TOBU





- No visible difference is observed in Te prediction with 'usual' BOLO/TOBU.

ExB flow shear stabilisation model in GLF23



$\gamma_{net} = \gamma_{\max} - \alpha_E \gamma_{ExB}$

where

$\gamma_{\max}$ = maximum growth rate of the drift-wave instabilities in the absence of rotation shear,

α_E = ExB shear stabilisation factor,

γ_{ExB} = ExB shearing rate $= \dfrac{r}{q}\dfrac{d(qV_{ExB}/r)}{dr}$

where V_{ExB} is poloidal ExB flow velocity $= \dfrac{E_r}{B_t}$.

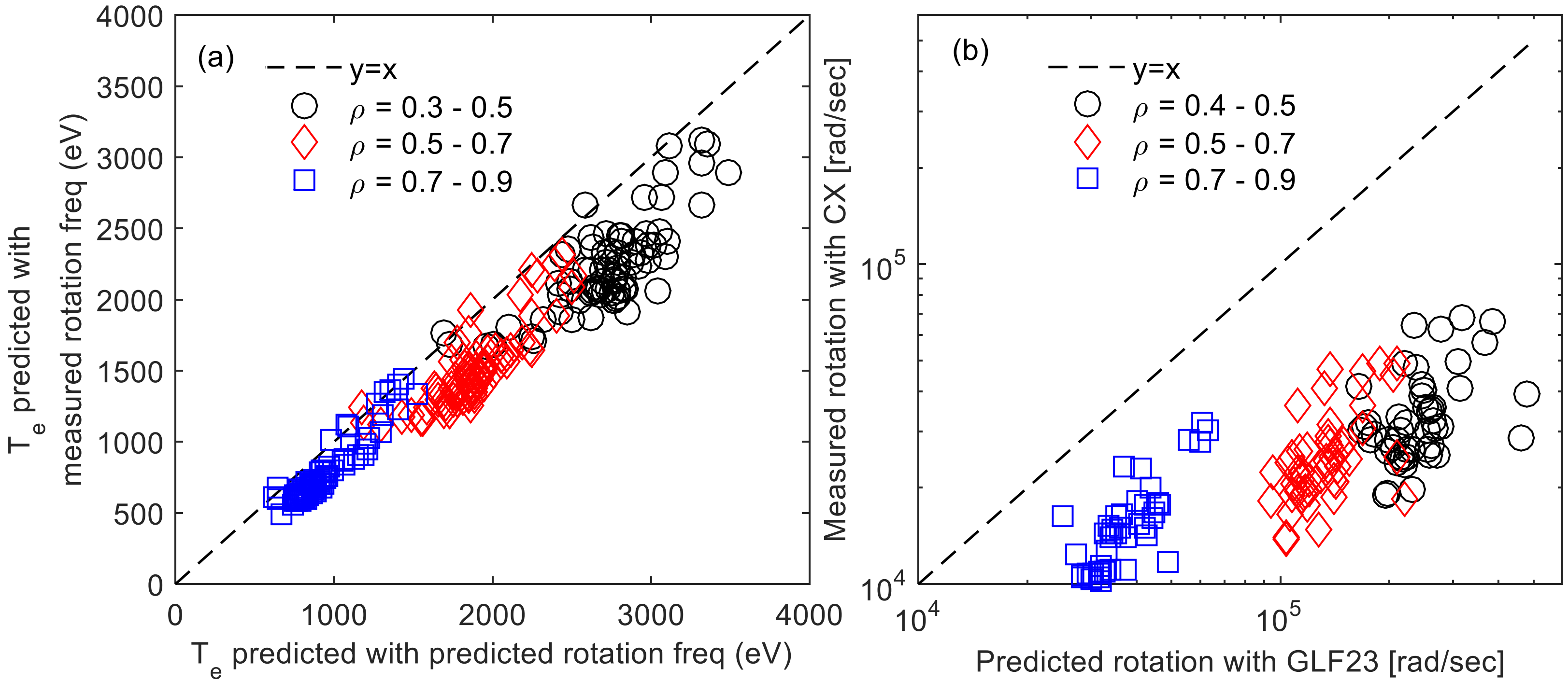
E_r is calculated by assuming that the force due to E_r is balanced with Lorenz force i.e. $eE_r = eV_t B_p$ where V_t is toroidal rotation velocity.

