PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

Understanding the RMP-Driven Density and Heat Transport in Tokamak Edge Plasma from Gyrokinetic-MHD coupled study

R. Hager, C.S. Chang, N. Ferraro, R. Nazikian
PPPL

HBPS High-fidelity Boundary Plasma Simulation

Argonne NATIONAL LABORATORY

NERSC National Energy Research Scientific Computing Center

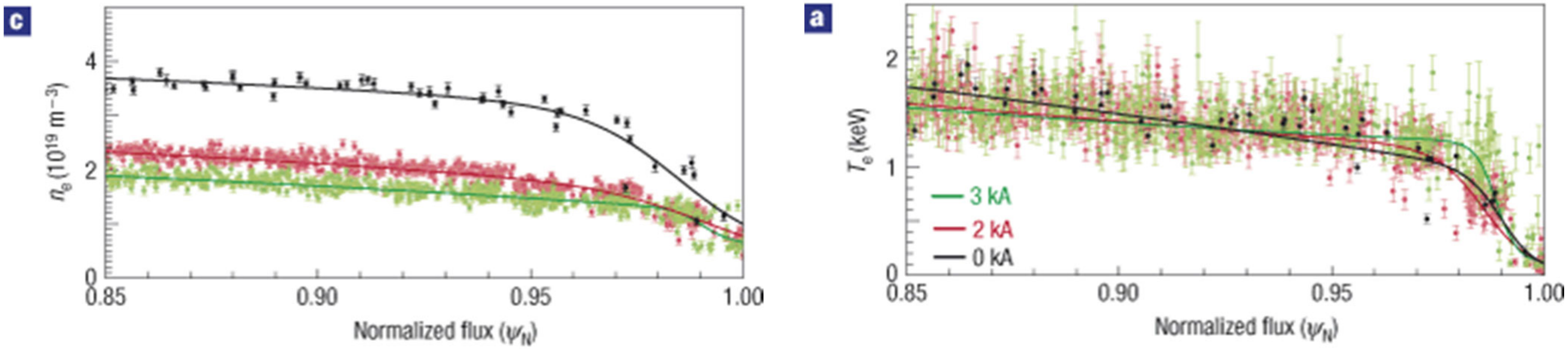
DIII-D NATIONAL FUSION FACILITY

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” that may decrease 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?**



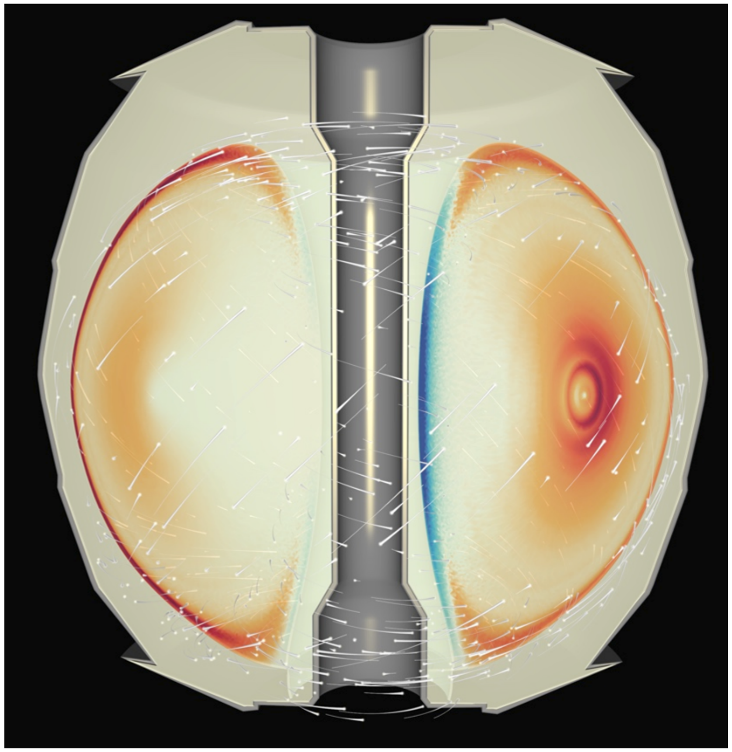
Density pumpout
(on ∼100 ms time scale)

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

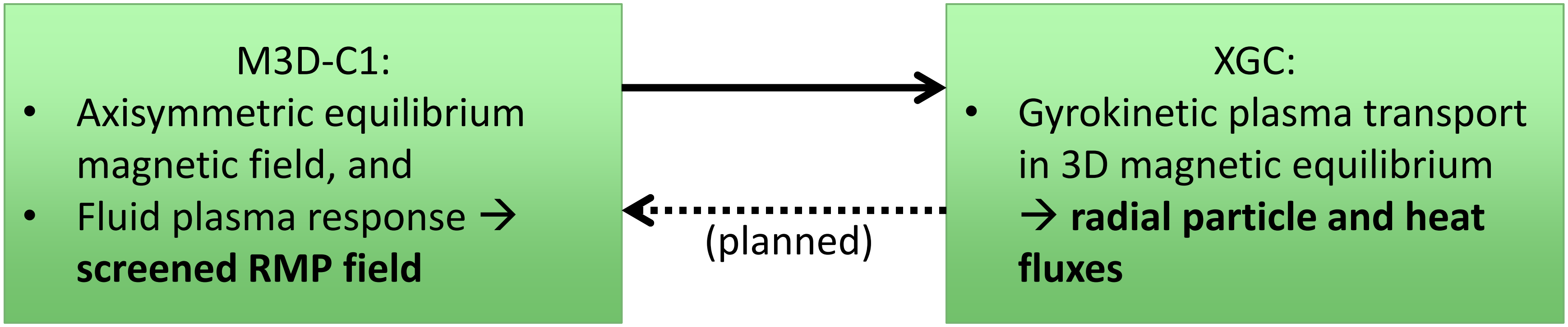
- XGC1 is a **global 5D** (3D configuration + 2D velocity space) **gyrokinetic**, total-f particle-in-cell code
- Advantages of using the total-f gyrokinetic code XGC1
  - Whole volume simulation including SOL
  - Kinetic-consistent radial, poloidal, and toroidal electric field
  - Nonlinear Fokker-Planck-Landau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



