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Hyun-Tae Kim et al.

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Statistical validation of predictive TRANSP simulations on baseline discharges in preparation for the extrapolation to JET D-T

Hyun-Tae Kim[1,2], M. Romanelli[2], X. Yuan[3], S. Kaye[3], G. Sips[4], L. Frassinetti[5], C. Giroud[2], G. Maddison[2], E. Joffrin[6], and JET Contributors*

*EUROfusion Consortium, JET, Culham Science Centre, Abingdon, Ox14 3DB, UK.

[1]EUROfusion PMU, Culham Science Centre, Abingdon, OX14 3DB, UK.

[2]Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, OX14 3DB, UK.

[3]Princeton Plasma Physics Laboratory, Princeton University, USA.

[4]JET Exploitation Unit, Culham Science Centre, Abingdon OX14 3DB, UK.

[5]Division of Fusion Plasma Physics, KTH Royal Institute of Technology, SE-10691 Stockholm, Sweden

[6]CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France

E-mail contact of main author: hyun-tae.kim@euro-fusion.org

Abstract. This paper presents a statistical validation of TRANSP predictive simulations of plasma temperature using two transport models, GLF23 and TGLF, over a database of 80 baseline H-mode discharges in JET-ILW. While accuracy of the predicted T_e with TRANSP-GLF23 is affected by plasma collisionality , the dependency of predictions on collisionality is less significant when using TRANSP-TGLF, indicating that the latter model has a broader applicability across plasma regimes. TRANSP-TGLF also shows a good matching of predicted T_i with experimental measurements allowing for a more accurate prediction of the neutron yields. The impact of input data and assumptions prescribed in the simulations are also investigated in this paper. The statistical validation and the assessment of uncertainty level in predictive TRANSP simulations for JET-ILW-DD will constitute the basis for the extrapolation to JET-ILW-DT experiments.

1. Introduction

1.1. Motivation

The EUROfusion Consortium is planning deuterium-tritium (D-T) experimental campaigns in 2019 in JET with the ITER-Like Wall (ILW) to address physics issues which are important for ITER-D-T experiments [1]. To achieve the scientific objectives, JET operation should demonstrate 10-15MW of fusion power for at least 5 seconds, a performance never attempted before in fusion-research history. In order to prepare this unprecedented JET operational scenarios with D-T mixture, reliable predictive simulations are of crucial importance. However, the current capability to predict plasma temperature evolution and the resultant fusion power is still limited. This is mainly due to the incompleteness of turbulent transport models and the uncertainties of the input data (e.g. pedestal temperature, radiation, rotation profiles, etc.). In addition to these issues limiting the present prediction capability, D-T mixture would add even further uncertainties resulting from hydrogenic isotopes and alpha particles physics. Quantification of the impact of the foreseen uncertainties on reproducing the present discharges has therefore a high priority in preparation for the extrapolation to JET D-T experiments. In this paper, the current predictive capability of T_e, T_i, and neutron yields with TRANSP [2] [3] - GLF23 [4] [5] is assessed statistically over 80 baseline H-mode

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*See the author list of “Overview of the JET results in support to ITER” by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016) discharges at JET-ILW. In order to take into account the uncertainties arising from the error bars of input data and assumptions, an identical default simulation setting was used for all 80 reference simulations, and the impact of collisionality regime, pedestal T_e, radiation profile, and toroidal rotation on T_e prediction are investigated by modifying the same simulation setting. The default simulation setting was also used to assess the TGLF transport model [6], which is computationally expensive but contains more physics than GLF23. The above statistical validation of predictive TRANSP simulations at JET-ILW-DD will constitute the basis for the extrapolation to JET-ILW-DT experiments.

1.2. Database

The database consists of 80 baseline H-mode discharges with JET-ILW which cover a large range of engineering parameters as well as dimensionless parameters.

