Gyrokinetic study of RMP-driven plasma transport in tokamak edge pedestal using MHD screened RMP field

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Outline

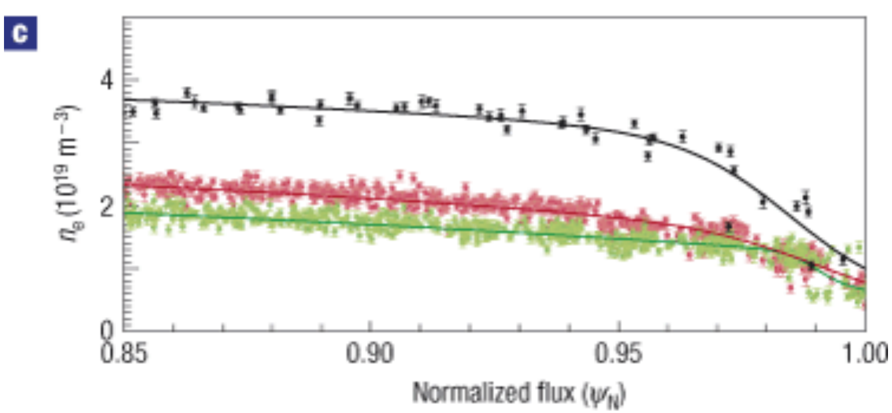
- Introduction
- Numerical Approach
- RMP-Driven Non-Turbulent Transport With XGCa: Baseline
  - With axisymmetric potential solution
  - With axisymmetric + n=3 potential solution
- Combined Neoclassical and Turbulent Transport With XGC1
- Conclusions

Introduction

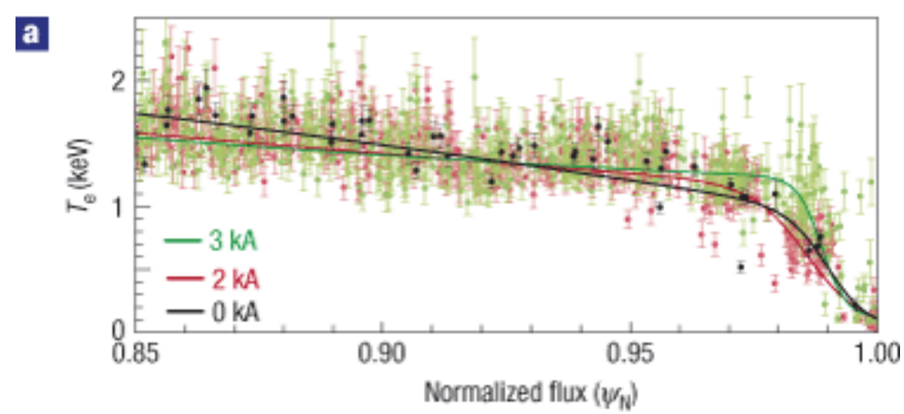
Introduction

- ITER plans to use 3D fields, **R**esonant **M**agnetic **P**erturbations (RMP), for ELM suppression
- But RMP fields can lead to the so-called "density pump-out", decreasing fusion efficiency (while leaving the T_e pedestal intact)

→ **Goal of XGC study: What are the physics behind the density pump-out, while still keeping the electron heat confined?**



Density pumpout
(on ∼100 ms time scale)

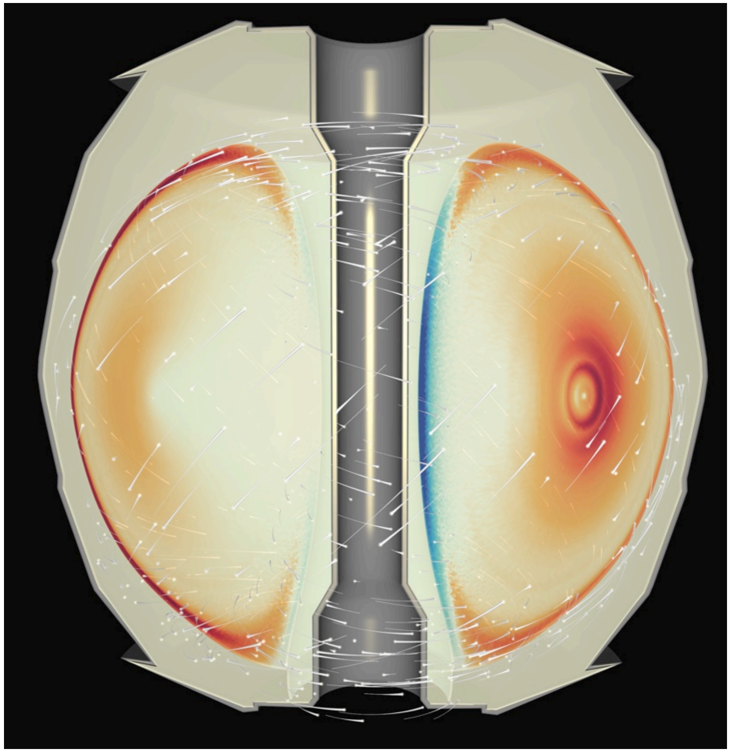


Steeper and higher
T_e pedestal

T. Evans et al., Nature 2006

The Gyrokinetic Codes XGC1 and XGCa are Used to Study the RMP Induced Transport

- XGC1 is a **global 5D** (3D configuration + 2D velocity space) **gyrokinetic**, total-f particle-in-cell code
- Advantages of using the total-f gyrokinetic code XGC1
  - Whole volume simulation including SOL and magnetic axis
  - Kinetic-consistent radial, poloidal, and toroidal electric field solution
  - Nonlinear Fokker-Planck-Landau collision operator
  - Neutral particle recycling
- XGCa uses an axisymmetric electric field solver for faster and longer simulation compared to XGC1



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)

Numerical Approach

XGC and M3D-C1 Are Coupled for Transport Study in MHD-Screened RMP Field

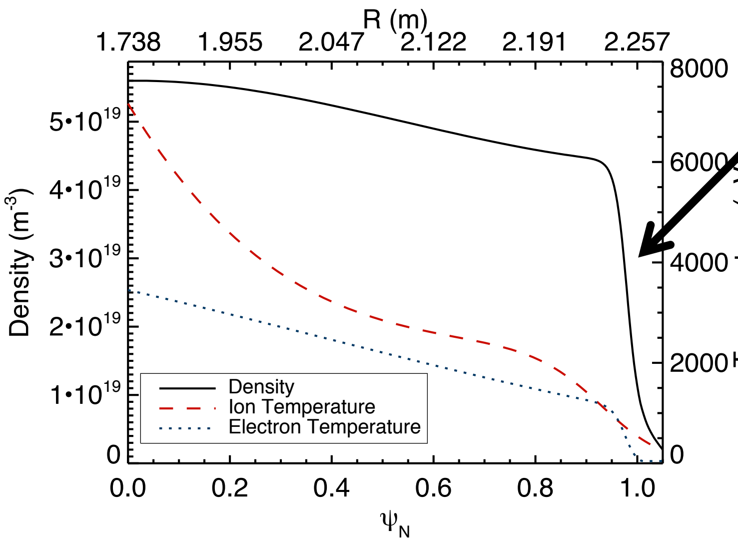
M3D-C1:
- Axisymmetric equilibrium magnetic field, and
- Fluid plasma response → **screened RMP field**

(planned)

XGC:
- Gyrokinetic plasma transport in 3D magnetic equilibrium → **profile evolution, radial fluxes, 3D potential solution**

- M3D-C1 provides perturbed 3D magnetic equilibrium
- XGC computes time evolution of the plasma
- 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)

