VALIDATION OF GKEYLL GYROKINETIC TURBULENCE SIMULATIONS AGAINST TCV EXPERIMENTAL DATA AND TRIANGULARITY PHYSICS

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Understanding and characterizing turbulence in tokamak plasmas remains a critical challenge, with significant implications for reducing the cost of future commercial fusion devices. Experiments conducted on the Tokamak à Configuration Variable (TCV) [1], followed by studies on DIII-D [2] and ASDEX Upgrade [3], have shown that negative triangularity (NT)—a plasma shape with the triangle pointing toward the tokamak's symmetry axis—can substantially suppress turbulence in L-mode. Notably, NT configurations often achieve H-mode-like ion core pressure without requiring a pedestal, thus avoiding the risk of vessel-damaging edge localized modes (ELMs) and allowing highly radiative configurations, which reduces the divertor heat load substantially [4].

Microscale turbulence are challenging to measure experimentally, making numerical simulations essential for understanding the interaction between triangularity and transport. While fluid models successfully capture NT's impact at the hydrodynamic scale [5–6], recent gyrokinetic (GK) studies [7–9] indicate that a substantial part of NT's transport reduction also occurs at the ion gyro-radius scale. These microinstabilities are highly sensitive to triangularity but require computationally intensive GK simulations for analysis. Most current GK studies focus on core-region fluctuations, leaving experimentally relevant open-field line simulations largely unexplored.

This work presents the first validation test of flux-driven GK simulations of the edge and scrape-off layer (SOL) of NT discharge in TCV. Unlike previous studies, our simulations self-consistently evolve plasma turbulence by solving the long-wavelength full-f GK equations in a global geometry that includes both closed and open field lines. This setup enables a high-fidelity evolution of the last closed flux surface (LCFS) region, where energy flows from a source located in the closed field line region – adjusted to match the experimental input power and temperature – to the SOL, where conducting sheath boundary conditions are applied at the limiter position. Such simulation setup is made possible by the state-of-the-art Gkeyll code [10–11], which uses an energy-preserving discontinuous Galerkin method using field-aligned coordinates. Gkeyll is used to solve a wide range of problems, including astrophysical plasma dynamics and general relativity [12-13]. For tokamak turbulence simulation, Gkeyll can evolve milliseconds of plasma dynamics with kinetic electrons and ions in only a few hundred GPU hours. This work leverages the recent implementation on twist-and-shift boundary conditions for the core region [14] and is built upon pioneering simulations of NT discharges in DIII-D [15].

Figure 1 illustrates a comparison of a Gkeyll simulation with TCV discharge #65130 in a limited configuration. The simulation domain encompasses flux surfaces of radii r spanning both closed field lines ($r < a$) and open field lines ($r > a$), with a the minor radius of the toroidal magnetic equilibrium. Profiles are averaged over the final millisecond of a 4 ms 5D GK turbulence simulation, performed with a 0.45 MW source input power – localized in the buffer region, $r/a < 0.9$ – and a Miller magnetic equilibrium model. The Gkeyll predictions closely match experimental data near the LCFS ($r \sim a$) and within the SOL, demonstrating the code's capability to capture edge physics accurately.

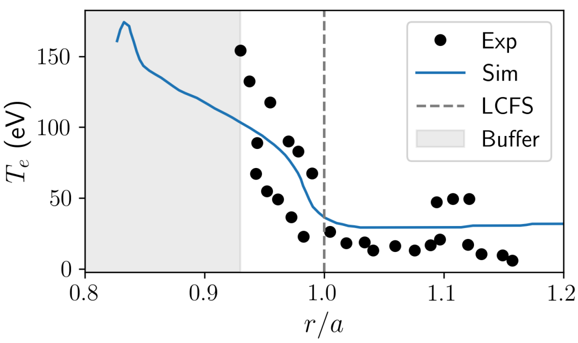

Fig. 1: *Electron temperature profile obtained with Thompson and Langmuir probe data in TCV shot #65130 (black dots) and time averaged profile obtained with Gkeyll turbulence simulation. The resolution is 48x32x16x12x6 DG cells with 32 basis functions per cell and ran during 144h on 4 GPUs on Perlmutter.*

The magnetic equilibrium geometry of a similar TCV discharge (#65125) with positive triangularity (PT) allows a direct comparison to assess whether Gkeyll reproduces the improved confinement observed in NT configuration. Experimentally, NT yields a ~15% increase in electron temperature and density profiles compared to PT. This enhancement, accurately reproduced by Gkeyll simulations, is attributed to the formation of an internal transport barrier (ITB) in NT near the LCFS, as illustrated in Fig. 2. Additionally, the ITB is located close to a $q = 2$ flux surface, consistent with observations reported in [7].