- 46 discharges selected for ITPA database **[7]**: low q_{95}(=2.7 ~ 3.3) experiments for 2012-2014, stationary state for 5 confinement times (τ_E) in baseline H-mode (i.e. β_N>0.85 β_N,max), rotation profile available, I_p (=2~3.5 MA), B_t (=1.9~3.2 T), P_{heat} (=10.8~27.7 MW), Te0 (=2.2~6 keV), <n_e> (=4~10.2 m^{-3}), β_N (=1~2)
- 22 discharges selected for dimensionless parameter scanning **[8]**: ν*=0.04 – 0.15 at (ρ=0.4), ρ*=0.003~0.005
- 10 discharges selected for comparative confinement study **[9]**: I_p (=2.5 MA), B_t(=2.7 T), P_{heat}(=14~17 MW), <n_e>(=7.1~10.2 m^{-3})
- 2 reference discharges selected for the task of DT scenario extrapolation at JET (called T15-01) i.e. 87215 and 87412

1.3. Input and assumptions

For the 80 predictive simulations, the following input setting and assumption are used to assess the predictive capability of T_e and T_i.

- Pedestal T_e prescribed by the measurement of High Resolution Thomson Scattering (HRTS) at ρ=0.9
- Pedestal $T_i = T_e$
- Whole profile of n_e prescribed by HRTS measurement
- Turbulent transport is computed by GLF23 (or TGLF)
- Neoclassical transport is computed by NCLASS
- Uniform radiation profile prescribed by bolometry measurement (i.e. BOLO/TOBU)
- Uniform Zeff profile prescribed by bremsstrahlung assuming Be is the only impurity.
- Toroidal rotation profile prescribed by the measurement of Charge eXchange spectroscopy (CX)
- Heating and particle source terms calculated consistently by NUBEAM and TORIC

In order for individual investigation of the impact of pedestal T_e, radiation profile, and toroidal rotation, only one simulation setting was modified, otherwise maintaining the same default setting.

2. T_e prediction

2.1. Impact of collisionality regime

The current T_e prediction capability with TRANSP-GLF23 for baseline H-mode JET-ILW discharges is presented in *FIG.1(a)* where the predicted T_e values are compared to the T_e measured by HRTS. Each symbol indicates T_e averaged over different radial windows (i.e. ρ=0.3-0.5, ρ=0.5-0.7, and ρ=0.7-0.9.). As the line of sight of HRTS measurement in the discharges is deviated from the magnetic axis, T_e data for ρ=0 – 0.3 is not available to compare in *FIG.1(a)*. Overall, the reference predictive simulations with TRANSP-GLF23 predict T_e at about 20% accuracy (Pearson correlation coefficient = 0.7529), except the under-predicted T_e indicated by the green dashed ellipse. These discharges have low collisionality ν^*(<0.08) in common, and *FIG.1(b)* shows that the T_e reproducibility with TRANSP-GLF23 is subject to the collisionality regime i.e. under-prediction at low ν^* and over-prediction at high ν^*. This is observed more clearly in the discharges selected for ν^* scan (see *FIG.2 (a) and (b)*) where the other dimensionless parameters (i.e. ρ^* and β_N) are maintained. Reminding that ν^* is the ratio of the effective collision frequency for trapped particles to their bounce frequency, the observed trend implies that turbulent heat fluxes associated to trapped particles are over-calculated at low $\nu^*$and vice versa. This is probably due to the fact that the trapped particle model in GLF23 is oversimplified.