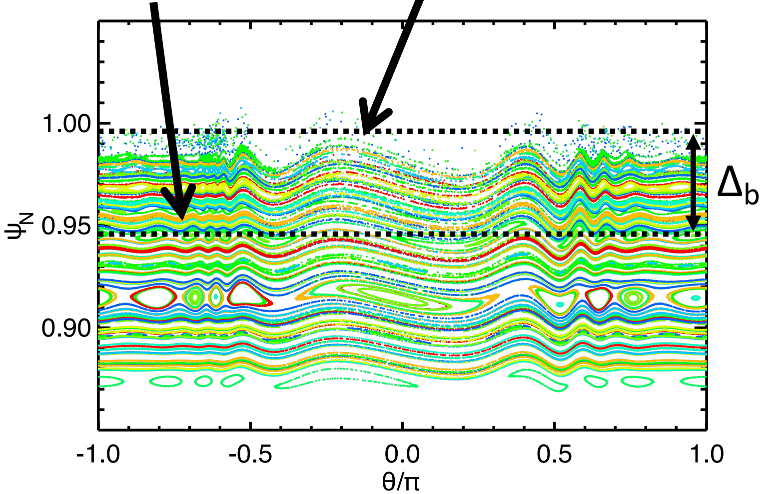
Starting from DIII-D #157308 H-Mode Plasma Profiles → M3D-C1 Yields 3D Field with Good KAM Surfaces at Pedestal Top



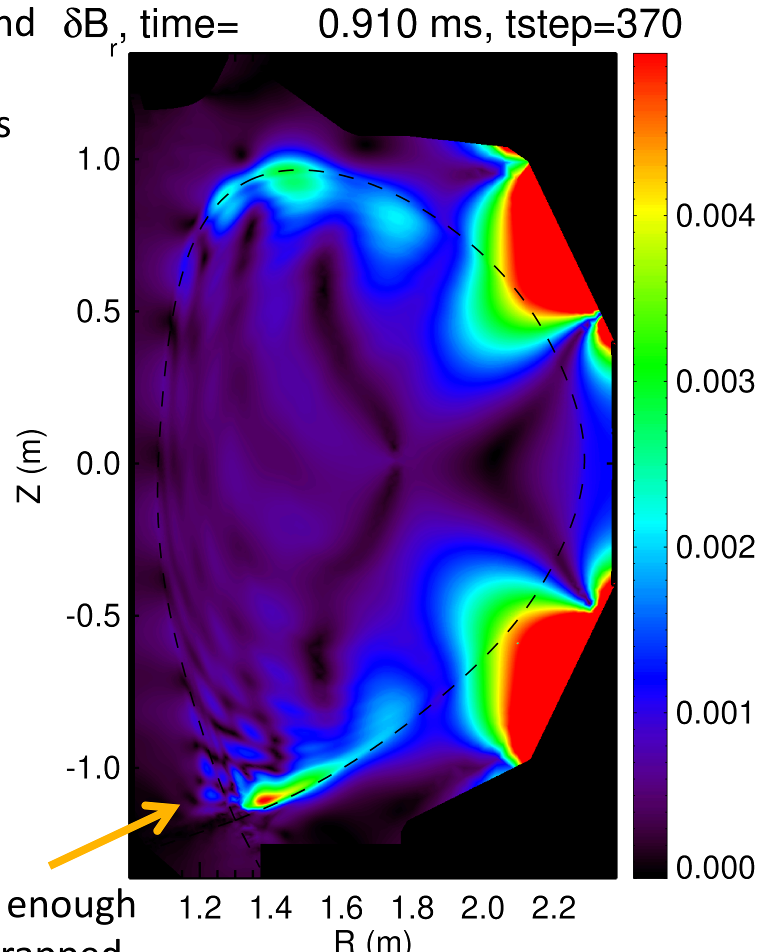
Thermal ion banana orbit width is comparable to pedestal width and spans multiple resonant surfaces

Good KAM surfaces at pedestal top

Thin stochastic layer close to the separatrix



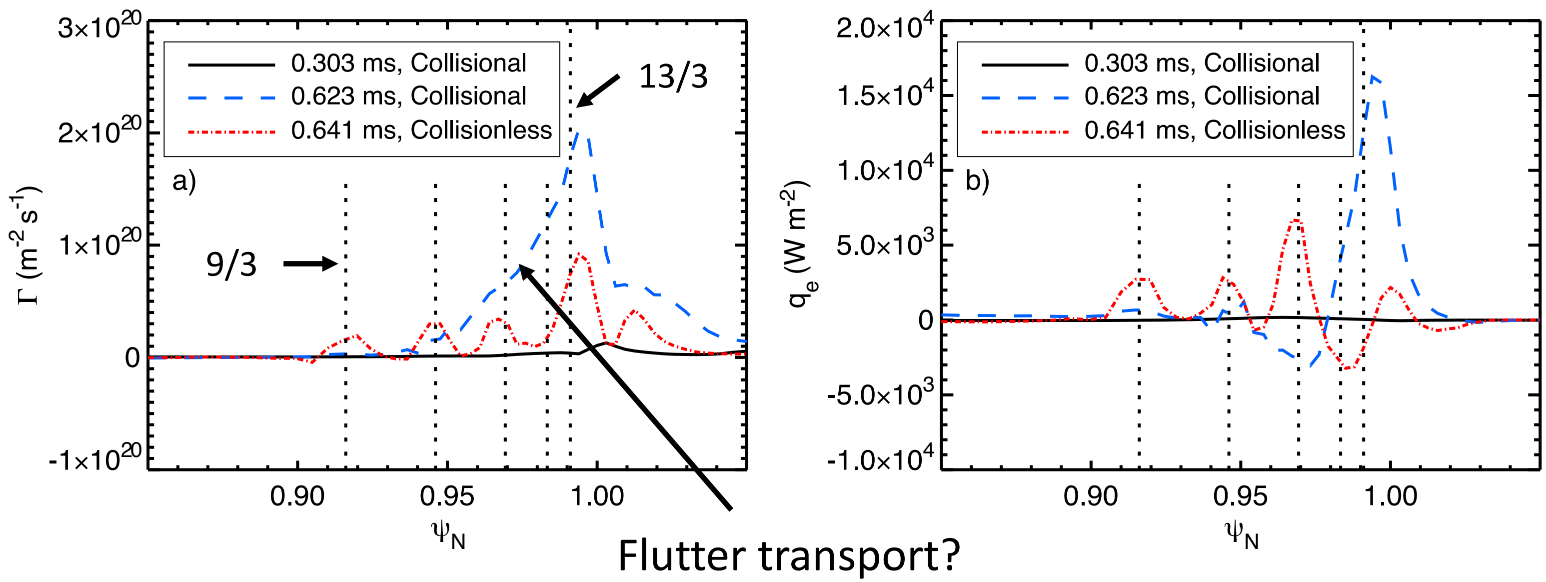
Radial component of n=3 RMP field from M3D-C1



δB strong enough to affect trapped particle dynamics

Simulation of Non-Turbulent (Neoclassical) RMP-Driven Transport in XGCa

With Axisymmetric Potential Solution in XGCa, Particle Flux is Increased and Electron Thermal Barrier Remains



- Collisionless XGCa simulations exhibit increased particle and heat flux only locally around n=3 rational surfaces
- Collisionless transport causes only local profile flattening over magnetic islands
- With collisions included, outward particle flux is increased from the pedestal shoulder into the SOL
- Electron heat is still confined except near the separatrix where B is stochastic

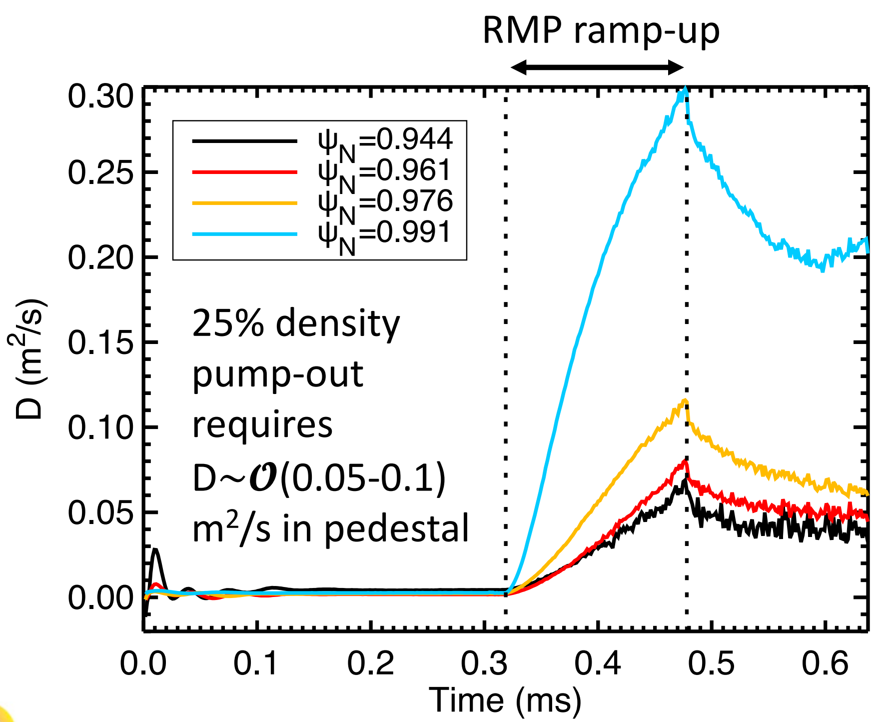
Axisymmetric ϕ in XGCa: Neoclassical Simulations Show Higher Particle Flux and Electron Thermal Pinch at Pedestal Slope

