Gyrokinetic-MHD Coupled Simulation of RMP Plasma Interaction Reproduces Density Pump-Out Seen in the Tokamak Edge

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PPPL
• Edge Localized Modes (ELMs) are an important heat and impurity exhaust mechanism
  – Intermittent, sometimes very violent (up to 50% of stored pedestal energy) bursts may damage divertor plates in fusion reactors
• ITER plans to use 3D fields, Resonant Magnetic Perturbations (RMP), for ELM suppression
• But RMP fields can lead to the so-called “density pump-out” that may decrease fusion efficiency, but without a similar pump-out of electron heat.
→ What are the physics behind the density pump-out? Why not a $T_e$ pump-out?

![Graph showing RMP on ELM suppressed and Density pump-out due to RMP](image)

T. Evans et al., Nature 2006
L. Cui et al., Nucl. Fusion 2017
The Gyrokinetic-Neoclassical Code XGCa Is Used to Study the RMP Induced Transport

- XGCa is a **global 5D** (3D configuration + 2D velocity space) **gyrokinetic**, total-f particle-in-cell code
  - Whole volume simulation **including SOL**
  - Kinetic-consistent mean radial and poloidal electric field
  - Nonlinear Fokker-Planck-Landau collision operator
  - Neutral particle recycling

- Goals:
  - High-fidelity study of **non-turbulent** (parallel- and cross-field) transport due to resonant magnetic perturbations (RMPs)
  - Add **turbulence with XGC1** later

Parallel current density from trapped and passing particles in NSTX #132543 computed with XGCa (R. Hager and C. S. Chang, PoP 2016, illustration by F. Sauer, T. Neuroth and K.-L. Ma, UC Davis)
M3D-C1:
- Axisymmetric 0th-order magnetic field
- Steady-state fluid plasma response → screened 3D RMP field

XGC:
- Gyrokinetic plasma transport in 3D magnetic equilibrium → profile evolution, transport coefficients

• M3D-C1 provides perturbed 3D magnetic equilibrium
• XGCa computes time evolution of the plasma
  – Whole volume simulation
  – Radial and poloidal (n=0, no turbulence) electric field solution
  – Assuming poloidal \( \phi \) variation is more significant than toroidal \( \phi \) variation
  – Nonlinear Fokker-Planck-Landau collisions
  – Neutral particle recycling
• Updated plasma profiles (and transport coefficients) can be returned to M3D-C1 for longer time-scale coupled simulation
Starting from (a Model DIII-D) H-Mode like Plasma Profiles → M3D-C1 Yields 3D Field with Good KAM Surfaces at Pedestal Top

Thermal ion banana orbit width is comparable to pedestal width and spans multiple resonant surfaces.

Good KAM surfaces at pedestal top

Thin stochastic layer close to the separatrix

Radial component of the M3D-C1-screened n=3 RMP field

\[ \delta B_r, \text{ time} = 0.910 \text{ ms, tstep} = 370 \]
XGCa Simulation Setup

- Run XGCa with axisymmetric magnetic field for ~4 toroidal ion transit times $\tau_i \rightarrow$ establish reference neoclassical transport level
- Rapid ramp up of 3D RMP field over ~2 $\tau_i$ (experimental ramp-up time ~100 ms)
- Continue at constant RMP field for another couple of $\tau_i$
- A radiative SOL cooling-model is applied to keep $T_e$ at separatrix at 70-100 eV as seen in experiment
- Neglect core heat and torque sources due to short time scale of simulations
- Study 3 cases to assess effects from collisions and rotation
  - w/o initial rotation, w/o collisions
  - w/o initial rotation, w/ collisions
  - w/ initial rotation, w/ collisions
Collisionless 3D Transport at the Pedestal Top Is Small

- RMP field switched on at $t=0.319\ \text{ms}$
- Approx. boundary between KAM surfaces and stochastic field $\psi_N \approx 0.98$
- Neoclassical reference transport level
- RMP induced transport is mostly confined to stochastic region
Enhanced Outward Particle Flux is Observed in the Pedestal When Collisions are Included

- Particle flux remains significantly elevated above the axisymmetric neoclassical level in collisional simulations
- Toroidal rotation in XGCa with fixed RMP field does not change transport

Enhanced outward particle flux at pedestal top

Steepening $T_e$ pedestal

Decreasing pedestal top $T_e$

Pedestal top

KAM – stochastic boundary

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Particle Diffusivity in the Pedestal Region is Sufficient for Density Pump-Out on Experimental Time Scale

- Apply simple transport model

\[
\frac{\partial \langle n \rangle}{\partial t} = -\nabla \cdot \Gamma = \nabla \cdot (D \nabla \langle n \rangle),
\]

\[
\frac{3}{2} \frac{\partial (nT)}{\partial t} = -\nabla \cdot \left( q + \frac{5e\langle T \rangle}{2} \Gamma \right) = \nabla \cdot \left[ \langle n \rangle \chi \nabla \langle T \rangle + \frac{5e\langle T \rangle}{2} D \nabla \langle n \rangle \right]
\]

