GLOBAL GYROKINETIC SIMULATION OF ELECTROSTATIC MICROTURBULENT TRANSPORT IN ADITYA-U

ANIMEH KULEY and TAJINDER SINGH
Department of Physics, Indian Institute of Science Banglaore-5600112, India
Email: akuley@iisc.ac.in

SARVESHWAR SHARMA, JOYDEEP GHOSH, ABHIJIT SEN
Institute for Plasma Research, Bhat, Gandhinagar 382428, India
Homi Bhabha National Institute, Anushaktinagar, Mumbai, Maharashtra 400094, India

ZHIHONG LIN
Department of Physics and Astronomy, University of California Irvine, California 92697, USA

Abstract

A first-principles global gyrokinetic simulation of the electrostatic microturbulence driven by the pressure gradients of thermal ions and electrons is carried out for the ADITYA-U tokamak geometry using experimental plasma profiles with collisional effects. The dominant instability is determined to be trapped electron mode (TEM) based on the linear eigenmode structure and its propagation in the electron diamagnetic direction. The turbulent transport level of ion diffusivity determined by the nonlinear simulations is found to match well with the experimentally measured value of ~ $0.2m^2$ /sec. The frequency spectrum of the electrostatic fluctuations, with a broadband from 0 to ~ 50kHz, is also found to be in good agreement with the experimentally recorded spectrogram in ADITYA-U.

1. INTRODUCTION

Microturbulent transport, such as ion temperature gradient (ITG) and trapped electron mode (TEM), will play an essential role in the overall confinement of the plasmas. The design and construction of future machines depend upon the extrapolated turbulent transport level of the present experimental observations. Due to the enormous advancement of supercomputing power, sophisticated numerical tools, and simulation models, accurate modelling and prediction of the turbulent transport level help to understand and validate the experimental observations. ADITYA-U is a medium-sized tokamak with a major radius of 75cm, a minor radius of 25cm and on-axis magnetic field of 1.44T [1]. In this work, we have considered discharge (shot # 33536) with hydrogen plasma in a limiter configuration. In this experiment, transport coefficients related to the fluctuations are measured near the edge region and observed broad frequency spectrum. The plasma equilibrium is constructed with the IPREQ code. In keeping with the ITER's future operation, many experiments are carried out related to transport, runaway electrons, plasma disruptions, impurity transport, plasma detachment etc. However, there are very few realistic simulation studies on ADITYA-U tokamak. The present work is the first-ever simulation study to understand turbulence and transport in ADITYA-U using GTC [2].

GTC uses the field-aligned coordinate system to study the magnetically confined plasma with nested flux surfaces. GTC is applied to study the physics of microturbulent transport [2], Alfven waves [3], energetic particles [4] and radio frequency waves [5-8]. Recently, GTC has been extended to 3D non-axisymmetric systems such as W7-X and LHD stellarators [9] and field reverse configuration [10] to understand microturbulent transport. In this work gyrokinetic ion and fluid kinetic electron model are used to capture the turbulent transport of ADITYA-U tokamak. Fokker–Planck collision operator for the collisions between like species and Lorentz pitch angle scattering operator for the collisions between unlike species, are implemented where the momentum and energy conservation are enforced on the neo-classical mesh.

We have carried out the linear electrostatic simulation for the plasma profile of discharge number 33536 and found that the dominant mode propagates in the electron diamagnetic direction, describing that the TEM turbulence is unstable. Fig. 1 shows the contour plot of the electrostatic potential at the linear phase of the simulation at t= $3.5R_0/C_s$. Fig. 2 shows the contour plot of the electrostatic potential in the nonlinear phase at t= $9.5R_0/C_s$ with Zonal flow (left) and without zonal flow (right).

The role of zonal flow in regulating turbulence and transport is carried out in this work. It is found that zonal flow does not play an important role in regulating turbulence. Electrostatic potential, ion diffusivity and electron heat conductivity show similar saturation levels in the presence and absence of the zonal flow. This phenomenon is consistent with the previous observations from different gyrokinetic codes.