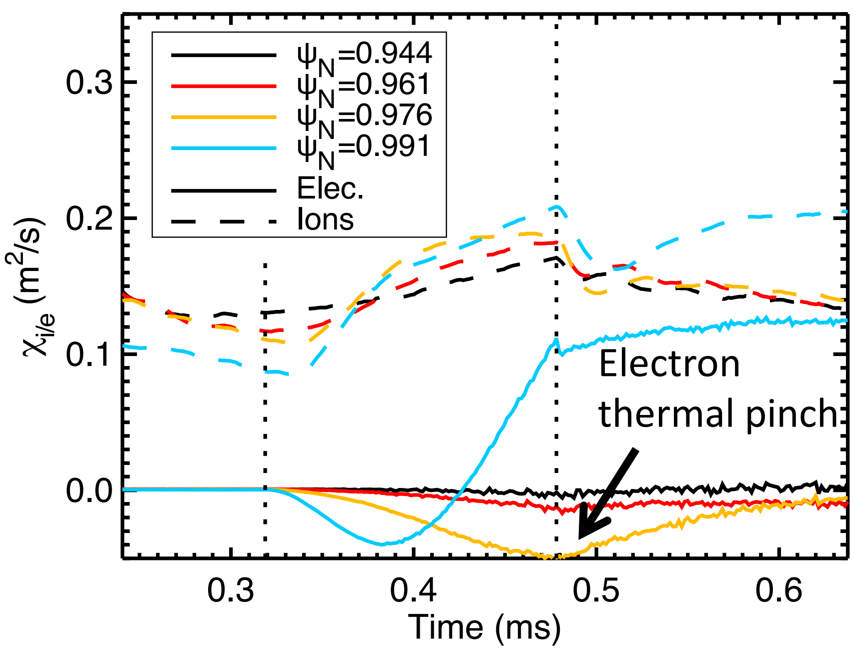
- Apply simple transport model to estimate effective transport coefficients

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

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

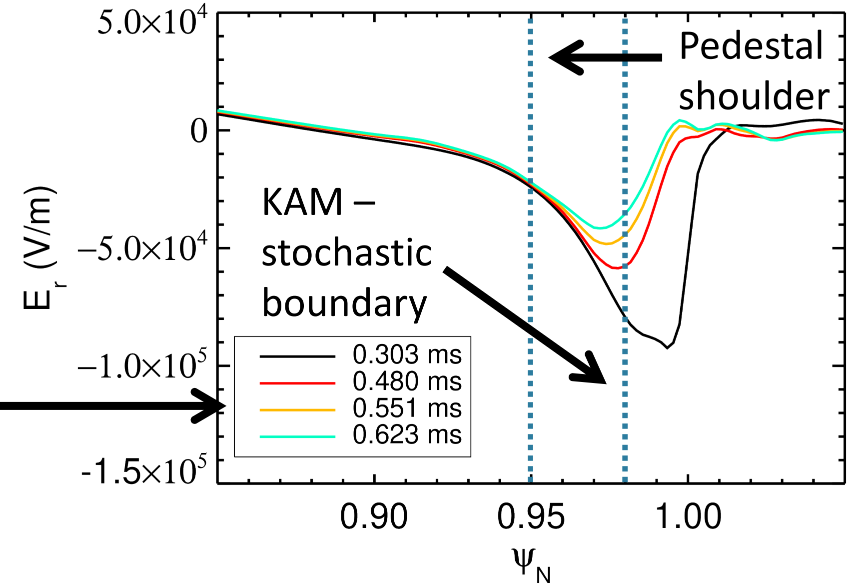
- Radial fluxes are evaluated along the unperturbed flux-surfaces





Axisymmetric ϕ in XGCa: The Electrostatic Field Adjusts to RMP Field to Maintain the Ambipolarity of the Radial Particle Flux

Outer midplane E_r



RMP field switched on t=0.32 ms

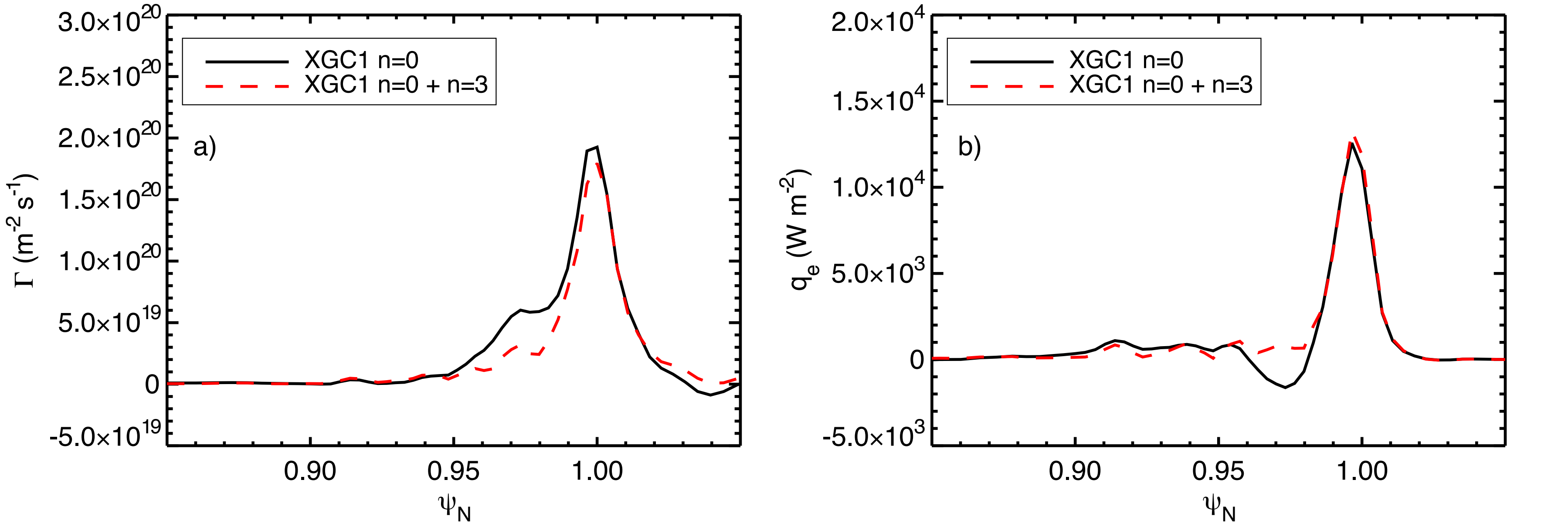
After adjusting for the fast prompt electron losses, E_r is still negative throughout the pedestal region → pulls electrons outward

→ **Suggests that transport is still driven by ion banana orbit motion**

→ **Reduced shearing rate around separatrix and ψ_N≈0.97**

XGC1: Including n=3 Nonaxisymmetric (And Nonturbulent) ϕ Reduces Transport Except in Stochastic Layer $\psi_N \gtrsim 0.98$

- To test accuracy of XGCa n=0 results → run XGC1 with Fourier filter
  - Retaining n=0 only first
- What happens with n=0 + 3 electric field with nq-5≤m≤ nq+5?
  - Transport is reduced at $\psi_N \lesssim 0.98$ if resonant electric field is included
  - But transport in stochastic layer $\psi_N \gtrsim 0.98$ does not change much compared to n=0 only



Particle Diffusivity in the Stochastic Layer ($\psi_N \gtrsim 0.98$) is at Experimental Level, Turbulence is Needed Inside Pedestal Center

