Global electromagnetic symmetry-breaking effects on momentum transport and current generation in tokamaks

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ABSTRACT

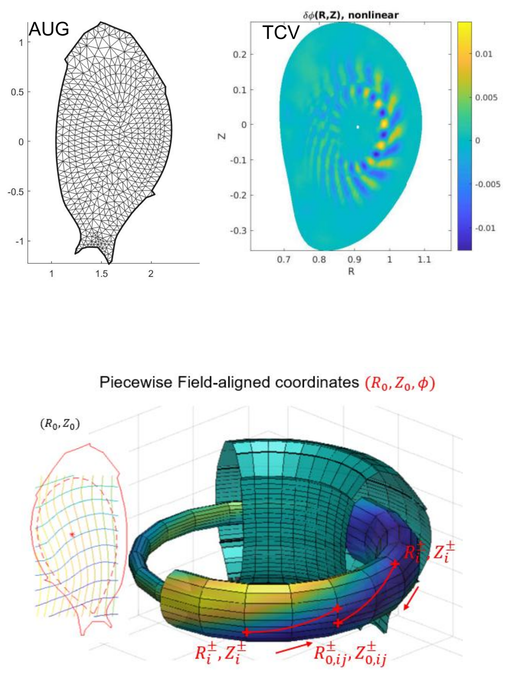
Symmetry breaking in the global gyrokinetic solution modifies the plasma current density profile and plays a critical role in the development of observed ion rotation.

- Current generation affects MHD equilibrium and instabilities.
- Plasma rotation can suppress microinstabilities and prevent MHD mode locking, thereby improving confinement and stability.
- In ITER (early phase), the external torque from neutral beam injection (NBI) is insufficient to drive a strong toroidal rotation, and intrinsic sources of rotation are expected to play a significant role.
- Experimental/theoretical/modelling suggest the importance of off-diagnal particle and toroidal momentum transport [1]; studied in AUG [4,10]
- Previous rotation studies: in electrostatic(ES) limit, ignoring electromagnetic modes/effects [2,3,4]; current drive studies: in ES limit [14] or low β [8,9]

TRIMEG CODE: ELECTROMAGNETIC PIC CODE

The triangular mesh-based gyrokinetic scheme (XGC, TRIMEG) enables comprehensive axis-to-edge studies across the entire plasma volume [2,5].

- TRIMEG employs high-order finite element method (Cubic spline/C1) [7]
- Numerical/physics methods tested: implicit full f scheme [12], high-order stochastic integrator for nonlinear collisions [11]; mixed full f-delta f scheme [6]
- The mixed variable/pullback scheme is adopted [6,7]
- Piecewise Field-aligned finite element is developed [13]
- Goal: gyrokinetic simulations with edge geometry/physics
- This work: plasma core; structured mesh



CURRENT GENERATION

- Parameters: circular magnetic surfaces, Cyclone-like case. The plasma temperature is tuned to study the cases with different orbit width by shifting the normalized device size to a/ρ_{ref}=90, ρ_{ref}: reference Larmor radius using proton mass, B_{axis}.
- Single-n simulations are performed

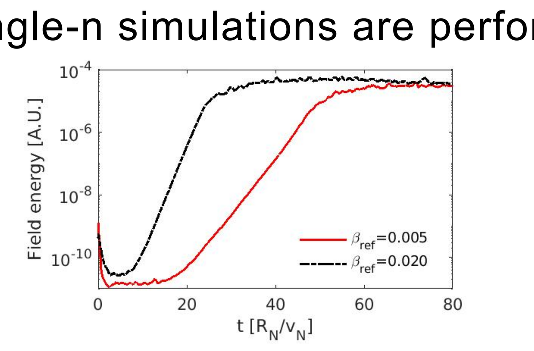
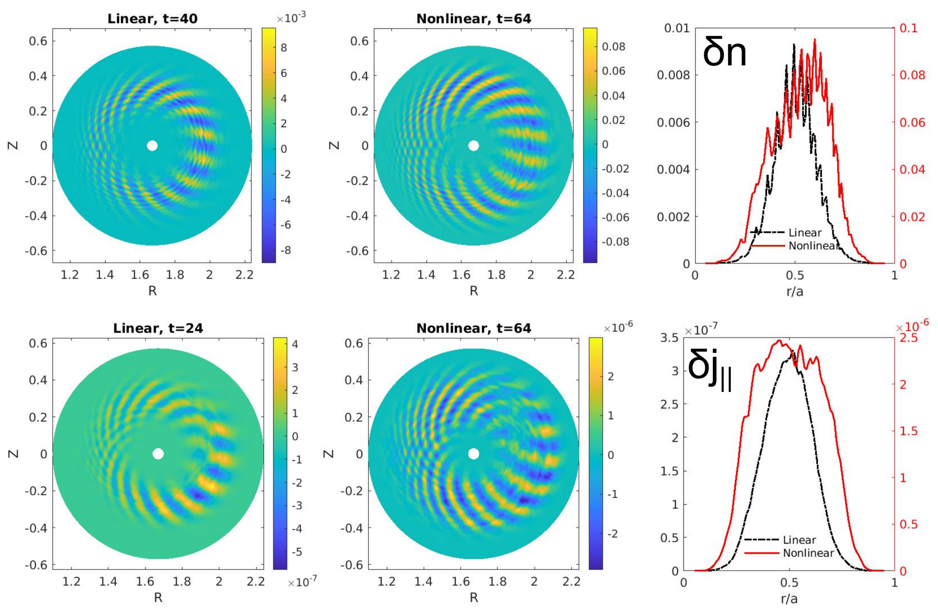