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**

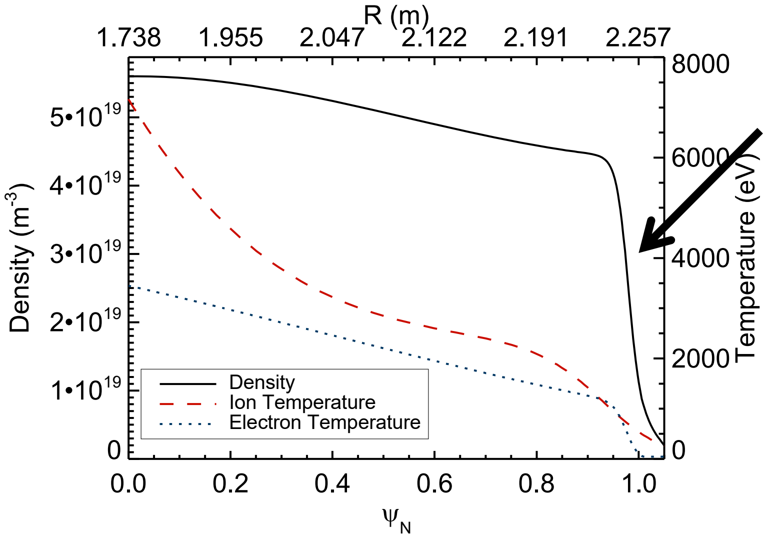
(planned)

XGC:

- Gyrokinetic plasma transport in 3D magnetic equilibrium **→ radial particle and heat fluxes**

- M3D-C1 provides perturbed 3D magnetic equilibrium
- XGC computes radial fluxes
  - Whole volume simulation with consistent electric field, nonlinear Coulomb collision operator, heat and torque sources, and neutral particle recycling
- In the future, updated plasma profiles, effective transport coefficients, kinetic response currents, etc. can be returned to M3D-C1 for longer time-scale coupled simulation with profile evolution

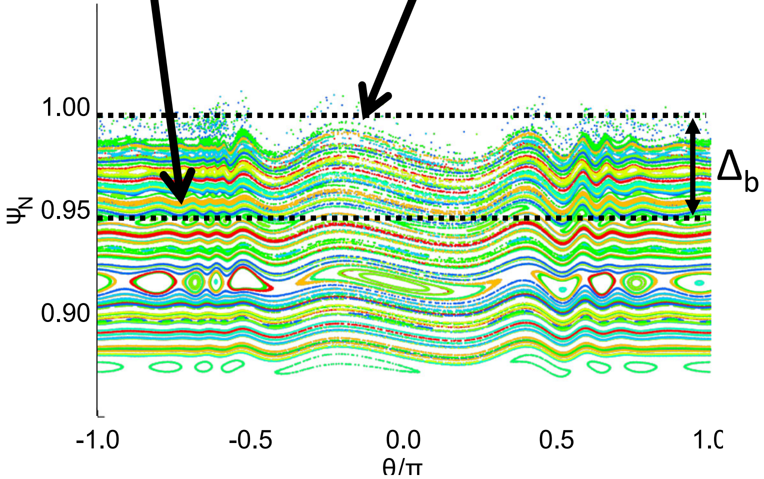
Starting from (a model DIII-D) H-Mode like Plasma Profiles → M3D-C1 Yields 3D Field with Good KAM Surfaces at Pedestal Top



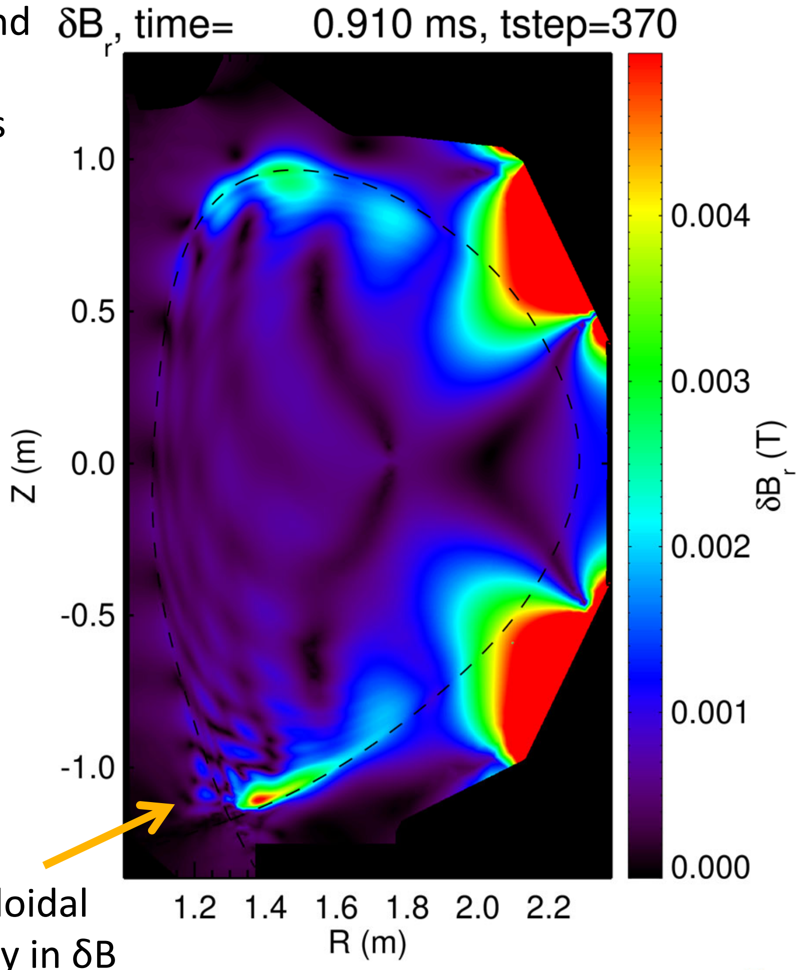
Thermal ion banana orbit width is comparable to pedestal width and spans multiple resonant surfaces

