Gyrokinetic simulation of the effect of transient fueling on plasma turbulence in ADITYA-U tokamak

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Abstract

The gradient-driven microturbulence in ADITYA-U tokamak plasmas has been suppressed by injecting short gas puffs. The suppression of microturbulence increases the core temperature and subsequently the energy confinement time following the gas puff. The gas injection modifies the radial density profile, making it relatively flatter near the mid-radius. Global electrostatic gyrokinetic simulations show that this modification to the radial density profile due to gas injection suppresses the existing trapped electron mode (TEM). Simulation results show that the TEM-dominated turbulence suppression reduces the turbulence-driven heat transport, leading to an increase in core temperature. Applying multiple periodic gas-puffs leads to multiple periodic events of TEM suppression, improving the overall energy confinement time, and is used as an active control mechanism to influence microturbulence in ADITYA-U tokamak.

Keywords: Plasma turbulence control, Gyrokinetic simulation, Tokamak

Introduction

Control of plasma turbulence remains a central challenge for achieving enhanced energy confinement in tokamaks [1, 2], where gradient-driven microturbulence produces anomalous particle and heat transport that limits performance. Traditional approaches in both tokamaks and stellarators rely on impurity injection to modify turbulence through changes in collisionality, dilution, and instability drive [3–5], while edge modification techniques—including on and off-axis auxiliary heating and current drive [6]—have long been explored for transport mitigation. Among these, gas puffing offers a uniquely versatile actuator [7]: short neutral gas pulses injected at the periphery enable temporally and spatially localized perturbations that preserves core purity while providing a controlled handle on turbulence-driven transport, rendering gas-puff–based approaches a fundamentally different and largely unexplored route for studying causal transport dynamics and active plasma control in fusion devices.

Experimental and gyrokinetic studies demonstrate that core and edge profile modifications directly impact turbulence [5, 8–10]. Edge density gradients modified by gas puffing suppress edge fluctuations and particle flux, while core density flattening reduces the drive of trapped-electron-mode (TEM) and electron temperature gradient (ETG) instabilities by lowering gradient scale lengths. Recent research suggests that for steep density profiles, the TEM driven by density gradient or coexisting ITG and TEM turbulence are dominant, resulting in outward particle diffusion and edge profile modification [11, 12].

We propose a general receipe that controlled flattening of core density profiles via short gas puffing can suppress micro-instabilities such as trapped-electron-mode (TEM) turbulence, thereby reducing electron heat transport and enhancing core confinement. In regions of significant trapped-electron fraction, reduced density gradients weakens the drive of these modes even when temperature gradients remain finite, shifting the turbulence spectrum toward more benign ion-scale-dominated regimes. As a case study, we analyze ADITYA-U experiments where short gas puffs produced core density flattening and enhanced sawtooth periods [13]. Gyrokinetic simulations using the GTC code [4, 14–16] reveal that the before gas puffing case exhibits strong TEM-driven turbulence, while after gas puffing, the flattened core density substantially reduces TEM drive shifts dominant mode structures outward (propagates lesser to the core and not enough drive in the core), and lowers net turbulent transport levels—directly correlating with the observed core temperature enhancement and improved confinement.

Overall, gas puffing experiments and simulations have emerged as an essential component of plasma control and diagnostic strategies in magnetic confinement fusion research [17]. The continued integration of high-resolution diagnostics with advanced plasma–neutral modeling is expected to further clarify the role of gas puffing in regulating turbulence, transport, and stability in tokamak.

Results

Experimental observations: Figure 1(a) shows the temporal evolution of plasma current I_P, loop-voltage V_{loop}, central chord-averaged SXR emission intensity, density and temperature with the application of periodic hydrogen gas puffing of ADITYA-U tokamak.

