PERFORMANCE AND TRANSPORT IN ITER: MULTI-CHANNEL VALIDATION IN DIII-D ITER-LIKE CONDITIONS AND PREDICTIONS OF ITER BURNING PLASMAS VIA NONLINEAR GYROKINETIC PROFILE PREDICTION

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Abstract

Performance and transport in ITER conditions has been studied extensively through gyrokinetic model validation in DIII-D ITER similar shape (ISS) plasmas and through nonlinear gyrokinetic profile prediction of the ITER baseline scenario (IBS). Dedicated experiments were performed in ISS conditions to compare nonlinear gyrokinetic profile predictions with measured kinetic profiles (n_e, T_e, T_i), heat and particle fluxes (Q_e, Q_i, Γ_e), turbulent fluctuations, and impurity transport across a large portion of the plasma minor radius ($\rho = 0.3-0.8$). Generally good agreement was found between simulation and experiment in the wide range of channels compared, providing confidence in applying gyrokinetic profile prediction to ITER conditions. Simulations of the ITER baseline scenario (IBS) suggest that ITER should obtain approximately its $500MW$, $Q = 10$ goal. Levering new modeling techniques, simulations indicate that ITER may be able to be optimized to obtain significantly higher Q when operating near its baseline scenario and should still be capable of obtaining burning plasma conditions, despite RMPs degradation of the anticipated density pedestal. Simulations of IBS conditions with varying fuel ion (H, D, and D-T) were performed that suggest that stiff ITG turbulence present in the plasma core is unlikely to exhibit any significant isotope effect of energy confinement. This result is largely in disagreement with the $\tau_{ITER98-y2}$ scaling, but is consistent with recent updates to the energy confinement scalings such as τ_{H20}. The work reported here provides a comprehensive look at turbulence and performance in ITER conditions and points towards potential avenues for optimization.

1 INTRODUCTION

With the anticipated completion and operation of ITER within the decade, the world is on the cusp of the burning plasma era. ITER and other next-generation fusion devices are expected to operate in a unique manner compared to current fusion devices, as it is expected that these plasma conditions will be simulated extensively before they are attempted via experiment. This requirement emphasizes the need for accurate prediction of plasma profiles and the resulting performance. Traditionally, prediction of plasma profiles has been performed with physics-based models such as TGLF [1] and Qualikiz [2] as it has generally been too computationally expensive to perform such predictions with our highest fidelity model of core turbulence and transport: nonlinear gyrokinetics. However, advances in computing and machine learning have pushed these predictions into a regime that is tractable and we are now able to routinely compare full kinetic profiles from current experiments with nonlinear gyrokinetic profile predictions [3]. This paper describes a comparison of nonlinear gyrokinetic profile predictions with measurements obtained in DIII-D ITER Similar Shape (ISS) conditions as well as predictions and optimization of conditions around the ITER baseline scenario.

2 TURBULENCE AND TRANSPORT IN A DIII-D ITER SIMILAR SHAPE (ISS) PLASMA

Dedicated experiments were performed on DIII-D to study core to edge impurity transport in ITER similar shape (ISS) conditions. These experiments focused on H-mode conditions operated with RMP ELM suppression, $B_T = 2.0T$, $I_p = 1.6MA$, $q_{95} = 3.45$, line averaged $n_e \sim 3.0 \times 10^{19} m^{-3}$, and $\beta_N \sim 1.35$, with mixed neutral beam ($P_{NBI} \sim 4.0$MW) and electron cyclotron heating ($P_{ECRH} = 1.6$MW) deposited

