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

R. Hager, PPPL

Thanks to: C.S. Chang, N. Ferraro, R. Nazikian, Brian Grierson, the XGC team and the DIII-D Team

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

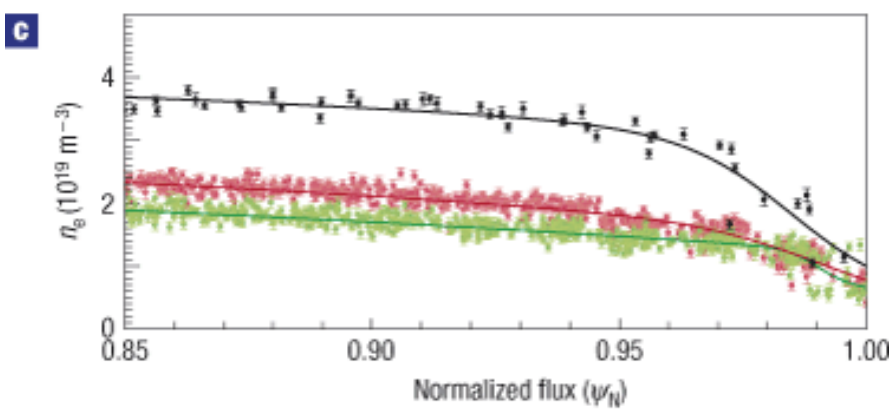
Introduction

Introduction

- ITER plans to use 3D fields, **R**esonant **M**agnetic **P**erturbations (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)

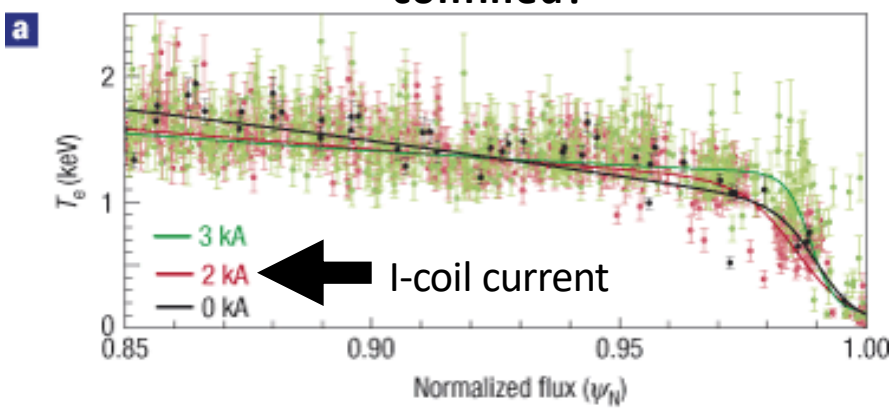
→ **Goals of XGC study:**

What are the physics behind the density pump-out?



Density pump-out (>25%)
(on ~100 ms time scale)

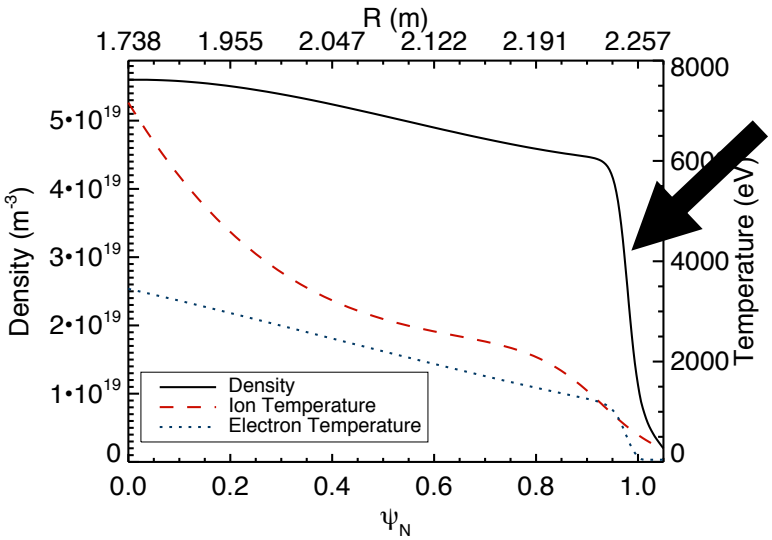
Why is electron heat still confined?



Steeper and higher
T_e pedestal

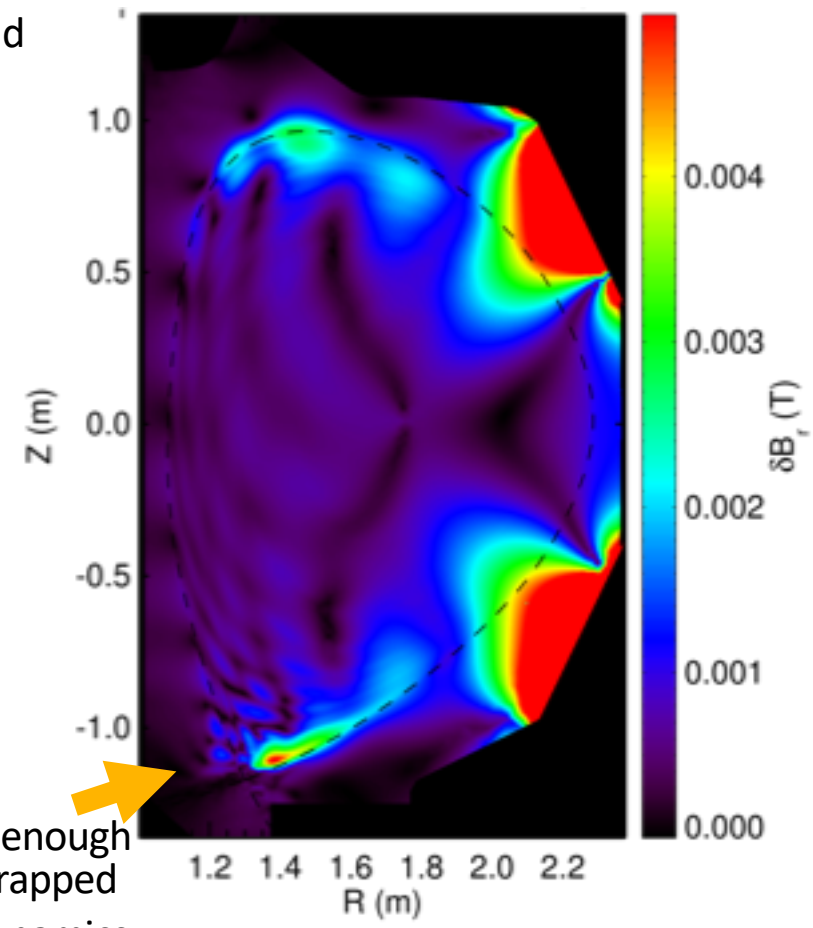
T. Evans et al., Nature 2006

From DIII-D #157308 H-Mode Plasma Profiles M3D-C1 Yields 3D Field with Good KAM Surfaces at Pedestal Slope and Top



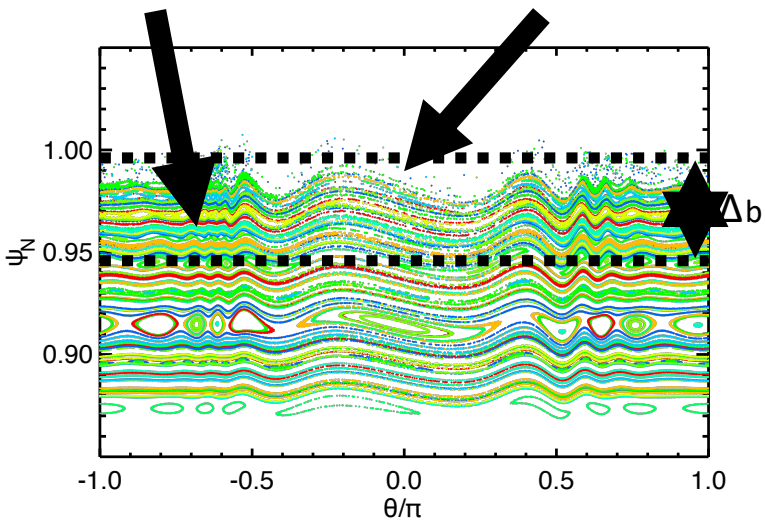
Thermal ion banana orbit width is comparable to pedestal width and spans multiple resonant surfaces