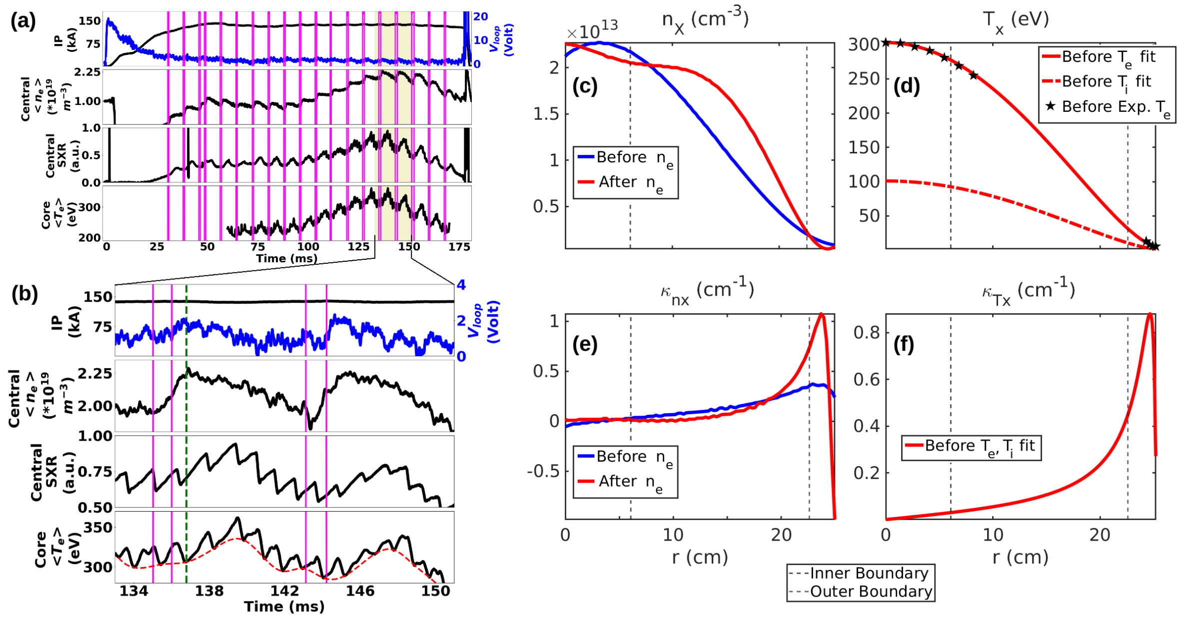

Fig. 1: (a) Temporal evolution of plasma parameters (Shot #36136); I_P (black), loop voltage V_{loop} (blue), central chord averaged electron density $\langle n_e \rangle$; central chord averaged SXR intensity and core temperature $\langle T_e \rangle$. (b) The time span $133 - 151$ ms during the plasma current flat-top (yellow shaded area in (a)) is expanded for all the parameters. The experimental plasma density profiles are shown in (c) and the electron temperature data with a fit is given in (d); here T_i profile is assumed to be one third of T_e; The gradients are given in (e) and (f), where $\kappa_X := -d(\log X)/dr$. In (c), the core density is flattened after gas puffing. Correspondingly there is a dip in the gradients shown in (e). The region between the vertical dashed lines indicate the simulation domain, with inner boundary at $\psi/\psi_X = 0.1$ and outer boundary at $\psi/\psi_X = 0.95$.

To explore the alterations of these plasma parameters due to a gas-puff, the temporal variations current flat-top phase (133–155 ms), are illustrated in Fig. 1(b) containing two gas-puff pulses. Note that the injected gas amount is controlled by the voltage pulse width applied to the piezo valve; a pulse width of ~ 1 ms injects 10^{17} molecules. Following a gas-puff, the central line-averaged density ($\bar{n}_e$) rises rapidly and reaches its maximum in ~ 1 ms. After the density reaches to its peak value, the central chord-averaged electron temperature (T_e) starts increasing, indicated by the green dashed line in Fig. 1(b), and peaks subsequently in 3–4 ms after the gas injection. These observations suggest that the core temperature increases with gas-puff in ADITYA-U tokamak. Furthermore, it has been observed that following the gas-injection, the increase in density is primarily located in the mid-radius region of the plasma column ($0.3 < \rho < 0.8$), causing the radial density profile flatter in this region compared to those without the gas-puff. The density remains almost constant in the plasma core ($\rho < 0.3$) after the gas-puff. Details of these experiment results can be found in references [18–20].

Modelling and Simulations: The rise in core-temperature following a gas-puff occurs in a time-scale ($\sim 3-4$ ms) shorter than the energy confinement time ($\sim$ 5–10 ms) in typical discharges of ADITYA-U tokamak. Similar observations are reported from several tokamaks with impurity injection [21, 22]. The physical phenomena behind this fast temperature rise with impurity injection are attributed to turbulence spreading [23] or to fluctuation suppression [21]. Turbulence is spreading is not observed in ADITYA-U as the core density fluctuations are observed to be decreasing after the gas-puff [20]. Therefore to investigate the role of fluctuation suppression in core temperature rise with gas-puff in ADITYA-U, Gyrokinetic simulations [14] are performed incorporating the equilibrium and radial profiles of density and temperature of the above-mentioned discharges of ADITYA-U. The radial density profile is measured using microwave interferometry [13]. The radial profile of the electron temperature is reconstructed by combining temperature data from multiple soft X-ray (SXR) chords [13] covering the core region ($\rho = 0 - 0.35$) with measurements from triple Langmuir probes located in the edge region ($\rho = 0.97 - 1.008$) [18].

