CORE PERFORMANCE PREDICTIONS WITH NONLINEAR GYROKINETICS AND IMPLICATIONS TO SCOPE BURNING-PLASMA TOKAMAKS

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Abstract

Surrogate-based techniques as implemented in the PORTALS framework [P. Rodriguez-Fernandez Nucl. Fusion 2023] are used to predict core kinetic profiles and fusion performance in tokamaks directly with nonlinear gyrokinetic simulations. The unprecedented fidelity of the profile predictions (enabled by the use of nonlinear CGYRO for turbulent transport) at a moderate computational cost opens up new pathways for the study of core transport. Predictions of performance in upcoming burning plasmas in SPARC and ITER are used to build confidence in their design and to plan and optimize experimental campaigns. Multi-channel predictions of core kinetic profiles with self-consistent energy exchange are utilized to validate ion scale gyrokinetics in the study of isotope effect in JET Ohmic plasmas. It is found that ion-scale nonlinear CGYRO underpredicts ion transport as the ion mass decreases from tritium to deuterium to hydrogen, which points to the potentially important role of high wavenumber or cross-scale effects in the explanation of isotope effect in JET Ohmic plasmas.

1. INTRODUCTION

Prediction of kinetic profiles in the core of tokamak plasmas requires the simulation of turbulence and neoclassical transport, simultaneously with the evolution of the macroscopic power balance. The large separation of spatiotemporal scales between turbulence and transport makes the direct simulation of the evolution of the full distribution function intractable. So-called flux-matching methods exist that leverage optimization techniques and δf simulations of turbulence to achieve stationary transport conditions. Conventional optimization techniques such as Newton methods were used for this in frameworks such as TGYRO [1], but the computational cost remained prohibitive for routine prediction of multi-channel profiles with nonlinear gyrokinetic codes. The newly developed PORTALS framework [2] leverages Bayesian optimization techniques to achieve flux-matching conditions with a reduced number (usually 12-15) of evaluations of δf nonlinear gyrokinetic codes, opening up

new avenues for the study of core turbulence and transport and the prediction of gradients and performance in fusion devices. In this work, the PORTALS framework is utilized to find flux-matching solutions using the nonlinear CGYRO code [3] with high-fidelity physics.

2. SURROGATE-BASED OPTIMIZATION IN THE PORTALS FRAMEWORK

Surrogate-based or Bayesian optimization refers to the use of surrogate models (usually Gaussian Processes) to aid in the optimization of some metric of interest, in situations where each individual forward evaluation is expensive and black-box in nature. In PORTALS, we aim at minimizing the multi-channel flux residual, i.e., the difference between target fluxes (which includes radiation, energy exchange, alpha heating, and input powers) and transport fluxes (turbulent and neoclassical) at all radii simulated. Simulations start with initial gradient scale length profiles that are varied using a simple relaxation method. This technique, which is run for 5 iterations, provides the initial training database for the Gaussian processes (GPs). The GPs then provide an inexpensive estimation of the nonlinear gyrokinetic fluxes as the input gradients vary and are used to find the next profile to evaluate with CGYRO. This process is repeated, updating the training database after each iteration, until flux matching (steady-state condition) is achieved. Since its inception, this technique has been applied to the study of plasmas in SPARC [2], DIII-D [4], ITER [5], JET [6] and ARC [7], providing the largest database of nonlinear gyrokinetic profile predictions to date.

Further details of how the Bayesian, surrogate-based optimization techniques in PORTALS work, the reader is referred to the original publication in Ref. [2].

3. PREDICTION OF PERFORMANCE OF SPARC BURNING PLASMAS

Burning plasmas in the SPARC and ITER tokamaks were scoped using empirical modelling of the parameter space, a technique that allows for the quick evaluation of performance while keeping track of stability and engineering limits. Physics-based simulations with reduced models such as TGLF [8] and QuaLiKiz [9] had also been performed. However, nonlinear gyrokinetic simulations had never been used to predict core gradients and performance in these plasmas. Predictions of the Primary Reference Discharge (PRD) [10] in SPARC and the ITER Reference Baseline plasma [11] have now been performed with nonlinear CGYRO using PORTALS, employing ELMy H-mode pedestal predictions with EPED as the core boundary condition. It is found that these two scenarios will enable the execution and study of burning plasma conditions in the two D-T machines.