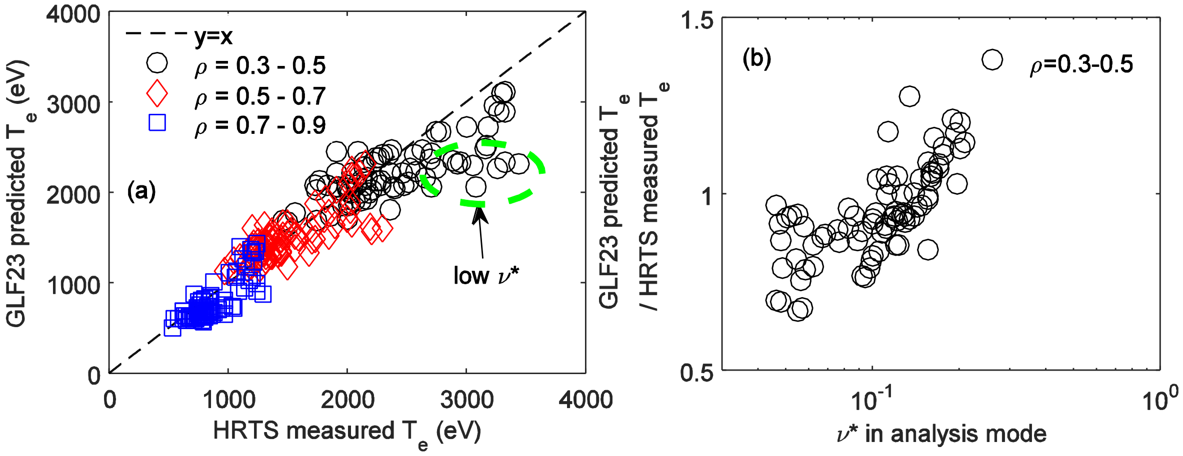

FIG. 1 (a) T_e predicted by TRANSP-GLF23 with default simulation setting is compared to T_e measured by HRTS. The comparison is made over 80 baseline H-mode JET-ILW discharges. The radial windows in which T_e is averaged are indicated by Blue square (ρ=0.7-0.9*), red diamond (*ρ=0.5-0.7*), and black circles (*ρ=0.3-0.5). *(b) The impact of* ν^* on *the ratio of the predicted T_e to the measured T_e. T_e and* ν^* are averaged over ρ = 0.3-0.5.

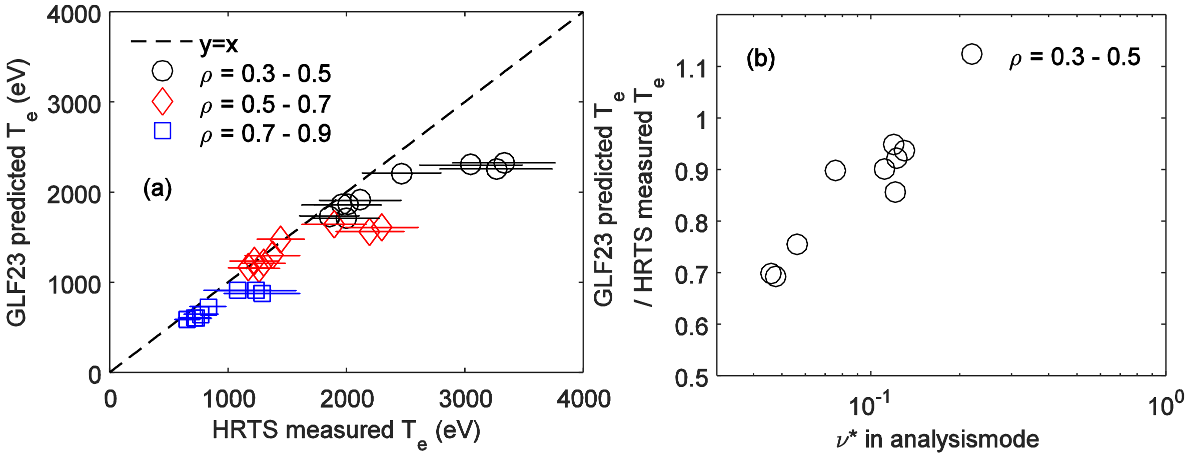

FIG. 2(a) (b) The same comparison has been made as Fig.1, but it is made over ν^* *scan database where the other dimensionless parameters do not vary.*

'Trapped' GLF (TGLF) is a more complete turbulent transport model, which solves Gyro-Landau-Fluid (GLF) equations [10] with better accuracy than GLF23 [11]. While GLF23 solves 8x8 matrix eigenvalue problem i.e. 4 moments equations with 2 species +1 poloidal basis function, TGLF solves 120x120 matrix eigenvalue problem i.e. 15 moments (12 for passing particles and 3 for trapped particles) with 2 species + 4 poloidal basis functions [12]. This enables trapped particles being modelled in a more complete way in TGLF. Although TGLF is computationally much more expensive than GLF23, it is still affordable to routinely perform full radius simulations, together with consistent source calculations of heat and particles from NBI and ICRH. The consequence of the main improvement in TGLF is indeed shown in *FIG.3 (a).* T_e predicted by TRANSP-TGLF in 6 selected representative discharges agrees very well with T_e measured by HRTS within the measurement error bars (Pearson correlation coefficient = 0.9779). The under-prediction of T_e at low $\nu*$ is not also observed in *FIG.3 (b).*