Driving micro-instability: Gradient-driven global gyrokinetic simulations of microturbulence for the ADITYA-U tokamak with gas injection, using the GTC code, employ the realistic equilibrium obtained using IPREQ [24] and plasma profiles in Fig. 1(a)-(d), to model conditions both before and after gas injection. Both passing and trapped electrons are treated kinetically. The simulation time step is set to $0.005R_0/C_s$, where $C_s = \sqrt{T_e/m_i}$ is the ion sound speed and R_0 the major radius. Electron subcycling is applied with two substeps per ion step, and 50 marker particles are loaded per cell. The radial simulation domain spans $r/a \in [0.2428, 0.9028]$, corresponding to flux coordinates $\psi/\psi_X \in [0.1, 0.95]$, where a is the minor radius and ψ_X the magnetic flux at the last closed flux surface. The innermost region $\psi/\psi_X \in [0, 0.1]$ is excluded, since the plasma profile is nearly flat there (see Fig. 1(c)-(d)), yielding negligible gradients. Non-uniform plasma density and temperature profiles drive the micro-instabilities. To analyze such instabilities, we carry out a converged GTC simulations with 120 flux surfaces, 4000 poloidal grid points, 32 grid points in the parallel direction and 50 particles-per-cell.

The linear-regime mode structure in ADITYA-U's electric potential, $\delta\phi$ for the Before- and After-gas puff cases are shown in Fig. 2, at $t = 12\ R_0/C_s$. The analysis of the microinstabilities in both cases show that the TEM (Trapped Electron Mode) is the dominant instability, compared to the ITG (Ion Temperature Gradient), as signaled by the sign of diamagnetic frequency. The right panel of Fig. 2 show that the gas puffing leads to small reduction in the growth rates of the instabilities from

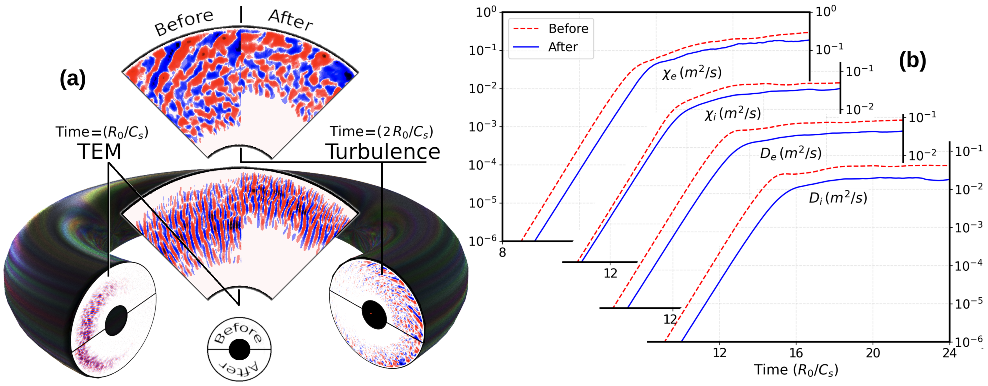

Fig. 2: (a) The poloidal cross-section of ADITYA-U flux surface and the corresponding mode structure in the electric potentials are shown for both before and after cases in the linear (TEM) and turbulent regimes. The electrostatic potential is normalized by T_e/e; (b) Comparing the energy transport and particle transport for the Before- and After-cases we find all diffusivities have similar growth rates. In particular, The saturation level for After case is reduced by $\approx 84\%$ in D_e and $\approx 94\%$ in D_i. The saturation values χ_e is an order of magnitude higher than χ_i.

$\gamma\, C_s/R_0 \approx 0.82$ (Before) to 0.79 (After). The location of the flux surface averaged mode rms peak shifts from $\psi/\psi_X \approx 0.5$ (Before) to 0.75 (After) and comparing the radial extent of ϕ for before and after cases show localization of modes such that after gas puffing the TEM is expelled from the core. The mode structure sizes show that mode number reduces from $m \approx 160$ to 120 after gas puffing.