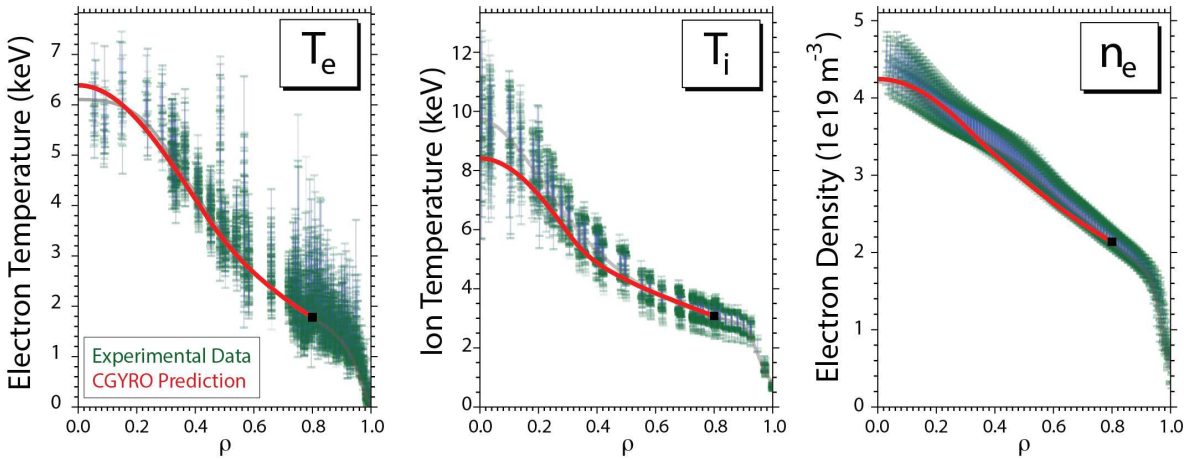

FIG. 1: *Profiles predicted via nonlinear gyrokinetic simulation (red) are compared with data (green) obtained from experiment for the DIII-D ISS discharge*

around $\rho = 0.25$. High resolution profile data and impurity transport data were obtained during these conditions to enable validation of core heat and particle transport extending out to the plasma edge. Additionally, turbulent fluctuation measurements were provided via the DIII-D Beam Emission Spectroscopy (BES) [4] and Correlation Electron-Cyclotron Emission (CECE) [5] diagnostics on DIII-D. Profile data was processed and fit using the OMFIT [6] set of tools and the TRANSP code [7] was used to perform power balance analysis of the conditions. A wide range of impurities were introduced into the plasma condition, but this work will focus on comparisons with low and medium Z impurities: Li, C, and Ca. Lithium was introduced using the impurity powder dropper, carbon is intrinsic to the DIII-D as it is the first wall material of the device, and Ca was introduced via laser blow-off. Overall, validation quality data were obtain in a wide range of channels which motivated the core transport investigations presented here.

2.1 Nonlinear Gyrokinetic Profile Predictions of the ISS conditions

All gyrokinietic simulations performed for this work utilized the CGYRO gyrokinetic code [8]. Simulations in this paper focused on resolving ion-scale turbulence in the condition of interest. For simulation of DIII-D gyrokinetic simulations were performed at $\rho = 0.3$, 0.43, 0.62, and 0.8. Although resolutions varied somewhat depending on the radius simulated, nominal resolutions for the DIII-D simulations were approximately 300 radial modes and 20 toroidal modes with a box size of approximately $[L_x, L_y] = [100\rho_s, 100\rho_s]$ extending up to $k_\theta \rho_s$ values of approximately 1.2. Such numerical choices are sufficient for capturing ITG, TEM, and MTM turbulence. All simulations were electromagnetic, included 3 gyrokinetic species (D, C, and e), realistic geometry, rotation, and high fidelity Sugama collisions [9]. The inclusion of electron-scales was not deemed necessary to accurately simulate these plasmas. This was determined from the linear growth rates by applying the multi-scale rules of thumb in References [10][11] and through investigation of the heat flux ratios. Over most of studied radial region, the ion heat flux is equal to or exceeds the electron heat flux, suggesting that high-k TEM/ETG is likely not needed to match the experimental fluxes.

Prediction of the plasma profiles utilized surrogate accelerated profile prediction techniques implemented in the PORTALS code [3]. This machine learning based approach has been demonstrated to be much more efficient than traditional methods for reaching converged profile predictions, where simulations match target (experimental) fluxes. The approach generally works as follows: A small database of simulations (~ 5) is created with randomly generated profiles around the experimental conditions. Nonlinear gyrokinetic simulations are run at each of the 4 radial locations for each set of profiles (4 radial locations x 5 profiles = 20 total simulations). A surrogate model is built based on this data that attempts to reproduce the dependence of the fluxes at each radial location on known turbulence drives ($a/L_{T_i}, a/L_{T_e}, a/L_n, \nu_{ie}, T_e/T_i$). The surrogates are then used to predict the profiles that will match the target (experimental) heat fluxes. These new profiles are then run with nonlinear gyrokinetic simulation. If the simulations match the target fluxes, the profiles are considered converged. If not, the new gyrokinetic results are added to a database, the surrogates are regenerated, and the process continues until the nonlinear gyrokinetic simulations match the target fluxes.