Fig. Time evolution of the total field energy for β_{ref}=0.005 (ITG), 0.020 (KBM). β_{ref}: plasma beta using B_{axis} and n, T at r/a=0.5

- Radial broadening of perturbed density δn, current $\delta j_{||}$ is observed in nonlinear stage



ANALYSES METHOD

Flux diagnostics of particle, heat and parallel momentum have been implemented for both electrons and ions.

- Fluxes due to scalar potential and the parallel component of the vector potential are separated according to

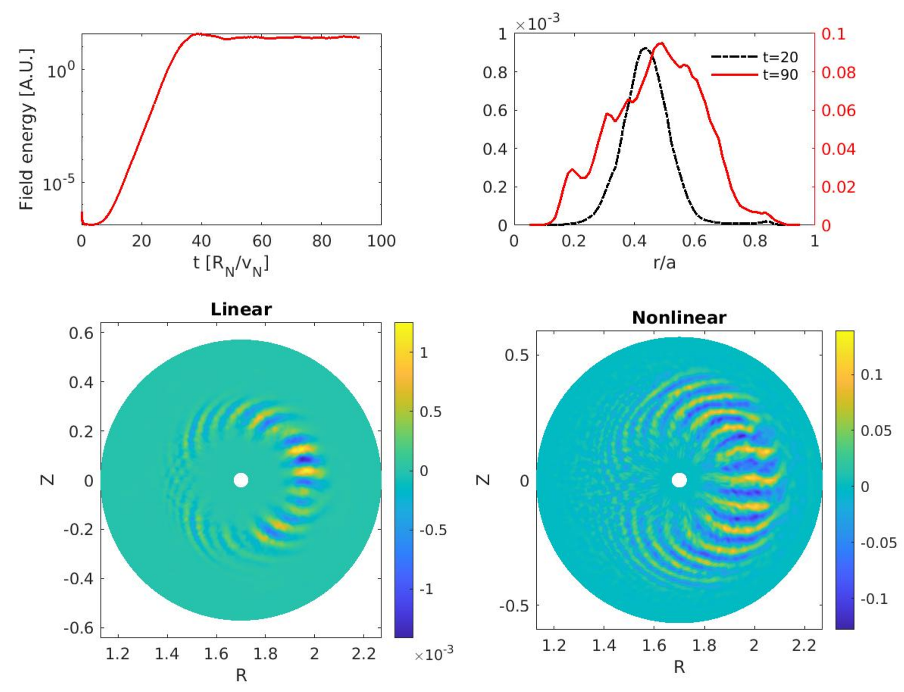
$$\Pi_{\delta\phi}=\left\langle\int dv\frac{\mathbf{b}}{B}\times\langle\nabla\delta\phi\rangle_{gy}\delta f_v v_\parallel\right\rangle_F\ ,\quad \Pi_{\delta\phi}=\left\langle\int dv\frac{\mathbf{b}}{B}\times\langle\nabla\delta A_\parallel\rangle_{gy}\delta f_v v_\parallel^2\right\rangle_F$$

- Electron current and ion velocity

$$\delta j_{\parallel,e}=-e\left\langle\int d^3v\delta f_{v,e}v_\parallel\right\rangle_F\ ,\quad V_\parallel=\left\langle\frac{1}{n_i}\int d^3v\delta f_{v,i}v_\parallel\right\rangle_F\ ,$$

MULTI-N SIMULATIONS (AUG)

- Radial boradening in nonlinear stage



ROTATION SIMULATION

- Parameters: AUG discharge #26170 at ~3.86 s [10]. H-mode, ~2.2 MW ECRH power, at 2.5 T and 0.6 MA.
- a/ρ_{ref}=90, multi-n nonlinear electrostatic simulations