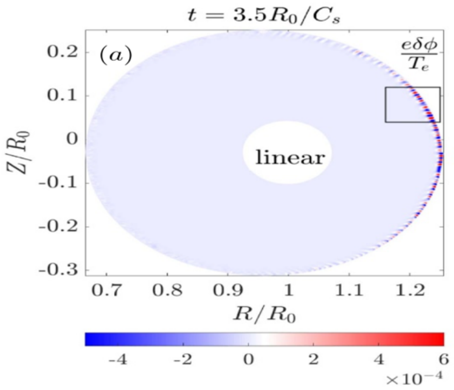

Fig. 1 The electrostatic perturbed potential on the poloidal plane in the linear phase at time t = $3.5R_0/C_s$.

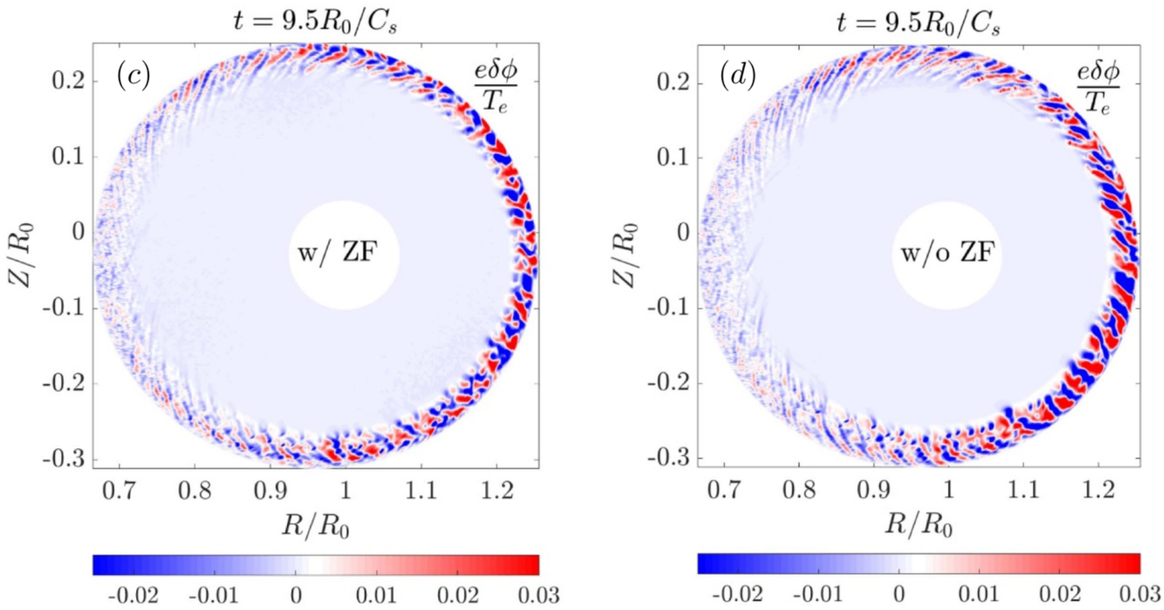

Fig. 2 The electrostatic potential in the nonlinear phase at time t = $9.5R_0/C_s$ with zonal flow (left), and without zonal flow (right).

In this case, the saturation of the transport level is governed by the inverse cascade of the higher toroidal and poloidal number to the lower one [cf. Fig.3]. This result is supported by the earlier observation of the earlier work [9]. The dominant eigenmode has n=73, m=272 with a growth rate of $2.98C_s$/R0 and real frequency $2.79C_s/R_0$.

In this simulation, we have considered the collision and found that the collision reduces the growth rate of the dominant mode and the electrostatic fluctuation due to the de-trapping of electrons. Typically, collision stabilises TEM, but TEM is still unstable due to lower collision frequency.