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



Good KAM surfaces in pedestal slope and top

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



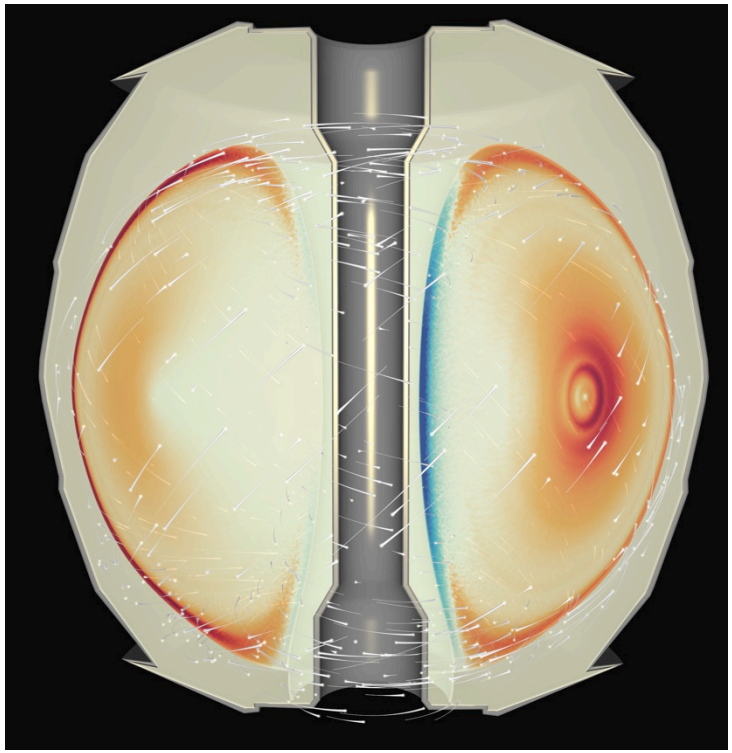
δB strong enough to affect trapped particle dynamics

Simulation setup: R. Hager et al., Nuclear Fusion 2019; M3D-C1 RMP: e.g. N. Ferraro et al., Phys. Plasmas 2012

Numerical Approach

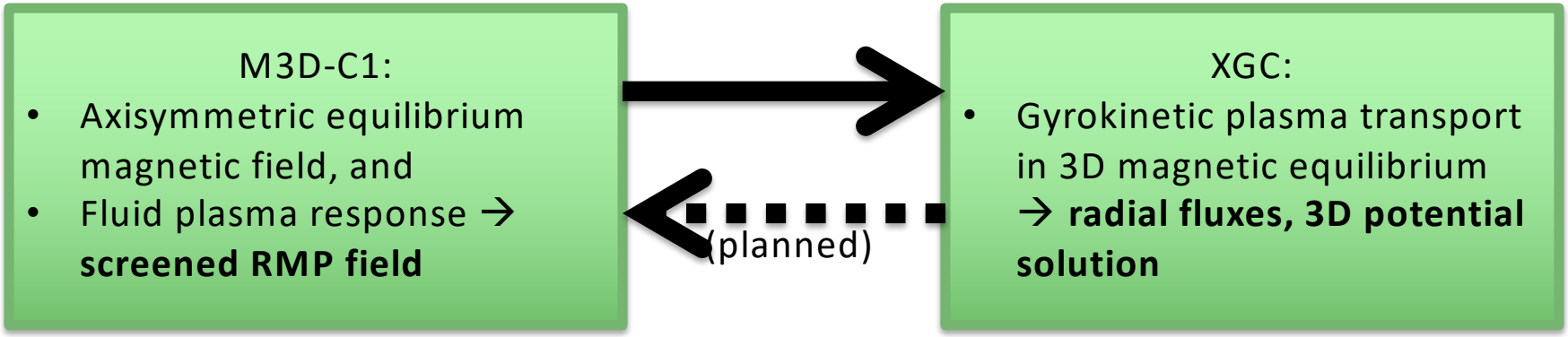
The Gyrokinetic Code XGC is used to Study the RMP Induced Transport

- 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

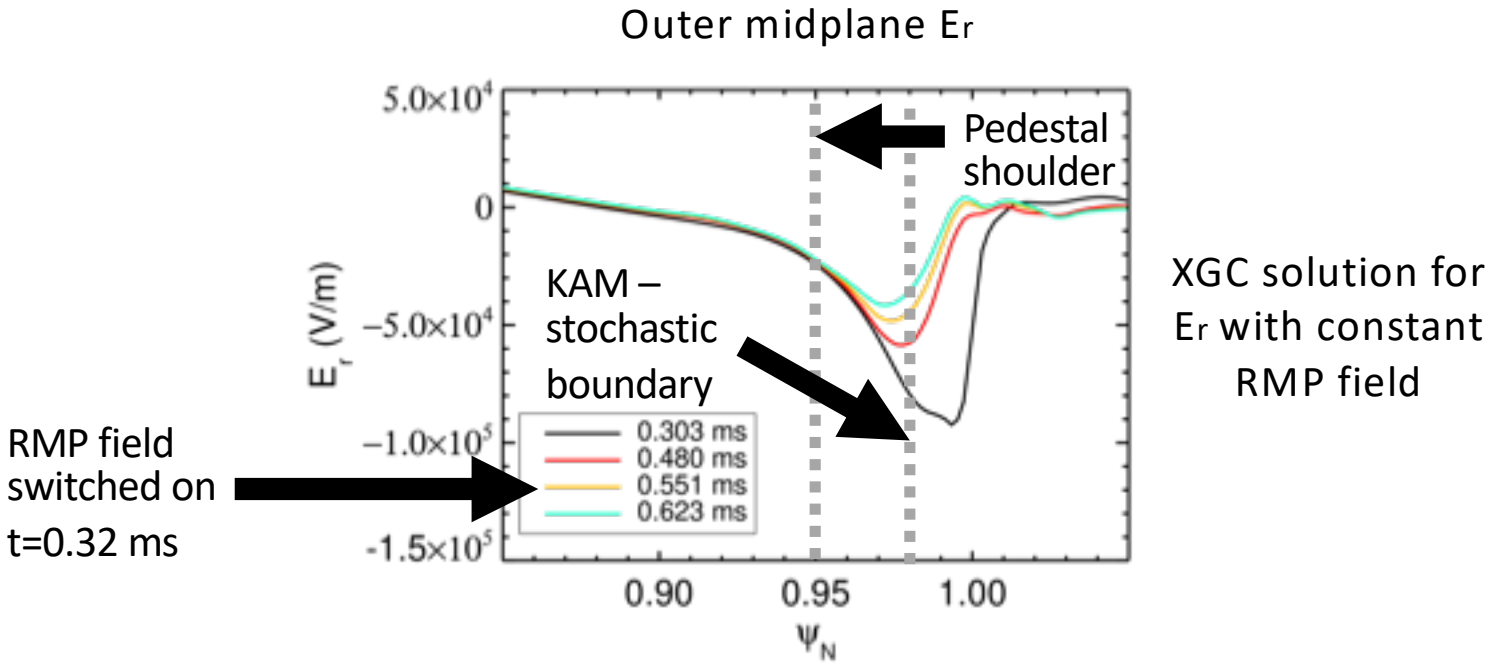


- M3D-C1 provides perturbed 3D magnetic equilibrium
- XGC computes plasma transport
- Planned extensions
  - Updated plasma profiles, effective transport coefficients, kinetic response currents, etc. can be returned to M3D-C1 for longer time-scale coupled simulation (to be done soon)
  - Self-consistent 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 ϕ: The Electrostatic Field Adjusts to RMP Field to Maintain the Ambipolarity of the Radial Particle Flux



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

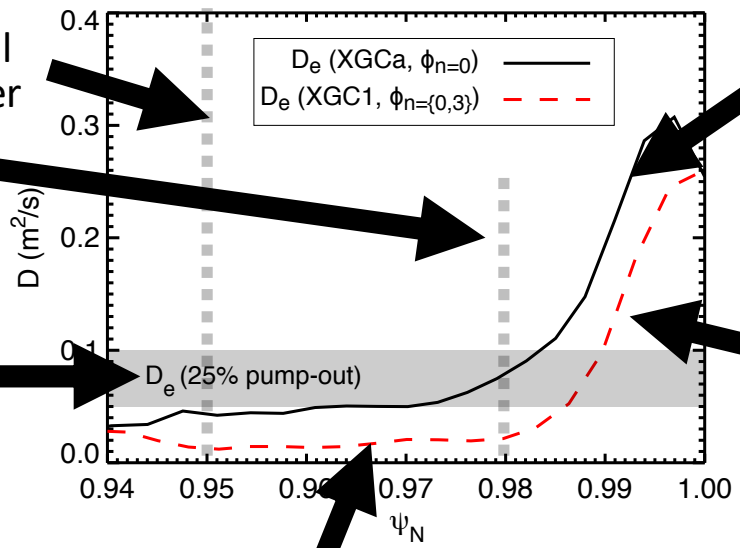
- With turbulence, this E_r profile can be somewhat modified.