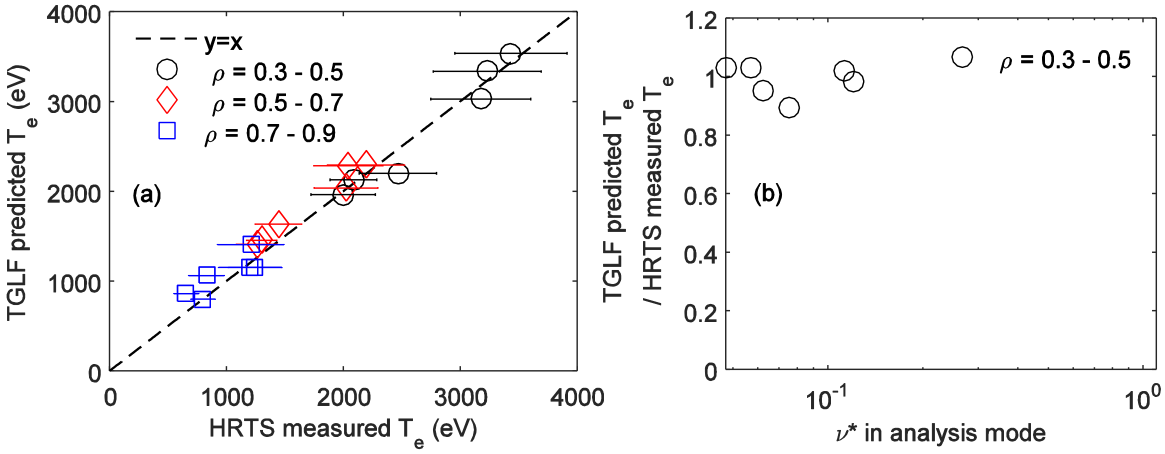

FIG. 3 (a) (b) TRANSP-TGLF is used for predictive simulations, and the comparison is made over 6 baseline H-mode JET-ILW discharges. Otherwise, the notation is the same as FIG.1.

2.2. Impact of T_e boundary condition

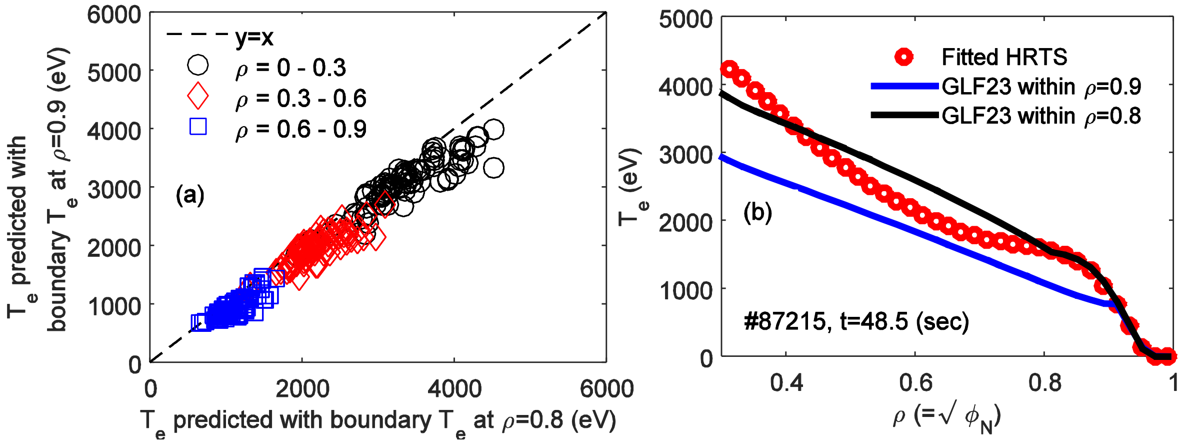

FIG.4(a) The impact of the boundary T_e position on T_e prediction with TRANSP-GLF23. The notation of the symbols are the same as FIG.1(a). (b) One of the typical discharges where the ETB region is wider than ρ =0.9 – 1 is shown.