Good KAM surfaces at pedestal shoulder and top

Thin stochastic layer close to the separatrix



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



Strong poloidal asymmetry in δB

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

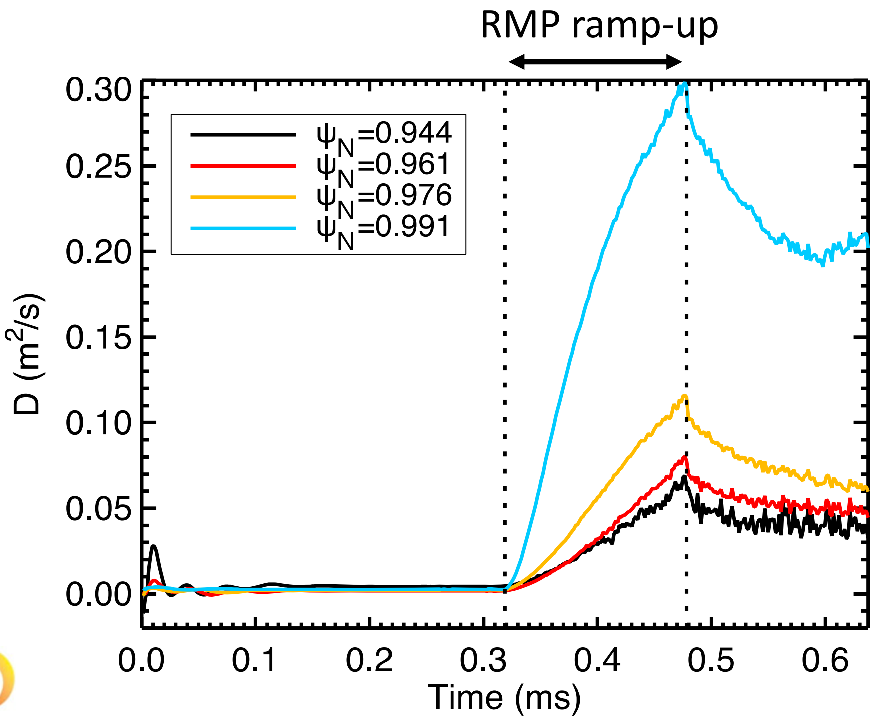
Neoclassical Simulations with XGCa Exhibit Enhanced Particle Flux and Electron Thermal Transport Barrier at $\psi_N \lesssim 0.98$

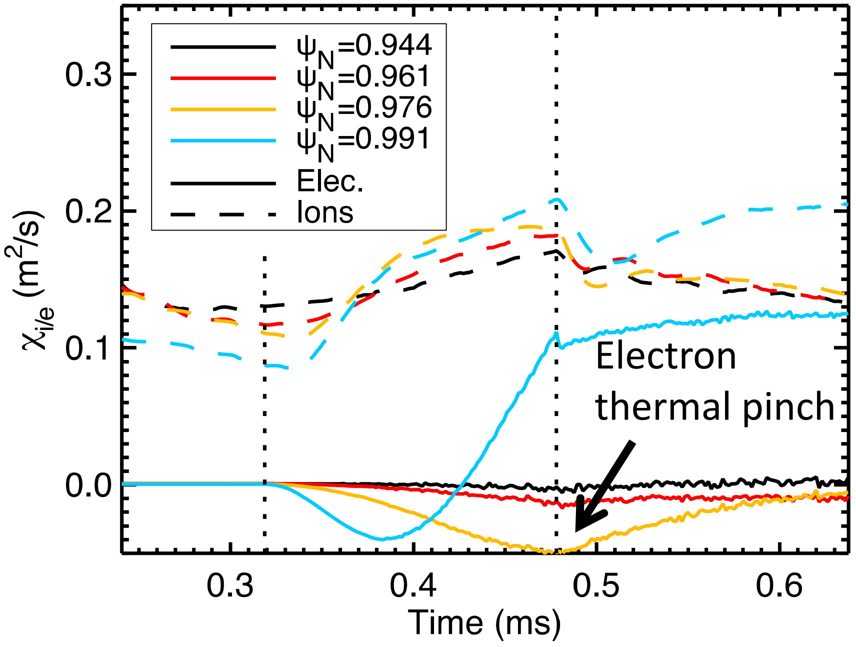
- Apply simple transport model to estimate effective transport coefficients