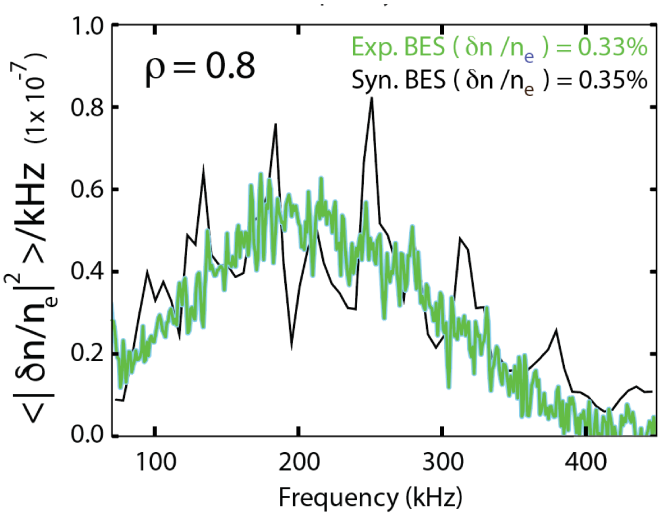

FIG. 2: *The Measured BES cross-power spectrum (green) is compared with the synthetic CGYRO fluctuations (black*

2.2 Comparison of Experimental Profiles, Fluctuations, and Impurity Transport with Nonlinear Gyrokinetic Profile Prediction

The profile prediction method described above was applied to predict the kinetic profiles (T_e, T_i, and n_e) by ensuring that the gyrokinetic modeling is able to reproduce the target heat and particle fluxes (Q_e, Q_i, and Γ_e). The predicted profiles required a total of 16 iterations for convergence and compared with the experimental data in Figure 1. As shown in this figure, the nonlinear simulations are able to reproduce the profiles well within the scatter of the experimental data, indicating generally good agreement between simulation and experiment in the 3 channels and providing some confidence that the nonlinear gyrokinetic model is accurate enough for both reproduction and likely prediction of ITER like plasma conditions.

Accurate prediction of kinetic profiles is a necessary condition to predict 0-D quantities and performance metrics of fusion devices. However, accurate prediction of fluxes and the corresponding profiles does not ensure that the modeling is reproducing the turbulence characteristics accurately. To validate the gyrokinetic model directly against turbulence measurements, experimental measurement of low-k density and electron temperature fluctuations were obtained at two of the radial locations studied $\rho = 0.62$ and 0.8. A comparison of the synthetic modeled BES fluctuations obtained from the converged gyrokinetic simulation at 0.8 is presented in Figure 2. As shown in this figure, there is excellent agreement between the simulation and experiment in terms of both the shape of the frequency spectrum and the overall amplitude of the density fluctuations. A similar result was found at $\rho = 0.62$ when comparing simulation with experiment. Comparisons with measured electron temperature fluctuations (CECE measurement) yield agreement in the radial trends (increasing fluctuations with radius) and excellent agreement in the shape of the spectra but some quantitative disagreement is found. Measured fluctuation levels exceed those from gyrokinetic prediction by approximately a factor of two. The origin of this discrepancy is not completely understood but it may result from physical mechanisms, the synthetic modeling approach, or even analysis differences, as differences in the literature exist on the approach used for CECE analysis. In summary, BES agreement is excellent in all quantities (fluctuation levels, radial trends, and spectra) whereas CECE agreement is good only in trends and spectra with some quantitative disagreement in fluctuation level.