The transport in the edge transport barrier (ETB) is not properly modelled by the core turbulent transport models (i.e. GLF23 and TGLF), and thus pedestal T_e is required as a boundary condition. For present discharges a correct pedestal T_e can be found from measurements, but for future discharges it needs to be predicted. The impact of pedestal T_e on core T_e prediction is assessed in *FIG.4(a).* 80 predictive TRANSP-GLF23 simulations with the boundary T_e measured at ρ=0.8 were compared to the reference simulations with the default setting (i.e. T_e boundary at ρ=0.9). Note, the simulation settings are otherwise identical. *FIG.4(a)* shows that in some discharges the predicted T_e is increased by setting boundary T_e at ρ = 0.8. This is due to the fact that in those discharges the width of the ETB region is wider than ρ= 0.9 – 1 as shown in *FIG.4(b)*. The radial position of boundary T_e is not inner enough to exclude the ETB region, and the pedestal T_e is underestimated, thereby decreasing core T_e. However, it is also worth noting that the gradient of the core T_e profile is not significantly modified by different pedestal T_e. Although it is not shown in this paper, the same feature is also observed in TRANSP-TGLF. This feature implies that the impact of pedestal T_e on the core T_e is not more than the error bars of pedestal T_e.

2.3. Impact of radiation profile

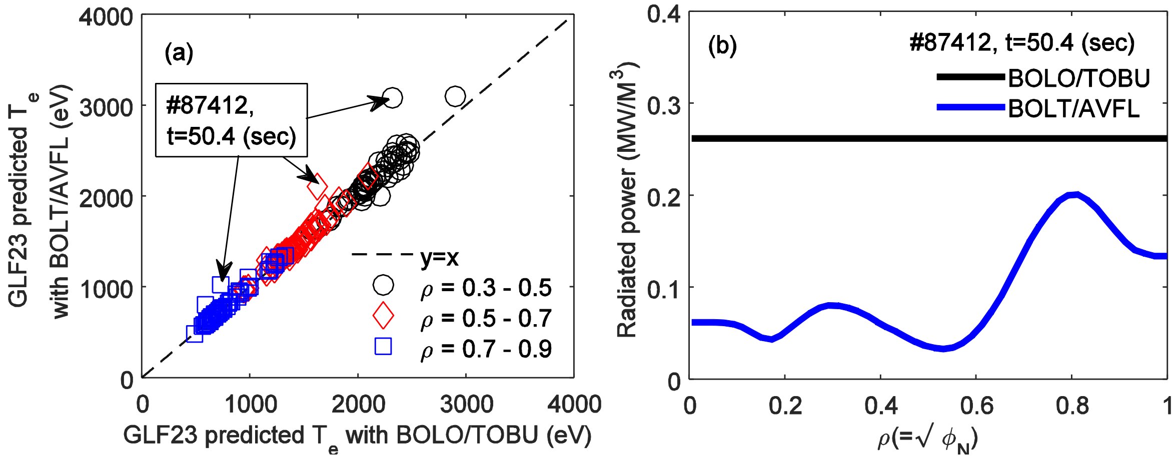

FIG. 5 (a) The impact of the radiation profile on T_e prediction with TRANSP-GLF2. The notation of the symbols is the same as FIG.1(a). (b) Uniform radiated power (BOLO/TOBU) and radiation profile (BOLT/AVFL) in #87412

In the bolometry measurement system at JET, the total radiated power is automatically produced by intershot analysis. While the total radiated power can be used as an input data in predictive simulations assuming a uniform radiation profile, there was a concern about the profile effects of radiated power on T_e prediction. However, as there is no automatic routine available to reconstruct radiation profiles, the radiation profile data can only be produced manually, requiring considerable human effort. This is not desirable to build a large database of predictive simulations. The impact of radiation profile is assessed by comparing 80 TRANSP-GLF23 simulations with reconstructed radiation profiles to the reference simulations with the default setting (i.e. with uniform radiation). As shown in *FIG.5 (a)*, for a vast majority of predictive simulations, the impact of profiles of radiated power is trivial. The impact is only visible in a discharge #87412, but it turned out that in the discharge the total radiated power differs significantly between uniform radiation and radiation profile (see *FIG.5(b)*). Hence, the profile effect of radiated power is not important for predictive simulations, as far as the estimate of the total radiated power is correct. This would also enable one to assume only total radiation power when predicting future discharges, rather than to assume complicated radiation profile.