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

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

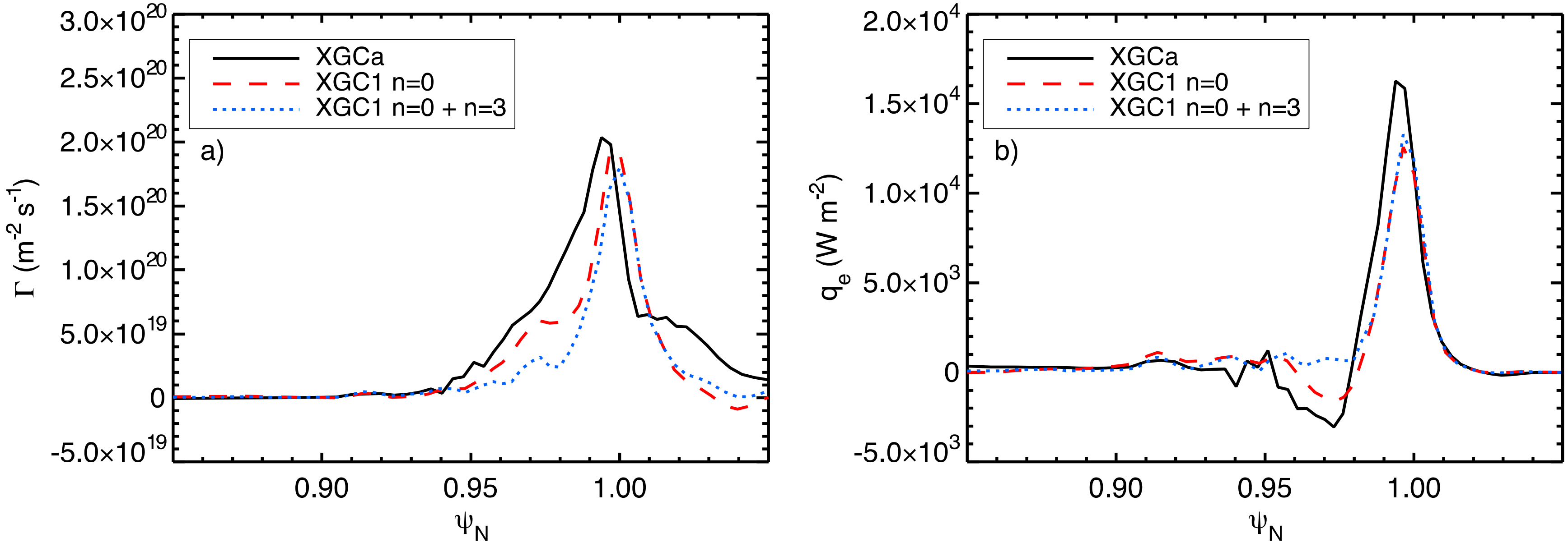
- Radial fluxes are evaluated along the unperturbed flux-surfaces
- Need to test these results in XGC1 including the n=3 mode in ϕ





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

- To test accuracy of XGCa results → run XGC1 with Fourier filter retaining n=0 and
  - No n=3 electric field
  - n=3 electric field with $nq-5 \leq m \leq nq+5$ to test the validity of XGCa results
- Transport is reduced at $\psi_N \lesssim 0.98$ if n=3 electric field is included
- But transport in stochastic layer $\psi_N \gtrsim 0.98$ does not change much

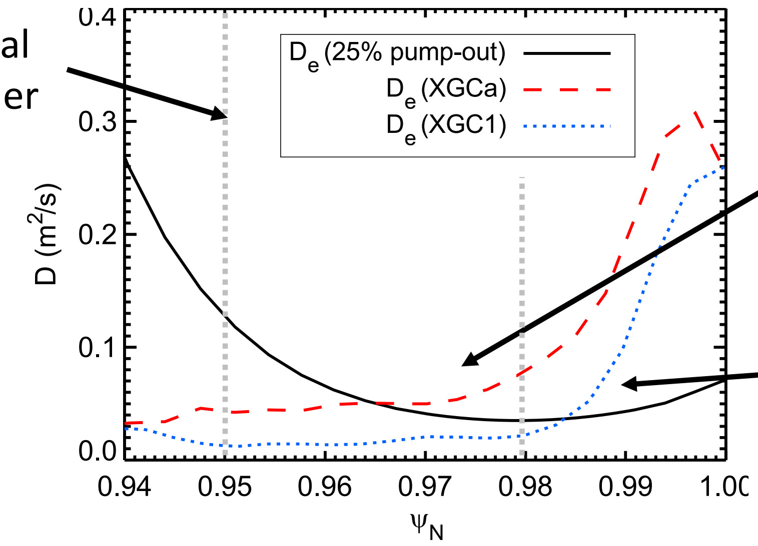


Particle Diffusivity in the Stochastic Layer ($\psi_N \gtrsim 0.98$) is at Experimental Level, Turbulence is Needed Inside Pedestal Center