- The ExB stabilisation model is a function of the toroidal rotation input.

i.e. low rotation → larger γ_{net} → larger heat transport → decrease in predicted T_e

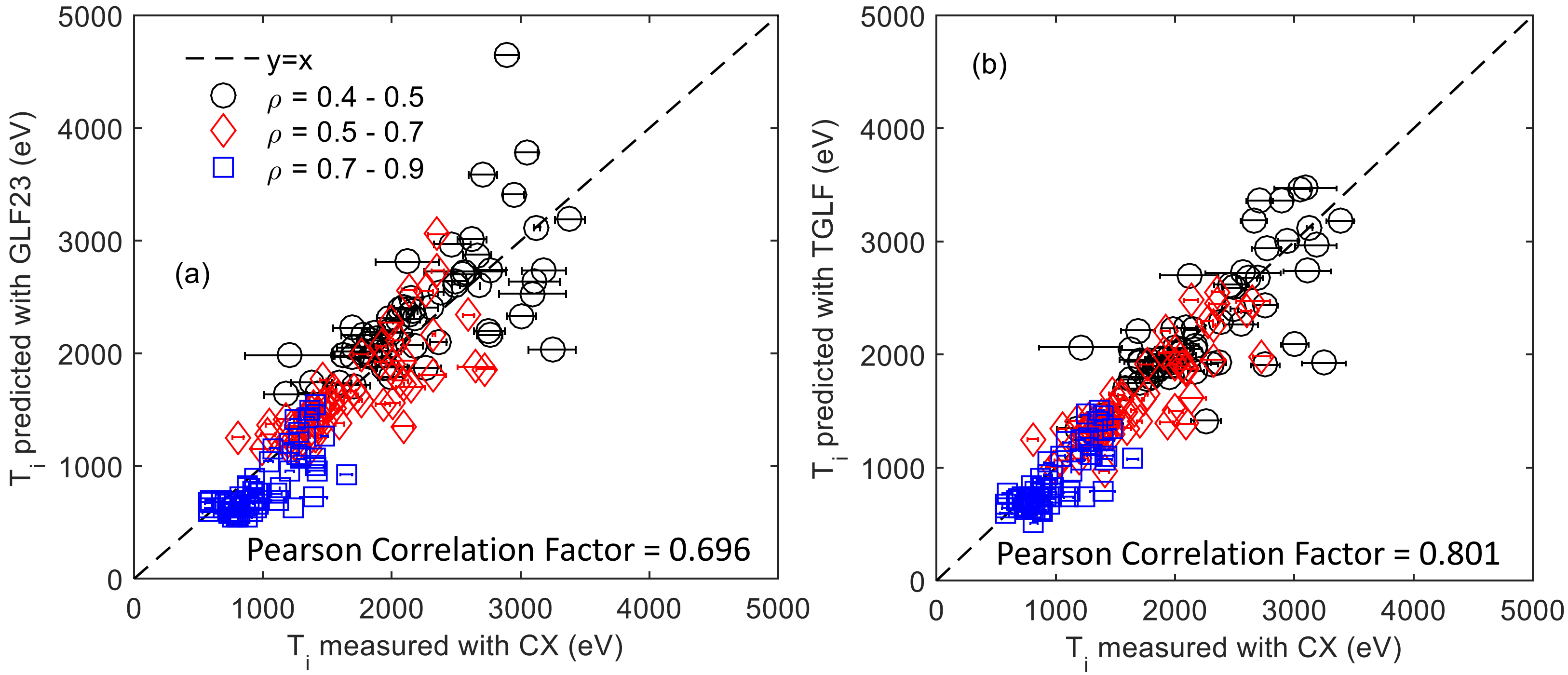
High rotation → smaller γ_{net} → smaller heat transport → increase in predicted T_e