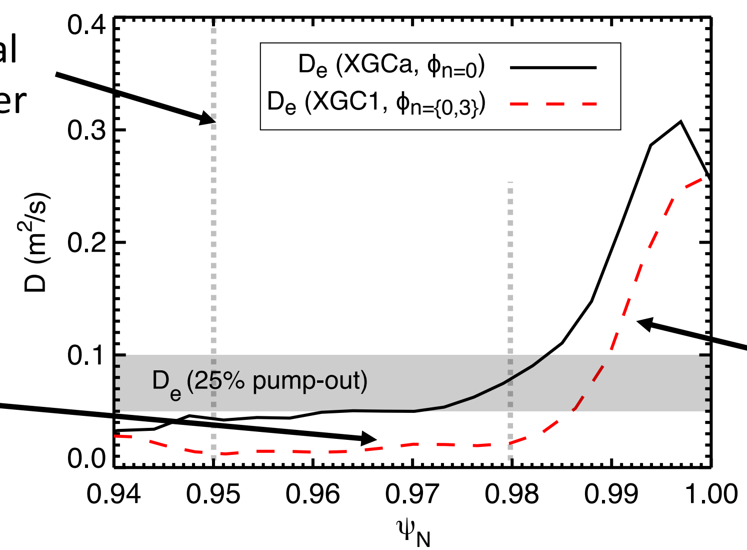
- Simple estimate for diffusivity required for density pumpout

$$D_{est} = \frac{2\,(\alpha-1)}{(\partial n_0/\partial r)\,(\alpha+1)}\,\frac{\int n_0 \mathrm{d}V}{\Delta t\, S(\psi)},$$

  - 1-α → pumpout fraction $n_0(t+\Delta t) = \alpha\, n_0(t)$ → α=0.75
  - S → flux-surface area
  - Δt → pumpout time → 100 ms

Pedestal Shoulder

Turbulent transport is needed from Pedestal center inward to produce sufficient pump-out

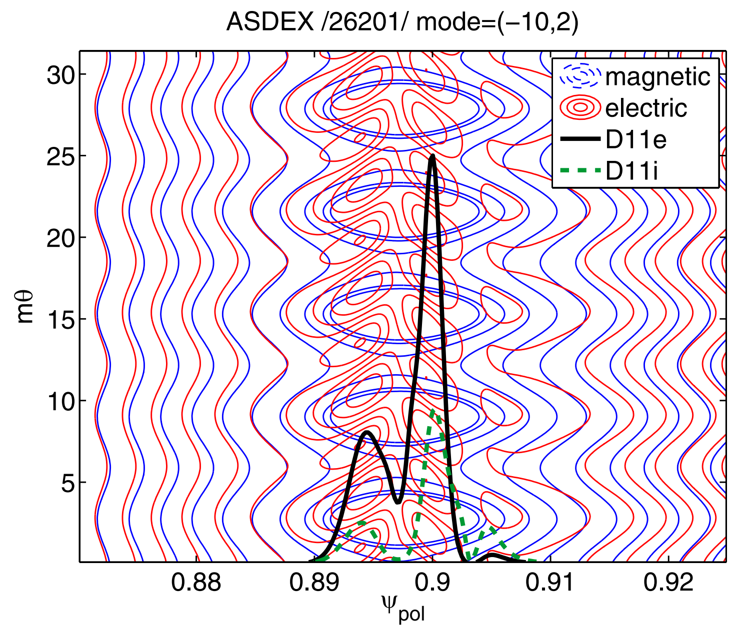


Transport in stochastic layer $\psi_N \gtrsim 0.98$ sufficient for >25% density pumpout

Why the n=3 Potential Solution Matters This Much

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

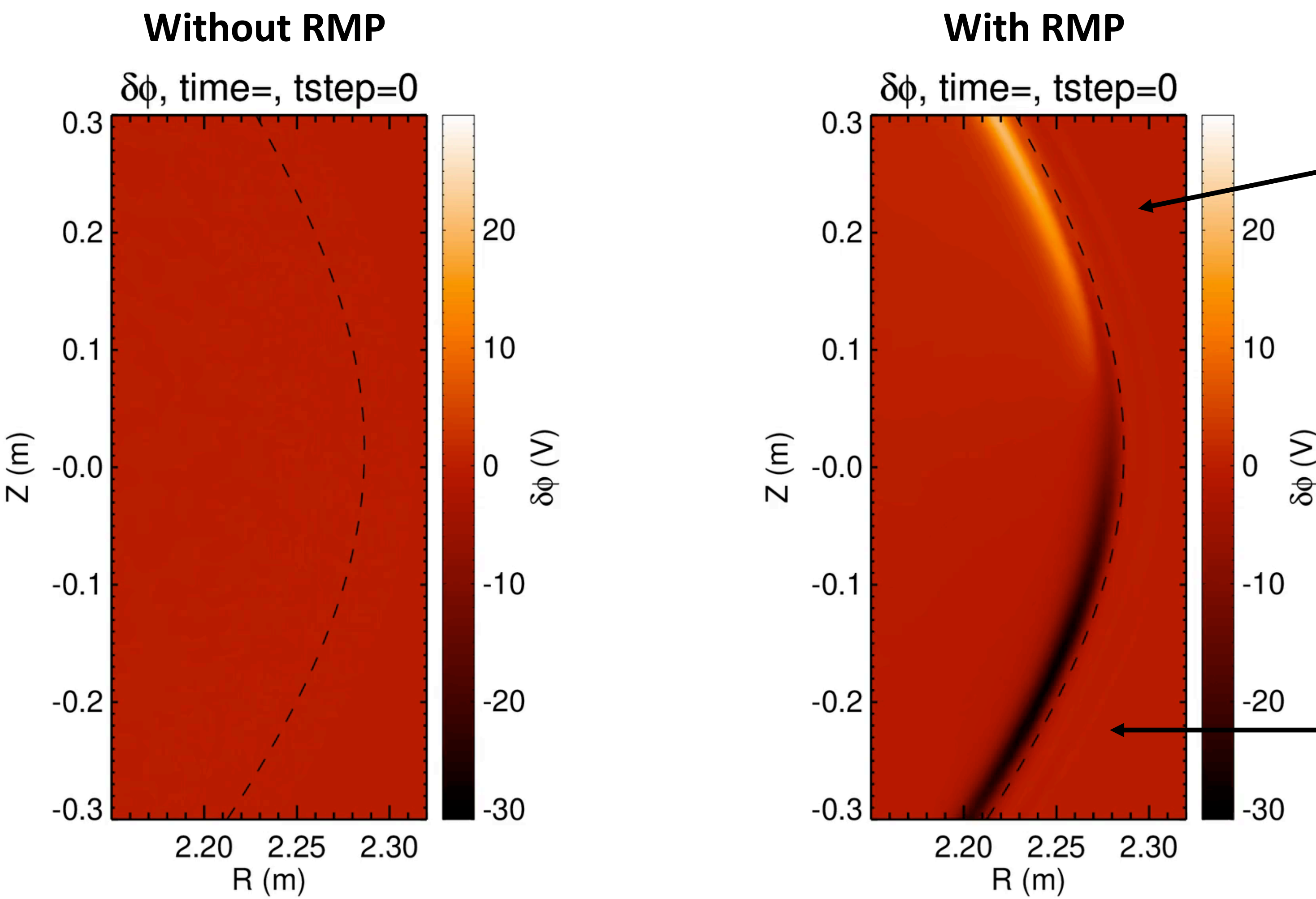
→ Enhanced radial transport if $\phi_{n=3}$ is not included!



Heyn et al., Nuclear Fusion 2014 → Higher transport where magnetic and electric equipotential surfaces do not match.