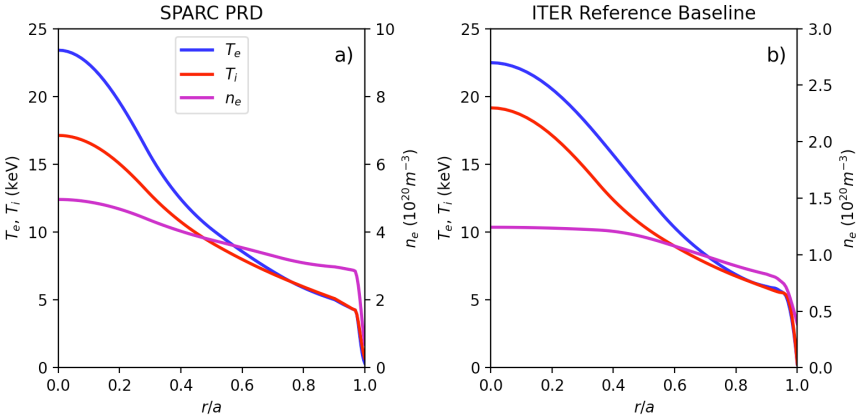

Fig. 1. Predictions of core kinetic profiles in (a) SPARC Primary Reference discharge and (b) ITER Baseline plasma.

An important advantage of using surrogate models to achieve steady-state profiles is that the trained surrogate models can be re-utilized to achieve new converged solutions with variations in heating power or boundary conditions. The re-utilization of surrogates further reduces the number of profile evaluations necessary to achieve a new steady state, often requiring less than 5 extra profile evaluations with nonlinear CGYRO. The SPARC PRD scenario was studied at two different input power levels (nominal, 11MW, and full power, 25MW) leveraging the surrogate re-utilization technique. Simulations reveal that the dominance of stiff ion temperature gradient (ITG) driven turbulence in the core of SPARC results in barely unchanged core profiles when the input power varies. It is also found that empirical scalings of energy confinement and density peaking are exceptionally well captured

by the nonlinear simulations (Fig. 2). This increases our confidence in the design and confirms the benefits of high-field operation in compact devices.

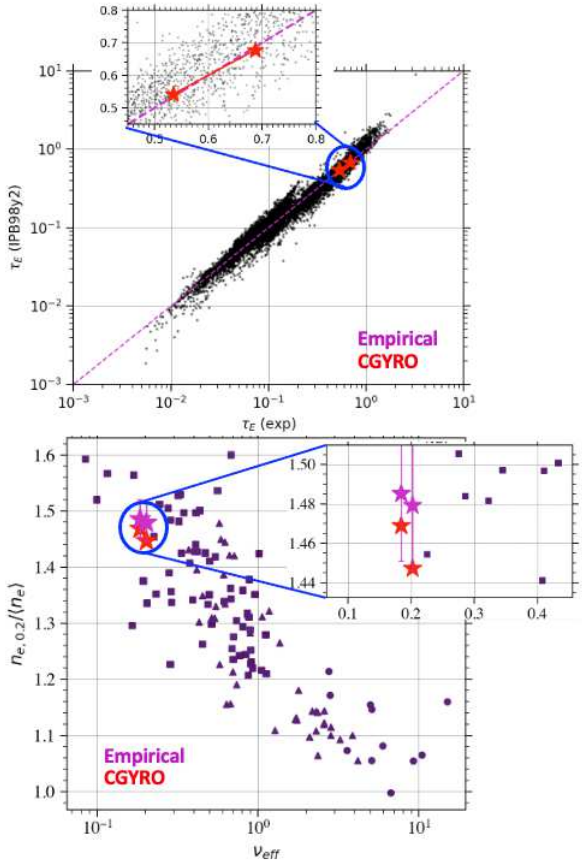

Fig. 2. (top) Energy confinement time and (bottom) density peaking in SPARC. Predictions with first-principles simulations are in remarkable agreement with the empirical scaling laws.

