Self-generated reversed radial electric field

in 3D global flux-driven fluid edge plasma turbulence simulations

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The formation of a strongly reversed radial electric field in the pedestal region of a tokamak plasma is of particular interest for the modelling of improved confinement regimes, as the related sheared flow is suspected to strongly impact turbulence, by stabilizing it [1], leading to the formation of an edge transport barrier and to the transition to high-confinement "H-mode" [2]. However, the mechanisms underlying its generation and interplay with turbulent transport are not elucidated. Here, the dynamics of a self-generated reversed radial electric field and its interaction with edge turbulence are investigated via global flux-driven simulations in three-dimensional geometry with the electrostatic fluid turbulence code TOKAM3X [3-6,10].

1. TOKAM3X fluid turbulence model and simulation numerical setup

TOKAM3X turbulence code [3] evolves the two-fluid, electrostatic, drift-reduced Braginskii coupled equations in the edge of a tokamak plasma (3D, 6 fields, non-isothermal model [4,6]). The flux-driven global approach does not impose any scale separation between mean profiles and fluctuations. The computational domain encompasses both closed and open magnetic field lines, in versatile geometry [5]. The magnetic equilibrium is assumed fixed and axisymmetric. A circular limited geometry is considered here with the limiter placed on the bottom of the tokamak. The direction of magnetic field is such that ion ∇B drift is downward, towards the limiter. Bohm–Chodura boundary conditions are enforced in the parallel direction, modelling the sheath physics next to the limiter. In the radial direction, homogeneous Neumann boundary conditions are imposed at the inner and outer boundaries for all variables.

Simulation parameters for plasma conditions typical of a small tokamak experiment, e.g. like COMPASS, are chosen here: aspect ratio $R/a=3.4$, normalised Larmor radius $\rho^*= 1/256$, $\nu^*(\nu_{coll}/\omega_{ci})= 5\cdot10^{-2}$ (corresponding to $n_0=5\cdot10^{18}m^{-3}$, $T_0= 20eV$, $B_0=1T$). The grid resolution in radial, poloidal and toroidal direction, is $64 \times 512 \times 64$ over half-torus, implying π-periodicity for the solution in the toroidal direction. Electrons and one ion species (Deuterium) are evolved. Particle and energy fluxes are modelled as incoming from the plasma core, with Gaussian shaped sources localised at the inner boundary of the simulation ($r/a=0.8$) extending over $4\rho_L$. The peak amplitudes of the core density and energy sources for the baseline case are equal to

S_N =5·10^{-4} $n_0\omega_{ci}$ and $S_{Ee/Ei}$=1·10^{-3} $n_0T_0\omega_{ci}$ per species, respectively. The perpendicular diffusion coefficients, constant in space and time, are chosen equal to D = 0.01$\rho_L^2\omega_{ci}$.

2. Spontaneous reversed radial electric field generation in response to increased power

A scan on the injected heating power, at constant particle influx from the core, is performed, by increasing both electron and ion energy sources by a factor 1.5 and 2. The simulations are run up to a quasi-stationary turbulent state e.g. assumed to be reached when the time derivatives of density, electron and ion energies integrated over a flux surface vary less than 5% over 1ms.
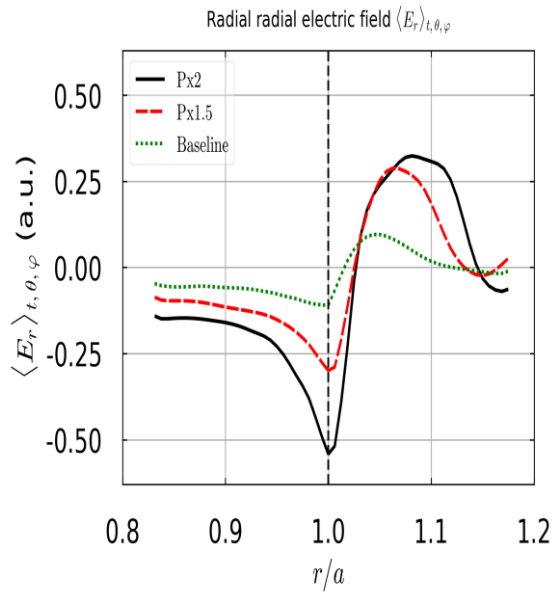

Figure 1 Radial electric field profile, flux surface and time averaged on the stationary state,: baseline case (green dotted line), Px1.5 (red dashed line), Px2 (black full line)