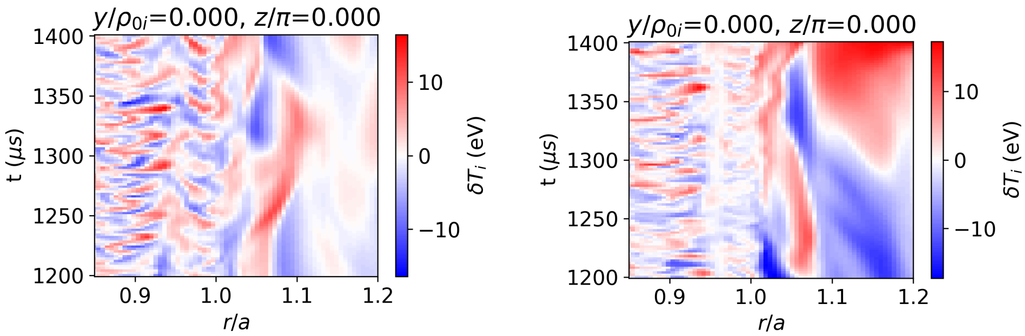

Fig. 2: *Time evolution of the ion temperature profile fluctuation at the outboard midplane during the quasi-steady state for PT (left) and NT (right) configurations. A strong reduction of turbulence is observed in the NT simulation at* $r/a{\sim}0.96$.

This work highlights the capability of the GK model to reproduce key experimental observations in the edge and SOL region. Leveraging the Gkeyll code, we uncover the microscale turbulent dynamics responsible for the improved confinement observed in TCV NT discharge, advancing our understanding of turbulence-driven transport in tokamak plasmas. These results demonstrate the potential of using numerical tools like Gkeyll to complement experimental studies and guide future efforts to optimize plasma performance in fusion devices.

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REFERENCES

[1] S. Coda et al., Enhanced confinement in diverted negative-triangularity L-mode plasmas in TCV, Plasma Phys. and Control. Fusion **64** (2022) 014004.

[2] M. Austin et al., Achievement of reactor-relevant performance in negative triangularity shape in the DIII-D tokamak, Physical Review Letters **122** (2019) 115001.

[3] T. Happel et al., Overview of initial negative triangularity plasma studies on the ASDEX Upgrade tokamak, Nuclear Fusion **63** (2023) 016002..

[4] M. Miller et al., Power handling in a highly-radiative negative triangularity pilot plant. Plasma Phys. and Control. Fusion **66** (2024) 125004.

[5] L. Aucone et al., Experiments and modelling of negative triangularity ASDEX Upgrade plasmas in view of DTT scenarios, Plasma Phys. Control. Fusion **66** (2023) 075013.

[6] K. Lim et al., Effect of triangularity on plasma turbulence and the SOL-width scaling in L-mode diverted tokamak configurations, Plasma Phys. Control. Fusion **65** (2023) 085006.

[7] A. Balestri et al., Experiments and gyrokinetic simulations of TCV plasmas with negative triangularity in view of DTT operations, Plasma Phys. Control. Fusion **66** (2024) 065031.

[8] G. Di Giannatale et al., System size scaling of triangularity effects on global temperature gradient-driven gyrokinetic simulations,. Plasma Phys. Control. Fusion **66** (2024) 095003.

[9] A.C.D. Hoffmann et al., Investigation of triangularity effects on tokamak edge turbulence through multi-fidelity gyrokinetic simulations. 2025 Plasma Phys. Control. Fusion **67** (2025) 015031.

[10] A. Hakim, The Gkeyll code: Documentation Home (2022), https://gkeyll.readthedocs.io/

[11] J. Juno et al., Discontinuous Galerkin algorithms for fully kinetic plasmas. Journal of Comp. Phys. **353** (2018) 110-147.

[12] J. Gorard et al., A tetrad-first approach to robust numerical algorithms in general relativity. arXiv (2024) 2410.02549.

[13] S. Conley et al., The kinetic analog of the pressure-strain interaction. Phys. of Plasmas 31 (2024) 122117.

[14] M. Francisquez et al., Conservative discontinuous Galerkin interpolation: sheared boundary conditions, Computer Physics Communications **298** (2024) 109109.

[15] T. N. Bernard et al., Plasma edge and scrape-off layer turbulence in gyrokinetic simulations of negative triangularity plasma,. Plasma Phys. Control. Fusion **66** (2024) 115017.