2.4. Impact of toroidal rotation frequency

One of the main impacts of the toroidal rotation frequency is through *ExB* flow shear stabilisation. In GLF23, the turbulence quench rule, $\gamma_{net} = \gamma_{\max} - \alpha_E \gamma_{ExB}$, is adopted [5] where $\gamma_{\max}$ is the maximum growth rate of the drift-wave instabilities, and γ_{ExB} (=

$(r/q)d(qV_{ExB}/r)/dr$) is *ExB* flow shearing rate. α_E is a coefficient to adjust the level of *ExB* flow shear stabilisation. In this paper, a fixed value of $\alpha_E=1$ is used for all discharges as other simulation setting. In TRANSP-GLF23, the poloidal *ExB* flow velocity V_{ExB} is calculated by E_r/B_t where E_r is a radial electric field and B_t is a toroidal magnetic field. The E_r is calculated by assuming that the electrostatic force due to E_r is balanced with the Lorentz force (i.e. $E_r = V_t B_p$), and here V_t is given by the toroidal rotation frequency. The toroidal rotation frequency can be obtained by analysing CX spectroscopy or by solving the internal momentum transport equation in TRANSP-GLF23. The impact of the toroidal rotation predicted by TRANSP-GLF23 is shown in *FIG.6(a)*. In a majority of discharges, the T_e predicted with predicted rotation is over-calculated. As shown in *FIG.6(b)*, this is because TRANSP-GLF23 significantly over-predicts the rotation frequency compared to the CX-measured value, thereby resulting in the excessive *ExB* flow shear stabilisation. For predicting future discharges, reasonable assumption of toroidal rotation will be necessary as the rotation prediction is not reliable.

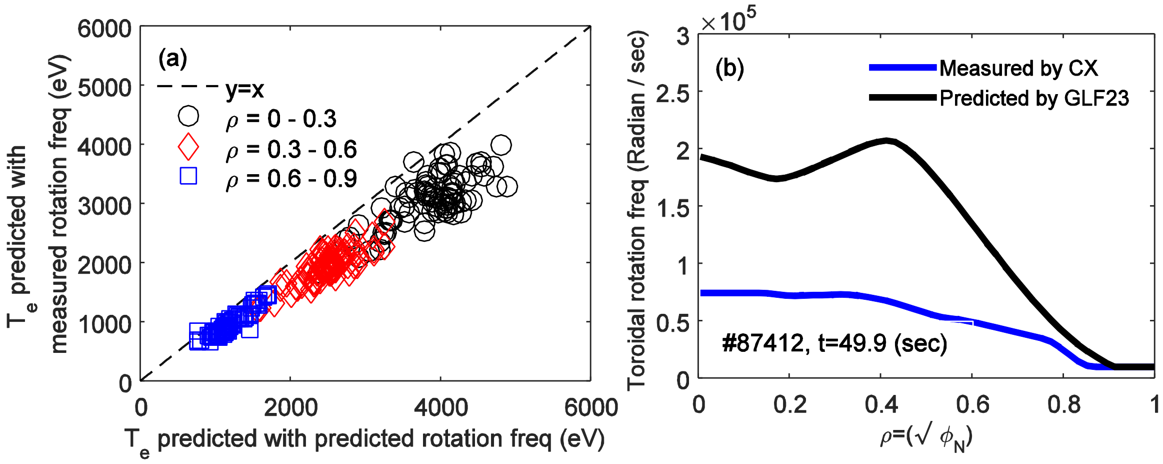

FIG. 6(a) The impact of predicted rotation frequency on T_e prediction with TRANSP-GLF2. (b) Comparison of toroidal rotation between CX and TRANSP-GLF23 in one of the typical discharges.