4. STUDY OF THE ISOTOPE EFFECT IN JET OHMIC PLASMAS

The isotope effect in H, D and T Ohmic plasmas in JET ILW [12, 13] has been studied self-consistently by accounting for variations in energy exchange power and plasma parameters, directly with CGYRO turbulent fluxes. In the plasmas of interest, all of the ion heating power comes from energy exchange with the electrons, and therefore the simultaneous simulation of turbulence and transport and the changes in energy exchange is critical to achieve reliable conclusions on the nature of the differences in energy confinement with isotope mass. Predictions show good agreement in the three kinetic profiles (T_e, T_i and n_e) for the tritium plasma, but overprediction of ion temperature occurs as ion mass is reduced, which becomes particularly strong in hydrogen (Fig. 3). This suggests the possibility of medium or high wavenumber effects on turbulent fluxes (not captured by ion-scale turbulence simulations), driven by the smaller separation between ion and electron scales as ion mass is reduced. While this hypothesis cannot be completely confirmed by the results presented here, the high fidelity of the CGYRO simulations and the self-consistent modelling enabled by PORTALS points to this direction of future work with multi-scale simulations of hydrogen plasmas.

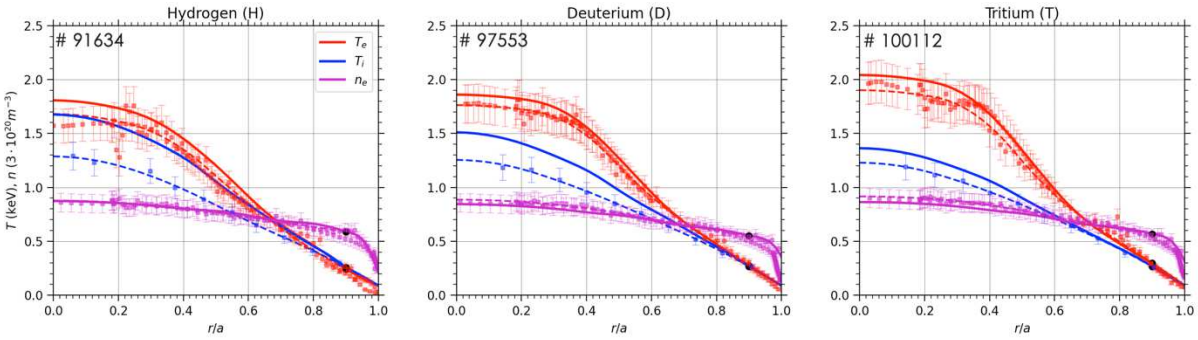

Fig. 3. (solid) Prediction of kinetic profiles in hydrogen, deuterium, and tritium Ohmic plasmas in JET, and compared to (data points) experimental measurements and (dashed) profile fits.

5. CONCLUSIONS

This work has presented the capabilities of the PORTALS framework to study core plasma through the lens of direct nonlinear gyrokinetics for profile predictions. The newly developed technique achieves such speed-up by leveraging a Bayesian optimization workflow applied to the flux-matching problem of multi-channel, δf core transport simulations. This allows the use of high-fidelity turbulent and neoclassical physics along with the evolution of alpha power, energy exchange, and impurity radiation. This is especially important when there is a strong coupling between transport and sources, such as in burning and Ohmic plasmas, a situation that complicates interpretation and prediction in standalone simulations and 1D parameter scans.

It is found that the performance of plasmas in ITER and SPARC are reasonably well captured by empirical and reduced transport modelling, and the attainment of burning plasma conditions in both devices is expected. The dominance of stiff ITG turbulence in the plasma core in both SPARC and ITER leads to minimal changes in kinetic profiles and fusion power when input power varies, which points to low-power operation when it is desired to maximize the fusion gain. Predictions of JET Ohmic plasmas with three hydrogenic isotopes reveal that profiles predicted with ion-scale simulations are in good agreement with experimental measurements with high isotope mass (tritium), but the agreement gets worse as the mass is decreased to deuterium and further to hydrogen.

In summary, this work presents a new tool that allows the execution of core profile predictions directly with nonlinear gyrokinetic simulations, an important step towards more complete validation studies of turbulence and more reliable predictions of burning plasmas and fusion pilot plants.

ACKNOWLEDGEMENTS

This work was funded by Commonwealth Fusion Systems under RPP005 and RPP020, and U.S. Department of Energy Award Nos. DE-SC0017992, DE-SC0014264 and DE-AC05-00OR22725. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02-05CH11231 using NERSC awards FES-ERCAP0023083 and FES-ERCAP0023083, and the Engaging cluster at the MGHPCC facility which was funded by Award No. DE-FG02-91-ER54109.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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