Simulation of Neoclassical + Turbulent RMP-Driven Transport with XGC1

XGC1 Simulations of Combined Neoclassical and Turbulent Transport Show Increased n=3 Activity with RMP Field



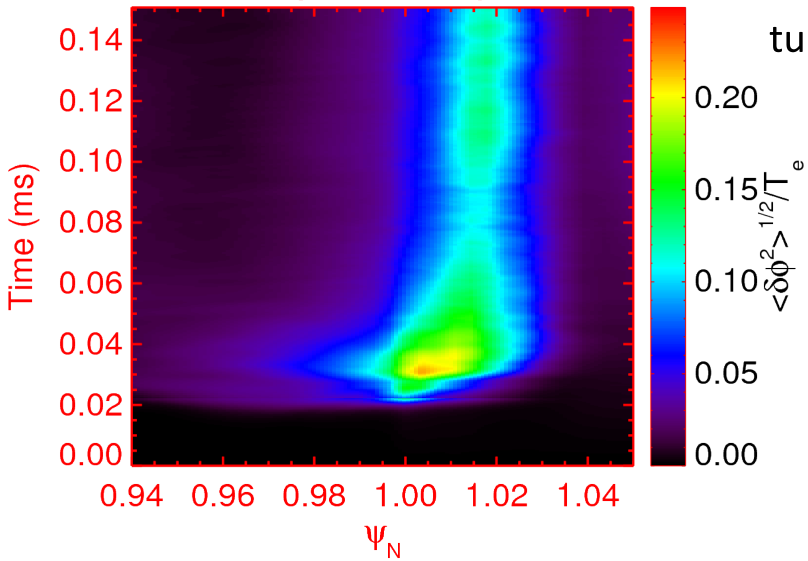
Early n=3 response to RMP field in electrostatic potential

Stronger SOL turbulence

(These simulations are still short and need to be run longer to reduce the uncertainty in the radial fluxes and to saturate turbulence in the core.)

RMP Field Increases Turbulence Intensity

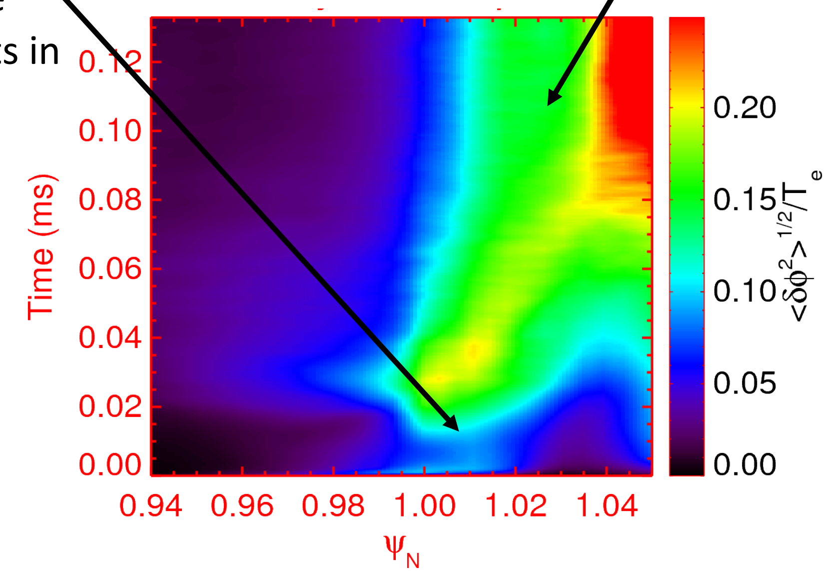
Without RMP



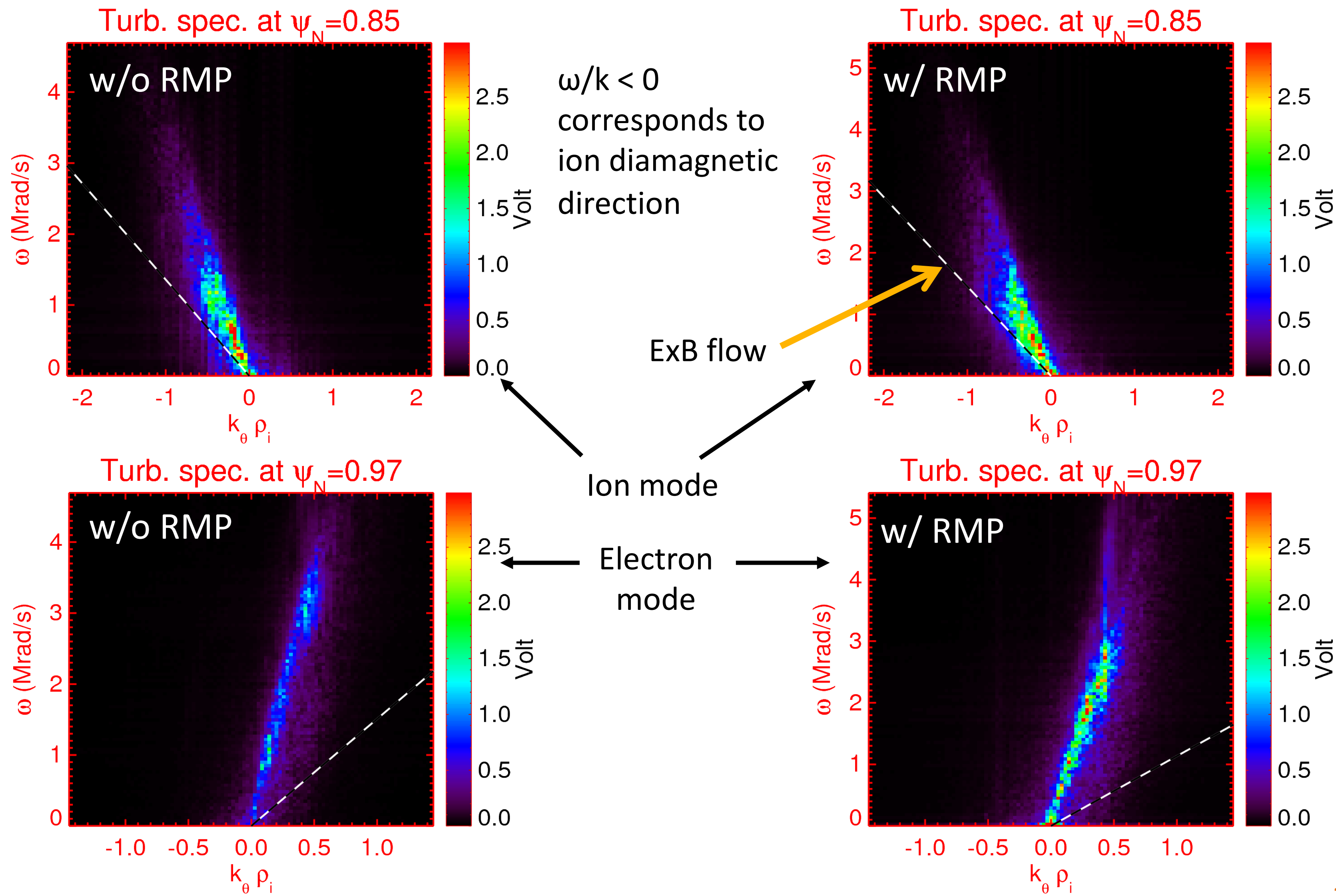
Immediate n=3 response to RMP field before turbulence sets in

With RMP

A significant fraction of δϕ is n=3

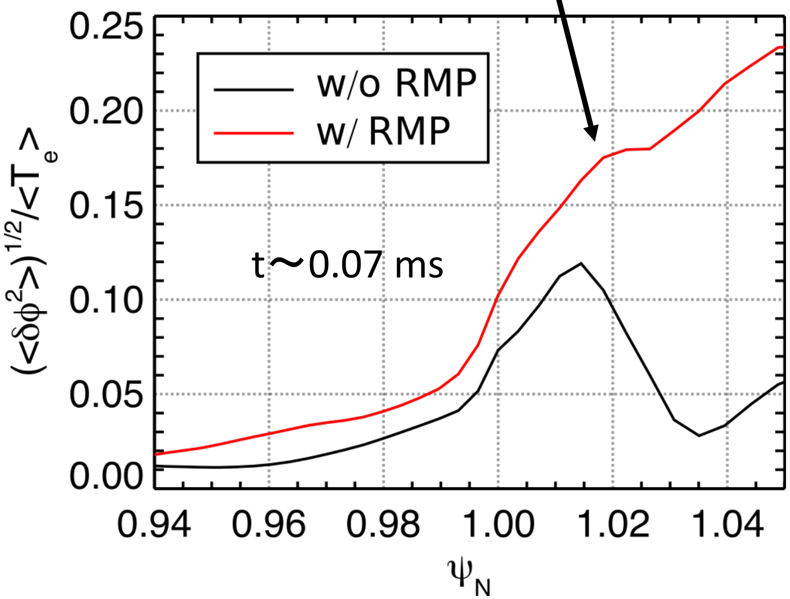


Spectra suggest enhanced TEM activity in Pedestal. ITG deeper inside does not change as much



Turbulence Intensity is Greater with RMP But what about Transport?