3. T_i prediction and neutron yields

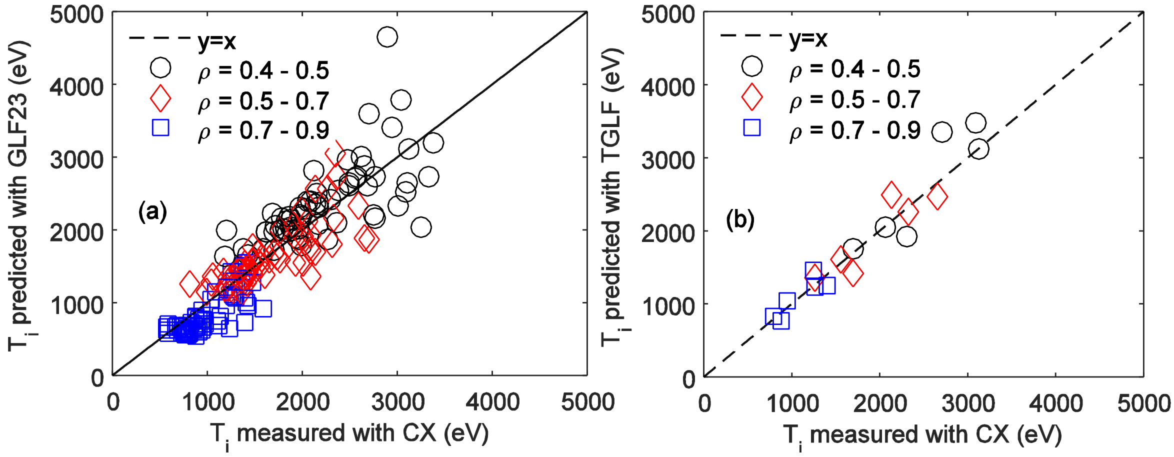

FIG. 7 (a) T_i predicted by TRANSP-GLF23 with default simulation setting is compared to T_i measured by CX. (b) T_i prediction with TRANSP-TGLF

T_i predicted by TRANSP- GLF23 over 80 baseline H-mode discharges and T_i predicted by TRANSP-TGLF over 6 discharges are shown to compare with T_i measured by CX spectroscopy in *FIG. 7 (a) and (b)*, respectively. The comparison of core T_i is limited up to $\rho = 0.4$ as the CX data is not available. This is because CX spectroscopy analysis has been difficult due to the issue of weak signal since the replacement of the plasma facing components to ILW i.e. Be and W. While significant uncertainty level of T_i prediction with TRANSP-GLF23 is observed (Pearson correlation coefficient = 0.6926), T_i prediction with TRANSP-TGLF has a much better accuracy (Pearson correlation coefficient = 0.9073).

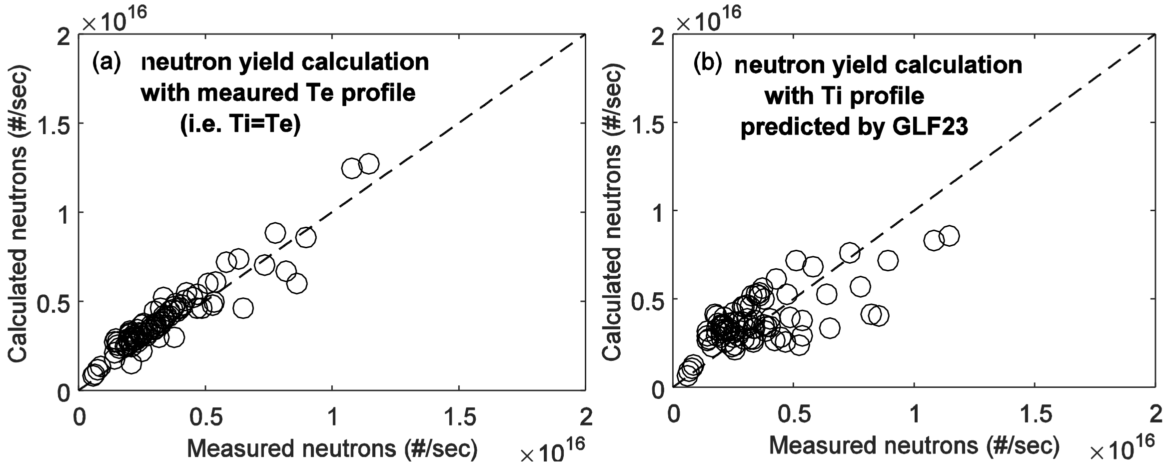

FIG. 8 (a) In the 80 baseline H-mode discharges, the neutron yields calculated with HRTS T_e assuming T_i=T_e are compared to the neutron yields measured by the fission chamber. (b) The predicted neutron yields is calculated with T_e predicted by TRANSP-GLF23.

