Gyrokinetic simulation of tokamak edge plasma under resonant magnetic perturbations in realistic divertor geometry

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• Introduction
• Numerical Approach
• RMP-induced transport in DIII-D and KSTAR
  • Density pump-out
  • Electron heat confinement
• Conclusions and Discussion
• ITER plans to use 3D fields, Resonant Magnetic Perturbations (RMP), for ELM suppression

What are the physics behind the density pump-out?

Why is electron heat still confined?

Pump-out (>25%) (over ~100 ms)

Steeper and higher $T_e$ pedestal

Apparent correlation between
• I-coil current
• Turbulence intensity and
• ELM intensity

What are the physics behind RMP ELM-suppression?
From DIII-D #157308 H-Mode Plasma Profiles M3D-C1 Yields 3D Field with Good KAM Surfaces at Pedestal Slope and Top

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

Good KAM surfaces in pedestal slope and top

Thin stochastic layer very close to the separatrix \( \psi_N \gtrsim 0.98 \)

Radial component of \( n=3 \) RMP field from M3D-C1

δB strong enough to affect trapped particle dynamics

Δb

Simulation setup: R. Hager et al., Nuclear Fusion 2019; M3D-C1 RMP: e.g. N. Ferraro et al., Phys. Plasmas 2012
The Gyrokinetic Code XGC is used to Study the RMP Induced Transport

- XGC is a **global 5D gyrokinetic, total-f particle-in-cell code**
- Advantages of using the total-f gyrokinetic code XGC
  - Whole volume simulation including SOL, separatrix, and magnetic axis
  - 3D electric field and plasma profile solutions consistently with gyrokinetic physics and magnetic equilibrium
  - No assumptions on fluid closures
  - Nonlinear Fokker-Planck-Landau collision operator
  - Neutral particle recycling

Parallel current density from trapped and passing particles in NSTX #132543 computed with XGC (R. Hager and C. S. Chang, PoP 2016, illustration by F. Sauer, T. Neuroth and K.-L. Ma, UC Davis)
XGC and M3D-C1 Are Coupled for Transport Study in MHD-Screened RMP Field

M3D-C1:
• 3D equilibrium magnetic field using fluid plasma response → screened RMP field

XGC:
• Gyrokinetic plasma transport in 3D magnetic equilibrium → radial fluxes, 3D potential solution

• M3D-C1 provides perturbed 3D magnetic equilibrium
• XGC computes plasma transport
• Planned extensions
  • Updated plasma profiles, effective transport coefficients, kinetic response currents, etc. can be returned to M3D-C1 for longer time-scale coupled simulation (to be done soon)
  • Self-consistent RMP penetration in XGC
  • Use electromagnetic version of XGC (mixed-variable formulation)
RMP Field Increases Turbulence Intensity $\langle \delta \phi^2 \rangle^{1/2}/T_e$

Without RMPs

With RMPs

Immediate (electron transit timescale) $n=3$ response to RMP field before turbulence sets in
RMPs Increase Density Fluctuations and Decrease Temperature Fluctuations in the Pedestal

- $n=3$ mode (RMP) is removed to study changes in relative RMS turbulence fluctuation levels.
- Potential fluctuations change only by $\sim10\%$.
- Density fluctuations increase with RMP (by up to $40\%$ at $\psi_N \approx 0.97$).
- Electron temperature fluctuations decrease with RMPs (by $\sim25\%$ at $\psi_N \approx 0.97$).
- These changes are correlated with changes in the transport fluxes.
- $\delta p_e$ is minimized by restricting $\delta T_e$. 
Spectra suggest enhanced TEM in pedestal slope. ITG deeper inside does not change as much (at t~0.2 ms).

Electron mode

Ion mode

Transition between ion and electron mode

Electron mode
There are three main transport channels:

- **Neoclassical flux**
  \[ \Gamma_D = \frac{\left\langle \int \left[ \nabla \psi \cdot (\mathbf{v}_D + \mathbf{v}_{ExB}) \tilde{f} \right] d^3v \right\rangle}{\left\langle |\nabla \psi| \right\rangle} \]

- **3D $\delta B$ flux**
  \[ \Gamma_{3D} = \frac{\left\langle \int \left[ \nabla \psi \cdot (\delta B/|B|) \mathbf{v}_\parallel \tilde{f} \right] d^3v \right\rangle}{\left\langle |\nabla \psi| \right\rangle} \]

- **Turbulent $\text{ExB}$ flux**
  \[ \Gamma_{turb} = \frac{\left\langle \int \left[ \nabla \psi \cdot \tilde{\mathbf{v}}_{ExB} \tilde{f} \right] d^3v \right\rangle}{\left\langle |\nabla \psi| \right\rangle} \]

\[ \Gamma_{neo} = \Gamma_D + \Gamma_{3D} \]

\[ f = \bar{f} + \tilde{f} \]

\[ (\ldots) \rightarrow \text{toroidal average} \]
Electron Thermal Transport Barrier in the Steep Pedestal Region Survives with RMP Field from M3D-C1

Turbulent + neoclassical particle diffusivity with RMP is higher than without RMPs

\[ \Delta D = (D_{\text{neo}} + D_{\text{turb}})^{\text{(RMP)}} - (D_{\text{neo}} + D_{\text{turb}})^{\text{(no RMP)}} \]

determines density pump-out

Turbulent electron thermal diffusivity is suppressed between \(0.96 \lesssim \psi_N \lesssim 0.98\), neoclassical thermal diffusivity is slightly elevated

\[ \Delta = \]

\[ \psi_N \]

Electron thermal transport barrier in the steep pedestal region survives
RMP-Driven Particle Diffusivity (Turbulence+Neoclassical) is Sufficient for Density Pump-Out

- RMP-driven increase of **neoclassical+turbulent** particle diffusivity is largely sufficient for density pump-out in the steep pedestal region.