Stronger potential perturbation in SOL and pedestal with RMP field.
Increased SOL perturbation is not all turbulence, but includes n=3 RMP response.



There are three main transport channels:

- **"3D neoclassical" flux**

$$\Gamma_D = \frac{\left\langle \int \left[\nabla\psi \cdot (\boldsymbol{v}_D + \boldsymbol{v}_{ExB}) \overline{f} \right] \mathrm{d}^3 v \right\rangle}{\langle |\nabla\psi| \rangle}$$

- **3D δB flux**

$$\Gamma_{3D} = \frac{\left\langle \int \left[\nabla\psi \cdot (\delta\boldsymbol{B}/|B|)\, v_\parallel \tilde{f} \right] \mathrm{d}^3 v \right\rangle}{\langle |\nabla\psi| \rangle}$$

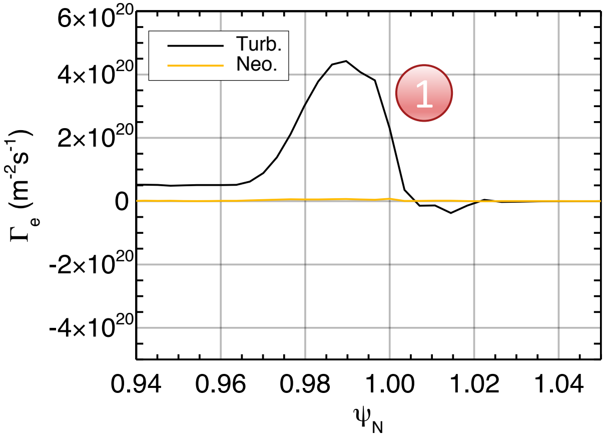
- **Turbulent ExB flux**

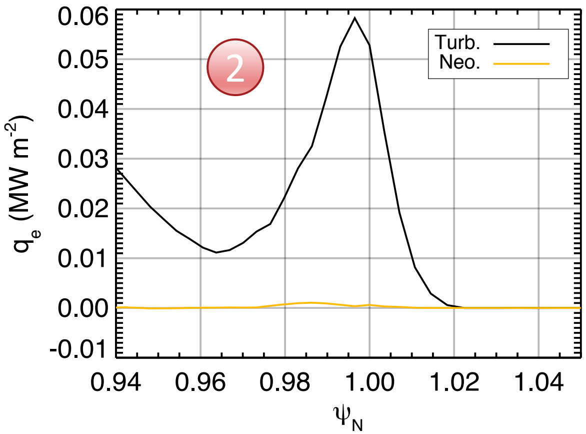
$$\Gamma_{turb} = \frac{\left\langle \int \left[\nabla\psi \cdot \boldsymbol{v}_{ExB} \tilde{f} \right] \mathrm{d}^3 v \right\rangle}{\langle |\nabla\psi| \rangle}$$

- Combine $\boldsymbol{\Gamma_D + \Gamma_{3D} = \Gamma_{neo}}$ because they are also present in neoclassical simulations

RMP Transport

Without RMP

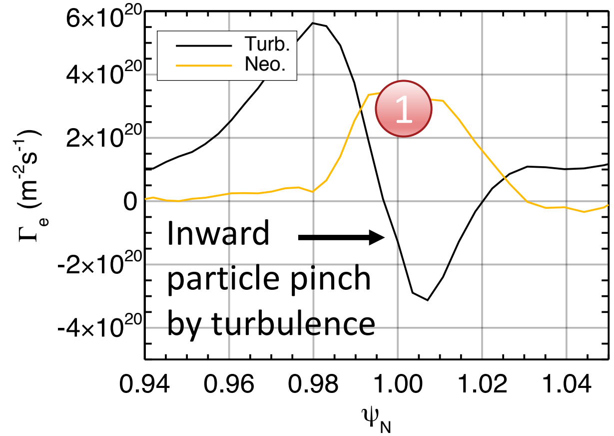


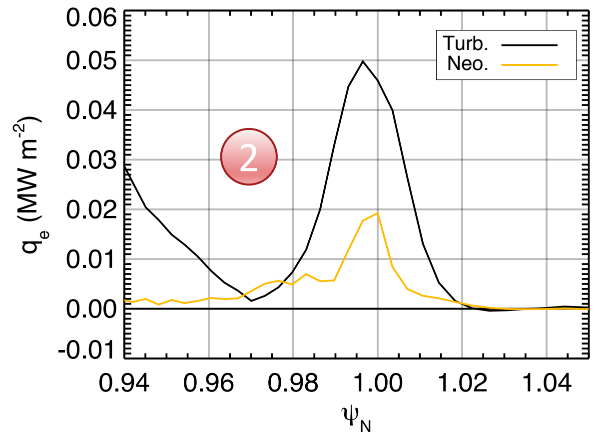


1. Turbulent particle flux is higher in the pedestal region $\psi_N>0.95$ with RMP field. Around the separatrix, the (stochastic) RMP field adds a sizeable contribution in the neoclassical transport channel (**3D δB flux**).

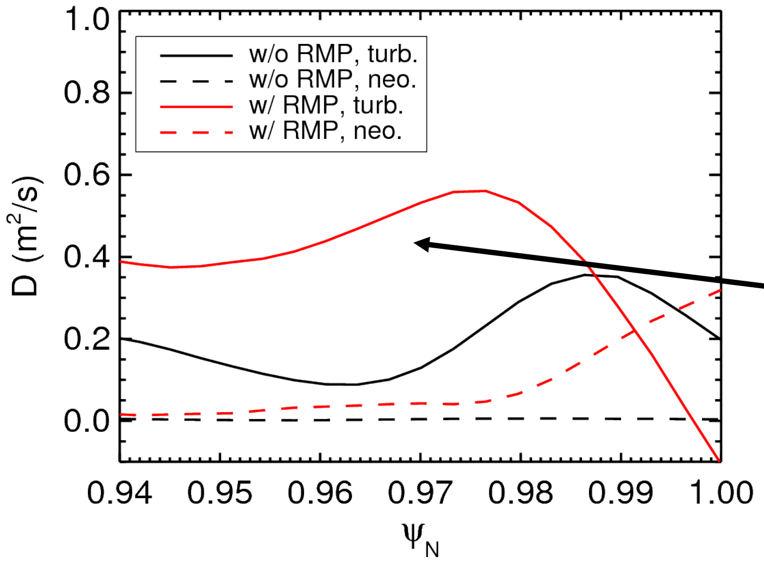
2. As in the neoclassical simulation, the electron heat flux is reduced around $\psi_N \sim 0.97$.