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

KAM – stochastic boundary

Pedestal Shoulder

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



Turbulent transport is needed from pedestal slope inward to produce sufficient pump-out

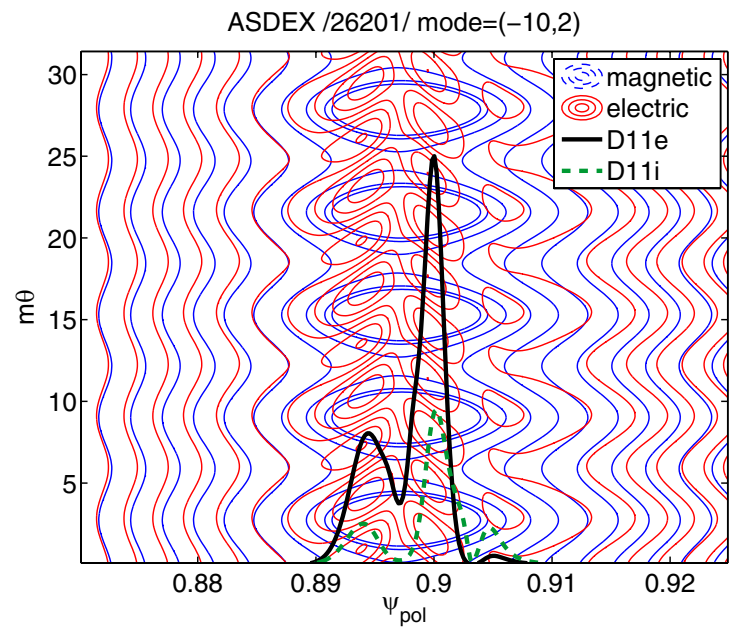
Neglection of n=3 potential **overestimates** RMP induced collisional transport (cf. G. Park, Phys. Plasmas 2010 with XGC0)

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

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

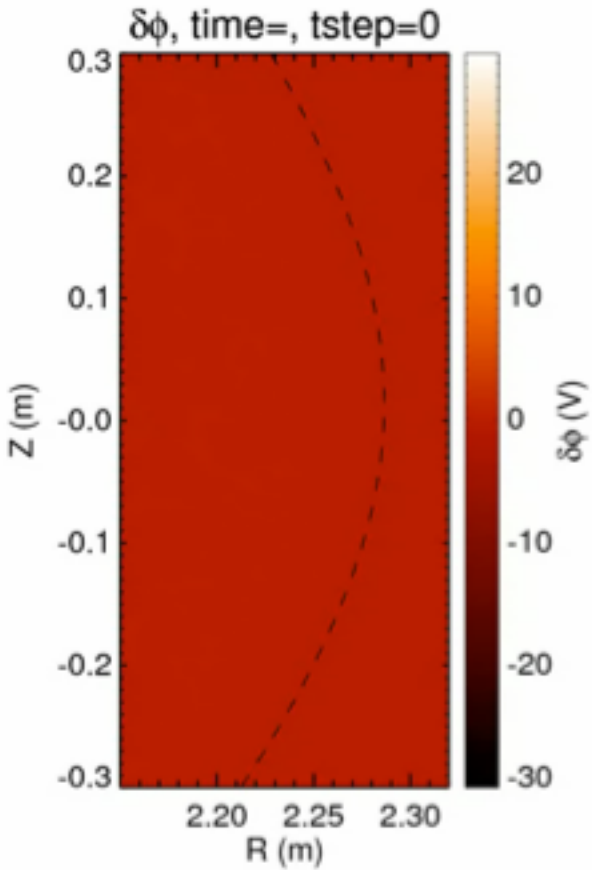


Heyn et al., Nuclear Fusion 2014 → Higher transport where magnetic and electric equipotential surfaces do not match.

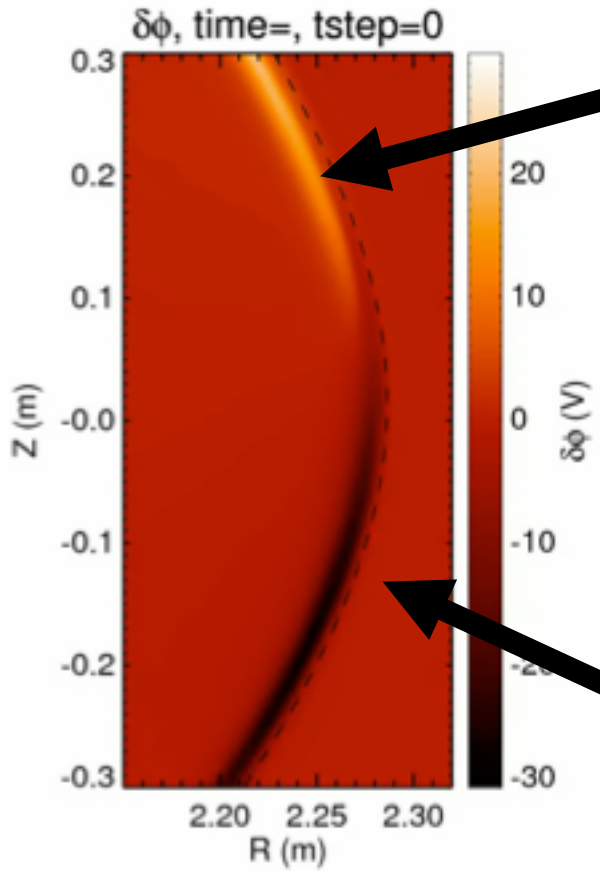
Simulation of Neoclassical + Turbulent RMP-Driven Transport