The experiments studied here were motivated by the validation of multi-Z impurity transport across the plasma radius. To validate the impurity transport predicted by gyrokinetics, predicted impurity profiles, and impurity transport coefficients (D, V) were compared with various measurements or inferences of impurity transport for Li, C, and Ca impurities. Measurements of lithium were obtained using charge exchange spectroscopy following its introduction via the DIII-D powder dropper [12]. The profiles following the lithium introduction were matched via modeling with the Aurora code [13] to determine the impurity peaking profile (V/D). This profile was then compared with predictions from the nonlinear gyrokinetics. Excellent agreement within uncertainties was found across most of the profile, with only slight disagreement around the sawtooth inversion radius. At this location hollow profiles were measured in contrast to the peaked profiles predicted by simulation. Measured carbon profiles were also compared directly with predicted profiles.

These profiles were also in excellent agreement with experiment within the scatter of the data. Although excellent agreement was found in low-Z impurities, mid-Z (Ca) impurities did not exhibit good agreement with experiment. Experimental profiles of D and V were inferred from spectroscopic measurements of Laser Blow-Off (LBO) introduced Ca impurities using the Aurora code. Inside of approximately mid-radius general good agreement was found but outside of this location simulation predicted inward convection which was in contrast to a large outward convection inferred from experiment. The origin of this disagreement is not completely understood but could arise from the dependence of impurity diffusion on the charge, Z in these plasma conditions. Additionally, the role of atomic physics uncertainties likely plays a role but it is difficult to quantify. Further investigations are left for future work.

3 TURBULENCE, TRANSPORT, AND PERFORMANCE IN THE ITER BASELINE SCENARIO

3.1 Prediction and Optimization of ITER Baseline Scenario Plasmas

The successful prediction of kinetic profiles, transport, and fluctuations of the DIII-D ISS conditions, motivated investigation into the ITER baseline scenario. This condition has been studied extensively with a wide range of medium fidelity modeling [14][15][16]. The modeling performed in this work built off of JINTRAC modeling performed in Reference [17] but includes some updates to the pedestal pressure and rotation that were introduced in References [14] and [16]. Our modeling starts with profiles that were derived from TGLF SAT2 modeling described in Reference [16].

The approach used for the profile prediction is nearly identical to that of the DIII-D modeling with a few exceptions. For the ITER conditions, 5 gyrokinetic species were maintained in the simulation: D, T, W, a grouped impurity (Z=5, A=10), and electrons. As with the DIII-D modeling, rotation, realistic geometry, Sugama collisions, and electromagnetic fluctuations were used to simulate ion-scale turbulence. Similar to the DIII-D conditions, the approximation of ion-scale turbulence was justified by the high ion to electron heat flux ratio observed in the power balancing modeling with values of $Q_i/Q_e = 1 - 2$ present across the plasma minor radius. A total of 5 radial locations were simulated corresponding to r/a locations of 0.35, 0.55, 0.75, 0.825, and 0.9 with gradient scale lengths interpolated to zero smoothly inside of the innermost simulated point. The values of kinetic profiles outside of the outermost simulated point are assumed fixed through the analysis. The results of the nonlinear gyrokinetic profile prediction for the IBS condition are plotted in Figure 3. Initial TGLF SAT2 predicted profiles were found to be in quite good agreement with those predicted via CGYRO modeling. However, it is important to point out that this is perhaps not a generic result as previous work has demonstrated more significant disagreements, particularly in the particle channel [3]. Overall, the nonlinear gyrokinetic modeling predicts performance that is in close agreement to the stated mission goals, generating about 498 MW of fusion power with just 53 MW of input power for a total plasma gain ($Q_{plasma} = 9.43$). The energy confinement time of this plasma condition is predicted to be 2.22 seconds which results in an H_{98} value of 0.89, within the 1 sigma uncertainty of the $\tau_{ITER98-y2}$ energy confinement scaling. Once converged profile predictions were obtained, trace He and W impurity species were introduced into nonlinear gyrokinetic simulations to predict potential impurity peaking and transport. The conclusion of this exercise was that no significant impurity peaking in both He ash or W was observed in the 0.35-0.9 range driven by turbulence. This is a generally favorable result for ITER operation as the peaking of W could potentially lead to significant energy losses and thus degrade performance.

