Self-generated reversed radial electric field in 3D global flux-driven fluid edge plasma turbulence simulations

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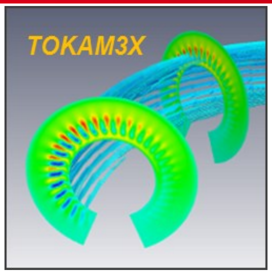

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INTRODUCTION

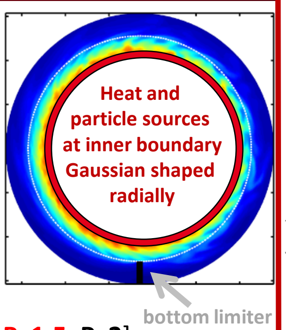
The formation of a strongly reversed radial electric field in the pedestal region of a tokamak plasma is considered to play a key role in the generation of improved confinement regimes, as the related sheared flow is suspected to strongly impact turbulence, by stabilizing it [1] and leading to the formation of an edge transport barrier and to the transition to high-confinement "H-mode" [2]. However, the mechanisms underlying its formation and interplay with turbulent transport are not yet elucidated.
Here, the dynamics of a **self-generated reversed radial electric field**, **Er** and its interplay with edge/SOL turbulence are investigated via global flux-driven simulations in 3D geometry with the fluid electrostatic code TOKAM3X [3-6], in response to increasing injected heating power.

Simulation set-up and parameters

Circular limited case, encompassing **closed field lines region (CFR) and Scrape-Off-Layer (SOL)** r/a=0.8-1.2 (including buffers)
COMPASS-like tokamak plasma parameters:

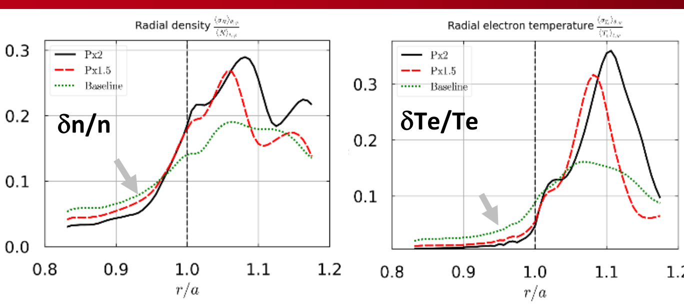
R/a	ρ_*	$\nu_* \left(\frac{\nu_{coll}}{\omega_c}\right)$
3.4	1/256	$5 \cdot 10^{-2}$

Scan on injected core heating:
n freely evolving



Mesh resolution on ½ torus : (ψ,θ,φ) 64 x 512 x 64
Injected heating increased in two steps from **baseline** simulation: [**P**, **Px1.5**, **Px2**]
Runs > 10^6 t (ω_{ci}^{-1}) up to quasi-stationary state ~ [5, 3.8, 1] ms

E_r shear interplay with turbulence: fluctuation level & λ_N ↘



Slight reduction of fluctuation level in CFR
increase in near SOL

Density radial decay length λ_N decreases with power

	$\lambda_n (\rho_L)$
P	24.9
Px1.5	18.8
Px2	15.3

$$\partial_\psi \langle N \rangle_t = \langle N \rangle_t / \lambda_N$$

Particle and energy fluxes: from turbulent to diffusive

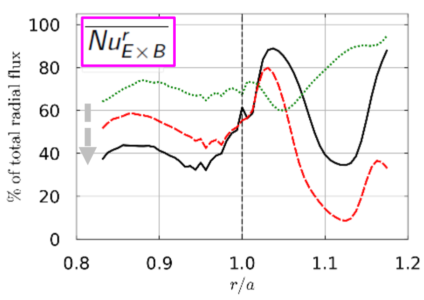
Flux-driven simulation, with constant particle flux incoming from the core ➔ radial particle flux constant.
The radial particle and electron energy fluxes can be decomposed as:

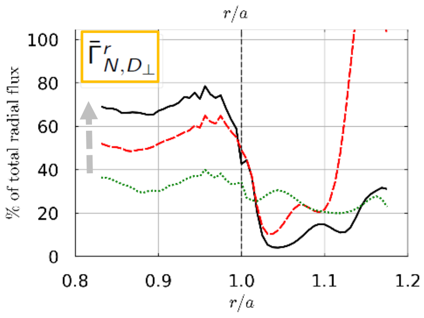
$$\Gamma^r_N = \overline{Nu^r_{E\times B}} + \overline{Nu^r_{\nabla B}} + \Gamma^r_{N,D_\perp}$$

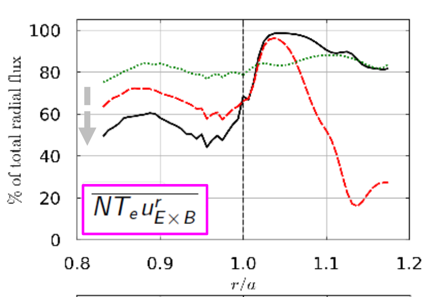
ExB flux dominating — diffusive flux

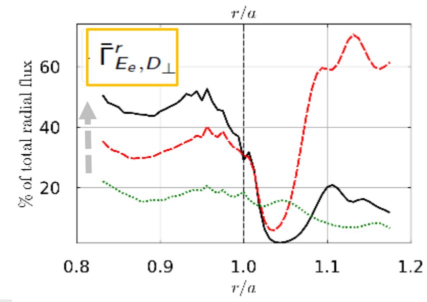
Baseline case
Power x 2 ↘
In SOL ∇B flux > 0 dominates
In CFR ↗ dominates

$$\Gamma^r_{E_e} = \overline{NT_e u^r_{E\times B}} + \overline{NT_e u^r_{\nabla B}} + \Gamma^r_{E_e,D_\perp}$$

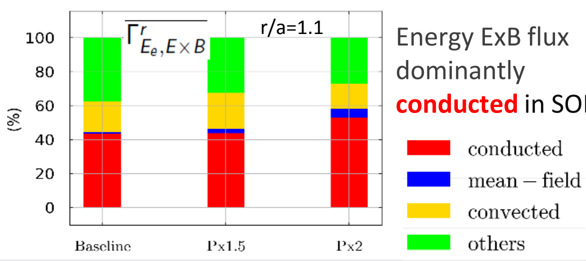








Increased power affects the particle and energy fluxes:
- **transport from turbulent to diffusive in the CFR** : no evident impact of Er shear on the **turbulence stabilization**
- interplay with Er shear in the pedestal

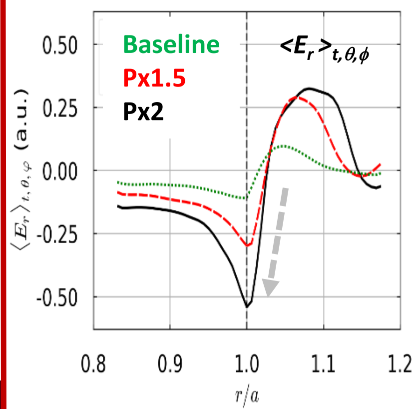


Energy ExB flux dominantly **conducted** in SOL

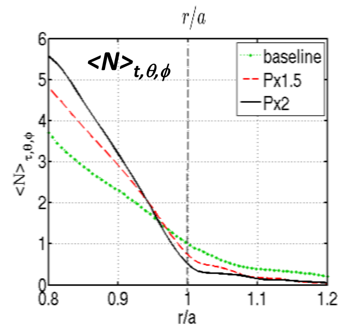
TOKAM3X 3D global flux-driven model [Tamain et al., JCP 321, 2016]