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

Without RMP



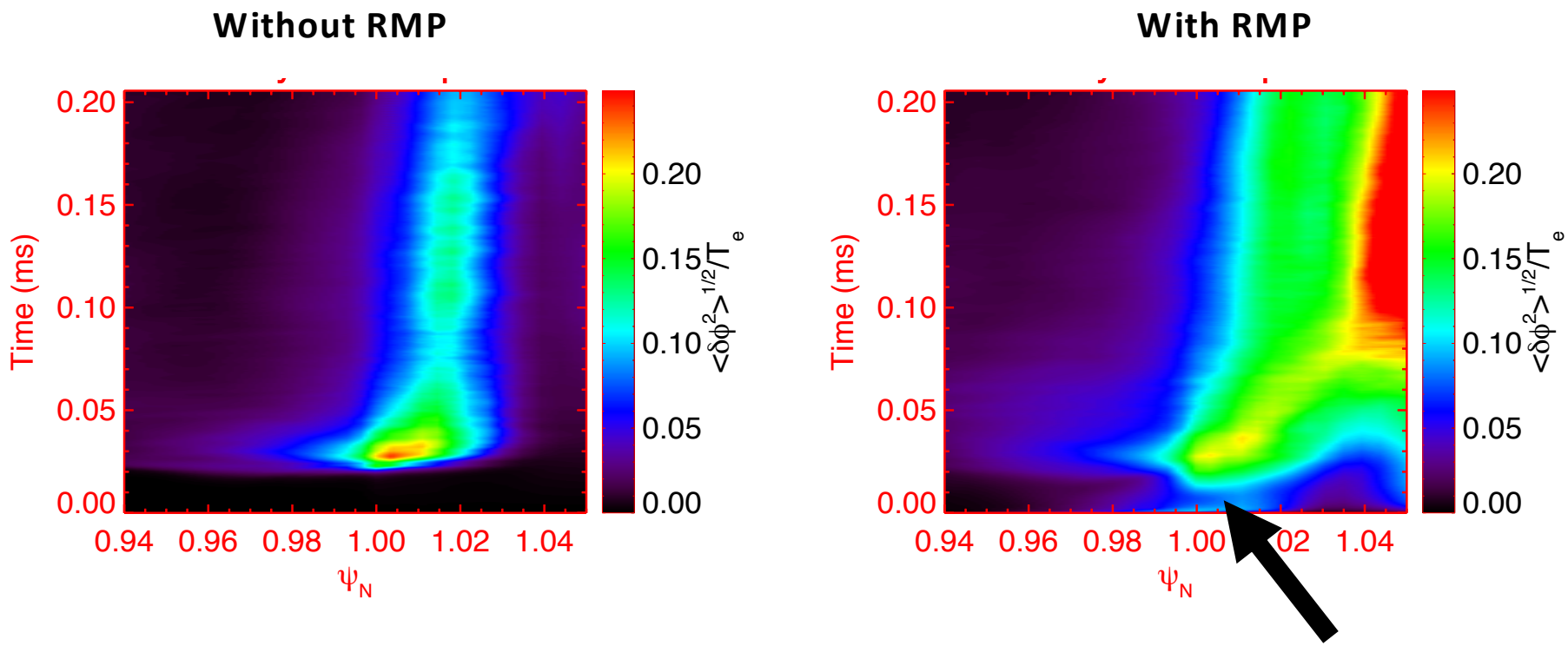
With RMP



Early n=3 response to RMP field in electrostatic potential

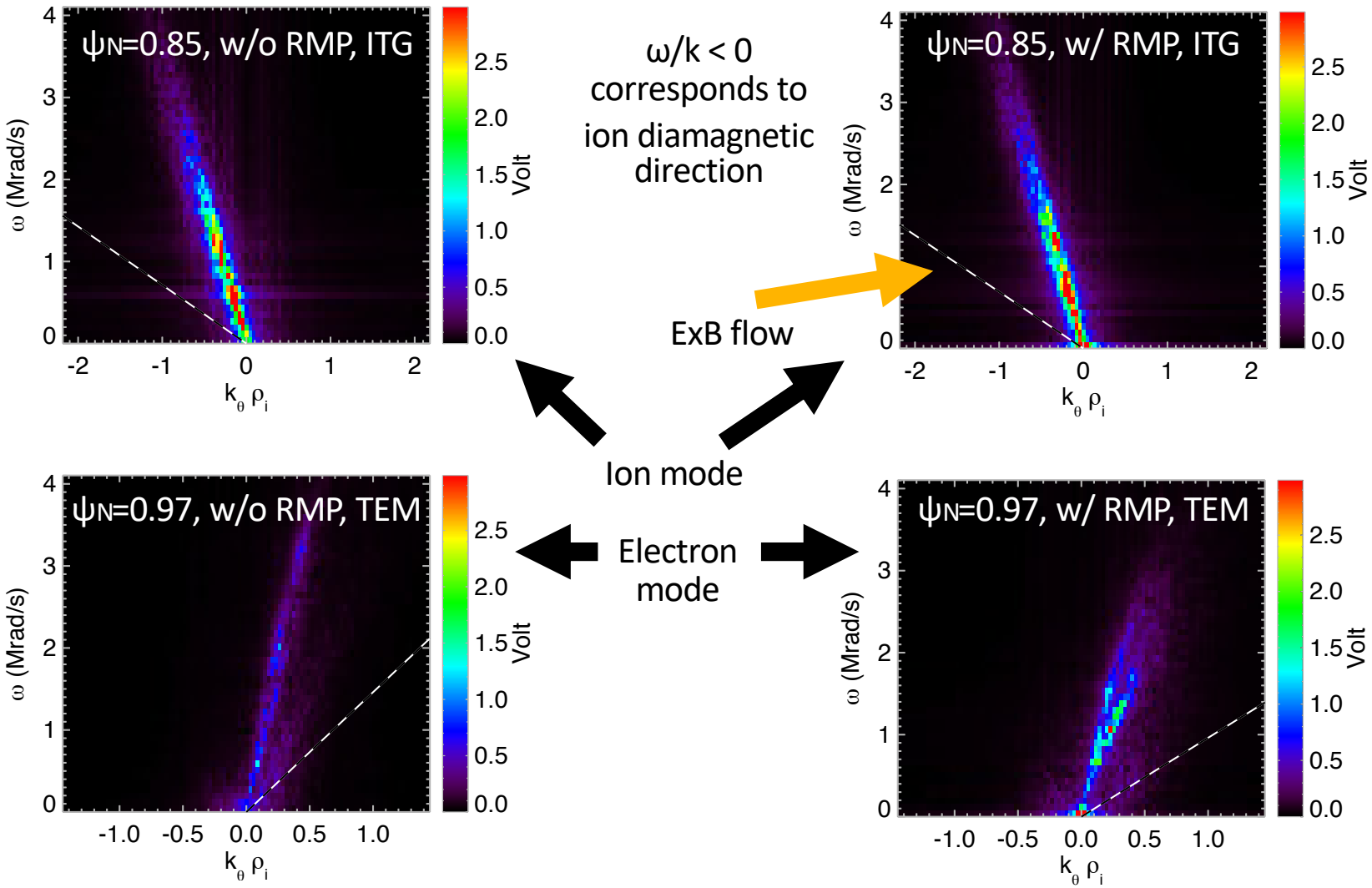
Stronger SOL turbulence

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)



Turbulence Intensity is Greater with RMP
But what about Transport?

There are three main transport channels:

- **Neoclassical flux**

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

- **3D δB flux**

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

- **Turbulent ExB flux**

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

$$f = \overline{f} + \tilde{f}$$

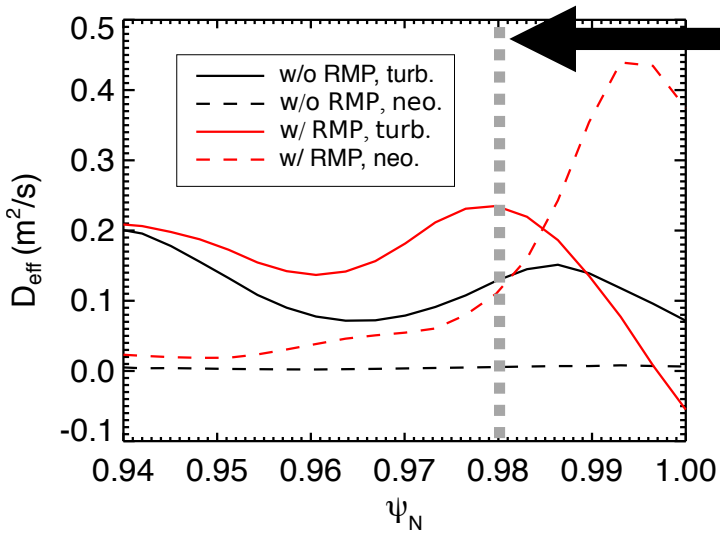
$$\overline{(\ldots)} \rightarrow \text{toroidal average}$$

$\Gamma_{neo} = \Gamma_D + \Gamma_{3D}$

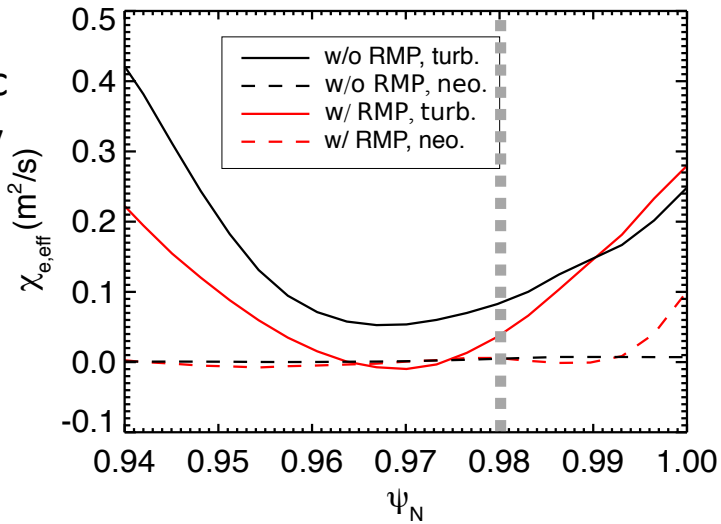
Electron Thermal Transport Barrier in the Steep Pedestal Region Survives with RMP Field from M3D-C1

Turbulent+neoclassical particle diffusivity with RMP is higher than without RMP
→ $\Delta D=(D_{neo}+D_{turb})^{(RMP)} - (D_{neo}+D_{turb})^{(no\ RMP)}$
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



KAM – stochastic boundary



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

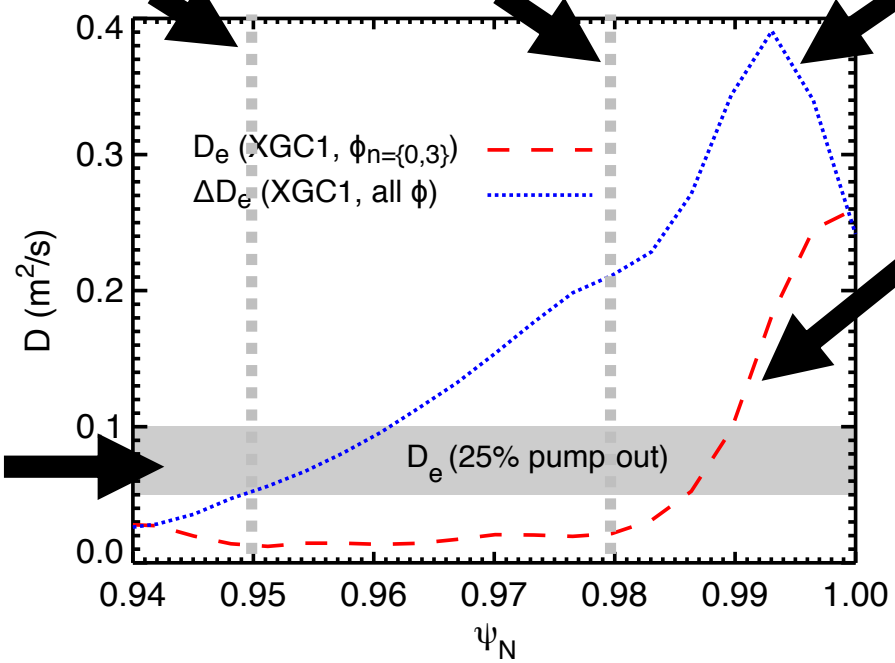
RMP-Driven Particle Diffusivity (Turbulence+Neoclassical) is Sufficient for Density Pump-Out

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

Pedestal Shoulder

KAM – stochastic boundary

Difference between neoclassical+turbulence particle diffusivity with and without RMP field

