NEURAL NETWORK-ASSISTED ELECTROSTATIC GLOBAL GYROKINETIC TOROIDAL CODE USING CYLINDRICAL COORDINATES

[1]ANIMESH KULEY, [1]JAYA KUMAR ALAGESHAN, [1]JOYDEEP DAS, [1]TAJINDER SINGH, [2,3]SARVESHWAR SHARMA

[1]Department of Physics, Indian Institute of Science, Bangalore 560012, India
[2]Institute for Plasma Research, Bhat, Gandhinagar 382428, India
[3]Homi Bhabha National Institute, Anushaktinagar, Mumbai, Maharashtra 400094, India

Email: akuley@iisc.ac.in

Gyrokinetic simulation codes are essential for understanding microturbulence in both the linear and nonlinear regimes of the tokamak and stellarator cores. These codes often employ flux coordinates to mitigate computational complexities arising from the anisotropic nature of confinement magnetic fields. However, this approach encounters a mathematical singularity in the metric at the magnetic separatrix surface and the X-point [1].

To overcome this constraint, we develop a neural network-assisted *Global Gyrokinetic Code using Cylindrical Coordinates* (G2C3) for studing electrostatic microturbulence in realistic tokamak geometries. In particular, G2C3 uses a cylindrical coordinate system for particle dynamics, which allows particle motion in arbitrarily shaped flux surfaces, including the magnetic separatrix of the tokamak. To enhance computational efficiency, we utilize a hybrid particle-locating scheme that combines a neural network with an iterative local search algorithm for charge deposition and field interpolation. Furthermore, G2C3 leverages numerically integrated field lines to train the neural network in universal function approximator mode to speed up the subroutines related to gathering and scattering operations of gyrokinetic simulation. Finally, to verify the accuracy and capabilities of the new code, we present self-consistent simulations of linear ion temperature gradient modes in the core region of the DIII-D and ADITYA-U tokamaks [2].

Beyond the core region, microturbulence and associated transport in the scrape-off layer (SOL) of tokamaks plays a crucial role in the steady-state operation of ITER and future fusion reactors. It also regulates the heat load on the diverter, plasma shaping effect, impurity accumulation and sheath physics. A detailed understanding of the turbulence and transport in SOL is an open problem. Most importantly, multiple temporal and spatial scales and different energy sources in the SOL region, in addition to its complex and open field line geometry, make this region computationally extremely challenging. Currently, SOL modelling relies on fluid and gyro-fluid codes based on the Braginskii equation, such as UEDGE, SOLPS, and BOUT++. However, experimental observations demonstrate that kinetic effect could play a significant role in several essential physics such as ion orbit loss, X-point loss, plasma sheath dynamics, nonlocal turbulent transport, parametric decay instabilities, etc. Additionally, diagnosing the SOL region is particularly challenging, making global gyrokinetic simulations a powerful tool for gaining meaningful insights into present and future fusion devices.

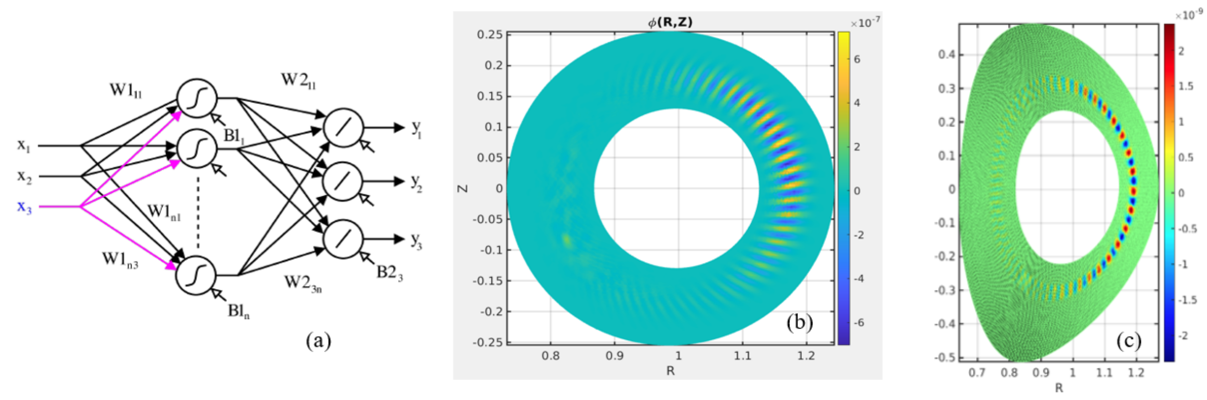

Figure 1: (a) Three layers of vanilla neural network. For training the parallel projection module and triangle locator, we used dataset sizes of 7.5×10^5. 2D poloidal mode structure of linear electrostatic modes for ADITYA-U (middle) and DIII-D tokamak (right).

