A LOW-COST GYROKINETIC CODE FOR INTERPRETIVE TRANSPORT ANALYSIS OF TOKAMAK EXPERIMENTS

[1]R. HAGER, [1]S. KU, [1]J. DOMINSKI, [1]G. WILKIE,[1]A. MOLLEN, [1]C.S. CHANG

[1]Princeton Plasma Physics Laboratory, Princeton, NJ, USA

Email: rhager@pppl.gov

The X-point Gyrokinetic Code (XGC) [1, 2, 3], which has been known so far primarily for high-fidelity tokamak edge turbulence simulations, now enables low-cost axisymmetric gyrokinetic transport analysis workflows that can be used for present-day experiments, ITER operation scenario development, and in the design and optimization of fusion reactors such as Fusion Pilot Plants (FPPs). We demonstrate and verify an interpretive transport analysis workflow with XGC using a set of thoroughly analyzed DIII-D discharges [6].

With the recently renewed interest from governments and private companies in nuclear fusion for energy production, it has become an essential challenge to provide powerful state-of-the-art tools for transport analysis with fast time-to-solution for, e.g., interpreting experimental measurements, predicting wall heat loads for given plasma profiles, or even predicting steady state profiles. Due to the relatively long time scales that have to be simulated, fluid codes (e.g. SOLPS-ITER [4]) or a combination of gradient-driven gyrokinetic codes (or quasi-linear turbulence models) and fluid transport codes (e.g. GX-Trinity, GENE-Tango, TGYRO) have long been the methods of choice for transport analysis applications. While they are widely used, these approaches have inherent limitations in both physics fidelity and time-to-solution (e.g., Ref. [5]).

For edge and scrape-off layer (SOL) modeling, axisymmetric gyrokinetic simulation with anomalous transport models is a practical higher-fidelity alternative to widely used fluid codes. The axisymmetric limit of the total-f gyrokinetic method used in XGC is a first-principles description of neoclassical physics. Kinetic effects like trapped particle dynamics, $E \times B$ and ∇B drifts, bootstrap current, the Ohmic current, Ware pinch, ion orbit loss, and parallel and perpendicular (neoclassical) transport are reproduced without relying on any of the approximations required to derive closures for fluid equations. Interpretive transport analysis with XGC is enabled by its broad array of physics features: realistic divertor geometry, a simulation domain from the magnetic axis to the inner material wall, a nonlinear Fokker-Planck collision operator, particle, heat and torque sources, impurity radiation cooling, neutral particle recycling consistent with the wall particle load, a dynamically adjusted loop voltage to match the MHD equilibrium current, an anomalous transport model, and impurity species with multiple charge states. Since XGC is a modern, modular code, adding new capabilities is straightforward.

Due to the numerical efficiency and portability acquired through SciDAC projects and the Exascale Computing Project, axisymmetric XGC simulations require only a fraction ($\lesssim 1\%$) of the computing resources required for self-consistent total-f simulations with micro-turbulence. For example, a millisecond-long axisymmetric simulation of a DIII-D-sized tokamak requires only 6-12 hours of wallclock time on about 16 GPU accelerated compute nodes of a modern capacity computing cluster like NERSC's Perlmutter. Some of XGC's physics features can be accelerated even more using AI/ML surrogate models. This makes axisymmetric XGC simulations accessible to a much wider group of users (compared to total-f turbulence simulations). And while not as fast as the fastest reduced models or fluid codes, XGC's turnaround time for axisymmetric simulations enables its use in FPP design and optimization workflows when higher fidelity than provided by fluid models is required.

We verify XGC's transport analysis capabilities using a set of thoroughly studied DIII-D H-mode discharges with ITER-similar shape that show that the fraction of the ion heat flux driven by turbulence increases significantly when the collisionality decreases [6]. We employ an interpretive transport workflow with the goal of identifying the anomalous transport fluxes that are consistent with the measured profiles of plasma density, temperature and toroidal rotation. In this setup, XGC solves the gyrokinetic Vlasov-Poisson system of equations with axisymmetric electrostatic potential, collisions, and sources. The sources are: neutral recycling with ionization and charge exchange calculated self-consistently with the parallel ion flux incident on the material wall; generic heat and torque sources to account for neutral beams and other heating methods; a loop voltage that is dynamically adjusted such that the sum of the bootstrap current density (which is calculated self-consistently in XGC) and the Ohmic current density matches the MHD equilibrium current; and anomalous transport perpendicular to the flux-surfaces given by a set of advection-diffusion equations for the density, parallel linear momentum, and temperature.