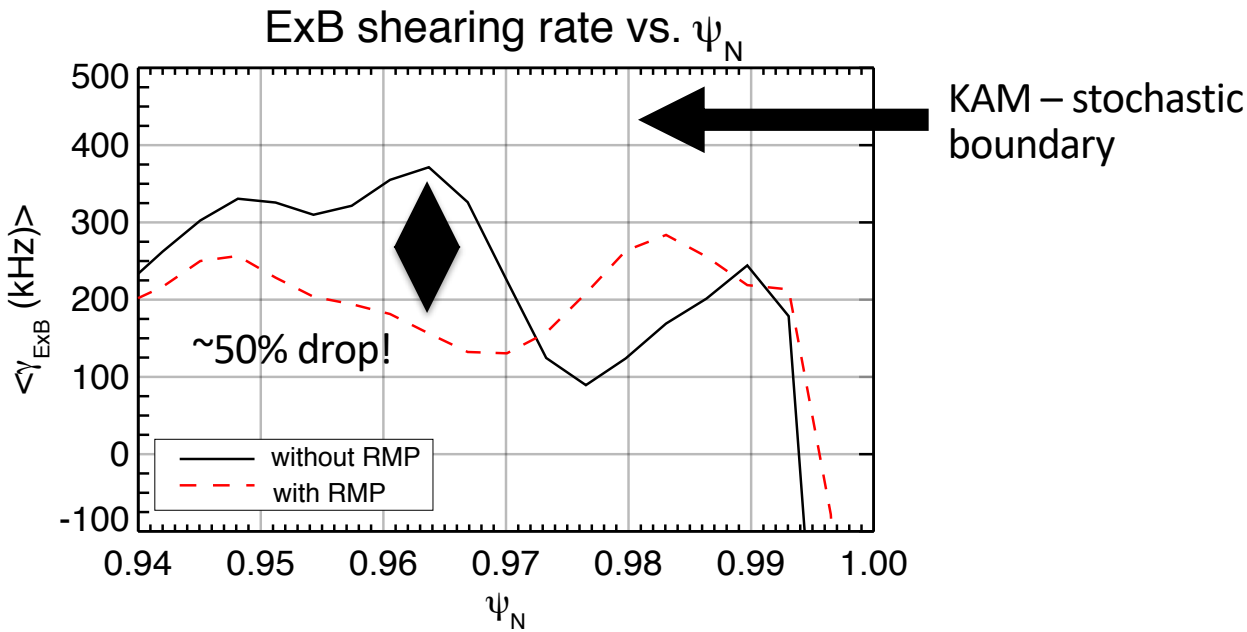


Collisional transport w/o turbulence from XGC1

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

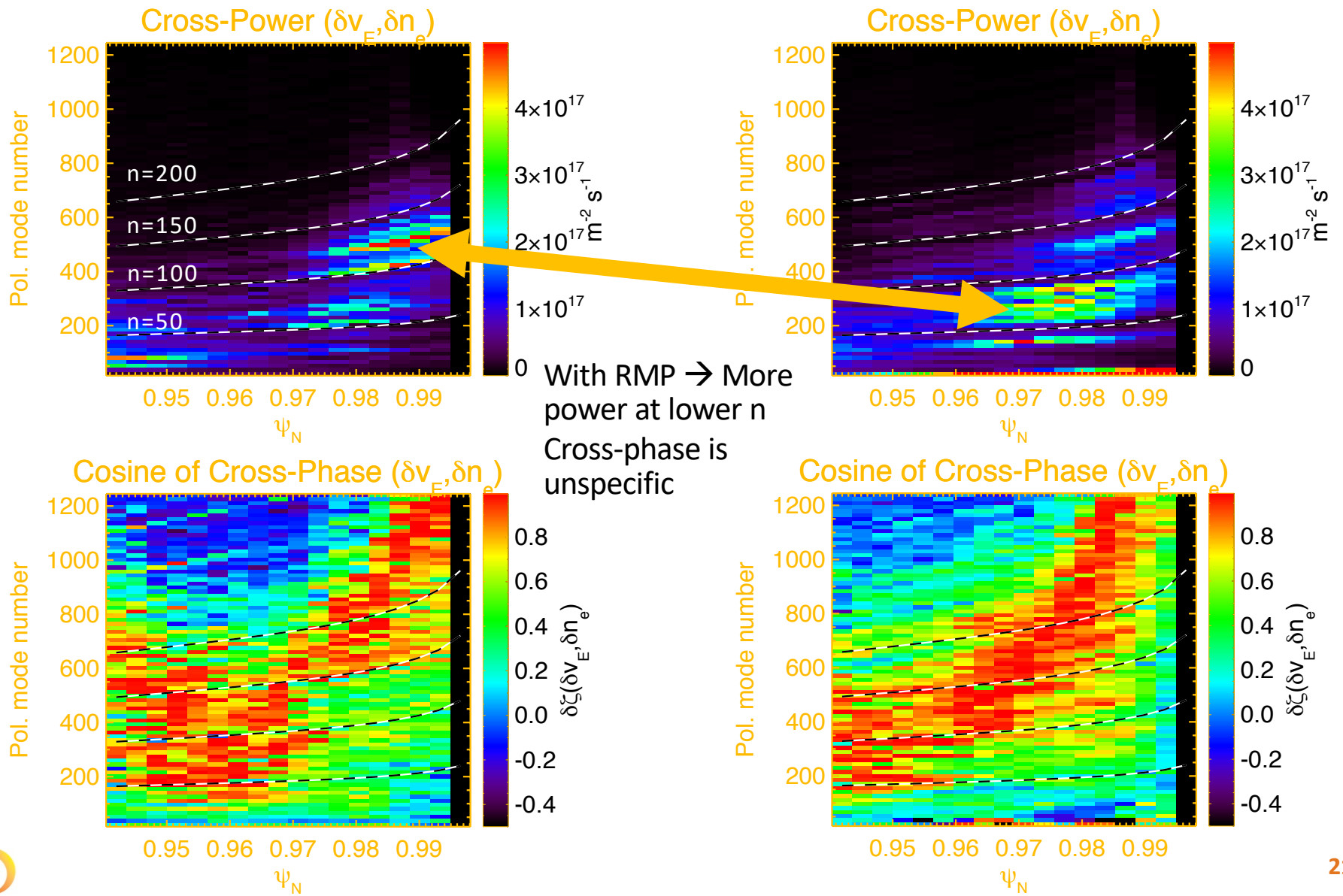


Lower ExB shear from pedestal shoulder to slope → similar reduction at pedestal shoulder is observed in neoclassical simulations (Hager et al., Nuclear Fusion 2019)

Cross-Spectral Density (v_E,n)