To address the challenges associated with flux-coordinate-based gyrokinetic codes, as discussed above, we have developed G2C3, a code in a similar spirit to XGC, GTC-X [3] and TRIMEG. These codes, like G2C3, are PIC codes based on fundamental cylindrical coordinates. A key challenge for gyrokinetic codes using cylindrical coordinates is the computational cost of field-aligned gather and scatter operations, which increases with machine size and numerical resolution. Different approaches have been adopted to mitigate this issue: TRIMEG employs PIC-PIF schemes, which are computationally efficient but restricted to a single mode number. XGC improves accuracy by incorporating more poloidal cross-sections, thereby reducing the numerical diffusion of particle weights on flux surfaces. In contrast, G2C3 uses an efficient supervised multilayer vanilla neural network to efficiently perform gather and scatter operations along the field lines, using the training data obtained from the numerical integration of field line geometry very accurately. Additionally, we have extended our hybrid neural network module and iterative particle-locating scheme, in addition to the commonly used box scheme, enabling particle localization in the poloidal domain. However, for the open field line region, the box scheme will be more beneficial due to the complexity of geometry.

As a testimony of G2C3's capability to reproduce existing physical phenomena, we have conducted self-consistent global linear simulations of the ion temperature gradient (ITG) mode in the core region of the DIII-D shape plasma and medium-sized limiter-based ADITYA-U tokamaks with circular plasma and considering adiabatic electrons. In this study, we considered realistic magnetic geometries of ADITYA-U (shot #33689) and DIII-D (shot #158103) using cyclone-based plasma profiles, as shown in Figure 1. We used 100 radial grid points, 550 poloidal grid points, 32 parallel grid points, and 32 million marker particles for these simulations. Since ITG activity near the magnetic axis is minimal, we performed the simulation in the annular region. We used dataset sizes to train the parallel projection module and triangle locator 7.5×10^5. The stochastic gradient descent optimizer was employed with a quadratic loss function. The parallel neural network module achieved convergence within 1%, while the triangle locator network successfully predicted the triangle within the next nearest neighbours, with final corrections applied through a hybrid iterative scheme. As a part of the cross-validation of our code, we compared our results with the well-established *Gyrokinetic Toroidal Code* (GTC) [4-5]. Despite these tokamaks' different operational temperature regimes and geometry differences, G2C3 successfully demonstrated its versatility, handling simulations across different tokamak regimes.

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REFERENCES

[1] M. OTTAVIANI, "An alternative approach to field-aligned coordinates for plasma turbulence simulations", Physics Letters A 375 (2011) 1677–1685.

[2] JAYA KUMAR ALAGESHAN, JOYDEEP DAS, TAJINDER SINGH, SARVESHWAR SHARMA, ANIMESH KULEY, "Neural network assisted electrostatic global gyrokinetic toroidal code using cylindrical coordinates", https://arxiv.org/abs/2408.12851

[3] S. DE, T. SINGH, A. KULEY, J. BAO, Z. LIN, G. Y. SUN, S. SHARMA, A. SEN, Kinetic particle simulations in a global toroidal geometry, Phys. Plasmas **26**, 082507 (2019). https://doi.org/10.1063/1.5108684

[4] TAJINDER SINGH, DEEPTI SHARMA, TANMAY MACWAN, SARVESHWAR SHARMA, JOYDEEP GHOSH, ABHIJIT SEN, ZHIHONG LIN, AND ANIMESH KULEY "Gyrokinetic simulation of electrostatic microturbulence in ADITYA-U tokamak", Nuclear Fusion **63**, 056008 (2023). https://doi.org/10.1088/1741-4326/acc344

[5] TAJINDER SINGH, KAJAL SHAH, DEEPTI SHARMA, JOYDEEP GHOSH, KUMARPALSINH A. JADEJA, RAKESH L. TANNA, M. B. CHOWDHURI, ZHIHONG LIN, ABHIJIT SEN, SARVESHWAR SHARMA, ANIMESH KULEY, "Gyrokinetic simulations of electrostatic microturbulence in ADITYA-U tokamak with argon impurity", https://doi.org/10.1088/1741-4326/ad5a20