One advantage of the surrogate-accelerated profile prediction is that the final trained surrogate models (trained on the nonlinear gyrokinetic simulations) provide information on how of the nonlinear gyrokinetic heat and particle fluxes respond to changes in input gradients. Traditionally, such information is obtained via 1-D parameter scans around a base condition, but in this work is provided for "free" through the completion of the profile prediction. The surrogates indicate a strong dependence of all fluxes on a/L_{T_i} independent of the radial location studied with non-negligible dependence on more traditional TEM drive terms such as a/L_{T_e} and a/L_n at the outermost radii. The overall conclusion of this modeling is that ITG turbulence is the dominant turbulence type present in the IBS conditions. This conclusion has important implications for future modeling, as it sets the scales and fidelity of simulations that are likely needed for accurate profile prediction.

In addition to providing insight into the nature of turbulence, the trained surrogates can be used to rapidly predict variations of the plasma conditions around the IBS. This feature was leveraged to optimize the total

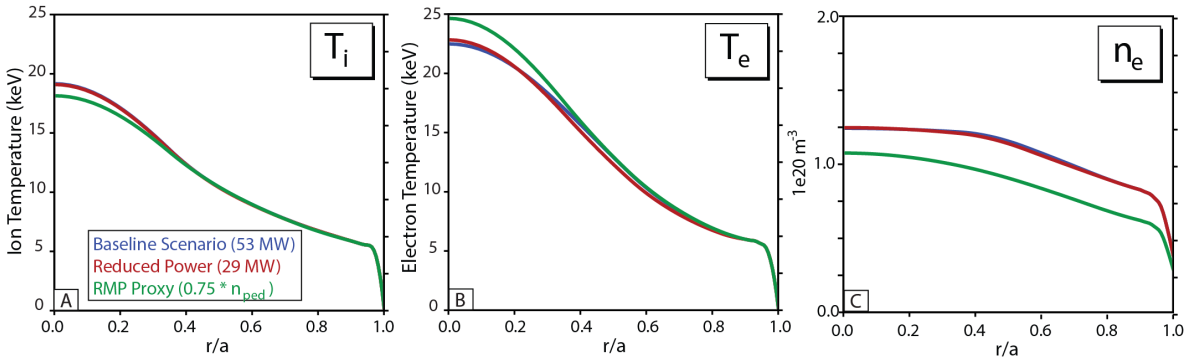

FIG. 3: *Profiles predicted by nonlinear gyrokinetics for the IBS (blue), Q optimized IBS scenario (red) , and RMP proxy (green) conditions are plotted*

plasma gain Q_{plasma} around the ITER baseline conditions. In the predicted IBS profiles found in Figure 3 (blue) , the total power through the scrape off layer (101 MW) is approximately 45% above the L to H threshold predicted for the IBS. This result suggests that, once the IBS conditions are obtained, it might be possible to reduce the total auxiliary input power to increase the fusion gain. To investigate this possibility, we performed another nonlinear gyrokinetic profile prediction with the total auxiliary power dropped from 53 to 29 MW. The modeling assumed that the pedestal conditions were unchanged during this reduction in the input power - motivated by the weak β_N dependence of the pedestal predicted by EPED around the IBS conditions. As shown in Figure 3, plotted in red, the reduction of the total input power was found to result in very little change in the predicted kinetic profiles, with only minimal changes predicted in n_e and T_e and essentially no change predicted in the T_i profile. The lack of change in T_i, although perhaps surprising, is consistent with extremely stiff ITG transport as discussed in the section above. The small changes in the profiles resulted in a very small reduction of the total fusion power (down to 490 MW) and therefore a significant increase in the gain to a value approach Q=17, all while still operating slightly above the L to H threshold.

It is well established that the H-mode pedestal can play a crucial role in reactor performance. Therefore additional investigations were performed looking into the potential impact of RMP ELM suppression on performance. The pedestal conditions studied above were predicted via EPED and therefore are those associated with type I ELMs. ITER will be unable to tolerate such ELMs and it is therefore assumed that ELM suppression may need to be applied to mitigate their effects. To study the potential impact of RMP ELM suppression, we reduced the IBS pedestal density down to 75% of its original value and re-predicted the profiles using nonlinear gyrokinetics. This reduction is roughly in line with observations from DIII-D reported by Evans et al. [18] and starts to give an idea into the potential performance reduction expected with RMPs. The RMP predicted profiles are plotted in Figure 3 in green. With the reduced density, the electron temperature profile increased in the core, and the density profile becomes more peaked due to the change in collisionality. Interestingly, the T_i profile is largely unchanged from the standard IBS condition which is a clear indication of the extremely stiff ITG transport of this condition. The total fusion power predicted in this condition is reduced from the standard IBS conditions to 316MW which results in a Q_{plasma} of approximately 6, still in the burning plasma regime. It is also worth noting that, like the IBS, this condition is still operating well above the L to H threshold which suggests that further gains in Q may be possible by reducing the overall auxiliary input power.