Spontaneous generation of a reversed radial electric field, E_r, in the proximity of the separatrix is systematically found in TOKAM3X edge/SOL simulations. The E_r well strongly increases with increasing injected power, consistently with experimental observations. It can be observed that he E_r shear is maximum, systematically, at a few Larmor radii outside separatrix, in the near SOL region, similarly to [7]. The increased power engenders a global steepening of the density profile and an increase of the overall temperature (thus lower collisionality), with the formation of a pedestal on the temperature profiles, in the same region where the E_r shear is maximum.
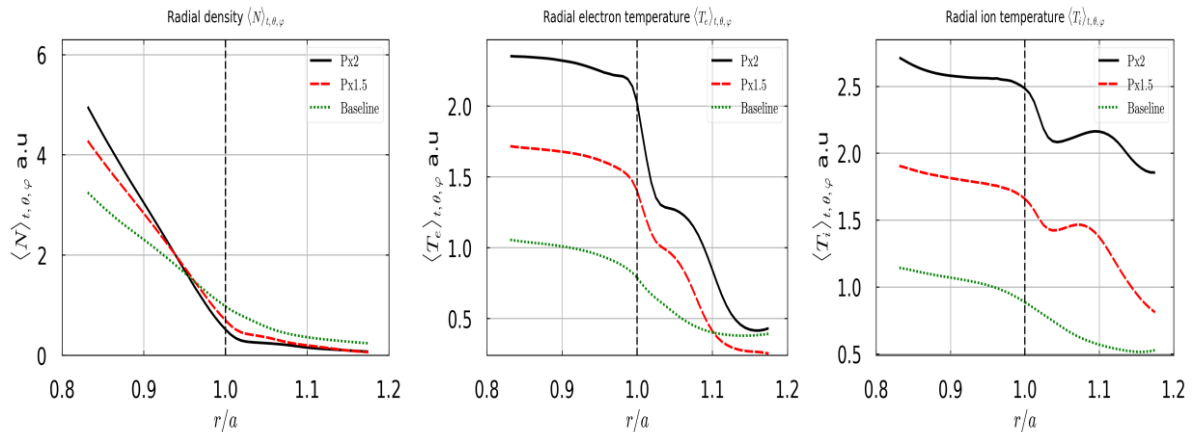

Figure 2 Density (left), electron middle) and ion (right) temperature average profiles (averages and colour code as in Figure 1)

The formation of a strong gradient in the near SOL region, is reminiscent of the narrow λ_q feature [8]. Density e-folding lengths have been estimated in this region for the three increasing power cases: λ_N = (25, 19, 15) ρ_L eg the SOL width coherently diminishes.

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3. E_r dynamics and interplay with edge/SOL turbulence.

Interestingly, the E_r dynamics shows the presence of a low frequency oscillation, particularly evident in the intermediate power case spectrum, over the whole radial E_r profile, comparable to the GAM frequency (estimated according to the fluid approximation [Sugama JPP2006]).

A similar oscillation is also observable in the temperature spectra, in the pedestal region. The relation to LCO / I-phase [9] should be further investigated.

The fluctuation rate profiles show a slight decrease of fluctuation level with power in the closed field-lines region (CFR), whereas fluctuations increase with power in the mid-far SOL. A different response to power is observed around the separatrix, where density fluctuations raise with power from the outer CFR outwards, despite the increasing E_r shear, whereas temperature fluctuations decrease there, strongly raising beyond the E_r shear maximum location in the SOL.
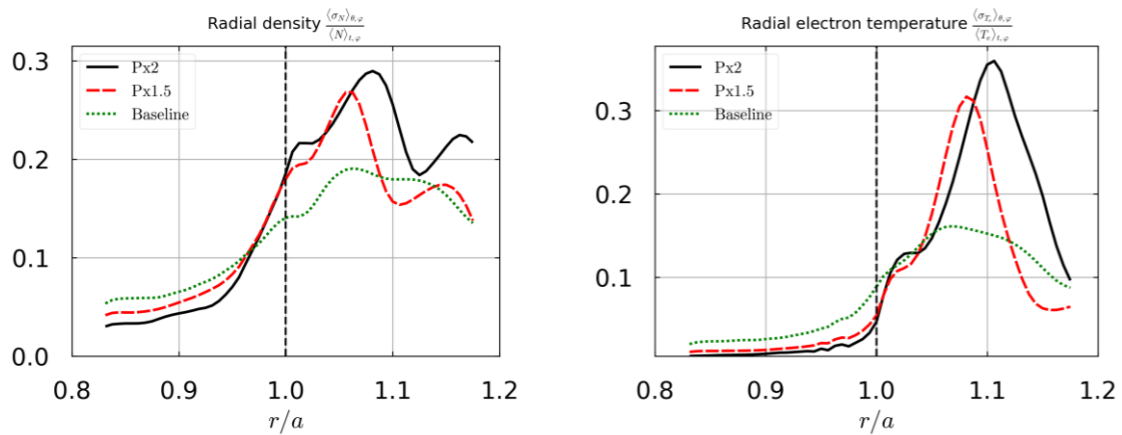

