Understanding the RMP-Driven Transport in Tokamak Edge Plasma from Gyrokinetic-MHD Coupled Simulation in Realistic Divertor Geometry

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Outline

• Introduction
• Numerical Approach
• RMP-Driven Non-Turbulent Transport
  – With axisymmetric potential solution
  – With axisymmetric + n=3 potential solution
• Combined Neoclassical and Turbulent Transport
  – Density pump-out
  – Electron heat confinement
• Conclusions and Discussion
Introduction
ITER plans to use 3D fields, **Resonant Magnetic Perturbations** (RMP), for ELM suppression

Experiment: RMP fields can lead to the so-called “density pump-out”, decreasing fusion efficiency (while leaving the $T_e$ pedestal intact, against Rechester-Rosenbluth)

**Goals of XGC study:**

*What are the physics behind the density pump-out?*

*Why is electron heat still confined?*

- Density pump-out (>25%)
  (on $\sim$100 ms time scale)

- Steeper and higher $T_e$ pedestal

T. Evans et al., Nature 2006
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.

Radial component of $n=3$ RMP field from M3D-C1

Simulation setup: R. Hager et al., Nuclear Fusion 2019; M3D-C1 RMP: e.g. N. Ferraro et al., Phys. Plasmas 2012
Numerical Approach
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
  - Kinetic-consistent radial, poloidal, and toroidal electric field solution
  - 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:
- Axisymmetric equilibrium magnetic field, and
- 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
Simulation of Non-Turbulent (Neoclassical) RMP-Driven Transport

R. Hager, C.S. Chang, N. Ferraro, R. Nazikian
Nuclear Fusion 59, 126009 (2019)
Axisymmetric $\phi$: The Electrostatic Field Adjusts to RMP Field to Maintain the Ambipolarity of the Radial Particle Flux

- Increased electron losses due to stochastic field at $\psi_N \geq 0.98$ lead to
  - **Reduction of $E_r$-well depth**
  - **Reduced shearing rate around separatrix and $\psi_N \approx 0.97 \rightarrow$ potentially influencing turbulence activity!**

- With turbulence, this $E_r$ profile can be somewhat modified.
Particle Diffusivity is at Experimental Level only in the Stochastic Layer ($\psi_N \gtrsim 0.98$), but Turbulence is Needed Inside Pedestal Center

Neglection of $n=3$ potential overestimates RMP induced collisional transport (cf. G. Park, Phys. Plasmas 2010 with XGC0)

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

Turbulent transport is needed from pedestal slope inward to produce sufficient pump-out
Why the n=3 Potential Solution Matters This Much

- $\phi_{n=3}$ is needed for potential equilibration on the perturbed flux-surfaces
- Particles:
  - Strong potential variation on perturbed flux-surfaces shifts trapped particle bounce points
- Ohm’s law:
  - Without non-axisymmetric potential, a continuous current along the perturbed field lines is needed to balance the radial electric field

$\Rightarrow$ Enhanced radial transport if $\phi_{n=3}$ is not included!

Heyn et al., Nuclear Fusion 2014 $\Rightarrow$ Higher transport where magnetic and electric equipotential surfaces do not match.
Simulation of Neoclassical + Turbulent RMP-Driven Transport
XGC1 Simulations of Combined Neoclassical and Turbulent Transport Show Increased n=3 Activity with RMP Field

Without RMP

With RMP

Early n=3 response to RMP field in electrostatic potential

Stronger SOL turbulence
RMP Field Increases Turbulence Intensity $<\delta\phi^2>^{1/2}/T_e$

Immediate $n=3$ response to RMP field before turbulence sets in.
Spectra suggest enhanced TEM in pedestal slope. ITG deeper inside does not change as much (at t~0.2 ms)

Ion mode

Electron mode

ω/k < 0 corresponds to ion diamagnetic direction

ExB flow

ψ_N=0.85, w/o RMP, ITG

ψ_N=0.85, w/ RMP, ITG

ψ_N=0.97, w/o RMP, TEM

ψ_N=0.97, w/ RMP, TEM
Turbulence Intensity is Greater with RMP
But what about Transport?