The anomalous transport fluxes are then defined through particle diffusivity D and pinch velocity v_p, and momentum and heat diffusivities μ and χ. XGC is initialized with the experimentally measured plasma density, temperatures, and toroidal rotation rates, and with an initial guess for the transport coefficients D, v_p, μ, and χ

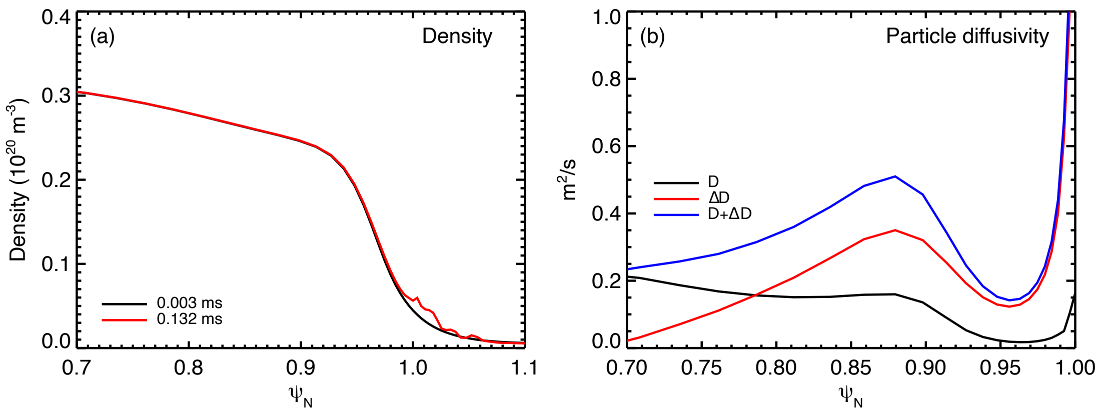

FIG. 1: (a) Time evolution of the density in XGC with diffusivity $D(\psi)$. (b) Steady state correction $\Delta D(\psi)$ assuming $v_p = 0$.

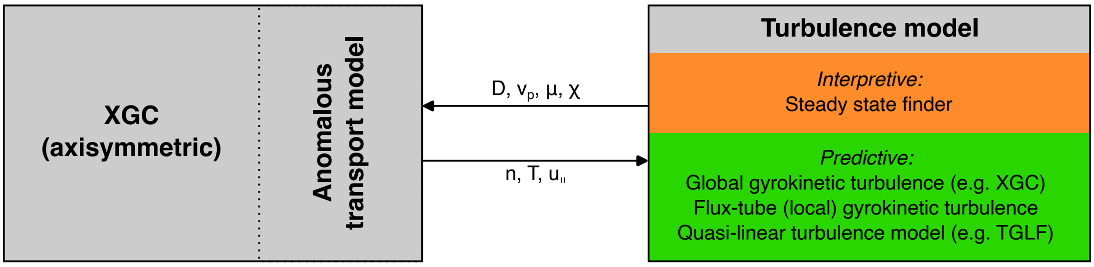

FIG. 2: An open interface to the anomalous transport model in XGC enables coupling to various turbulence models for interpretive and predictive workflows.

that can be obtained, e.g., from a prior TRANSP simulation. Based on the time evolution of the density, parallel mean flow, and temperature in the XGC simulation, a transport optimizer periodically calculates adjustments to the transport coefficients until they balance between neoclassical transport, recycling, and heat and torque sources, and a steady state is reached. Figure 1 shows an example of one iteration under the assumption $v_p = 0$. This approach is similar to earlier work with the drift-kinetic code XGC-0 [7], a predecessor of the current gyrokinetic XGC. However, the current implementation offers much more comprehensive neoclassical physics, and automated adjustment of the transport coefficients.

While the workflow used in this work is purely interpretive, predictive workflows using axisymmetric XGC simulations are possible by setting the anomalous transport coefficients based on XGC simulations with self-consistent turbulence, flux-tube gyrokinetic simulations, or quasi-linear turbulence models such as TGLF (see Fig. 2). Such predictive workflows could be applied for example in simulations of an ELM cycle (together with MHD codes), or for predicting SOL plasma profiles for radio-frequency antenna design.

ACKNOWLEDGEMENTS

This work is supported by the US Department of Energy (DOE) under the contract DE-AC02-09CH11466 via the SciDAC-5 projects CEDA and CETOP. Computing resources: ERCAP award at NERSC (DE-AC02-05CH11231). Thanks to D. Ernst for helping with TRANSP data.

REFERENCES

[1] S. Ku *et al.*, OSTI DOE Code, doi: 10.11578/DC.20180627.11062301 (2018),
[2] S. Ku *et al.*, Phys. Plasmas **25**, 056107 (2018),
[3] R. Hager *et al.*, Phys. Plasmas **29**, 112308 (2022),
[4] S. Wiesen *et al.*, Journal of Nuclear Materials **463**, 480-484 (2015),
[5] I. Veselova *et al.*, Nuclear Materials and Energy **26**, 100870 (2021),
[6] S. Haskey *et al.*, Phys. Plasmas **29**, 012506 (2022),
[7] D. J. Battaglia *et al.*, Phys. Plasmas **21**, 072508 (2014).