GLF23 rotation prediction and the Impact on predicted T_e



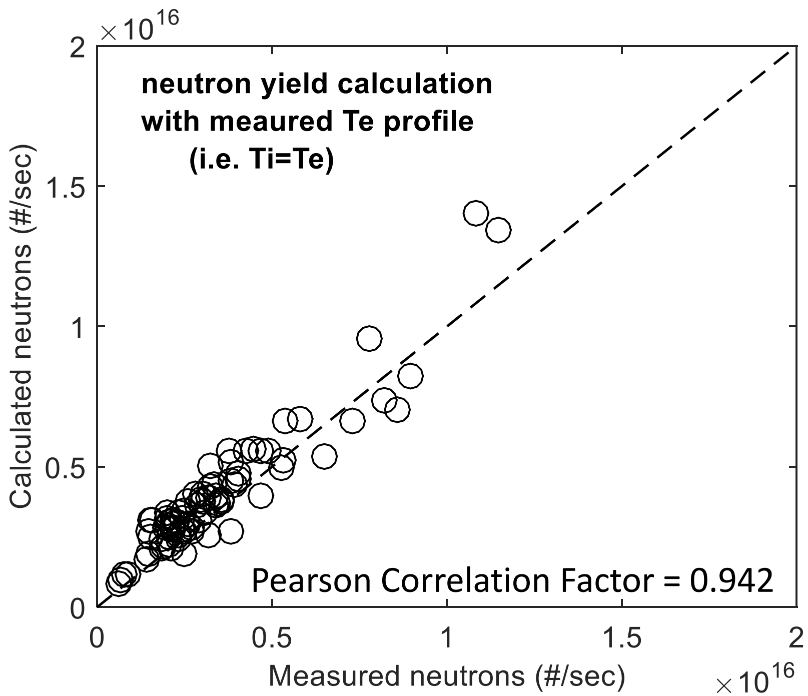
- GLF23 over-predicts rotation profiles significantly, and this leads to the over-calculation of the ExB stabilisation, thereby increasing the predicted T_e.
- Toroidal rotation input data from measurement or reliable assumption is necessary for predictive simulations.

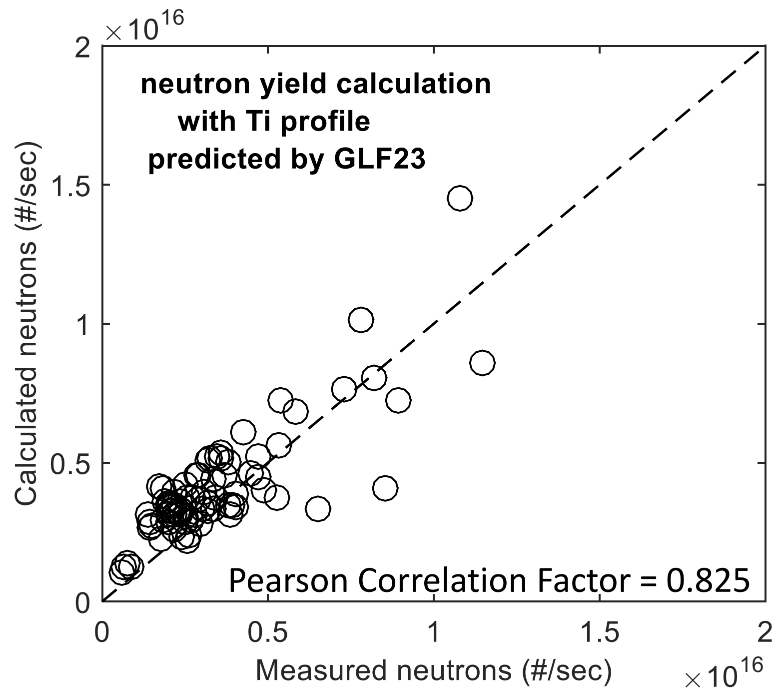
T_i prediction with GLF23 and TGLF



- While TRANSP-GLF23 has 20% - 30% of uncertainty window in T_i predictions, TRANSP-TGLF shows much better agreement with CX measured T_i.

Neutron yield predictions with GLF23





- In addition to other uncertainties such as Z_{eff}, n_e, anomalous fast ion transport, etc, the uncertainty of predicted T_i with TRANSP-GLF23 makes the neutron prediction less reliable.