- Simple estimate for diffusivity required for density pump-out

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

  - 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



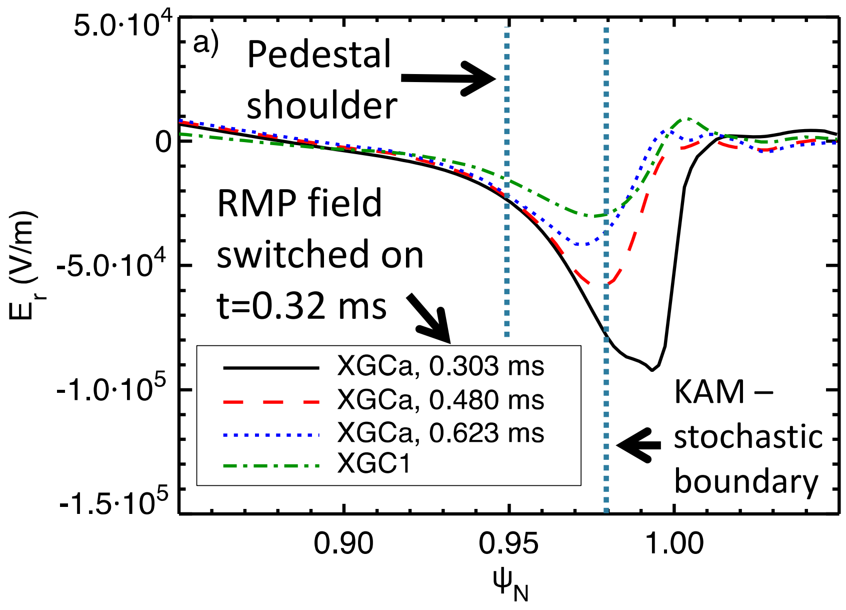
Pedestal Shoulder

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

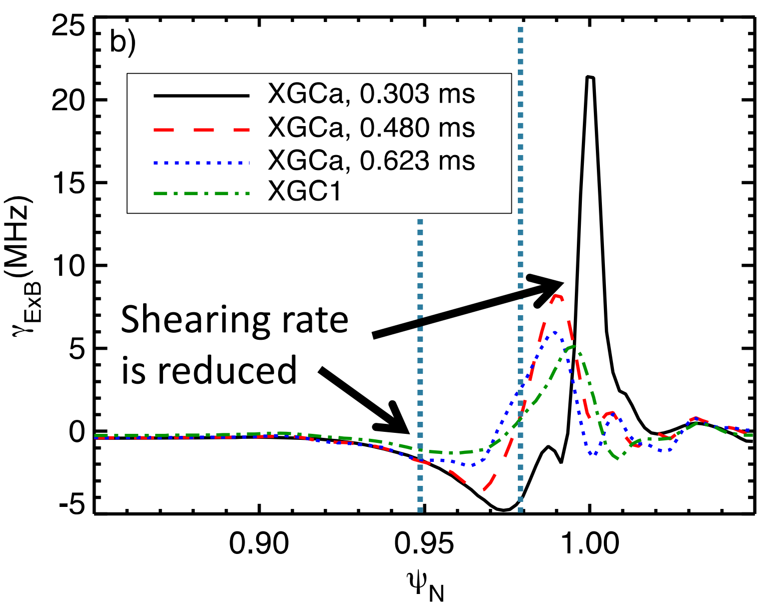
Transport in stochastic layer $\psi_N \gtrsim 0.98$ sufficient for >25% density pumpout

The Electrostatic Field Adjusts to RMP Field to Maintain the Ambipolarity of the Radial Particle Flux