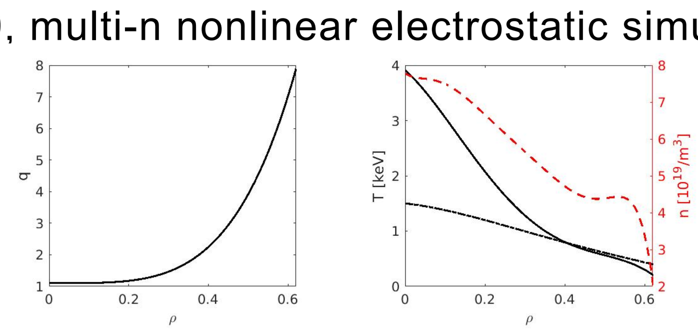


Fig. 2 profiles of safety factor (left); density and temperature profiles (right)

ROTATION FORMATION

Global nonlinear gyrokinetic simulations are applied to predict the intrinsic toroidal rotation profiles of an AUG H-mode plasma with ECRH only

- A nonlinear simulation based on the ASDEX Upgrade (AUG) experimental profiles, with a reduced normalized device size(a/ρ_i=90), directly produces an intrinsically generated parallel velocity profile.
- The general feature of a hollow ion toroidal rotation profile is produced from simulations
- The simulated velocity profile gradient follows the experimentally measured one in the region where the instability is excited. Advanced boundary needed.

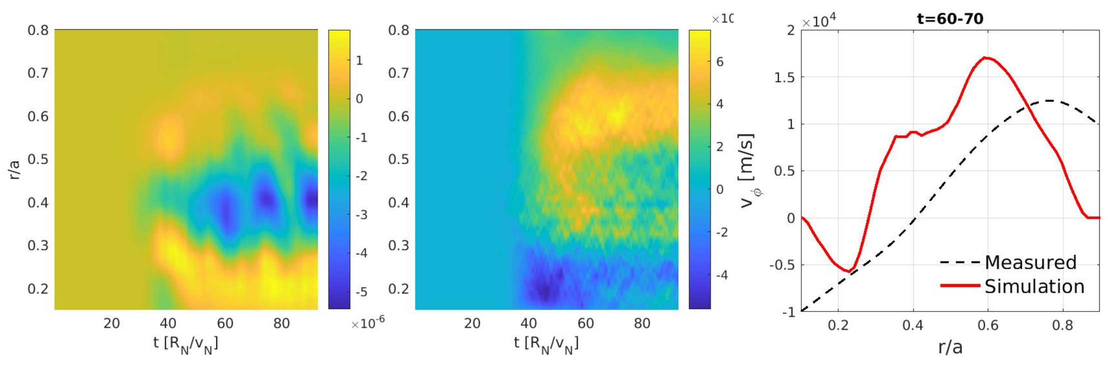


Fig. The time evolution of the ion parallel momentum flux $\Pi_{E,i}$ (left), the parallel velocity (middle) from simulations. The parallel velocity from simulations and from experiment measurement (right).

TWO-SCALES IN CURRENT

- Two scales in $\delta j_{||}$: fine-scale structure between two rational surfaces and a larger-scale structure