Without RMP

With RMP

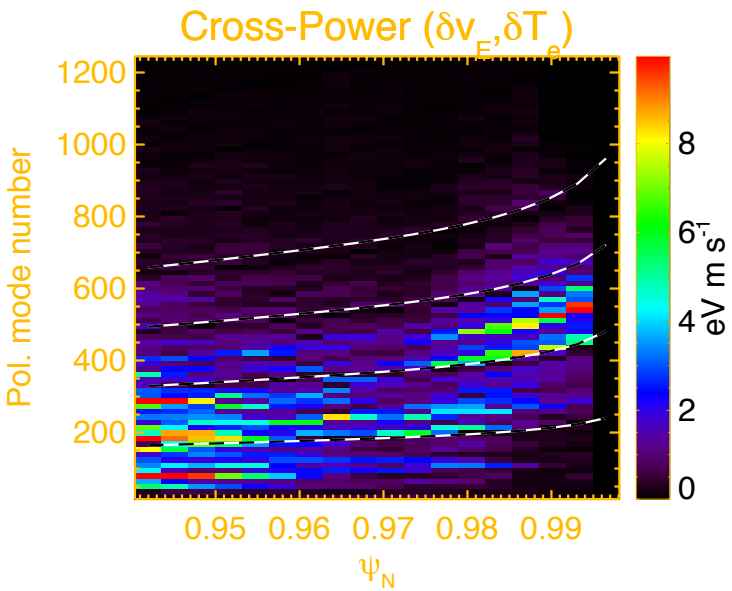


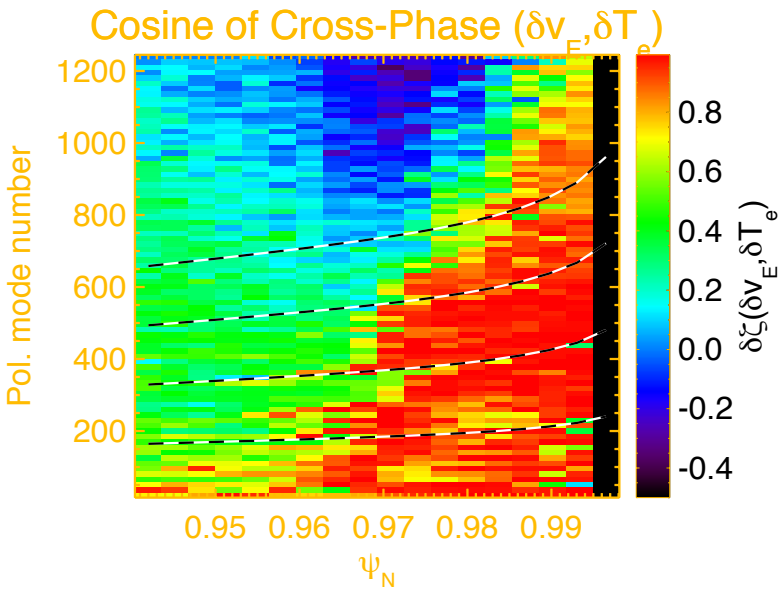
With RMP → More power at lower n

Cross-phase is unspecific

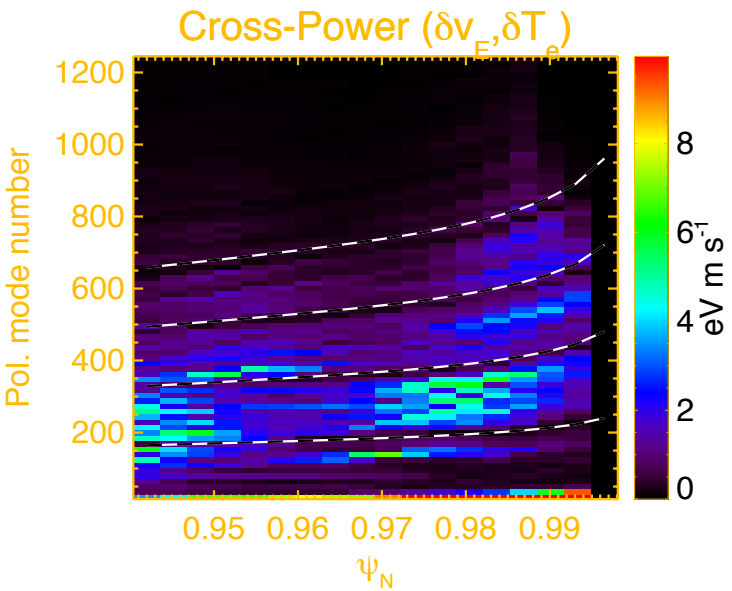
Cross-Spectral Density (v_E,T)

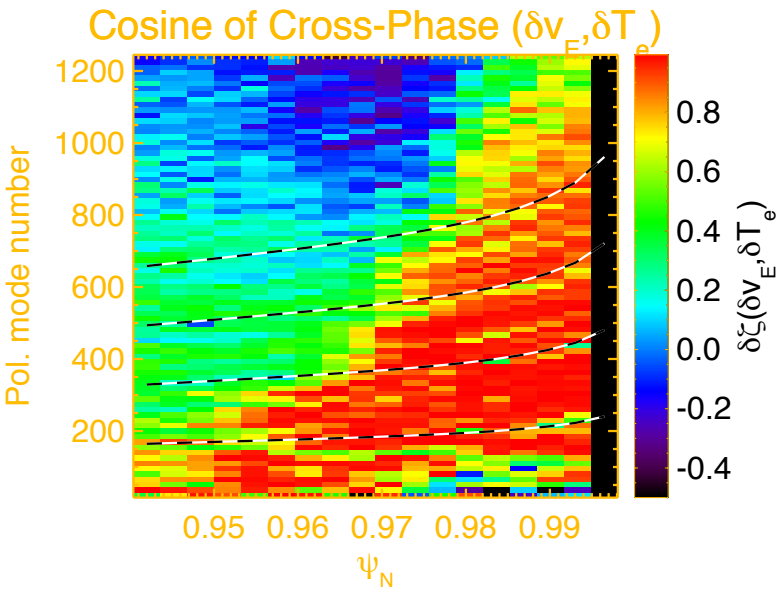
Without RMP





With RMP

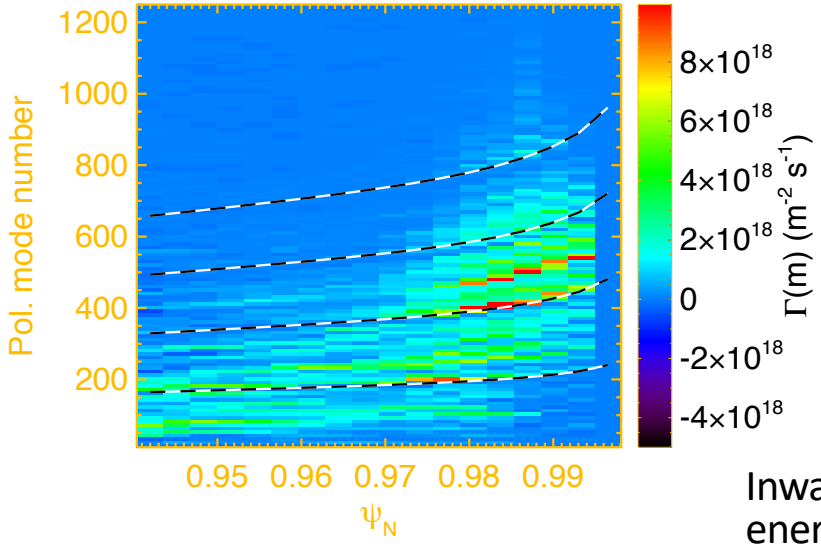




Fluxes per mode number

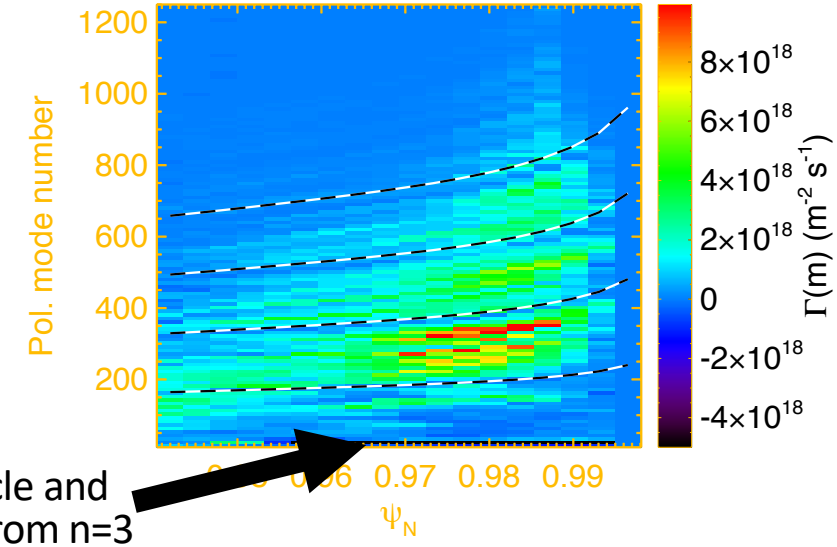
Without RMP

Ptl. Flux per mode number



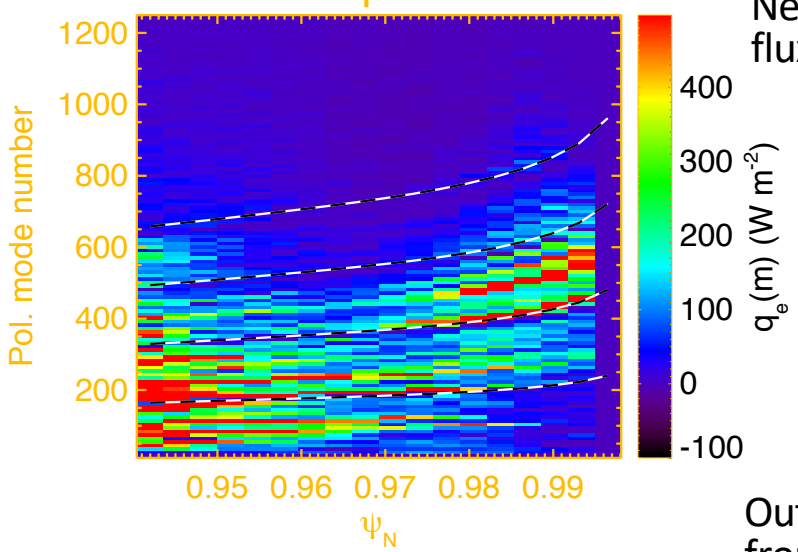
With RMP

Ptl. Flux per mode number



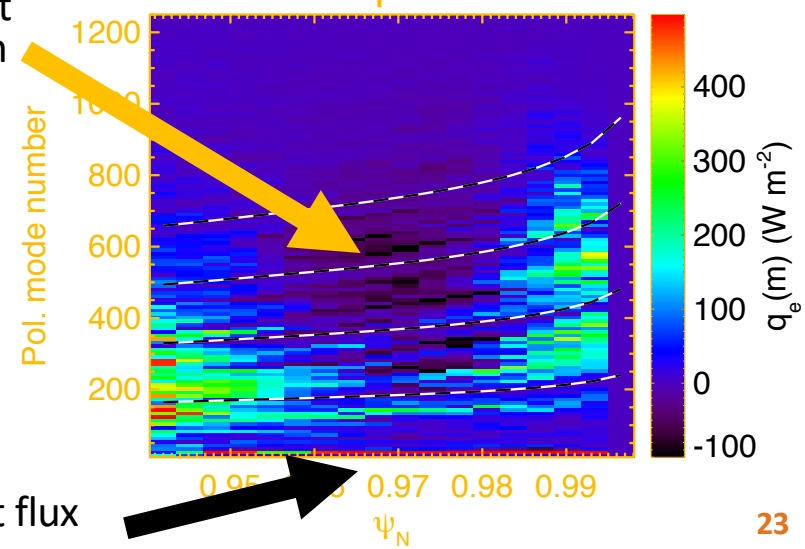
Inward particle and energy flux from n=3