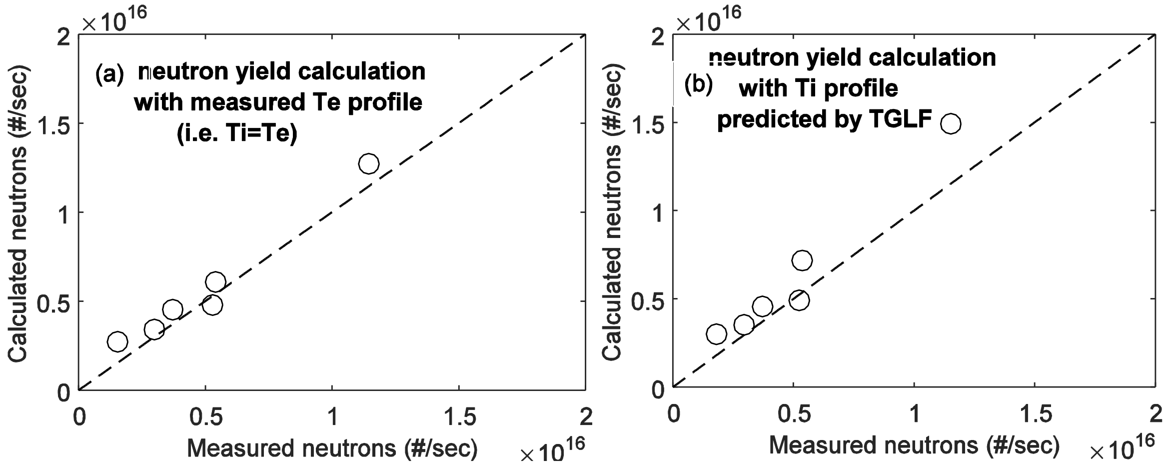

FIG. 9 (a) Same analysis as FIG. 8(a) for the 6 selected representative discharges. (b) The predicted neutron yields are calculated with TRANSP-TGLF.

The level of T_i prediction accuracy affects neutron yields prediction as the fusion cross-section is a strong function of T_i. *FIG.8(a)* and *FIG.9(a)* show the neutron yields calculated with the HRTS-measured T_e, compared to the neutron yields measured by the fission chamber. Here, $T_i = T_e$ is assumed as CX-measured T_i is not available within $\rho < 0.4$. The assumption can be justified as all discharges in this paper are baseline H-mode discharges where the equilibration between electrons and ions is high due to high n_e. It is worth noting that the measured neutrons tend to be lower than the calculated neutrons. This is called neutron deficit in the calculation, and further investigation on this can be found in [13]. The scattering of the data points in *FIG.8.(a)* and *FIG.9.(a)* results from error bars in the measured input data such as T_e, Z_{eff}, n_e, etc. In addition to these, the impacts of the uncertainty of T_i prediction on neutron yield prediction in TRANSP-GLF23 and TRANSP-TGLF are shown in *FIG.8(b)* and *FIG.9(b),* respectively. The significant scattering of T_i predicted by TRANSP-

GLF23 adds further uncertainty in the neutron yields calculation, reducing the prediction capability of fusion power. On the other hand, the impact of the predicted T_i is much less significant in TRANSP-TGLF, and the prediction capability of fusion power looks promising. However, it should be noted that this analysis has been done only over a small number of discharges due to the high computational cost of TRANSP-TGLF. In order to confirm the TGLF results, a larger database of TRANSP-TGLF simulations is needed.

4. Conclusion

Predictive TRANSP-GLF23 simulations of 80 baseline H-mode discharges have been carried out. Overall the simulations reproduce well the experimental T_e profiles, however a dependency of the prediction on the collisionality regime is found i.e. under-prediction at low $\nu *$ and over-prediction at high collisionality. The impact of $\nu *$ is less significant in the TRANSP-TGLF simulations where the trapped particle physics is modelled in a more complete way. The value of the core T_e predicted with GLF23/TGLF depends on the pedestal T_e, but the gradient is not sensitive to the pedestal T_e (due to stiffness of the transport model). A uniform profile of radiated power is enough for GLF23/TGLF simulations, as long as the total radiated power is correct. The *ExB* stabilisation model in GLF23/TGLF, is a function of toroidal rotation, but in the 80 baseline H-mode discharges TRANSP-GLF23 over-predicts the rotation significantly, so reliable rotation input is necessary for predictive simulations. The uncertainty in T_i predictions with TRANSP-GLF23 (i.e. 20-30%) adds further uncertainty to neutron yield predictions. T_i predictions with TRANSP-TGLF show much better agreement with measured T_i, and the predictions of the neutron yields also look promising. A large database of TRANSP-TGLF simulations for JET-ILW is needed for further investigation.

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