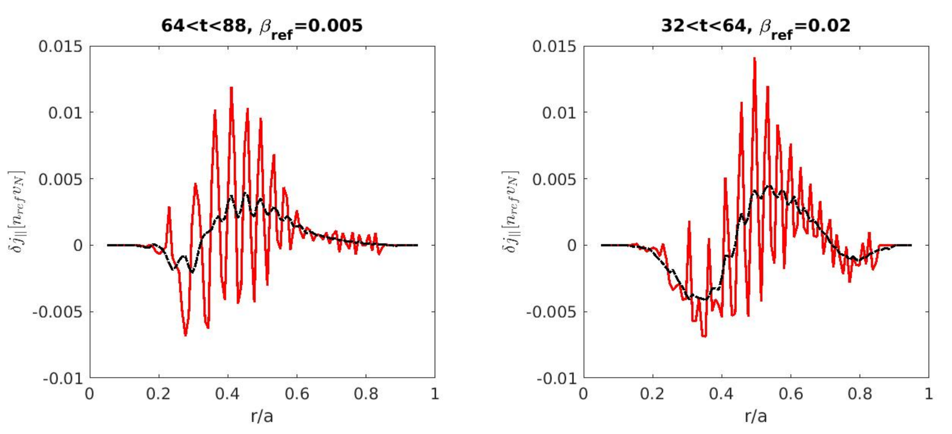


Fig. The parallel electron current for β_{ref}=0.5% and 2%

MAGNETIC EFFECT ON CURRENT

Magnetic effect contributes significantly to parallel momentum flux

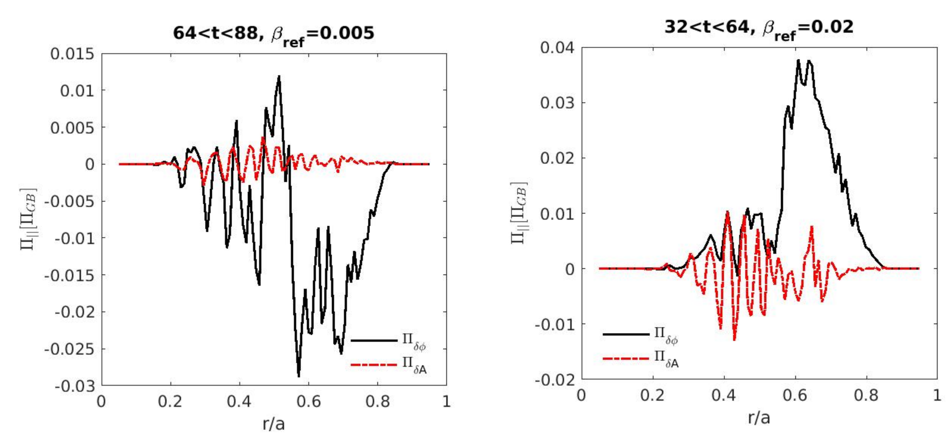


Fig. The parallel momentum flux of electrons for β=0.5% and 2%

CONCLUSION

The new electromagnetic global gyrokinetic code TRIMEG enables studies of turbulence-driven parallel ion momentum transport and current generation

- For turbulence-driven current, multi-scale structures are identified.
  - **In the high-β_{ref} (0.02) case, the electromagnetic correction in fine-scale flux is comparable to that driven by the electrostatic scalar potential.**
- The general feature of a hollow ion toroidal rotation profile observed in ECRH H-modes in ASDEX Upgrade has been reproduced by global multi-n nonlinear electrostatic gyrokinetic simulations.
- This work supports that turbulence can modify current and rotation profiles. As the turbulence is regulated, the current and rotation is also modified.
- Future work aims to perform simulations at reactor-relevant values of a/ρ_i with collisions and advanced boundary condition.

BENCHMARK/SIMULATION USING TRIMEG-GKX

- ITPA Energetic particle (EP) driven TAE
- AUG EP driven RSAE (NLED case)

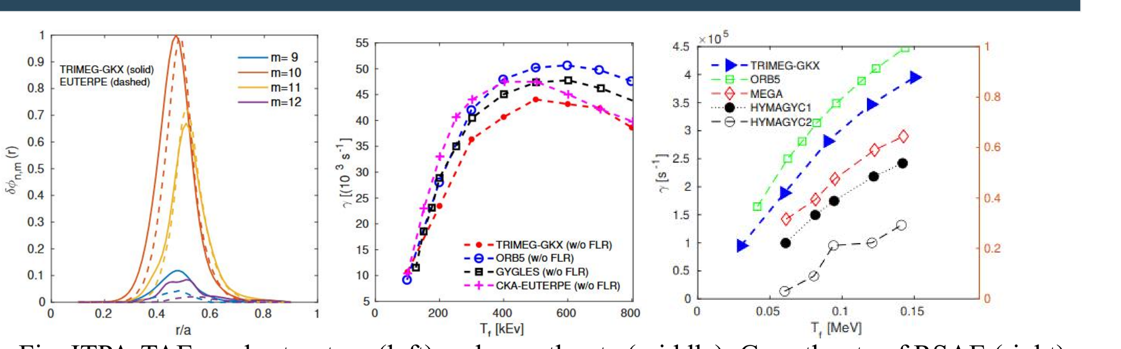


Fig. ITPA-TAE mode structure (left) and growth rate (middle); Growth rate of RSAE (right)

- Ion temperature gradient mode
- Kinetic ballooning mode

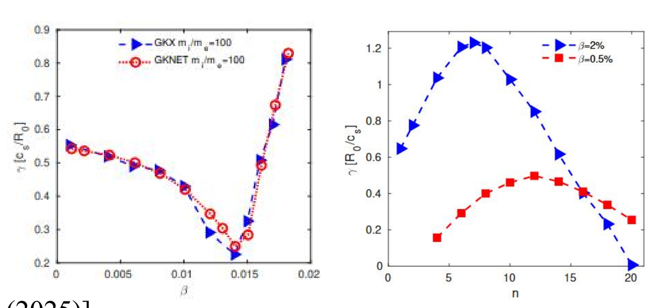


Fig. Left: Cyclone ITG/KBM case. Growth rate of ion temperature gradient mode and kinetic ballooning mode.

[Z. X. Lu, G Meng, R Hatzky, Ph Lauber, M Hoelzl, arXiv:2504.21837 submitted (2025)]

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