Fig.4 compares the frequency spectrum of the electrostatic fluctuation near the last close flux surface of the outer mid-plane. The experimentally measured spectrum of the electrostatic fluctuation shows a broad spectrum from ~0 to 50 kHz (red), which agrees well with the calculation of ADITYA-U tokamak's gyrokinetic simulations (blue) using GTC. The ion diffusivity near the last close flux surface is found to be 0.2 m^2/s from the GTC simulation, which is found to agree well with the experimental observations and cross-checked with UEDGE code. The estimate of the heat conductivity obtained from the experiment is 1.5 m^2/s, which is within 20% of the simulation result. All these findings demonstrate that TEM-driven turbulence is a dominant channel of turbulent transport in ADITYA-U tokamak.

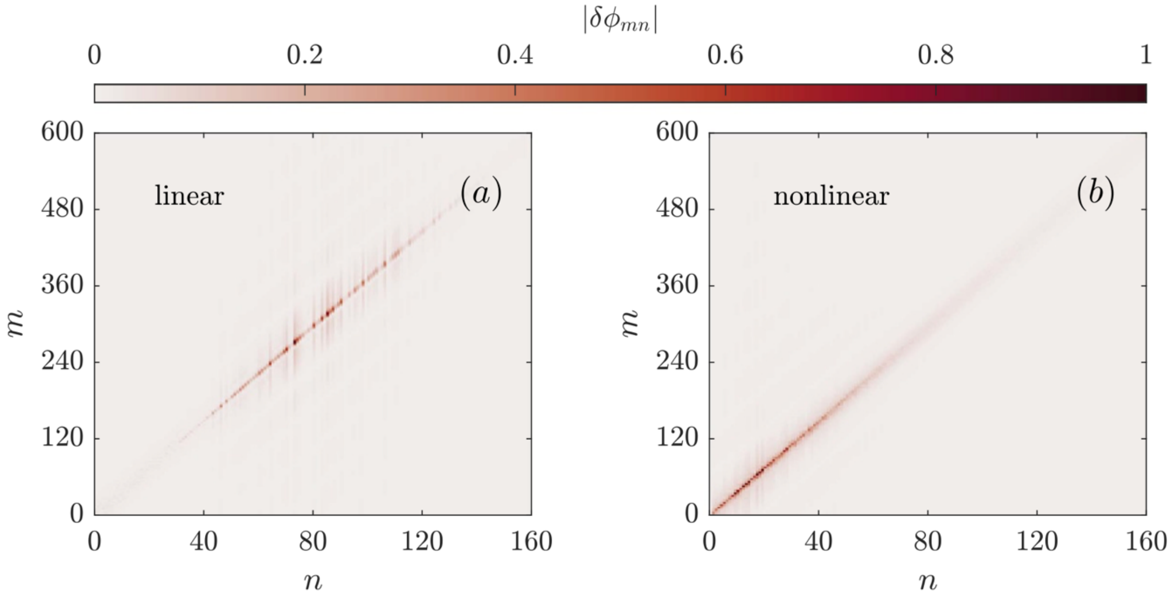

Figure 3. The 2D spectrum of the electrostatic potential on the flux surface ψ = 0.98 in the linear phase at time t = $3.5R_0/C_s$ (a) and in the nonlinear phase averaged over times t ∈ $[10,15]R_0/C_s$ (b).

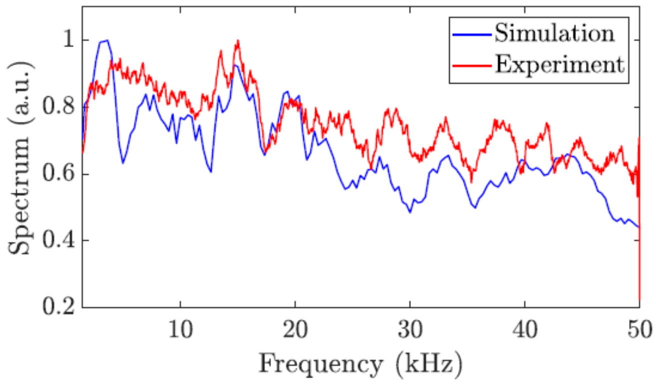

Fig. 4: The comparison of the spectra of the electrostatic fluctuations from simulation (blue) and experiment (red) near the LCFS.