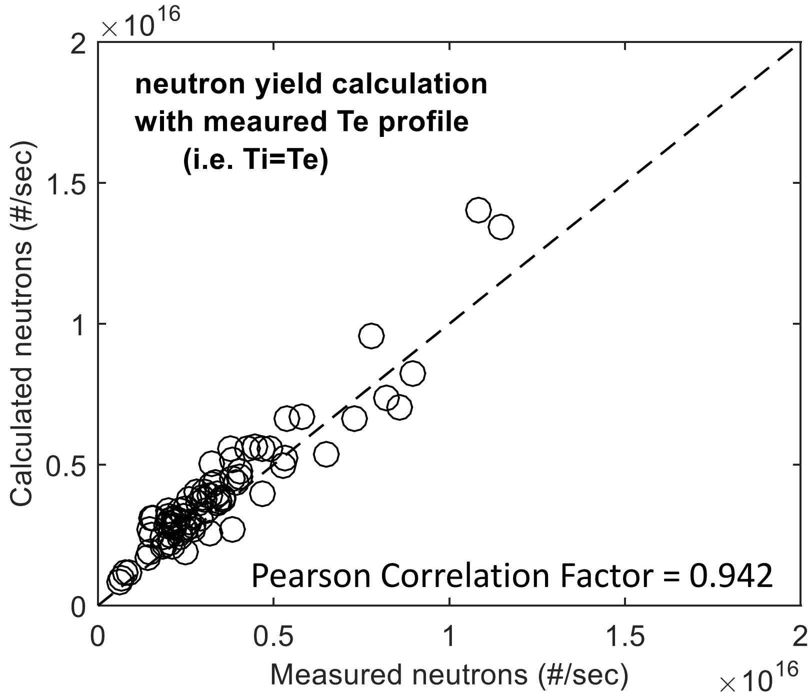
Total neutron yields =

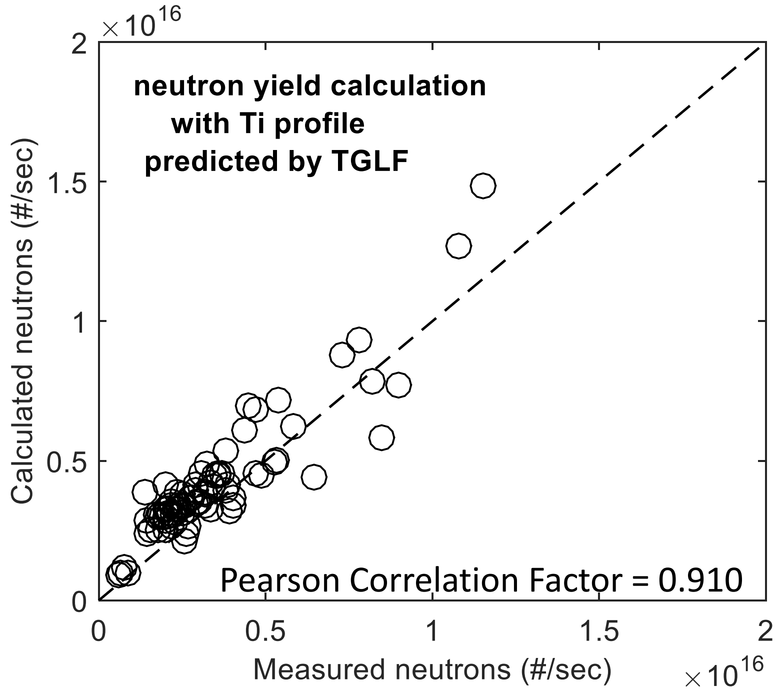
$$\int n_{thermal,D} n_{beam,D} < \sigma\upsilon > (T_i, f_{beam}(E)) dV + \int n_{thermal,D} n_{thermal,D} < \sigma\upsilon > (T_i) dV + \int n_{beam,D} n_{beam,D} < \sigma\upsilon > (f_{beam}(E)) dV$$