Elec. Heat Flux per mode number



Negative heat flux at high m

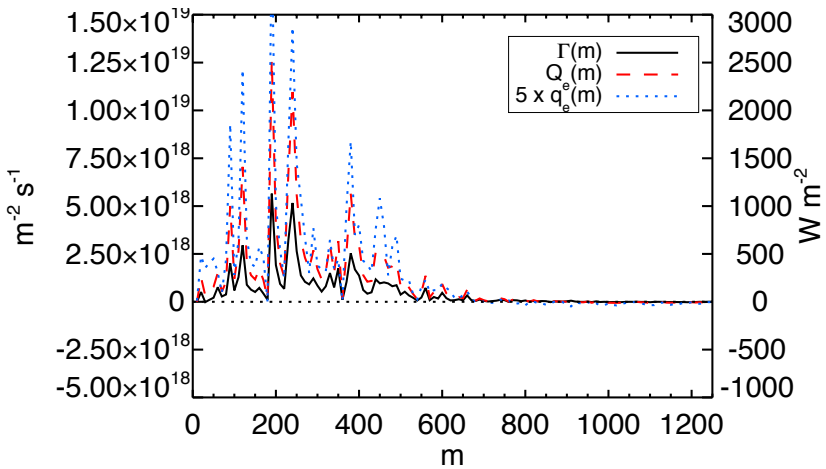
Elec. Heat Flux per mode number



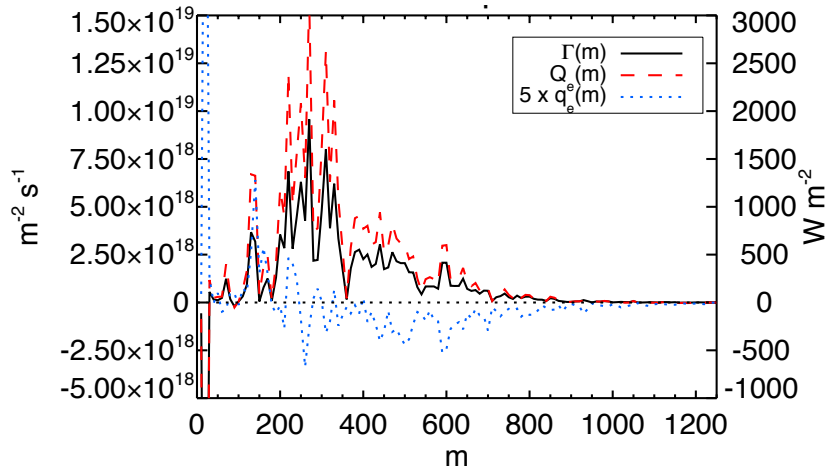
Outward heat flux from n=3

Fluxes per mode number at ψ_N=0.97

Without RMP



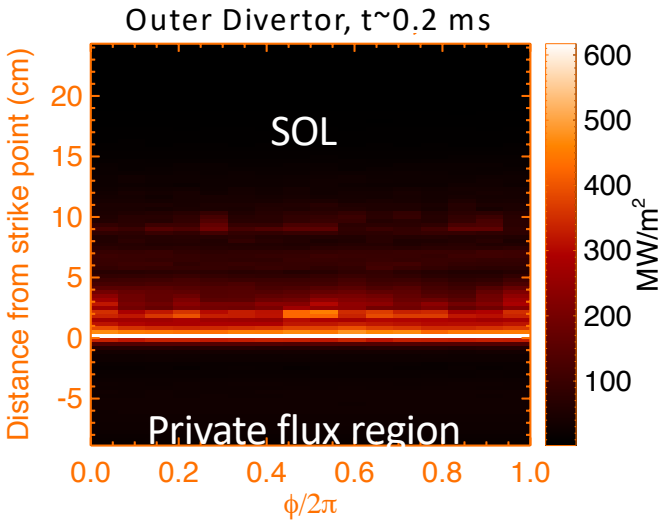
With RMP



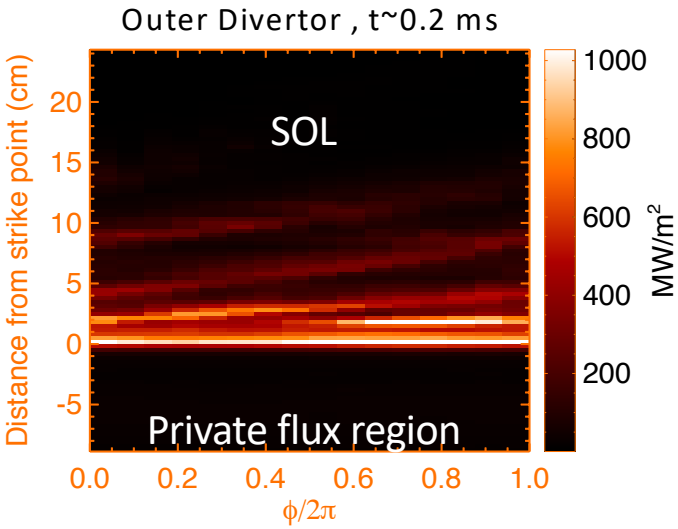
- Particle and energy flux are enhanced at m~300 ($k_\theta \rho_i$~0.2)
- But particle flux increases more → inward heat flux at higher $k_\theta \rho_i$
- Large particle and energy flux from n=3 (RMP) are inward, but heat flux is outward

Divertor Energy Load Footprint Shows Typical RMP Lobes

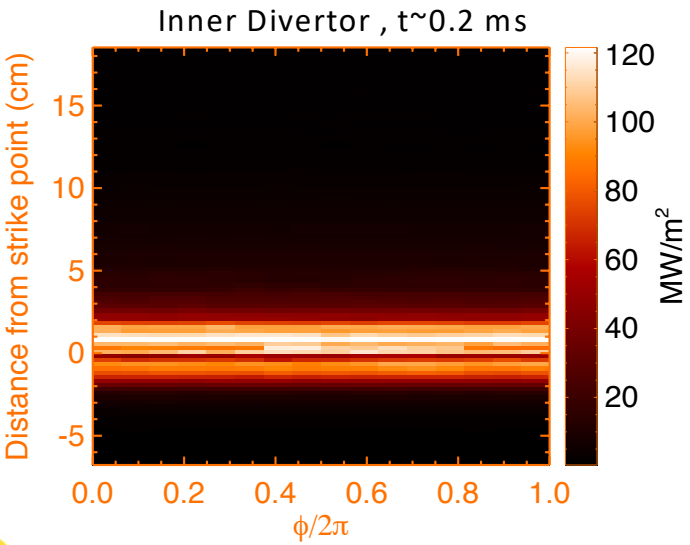
Without RMP



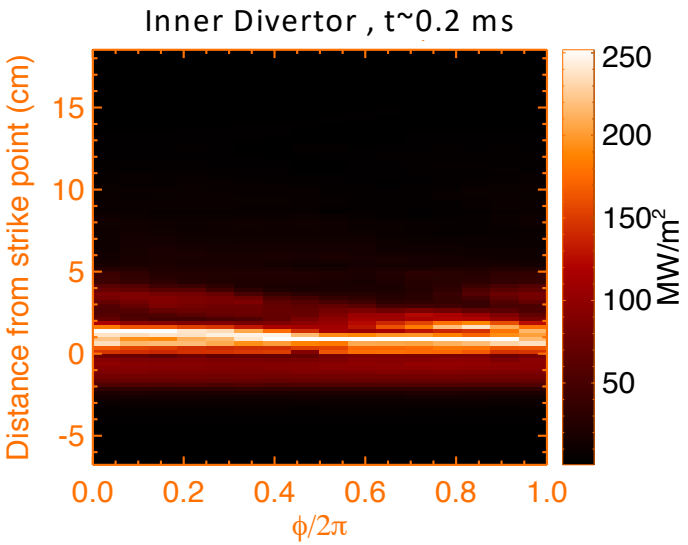
With RMP



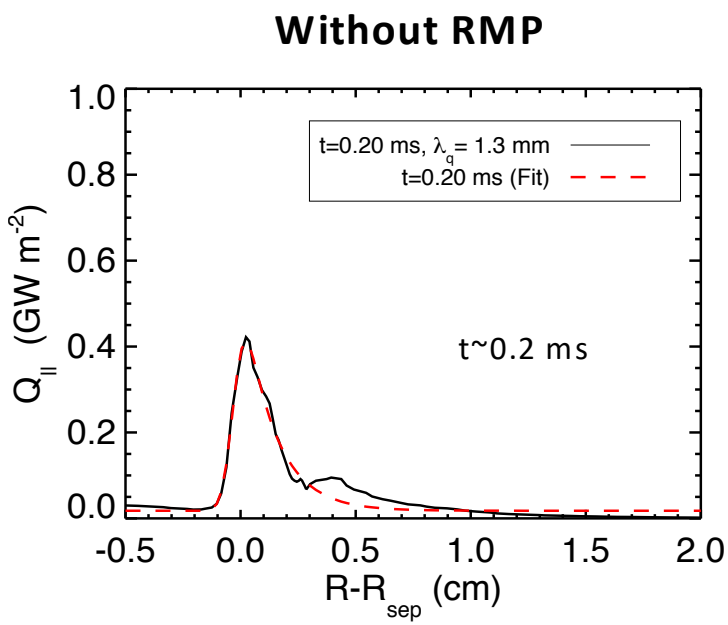
Parallel energy flux at outer divertor plates exhibits n=3 striations with RMP field turned on.