- Radial fluxes are evaluated with respect to the unperturbed flux-surfaces

25% density pump-out requires \( D \sim \mathcal{O}(0.05-0.1) \) m\(^2\)/s in pedestal
What Determines the RMP-Induced Transport Level at the Pedestal Top? → Study Kinetic Transport Channels

- The time lag between particle flux and ion gyro-center flux is comparable to the toroidal transit time of a 500 eV ion!
- The time lag implies a rapid change of the radial electric field during RMP ramp-up.
Cross-Field Electron Flux Is Dominated by Free Streaming Along \(\delta B_r\), Ion Gyro-Center Flux by Banana Orbit Motion

There are two distinct transport channels:

- **“3D neoclassical” flux**
  \[
  \Gamma_{neo} = \frac{\langle \iint [\nabla \psi \cdot (v_D + v_{ExB}) f] \, d^3v \rangle}{\langle |\nabla \psi| \rangle}
  \]

- **3D \(\delta B\) flux**
  \[
  \Gamma_{3D} = \frac{\langle \iint [\nabla \psi \cdot \delta B/|B| \, v_{||} f] \, d^3v \rangle}{\langle |\nabla \psi| \rangle}
  \]

  - Since electrons are much faster than ions, this result is not surprising
  - Ion transport can be explained by parallel (non-adiabatic) pressure gradients alone!
Collisions Are Required for Lifting Electrons Across KAM Surfaces, Then Free Parallel Streaming and $E_r$ Take Over

- The drift velocity $v_D$ yields a net cross field flux only if canonical angular momentum conservation is violated $\rightarrow$ 3D field + collisions
- Once electrons cross perturbed flux-surfaces, they react almost adiabatically to $E_r$ $\rightarrow$ are pulled outward
- This transport channel is inhibited by 3D collisions (friction on flow along perturbed magnetic field) and controlled by $E_r$
- If electrons are lost too fast along this channel, $E_r$ will flip and become positive
Radial Ion Particle Flux Can Be Understood from a Fluid Perspective \(\rightarrow\) Parallel Pressure Gradient

- Significant change of the non-adiabatic ion pressure due to RMP fields
- Increased ion gyro-center flux can be explained by the fluid radial diamagnetic flux!
The Electrostatic Field Adjusts to RMP Field to Maintain the Ambipolarity of the Radial Particle Flux

After adjusting for the fast prompt electron losses, $E_r$ is still negative throughout the pedestal region $\rightarrow$ pulls electrons outward $\rightarrow$ **Suggests that transport is still driven by ion banana orbit motion** (Remember that the thermal banana orbit width is comparable to the pedestal width!)

The change of the shearing rate around the pedestal top can have implications on turbulent transport $\rightarrow$ will use XGC1 to study this
RMP-Induced Changes of Toroidal Rotation May be Important for RMP Penetration Physics

- While toroidal rotation with fixed RMP field does not affect transport in XGCa, changes of the toroidal rotation and radial electric field may influence plasma screening of the RMP field.
- Dynamic coupling of XGCa and M3D-C1 or use of XGCa-internal Ampère solver may reveal interesting physics of RMP penetration.

Rapid change of edge toroidal rotation
XGC Calculation of the Global ITG Turbulence Response to RMP Penetration in DIII-D 126006 Plasma

• The RMP penetration was simulated in XGC0, with drift-kinetic electrons and ions, using an electromagnetic solver borrowed from M3D
  – G.Y. Park, Invited Talk, APS-DPP2010
• The RMP+ equilibrium magnetic field was imported into the full-f XGC1
  – ITG turbulence, ion neoclassical physics, 3D electric field, and plasma rotation are simulated together in realistic 126006 geometry
• This will be studied more carefully with gyrokinetic ions, drift-kinetic electrons and neutral recycling
Conclusions and Next Steps

• Coupled XGCa and M3D-C1 simulations find significant increase of the pedestal particle flux due to RMP fields
• Cancellation between inward electron thermal pinch and outward convective energy flux maintains $T_e$ pedestal
• The increased transport level cannot be explained by collisionless transport and stochasticity alone $\rightarrow$ Collisions on neoclassical orbits are required
• The overall particle transport level is still determined mostly by ion physics: ambipolarity requirement
• The RMP field causes changes of the pedestal top ExB shear $\rightarrow$ changes in turbulent transport can be expected
  – XGC1 saw a global increase in turbulence strength by RMP in a DIII plasma
Conclusions and Next Steps

• Next steps:
  – Apply anomalous transport model in XGCa simulations
  – Use Ampere solver in XGCa or dynamic coupling to M3D-C1 to study kinetic RMP penetration
  – Study self-consistent turbulence-neoclassical physics with RMP in XGC1