Turbulent transport: The kinetic electron based gyrokinetic simulations of the before gas puffing case indicate strong TEM-driven turbulence. After gas puffing, the flattened density in the core lead to reduced TEM drive and reduced trapped-electron activity, shifting the net turbulence transports to lower levels compared to before case.

In the nonlinear turbulent regime, the fluctuating $\mathbf{E}\times\mathbf{B}$ drift leads to cross-field transport of both energy and particles. The turbulent transport fluxes are computed from gyrokinetic moments of the fluctuating distribution and potential. The radial particle flux for species s is given by $\Gamma_s = \left\langle \int \delta f_s\, (\mathbf{v}_E \cdot \nabla\psi)\, d^3 v_s \right\rangle_\psi$, where $\mathbf{v}_E = (c/B)\mathbf{b}\times\nabla\phi$ is the $\mathbf{E}\times\mathbf{B}$ drift velocity, and $\langle\cdot\rangle_\psi$ denotes flux-surface averaging. The corresponding transport coefficients are then expressed as $D_s = \frac{\Gamma_s}{\partial n_s/\partial r}$, and $\chi_s = \frac{\langle \bar{\mathbf{q}}_s \cdot \nabla\psi\rangle_\psi}{n_s \langle |\nabla\psi|^2\rangle_\psi \frac{\partial T_s}{\partial \psi}}$. The plots in Fig. 2(b) show that the transport coefficients are lower after gas-puffing. Furthermore, Fig. 3 reveals that the propagation of turbulence across the flux surfaces and into the core region is suppressed after the gas-puffing.

Conclusions

Short gas puffing experiments in the ADITYA-U tokamak reveal a clear and reproducible increase in core electron density and temperature leading to an improvement

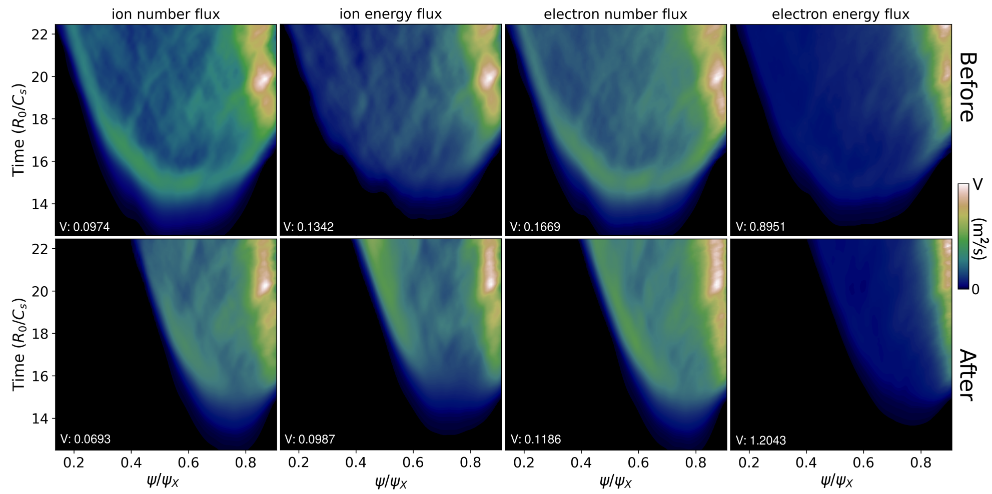

Fig. 3: Evolution plots of the radial profiles of turbulent transport fluxes show that in general the radial spread are lower in the after case compared to the before case. The fluctuations start to grow at location where the TEM is strong and spreads radially. The inward propagation of the fluctuations are curtailed after gas puffing.

in plasma confinement. The nonlinear GTC simulations show that trapped electron mode (TEM) turbulence is strongly suppressed post-injection, due to the flattened density profile in the mid-radius region of plasma column. The suppression of TEM leads to lower heat diffusivity, allowing core temperature to rise. Spatially, the strongest transport modification is observed in the mid-radius region rather than near the separatrix, suggesting that gas puffing influences core turbulence indirectly through profile relaxation mechanism. The simulations thus provide a self-consistent picture of turbulent transport in ADITYA-U. The simulations capture both the microinstability dynamics and their nonlinear saturation, enabling quantitative evaluation of turbulent particle and energy fluxes. The insights gained from such simulations are essential for understanding transport regulation mechanisms and for developing predictive models for tokamak confinement optimization. The experimental and simulation results clearly demonstrate that neutral fueling can function as an active turbulence control mechanism rather than merely a particle source.

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