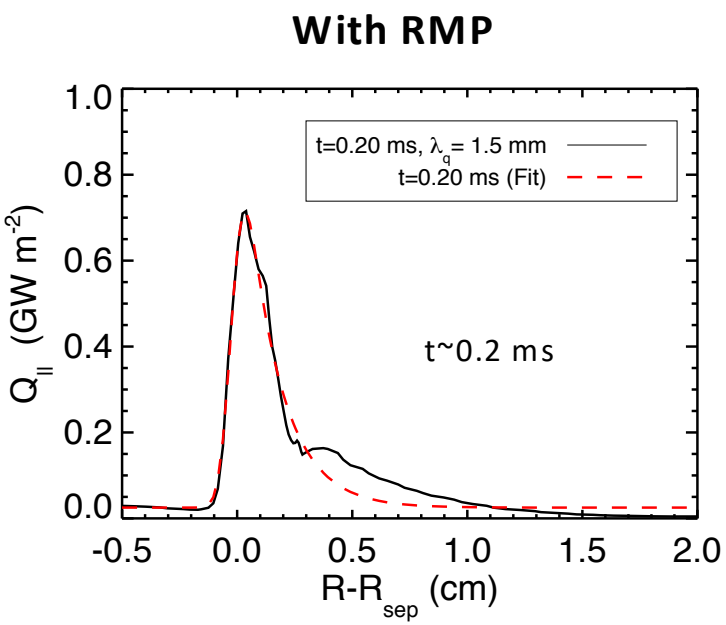


Less striation on the inner divertor plates but also larger



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 λ_q by ~15% for present 3D RMP field from M3D-C1

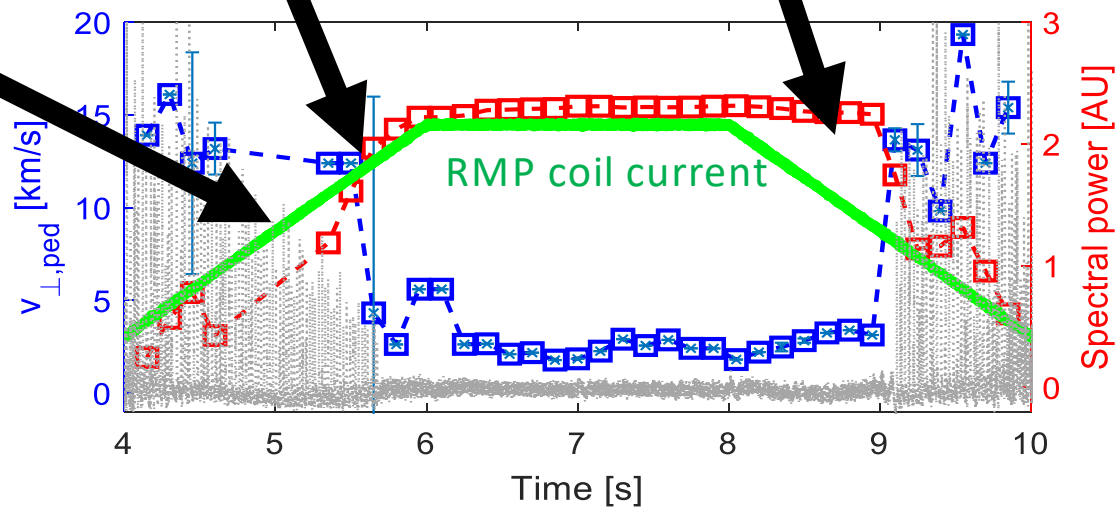
Conclusions

Outlook for XGC Study of a KSTAR RMP Experiment

Correlation 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?

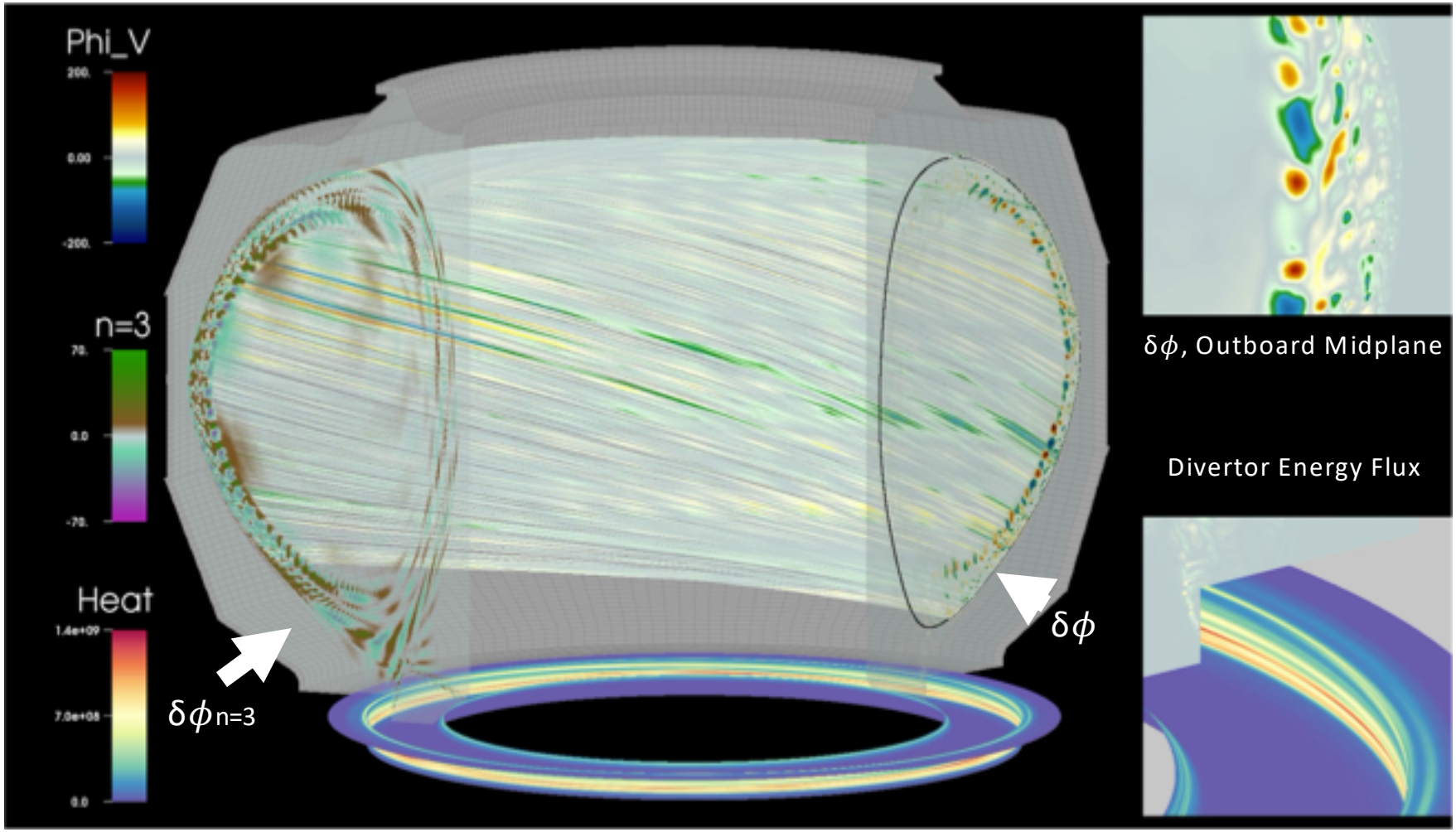


KSTAR, J. Lee et al., Nuclear Fusion 2019

Conclusions

- When using M3D-C1 RMP field in XGC simulations, combined neoclassical and turbulent transport are needed to explain experiment
- Electrostatic XGC (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
- Ongoing: More detailed analysis of how δB affects cross-phase among $\delta\phi$, δn, δT
- 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