Outer midplane E_r



Outer midplane E_r shearing rate

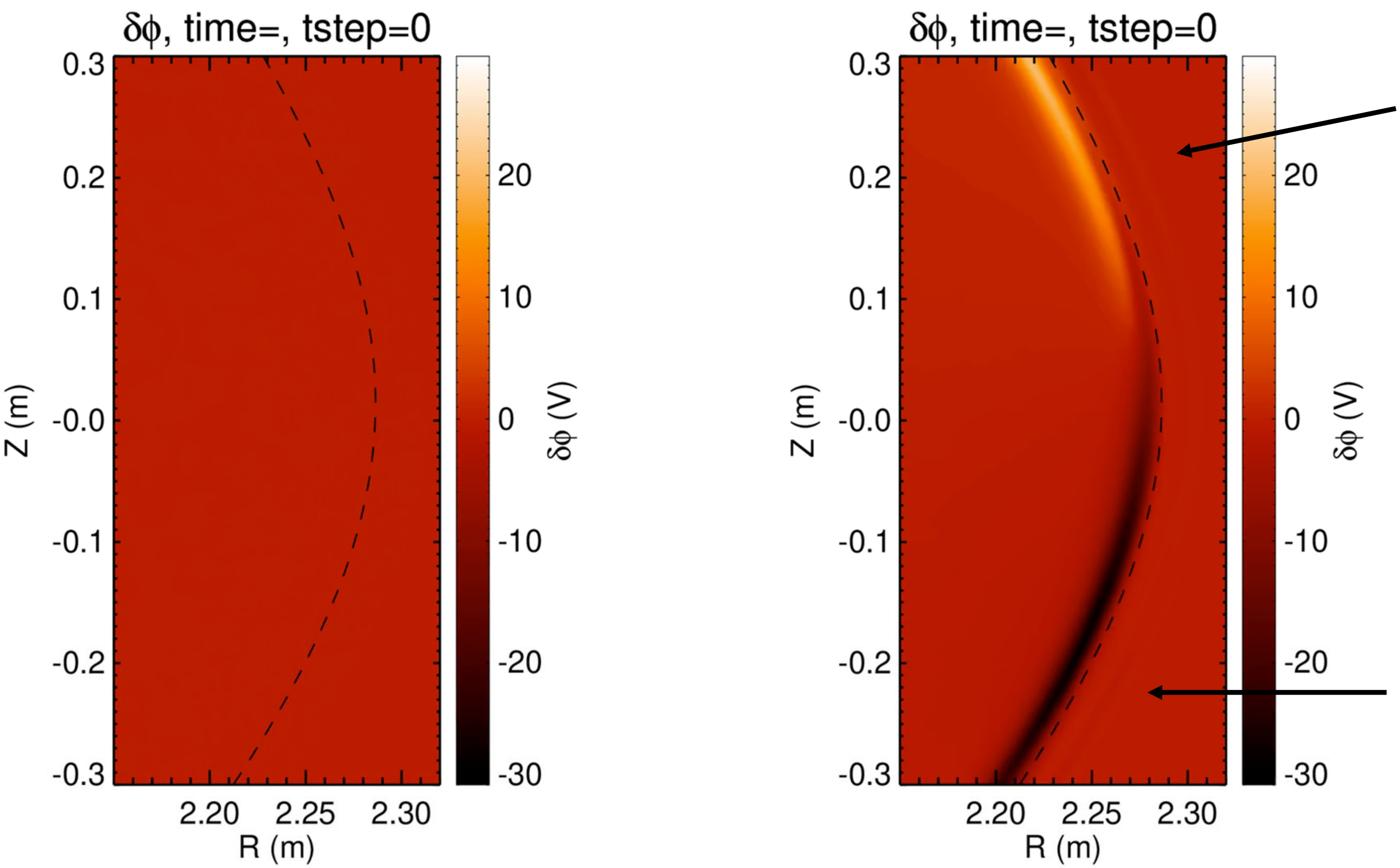


After adjusting for the fast prompt electron losses, E_r is still negative throughout the pedestal region → pushes electrons outward → **Suggests that transport is still driven by ion banana orbit motion**
(Remember that the thermal banana orbit width is comparable to the pedestal width!)

The change of the shearing rate around the pedestal shoulder can have implications on turbulent transport → will use XGC1 to study this

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



Without RMP

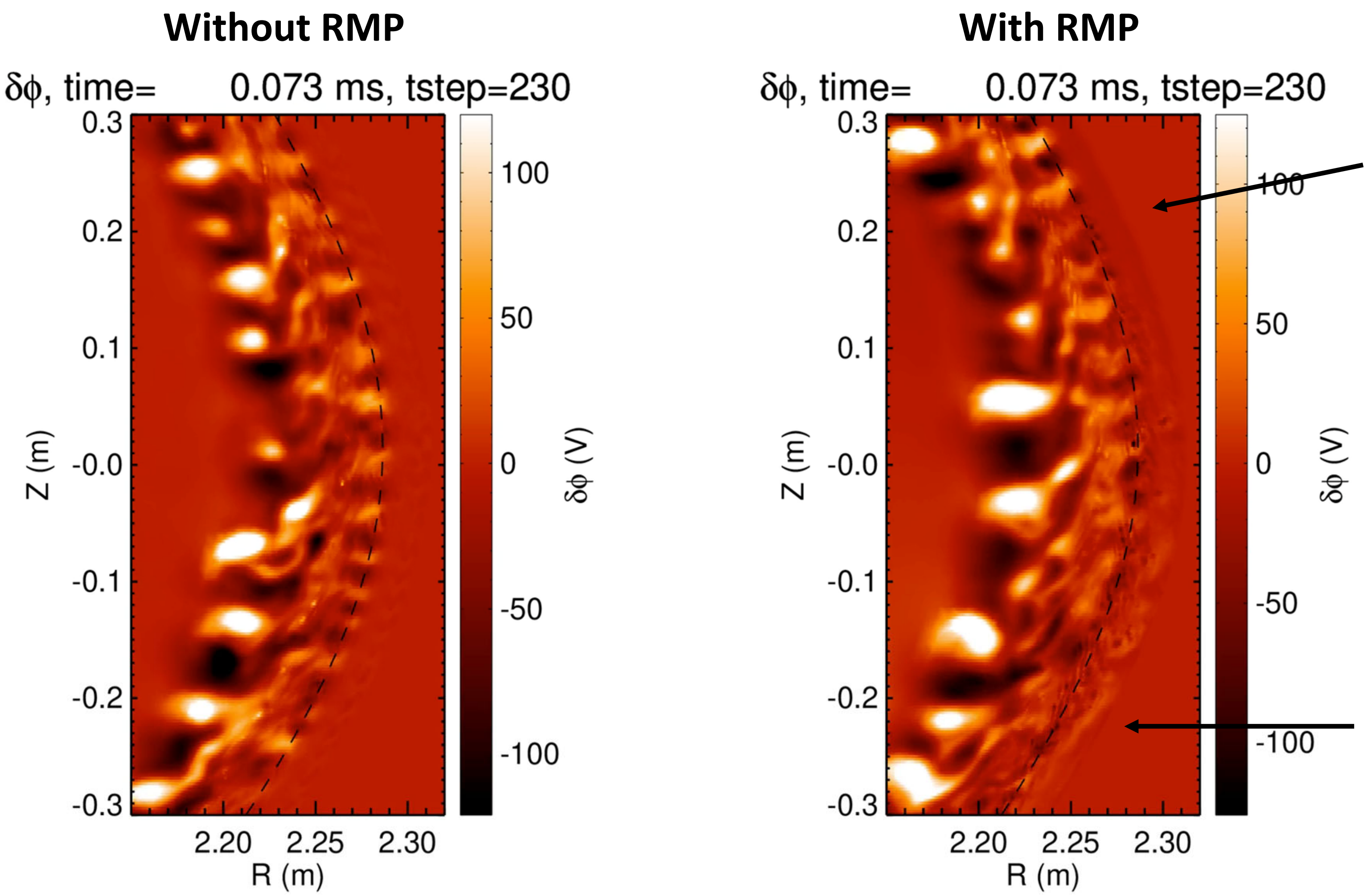
With RMP

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.)