TABLE 1. Comparison of the transport from the experiment with the simulations near last close flux surface

m^2/s	Experiment	Simulation
Ion diffusivity	0.2	0.25
Electron-heat conductivity	1.5	1.20

ACKNOWLEDGEMENTS

This work is supported by National Supercomputing Mission (NSM) (Ref. No.: DST/NSM/R&D_HPC_Applications/2021/4), Board of Research in Nuclear Sciences (BRNS Sanctioned No. 39/14/05/2018-BRNS), Science and Engineering Research Board EMEQ program (SERB sanctioned No. EEQ/2017/000164) and Infosys Young Investigator award and US DOE SciDAC ISEP Center. The results presented in this work have been simulated on ANTYA cluster at Institute of Plasma Research, Gujarat, India, and SahasraT, Param Pravega supercomputers at Indian Institute of Science, Bangalore, India.

REFERENCES

[1] R. L. TANNA et al., "Overview of recent experimental results from the ADITYA-U tokamak", Nuclear Fusion, 62 042017 (2022).

[2] 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

[3] Z. X. WANG, Z. LIN, W. J. DENG, I. HOLOD, W. W. HEIDBRINK, Y. XIAO, H. S. ZHANG, W. L. ZHANG, M. A. VAN ZEELAND, "Properties of Toroidal Alfven Eigenmode in DIII-D Plasma", Phys. Plasmas **22**, 022509 (2015).

[4] S. TAIMOURZADEH, E. M. BASS, Y. CHEN, C. COLLINS, N. N. GORELENKOV, A. KONIES, Z. X. LU, D. A. SPONG, Y. TODO, M. E. AUSTIN, J. BAO, A. BIANCALANI, M. BORCHARDT, A. BOTTINO, W. W. HEIDBRINK, Z. LIN, R. KLEIBER, A. MISHCHENKO, L. SHI, J. VARELA, R. E. WALTZ, G. YU, W. L. ZHANG, AND Y. ZHU, "Verification and validation of integrated simulation of energetic particles in fusion plasmas", Nuclear Fusion **59**, 066006 (2019).

[5] ANIMESH KULEY, Z. X. WANG, Z. LIN, AND F. WESSEL, "Verification of particle simulation of radio frequency waves in fusion plasmas", Phys. Plasmas **20**, 102515 (2013).

[6] J. BAO, Z. LIN, A. KULEY, AND Z. X. LU, "Particle simulation of lower hybrid wave propagation in fusion plasmas", Plasma Phys. Contr. Fusion **56**, 095020 (2014).

[7] A. KULEY, Z. LIN, J. BAO, X. S. WEI, Y. XIAO, W. ZHANG, G. Y. SUN, AND N. J. FISCH, "Verification of nonlinear particle simulation of radio frequency waves in tokamak", Phys. Plasmas **22**, 102515 (2015).

[8] J. BAO, Z. LIN, A. KULEY, AND Z. X. WANG, "Electromagnetic particle simulation of toroidal effects on linear mode conversion and absorption of lower hybrid waves", Nuclear Fusion **56**, 066007 (2016).

[9] TAJINDER SINGH, JAVIER H NICOLAU, ZHIHONG LIN, SARVESHWAR SHARMA, ABHIJIT SEN, and ANIMESH KULEY, "Global gyrokinetic simulations of electrostatic microturbulent transport using kinetic electrons in LHD stellarator" Nuclear Fusion **62**, 126006 (2022). https://doi.org/10.1088/1741-4326/ac906d

[10] WENHAO WANG, JIAN BAO, XISHUO WEI, ZHIHONG LIN, GYUNGJIN CHOI, SEAN DETTRICK, ANIMESH KULEY, CALVIN LAU, PENGFEI LIU, TOSHIKI TAJIMA, "Effects of equilibrium electric field on ion temperature gradient instability in the scrape-off layer of a field-reversed configuration", Plasma Phys. Contr. Fusion **63**, 065001 (2021).