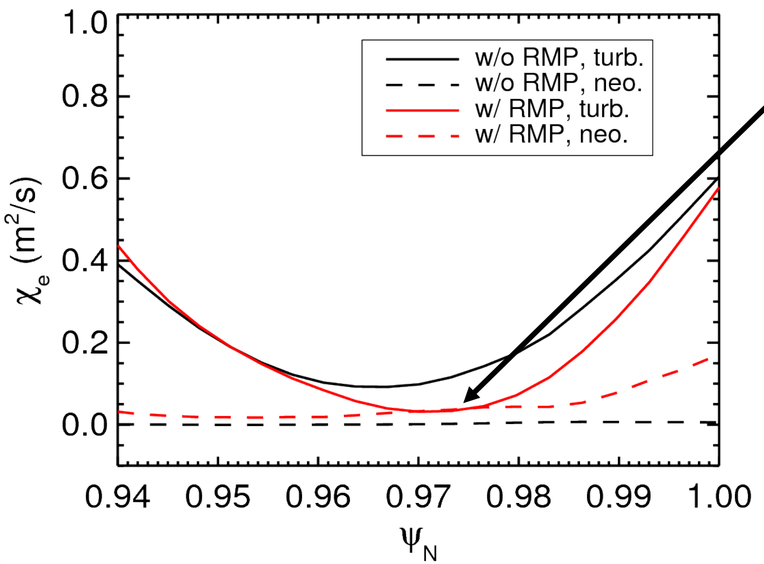
With RMP





RMP Transport



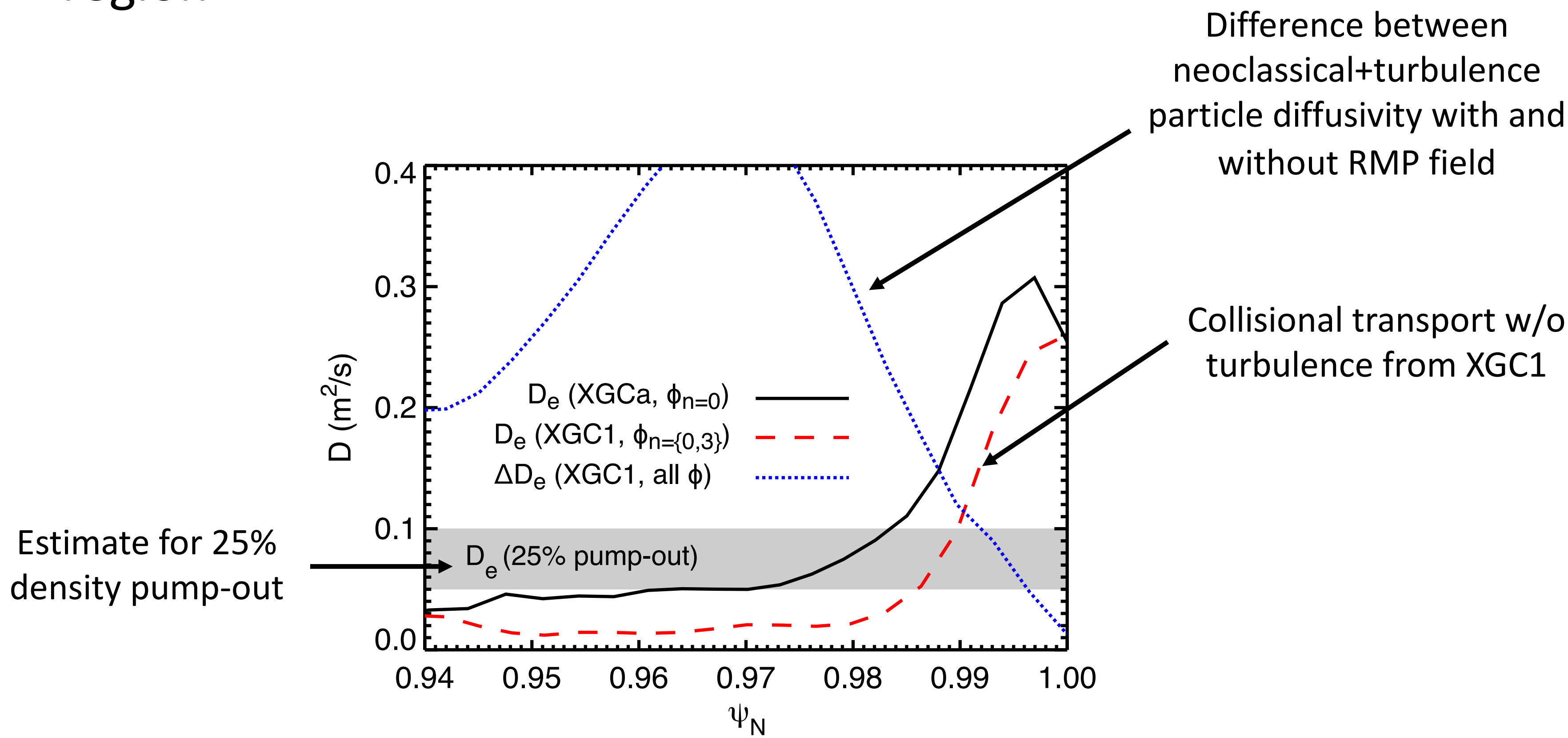


- Turbulent+neoclassical particle diffusivity with RMP is higher than without RMP
- Turbulent electron thermal diffusivity is suppressed between $0.96 \lesssim \psi_N \lesssim 0.98$, neoclassical thermal diffusivity is slightly elevated

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

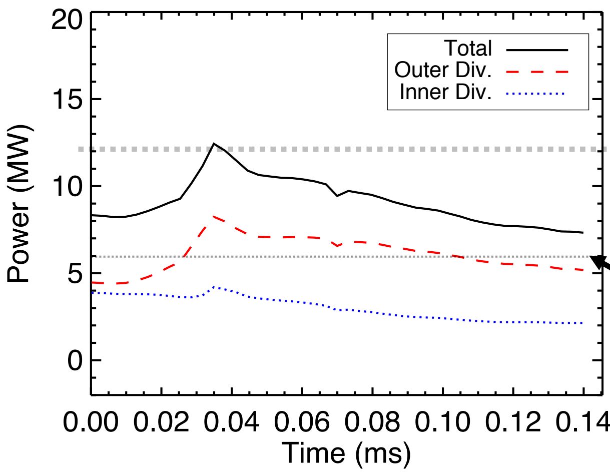
RMP-Driven Particle Diffusivity (Turbulence+Neoclassical)

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



Divertor Heat Load

Without RMP

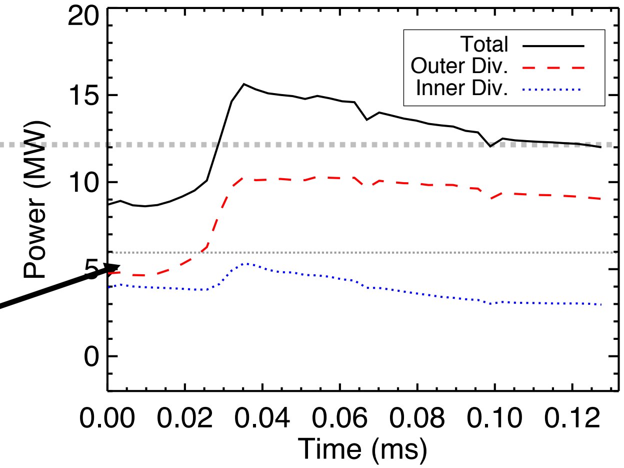


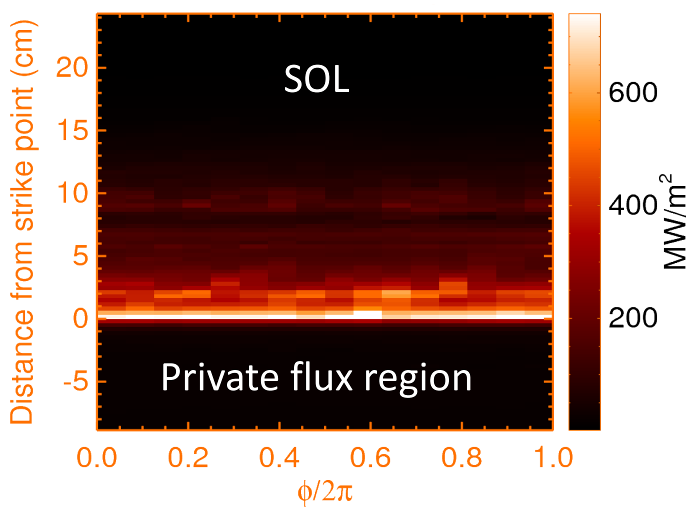
Divertor heat load is ~50% larger with RMP.