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

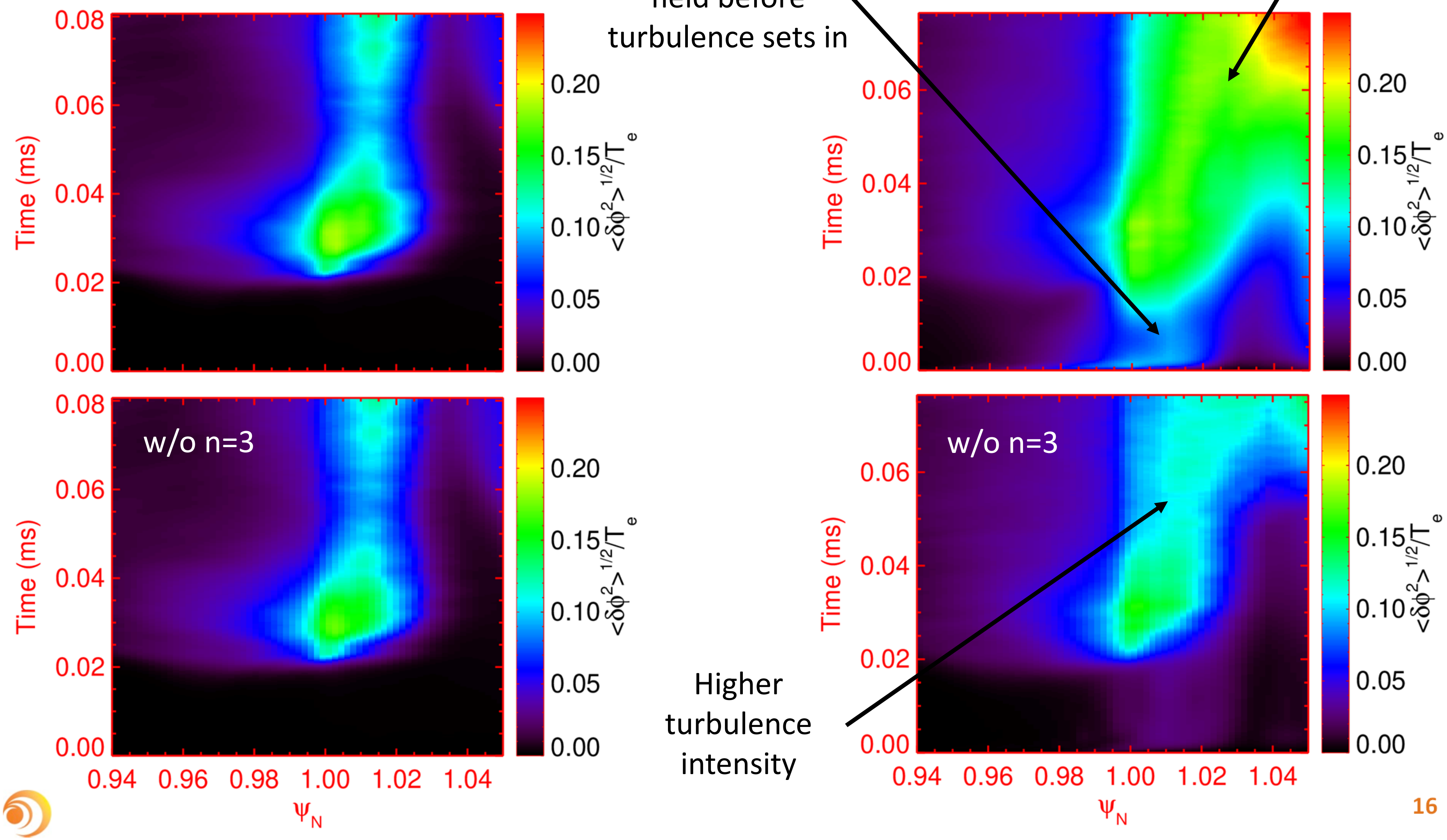
Stronger SOL turbulence

(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

With RMP

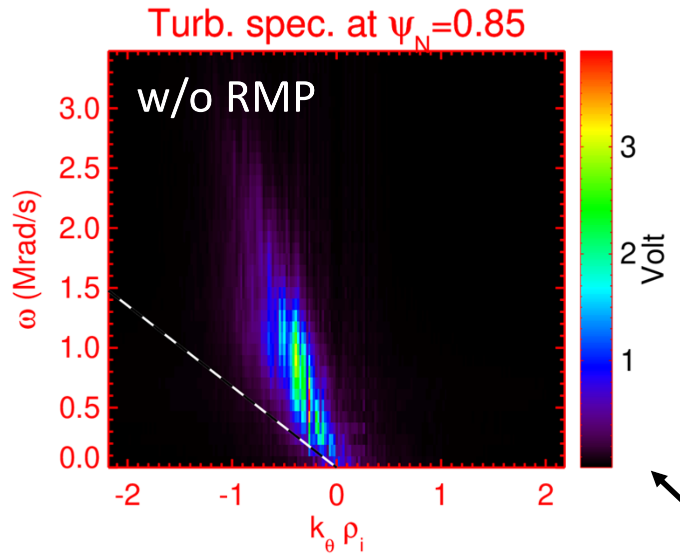


Immediate n=3 response to RMP field before turbulence sets in

A significant fraction of δϕ is n=3

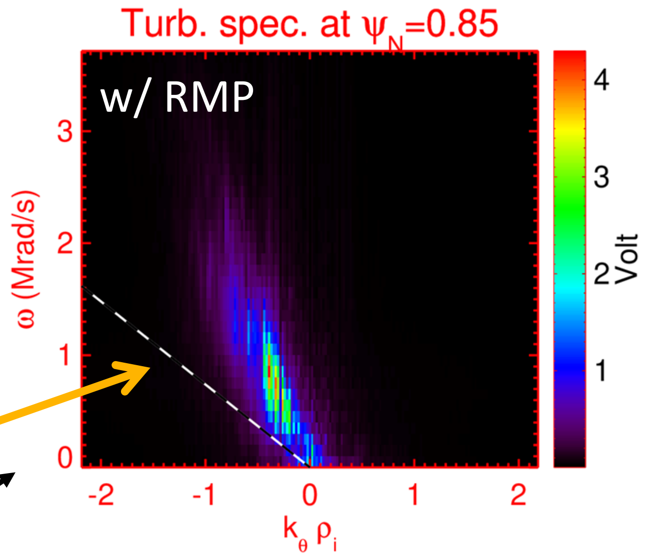
Higher turbulence intensity