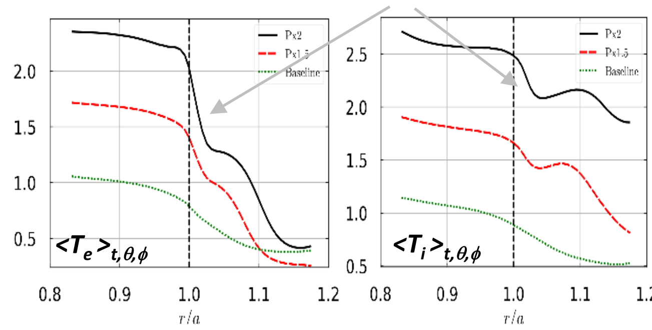
- Self-consistent **3D electrostatic drift-reduced Braginskii model**, 6 fields: $N, \Gamma\,(u_\parallel), E_e\,(T_e), E_i\,(T_i), W(\phi), J_\parallel$
- **Non-isothermal** turbulence *[Baudoin CPP 58 2018; Tatali NF 61, 2021]*
- **Flux-driven global** approach: no scale separation
- Bohm-Chodura boundary conditions in parallel direction at the limiter *[Stangeby, 2000]*
- Verified via MMS/PoPe/iPoPe (independent Projection on Proper elements) *[Cartier-Michaud et al., PoP 23, 2016; PoP 27, 2020]*
- Versatile geometry (slab/limiter/divertor/different plasma shapes/RMP) *[Galassi et al. NF 57, 2017; Nespoli et al. NF 59, 2019; Luce et al., PPCF 63, 2021]*
- Neutrals via coupling to EIRENE *[Fan et al. Nucl. Mat. Energy 18, 2019]*

Self-consistent reversed E_r generation & profile steepening

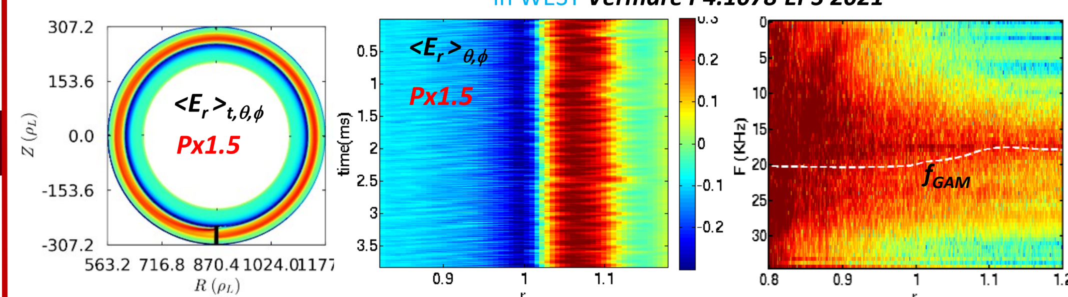


- E_r shear max in TOKAM3X simulations (w/o recycling) systematically @ few Larmor radii outside separatrix, in near SOL region similar to *[Chankin PPCF 2017]*
- **Reversed E_r peak @separatrix, strongly increases with increasing injected power**
- **Global density profile steepening with increasing power** and formation of a **pedestal in temperature**





- E_r **oscillation** ~ f_{GAM} *[Sugama JPP 2006]*
  -similarity to LCO/I-phase? *to be further investigated*
  Cfr in AUG *[Cavedon NF 2017 Medvedeva PPCF 2017]*
  in WEST ***Vermare P4.1078 EPS 2021***



Discussion and perspectives

- **Systematic spontaneous generation of a reversed radial electric field E_r** in the proximity of the separatrix is found in TOKAM3X electrostatic non-isothermal turbulence simulations in a limited circular plasma, encompassing CFR and SOL.
  - ✓ **E_r well strongly increases with increasing injected power**, consistently with experimental observations.
  - ✓ **Global steepening of the density profile** with increasing power.
  - ✓ **Plasma temperature profiles steepen**, with the creation of a **strong gradient in the near SOL, reminiscent of the narrow λ_q feature**.
- **Interplay of the self-generated reversed E_r with turbulence**:
  - **particle and energy transport fluxes in the CFR from turbulent to diffusive,**
  - **dominantly conducted energy fluxes in the SOL**
  - **turbulence stabilization in the closed field lines region mainly resulting from reduced collisionality due to the increased T** *[Falchetto PRL 2004; Tatali NF 2021]*
- Upcoming, simulations in **more realistic edge plasma conditions**
  - particle source at the limiter
  - recycling neutrals
  - divertor geometry
  - neoclassical viscosity
  - realistic collisionality

➔ Recently released **SOLEDGE3X code [8]**
cfr Bufferand IAEA 2021

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EUROfusion
This work was supported by the EUROfusion - Theory and Advanced Simulation Coordination (E-TASC).
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.