where

$$n_{thermal,D} = n_e - \sum_j n_{imp,j} Z_{imp,j}$$

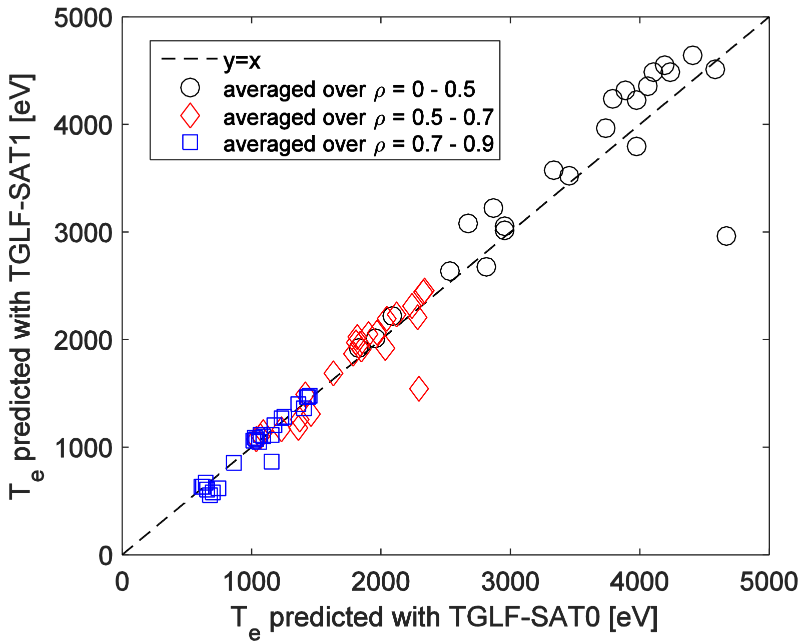
Neutron yield prediction with TGLF

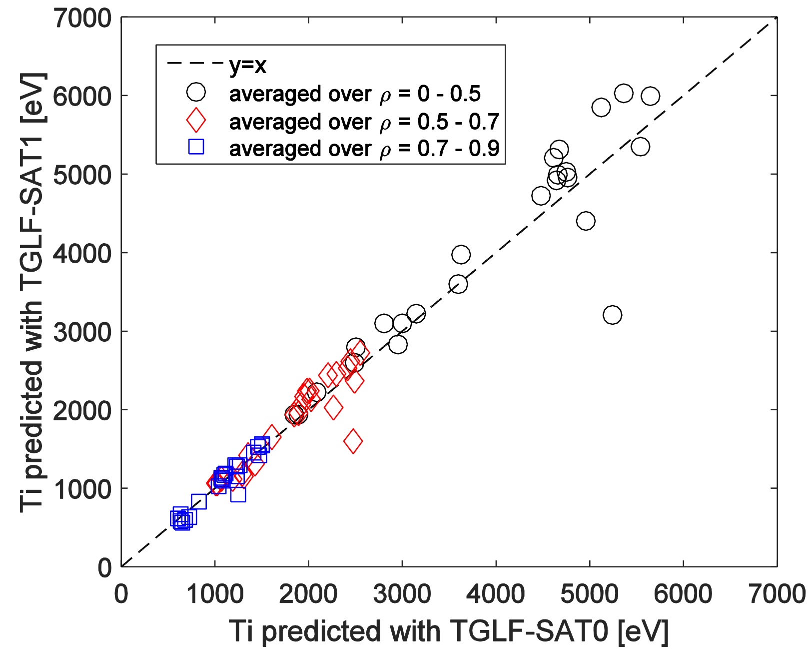




The better T_i predictions with TGLF also enables better predictions of neutron yield.

TGLF-SAT0 vs TGLF-SAT1





TGLF-SAT0: Original local saturation model in ky (*G.M. Staebler et al, PoP, 14, 055909, 2007)*
TGLF-SAT1: New saturation model that includes axisymmetric (Zonal) fluctuations coupling to all ky-scales and finite-ky inter-mixing (*G.M. Stabler et al, PoP 23, 062518, 2016)*

No significant changes observed with SAT1. This suggests that in the baseline H-mode discharges used here the ETG and multiscale physics is not important. It is likely because the ETG threshold is sufficiently large.

Summary: Prediction capability of TRANSP-GLF23/TGLF has been assessed over 80 JET-ILW baseline H-mode discharges.

- T_e reproducibility of GLF23 simulations is subject to ν^* i.e. under-prediction at low ν^*.
- The impact of ν^* is less significant in TGLF where the trapped particle physics is modelled in a more complete way, and the T_e predicted with TGLF agrees much better with measurement.
- The magnitude of predicted core T_e with GLF23/TGLF depends on the pedestal T_e, but the gradient is not sensitive to the pedestal T_e.
- For JET baseline discharges, reconstructed radiation profiles are not necessary for core Te prediction, unless the total radiation power is significantly wrong.
- GLF23 over-predicts the rotation significantly, thereby over-calculation of ExB stabilisaiton. Reliable rotation input or assumption is necessary.
- The uncertainty in T_i predictions with GLF23 adds further uncertainty to neutron yield predictions. T_i predictions with TGLF show much better agreement with measured T_i, and the predictions of the neutron yields also look promising.
- No significant changes were observed with TGLF-SAT1 compared to TGLF-SAT0. This suggests that in the baseline H-mode discharges used here the ETG and multiscale physics may not be important.
- Further details → Hyun-Tae Kim et al, Nuclear Fusion 57 (2017) 066032