There are three main transport channels:

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

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

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

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

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

\[
(\ldots) \rightarrow \text{toroidal average}
\]
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 RMP

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

determines density pump-out

\[ \psi_N \]

Turbulent electron thermal diffusivity is suppressed between

\[ 0.96 \leq \psi_N \leq 0.98 \]

neoclassical thermal diffusivity is slightly elevated

KAM – stochastic boundary

Electron thermal transport barrier in the steep pedestal region survives with RMP field from M3D-C1
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.

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

→ Increase of both neoclassical and turbulent transport is required for pump-out!
The ExB Shear Appears to be Largely Responsible for the Enhanced Turbulent Transport

ExB shearing rate vs. $\psi_N$

KAM – stochastic boundary

Lower ExB shear from pedestal shoulder to slope → similar reduction at pedestal shoulder is observed in neoclassical simulations (Hager et al., Nuclear Fusion 2019)
Cross-Spectral Density \((v_E, n)\)

**Without RMP**

- Cross-Power \((\delta v_E, \delta n)\)
  - Pol. mode number:
    - 200
    - 150
    - 100
    - 50

- Cosine of Cross-Phase \((\delta v_E, \delta n)\)
  - Pol. mode number:
    - 200
    - 150
    - 100
    - 50

**With RMP**

- Cross-Power \((\delta v_E, \delta n)\)
  - Pol. mode number:
    - 200
    - 150
    - 100
    - 50

- Cosine of Cross-Phase \((\delta v_E, \delta n)\)
  - Pol. mode number:
    - 200
    - 150
    - 100
    - 50

With RMP \(\rightarrow\) More power at lower \(n\)

Cross-phase is unspecific
Cross-Spectral Density ($v_{E,T}$)

**Without RMP**

**Cross-Power ($\delta v_{E}, \delta T_e$)**

**Cosine of Cross-Phase ($\delta v_{E}, \delta T_e$)**

**With RMP**

**Cross-Power ($\delta v_{E}, \delta T_e$)**

**Cosine of Cross-Phase ($\delta v_{E}, \delta T_e$)**
Inward particle and energy flux from n=3
Negative heat flux at high m
Outward heat flux from n=3
• Particle and energy flux are enhanced at m~300 \( (k_{\theta} \rho_i \sim 0.2) \)
• But particle flux increases more \( \Rightarrow \) inward heat flux at higher \( k_{\theta} \rho_i \)
• Large particle and energy flux from \( n=3 \) (RMP) are inward, but heat flux is outward
Divertor Energy Load Footprint Shows Typical RMP Lobes

Without RMP

Outer Divertor, t~0.2 ms

SOL

Private flux region

Distance from strike point (cm)

Parallel energy flux at outer divertor plates exhibits n=3 striations with RMP field turned on.

Inner Divertor, t~0.2 ms

Less striation on the inner divertor plates but also larger

With RMP

Outer Divertor, t~0.2 ms

SOL

Private flux region

Distance from strike point (cm)

Inner Divertor, t~0.2 ms

Distance from strike point (cm)
Divertor Energy Load Width in the RMP case is wider by ~15%

- 50% higher peak divertor energy load with RMP field during the early density pump-out phase
- Slight broadening of the divertor heat load width $\lambda_q$ by ~15% for present 3D RMP field from M3D-C1
Conclusions
Correlation between ELM suppression and rotation

Increase of I-coil current appears related to increase of turbulence intensity and reduction of ELM intensity: Turbulence-ELM energy exchange?

Hysteresis

RMP coil current

KSTAR, J. Lee et al., Nuclear Fusion 2019
Conclusions

• When using M3D-C1 RMP field in XGC simulations, combined neoclassical and turbulent transport are needed to explain experiment

• Electrostatic XGC (neoclassical+turbulence) simulations exhibit
  – Higher particle flux in the pedestal with significant neoclassical contribution around the separatrix $\rightarrow$ enough to explain density pump-out
  – Suppressed electron heat flux in the pedestal center $\rightarrow$ explains why $T_e$ steepens

• Ongoing: More detailed analysis of how $\delta B$ affects cross-phase among $\delta \phi$, $\delta n$, $\delta T$

• Self-consistent RMP penetration in XGC

• Electromagnetic XGC will be used to study effect on ELM-turbulence interaction
XGC Whole-Volume Gyrokinetic Simulation of RMP Driven Transport in Tokamaks

Visualization by E. Feibush, PPPL