3.2 Prediction of the Isotope Effect in IBS Conditions

The ability to predict kinetic profiles using high fidelity simulation opens up new avenues for comparisons that expand well beyond local quantities into global metrics such as density peaking and global energy confinement. It is well established that in certain regimes, energy confinement is known to increase with the mass of the fuel ions. According to the $\tau_{ITER98-y2}$ scaling, energy confinement should increase as $m^{0.18}$ where m is the mass in amu of the fuel ions. This has obvious benefits for operation in D-T plasma conditions. However, recent theoretical work by Belli et al [19] suggests that conditions dominated by ion turbulence will exhibit a reduced isotope effect compared with those dominated by electron turbulence. To determine whether the turbulence in the core of the IBS conditions would exhibit an increase in confinement with fuel mass, we performed additional simulations of pure H and D plasmas to compare with the existing D-T results. This exercise was performed by assuming a fixed heating profile for each profile prediction (assumed

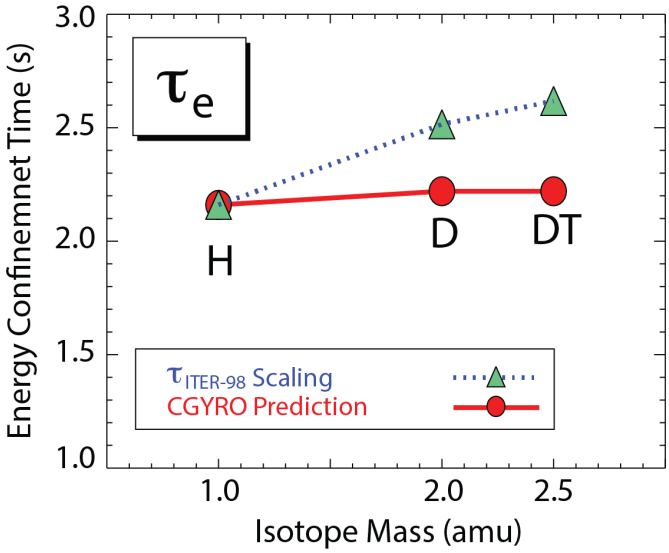

FIG. 4: *Predicted energy confinement times are compared with those expected from the $\tau_{ITER98-y2}$ scaling law.*

unchanged from the converged D-T prediction). With this fixed profile, nonlinear gyrokinetic simulations were used to predict the kinetic profiles. The results of this analysis indicate that D plasmas are statistically indistinguishable from D-T conditions, as the predicted fluxes were identical within the uncertainties. Thus, simulations predicts the profiles between D and D-T plasmas would be unchanged for a fixed heating profile. In contrast, there were differences observed in H plasmas, where the electron temperature was found to drop modestly and the electron density displayed modest changes with a nearly unchanged ion temperature profile. These changes in the profiles resulted in only a minimal decrease in overall energy confinement throughout the isotope scan. The predicted confinement times are plotted in Figure 4. As shown in this figure, there is only an approximately 3% increase in the overall confinement time going from H to D or D-T plasmas. This appears to be in disagreement with and expected $\sim 18\%$ increase in τ_e predicted by the H-mode scaling law. However, it is important to note that recent re-analysis of the H-mode database has derived both new scalings for the mass dependence as well as uncertainties. The work in Reference [20] indicates that the mass scaling is $m^{0.2\pm0.17}$ which would put the gyrokinetic results within the approximate 1σ uncertainty of the scaling. It is important to note that this exercise only evaluates the presence of an isotope effect in the core turbulence and any isotope effect arising in the pedestal would not be captured in this analysis. However, it is clear that these results suggest that core turbulence in the IBS is not predicted to exhibit a significant isotope effect which appears in qualitative agreement with recent theory work [19].

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