Exhaust power not in complete steady state yet → need longer simulation

Heating Power

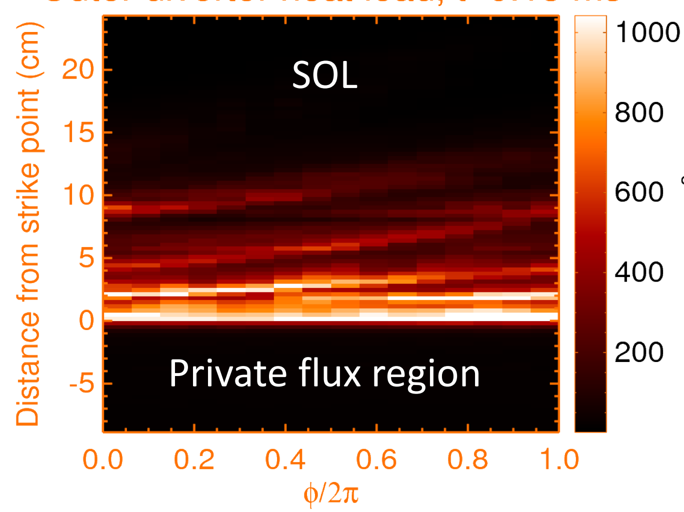
With RMP





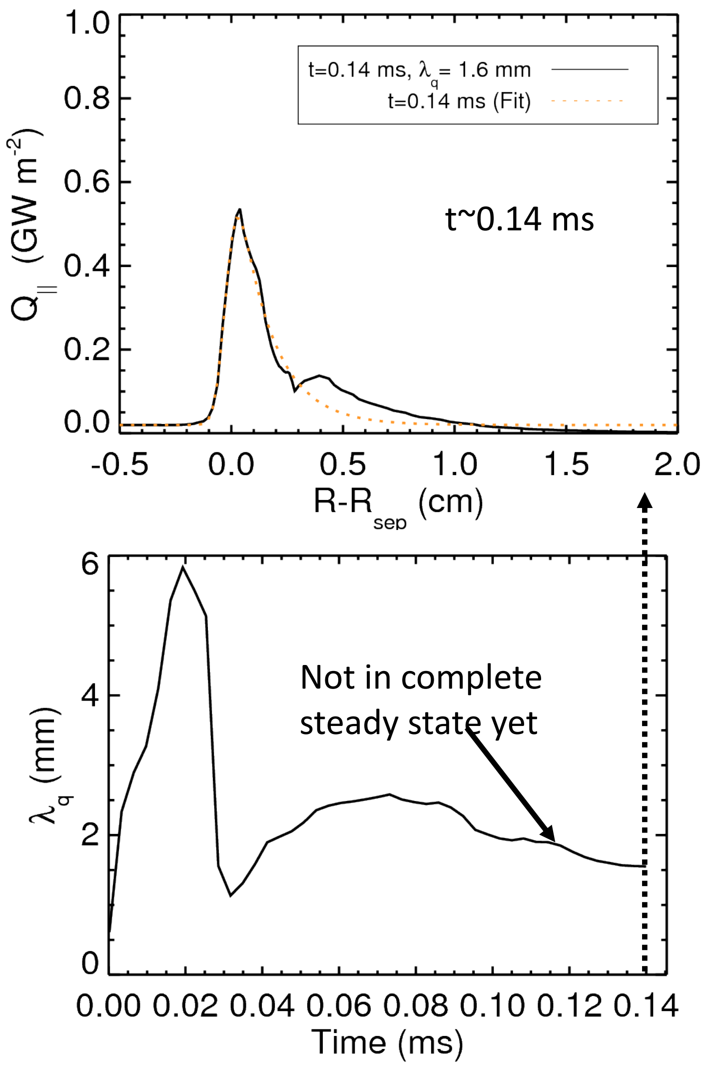
Parallel energy flux at divertor plates exhibits n=3 striations with RMP field turned on.

Outer divertor heat load, t=0.13 ms

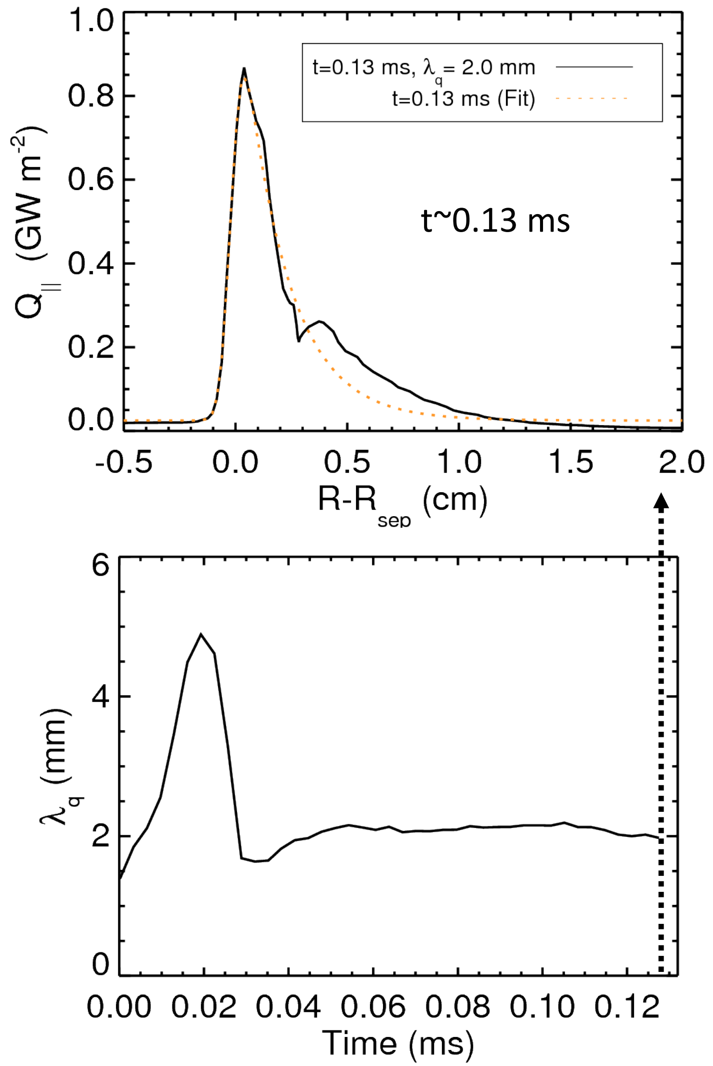


Divertor Heat Load Width is already saturating: The RMP case is wider by ~30%

Without RMP



With RMP



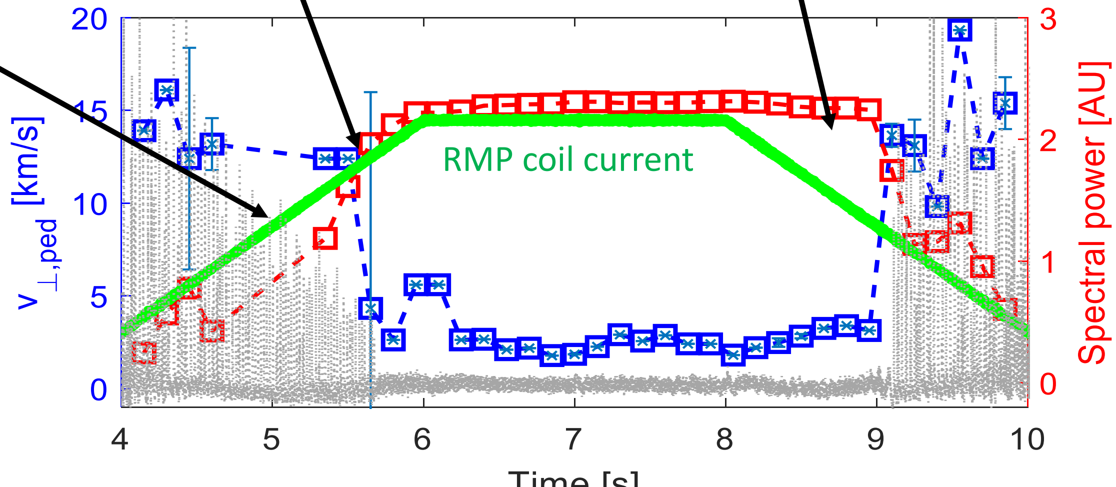
Conclusions

Outlook

Correction between ELM suppression and rotation

Hysteresis

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



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 XGCa (neoclassical) and XGC1 (neoclassical+turbulence) simulations 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 → explains why T_e steepens
- Detailed analysis of how δB affects cross-phase among $\delta\phi$, δn, δT
- Longer turbulence simulations queued to reduce statistical error
- Use kinetic response currents to compute RMP penetration in XGC
- Electromagnetic simulations are required complete understanding and to study effect on ELM stability: XGC-EM