Figure 3 Radial profiles of the relative standard deviation of density (left) and electron temperature (right) fluctuations (colour code as in Figure 1) .

Decomposition of the total radial particle and energy fluxes consistently shows a transition from predominantly turbulent (ExB flux) to diffusive transport in the closed field lines region.

The relative reduction of turbulent flux in the shear layer region appears as a result of the fluctuation level drop spreading from the CFR, rather than a local effect of the E_r shear.
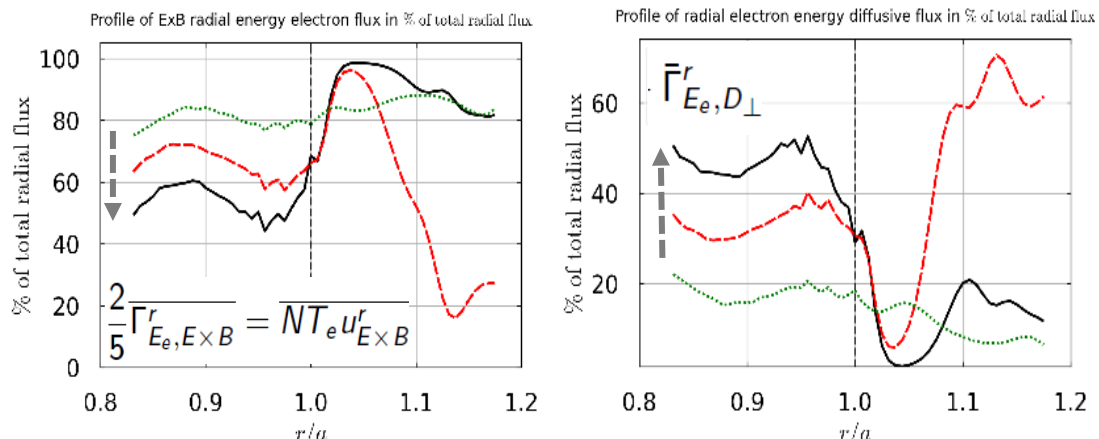

Figure 4 Electron energy radial fluxes integrated along the flux surfaces averaged in time, as % of the total radial flux: left, ExB and right, diffusive.

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4. Conclusions and discussion

Systematic spontaneous generation of a reversed radial electric field E_r, in the proximity of the separatrix is found in TOKAM3X non-isothermal flux-driven turbulence simulations in a limited circular plasma, encompassing both the closed field-lines edge region and the SOL. The E_r shear maximum at the outer midplane is systematically arising at a few Larmor radii outside the separatrix, in the near SOL region, similarly to [7]. As a result of a scan in injected heating, it is found that the reversed E_r well strongly deepens with the injected power, consistently with experimental observations. Concomitant steepening of the global edge plasma density profile is observed, whereas a pedestal in temperature is created, localised outside the separatrix, in the near SOL region where the E_r shear is maximum. Such a creation of a strong gradient in the near SOL is reminiscent of the narrow λ_q feature [8]. Indeed, a decrease of the estimated density decay length is found. A slight decrease of the fluctuation levels with increasing power is observed in the closed field lines region. Coherently, from the analysis of the particle and energy transport fluxes, a transition from dominantly turbulent to diffusive transport with power is also observed. While a clear impact of the separatrix on the E_r formation and system dynamics is highlighted, no direct local impact of E_r shear on the turbulence is evidenced: stabilization rather appears to be related to the local decrease of collisionality due to the raise of temperature [6] with power. It has to be noted that the choice of imposing a particle source from the core affects the transport so that the temperature profiles are flatter in the closed field lines region, as a result of the fact that energy is convected together with particles, instead of being conducted. Upcoming simulations in more realistic edge conditions shall account for the recycling from the target, e.g. by imposing a particle source at the limiter [10] or coupling to a recycling neutrals model, as well as for the divertor geometry [3,11].

References

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