Collisional transport w/o turbulence from XGC1 [R. Hager et al., Nuclear Fusion 5, 126009 (2019)]

Effective particle diffusivity must be greater than this rough estimate for 25% pump-out in ~100 ms.

$\rightarrow$ Increase of turbulent transport boosts pump-out from enhanced neoclassical transport
Use Cross-spectral Analysis to Pinpoint the Origin of the RMP-driven Particle Flux

- Find the origin of the increased turbulent particle flux density in:
  - Higher turbulence amplitude or
  - Shifted cross-phase between turbulent fluctuations
  - Which mode numbers are responsible?

**Cross-spectrum:**
\[ S_{AB} = \langle \hat{A} (\psi_N, m, \varphi) \hat{B}^*(\psi_N, m, \varphi) \rangle_{tor} \]

**Cross-power:**
\[ P_{AB} = |S_{AB}| \]

**Cross-phase:**
\[ \delta \zeta_{AB} = \arctan[\Im(S_{AB})/\Re(S_{AB})] \]

**Turbulent transport fluxes in terms of cross-power and cross-phase:**
\[ \Gamma_t (\psi_N, m) = \alpha(\psi_N) P_{vn} \cos(\delta \zeta_{vn}) \]
\[ Q_t (\psi_N, m) = \alpha(\psi_N) \frac{3}{2} k_B \left[ \langle n \rangle P_{VT} \cos(\delta \zeta_{VT}) + \langle T \rangle P_{vn} \cos(\delta \zeta_{nT}) \right] \]
\[ q_t (\psi_N, m) = Q_t - \frac{5}{2} k_B \langle T \rangle \Gamma_t \]

(\( \alpha \) is a geometric factor from the flux-surface average.)
Increased Particle Flux Density from $m \geq 200$ at $\psi_N \sim 0.97$

RMPs increase particle flux and decrease electron heat flux density around $\psi_N \sim 0.97$ at higher poloidal mode numbers $m \geq 200$ ($k_\theta \rho_i \approx 0.2-0.3$).

$\rightarrow$ Electron energy transport is convective, riding the particle flux, which does not alter the $T_e$ gradient much.
Study Correlation between $I_{\text{RMP}}$ and Turbulence Intensity in KSTAR H-mode discharge 18451

Y. In et al 2019 Nucl. Fusion 59 056009

KSTAR #18451
- $t=2.79$ s, $I_{\text{RMP}}=0$ kA/t → Before RMP application
- $t=3.39$ s, $I_{\text{RMP}}=2$ kA/t → ELM mitigation
- $t=4.69$ s, $I_{\text{RMP}}=2.69$ kA/t → ELM suppression

Equilibrium data →
$t=2.79$ s: kinetic EFIT
$t=4.69$ s: M3D-C1 based on kinetic EFIT
RMP Calculation with M3D-C1 is Very Sensitive to the Toroidal Rotation

Strong $m=3$ tearing response with experimental rotation profile
$\rightarrow$ no KAM surfaces left at $\psi_N \gtrapprox 0.65$

Tweak rotation profile by $\sim 5\text{-}10\%$ to avoid $m=3$ resonance

Modeling decision:
Try to make RMP field more consistent with current understanding of ELM suppression
$\rightarrow$ RMPs penetrate pedestal top
XGC Simulation: Unstable Trapped-electron Modes (TEMs) extends to pedestal top, covering $0.9 \leq \psi_N \leq 1$

- Available simulation too short to study saturated edge turbulence
- Study exponential growth phase instead ("quasi-linear")
- Initially unstable mode propagate in electron diamagnetic direction in ExB frame $\rightarrow$ TEM
- Growth rates in the steep-gradient region are largely similar between pre-RMP and RMP ELM-suppressed phase, but extend to pedestal top with RMPs.
Fast Neoclassical Profile Evolution is Observed around Magnetic Islands and in Stochastic Layer

- Neoclassical particle transport (including parallel transport along the perturbed field) is inward around the m=2 and m=3 islands → counter-intuitive (similar to J. Kwon et al., Physics of Plasmas 2018)
- Electron temperature flattens across magnetic islands → as expected
- This fast evolution is due to turbulence (confirmed with neoclassical simulations)
Conclusions

- Electrostatic XGC (neoclassical+turbulence) with M3D-C1 n=3 RMP field simulations of DIII-D exhibit
  - Higher particle flux in the pedestal with significant neoclassical contribution around the separatrix → **enough to explain density pump-out**
  - Suppressed electron heat flux in the pedestal center → **maintains steep $T_e$ gradient**
- XGC simulations of KSTAR n=1 RMP discharge exhibit
  - Unstable TEMs extend from the steep-gradient region to the pedestal top ($0.9 \leq \psi_N \leq 1$) during ELM-suppression.
  - Waiting for longer simulation to study saturated edge turbulence
- Working on self-consistent RMP penetration in XGC → **mitigate uncertainty due to toroidal rotation**
- Electromagnetic XGC will be used to study effect on ELM-turbulence interaction
Visualization by E. Feibush, PPPL