Turbulence Spectra are Similar in Both Cases: Suggests TEM in Pedestal and ITG Inside Pedestal

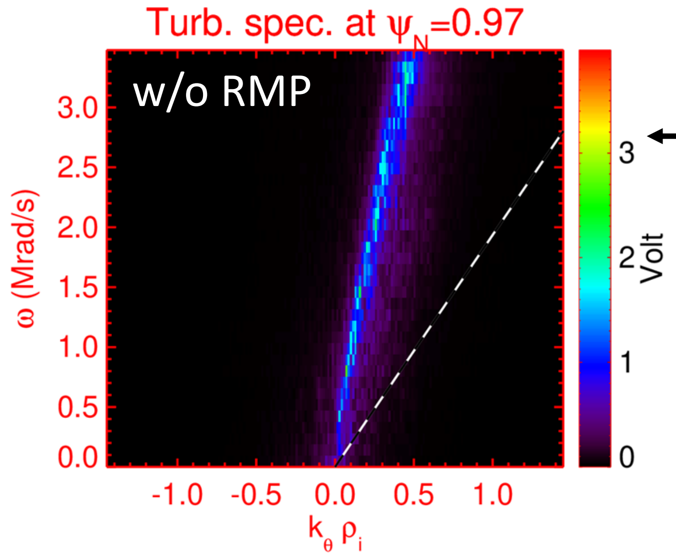


$\omega/k < 0$ corresponds to ion diamagnetic direction

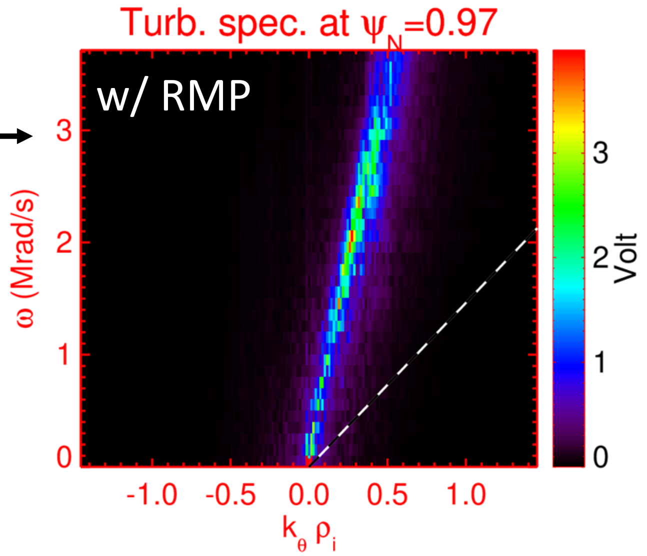
ExB flow



Ion mode

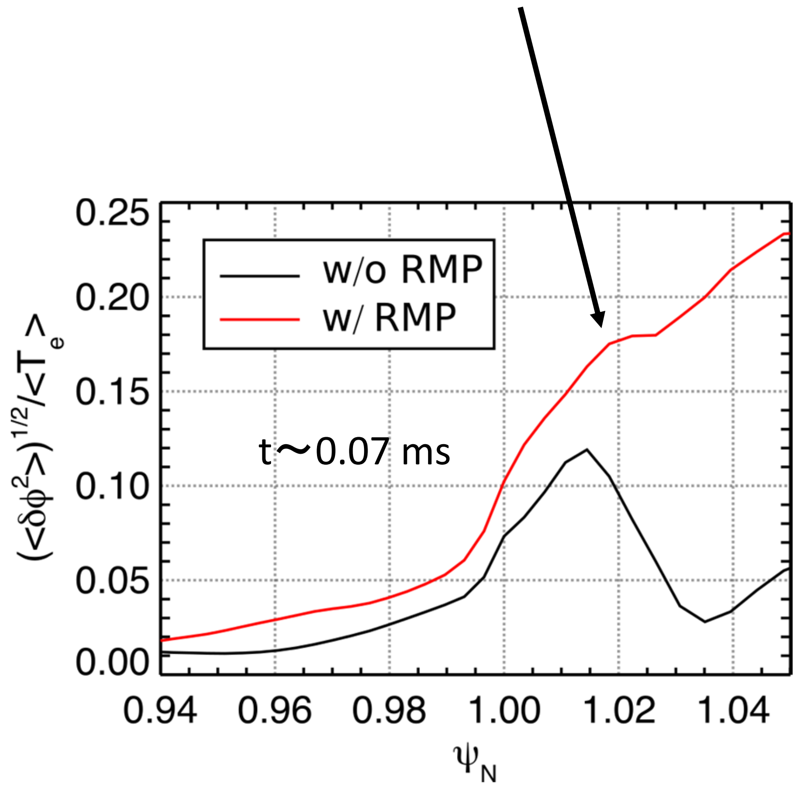


Electron mode



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**

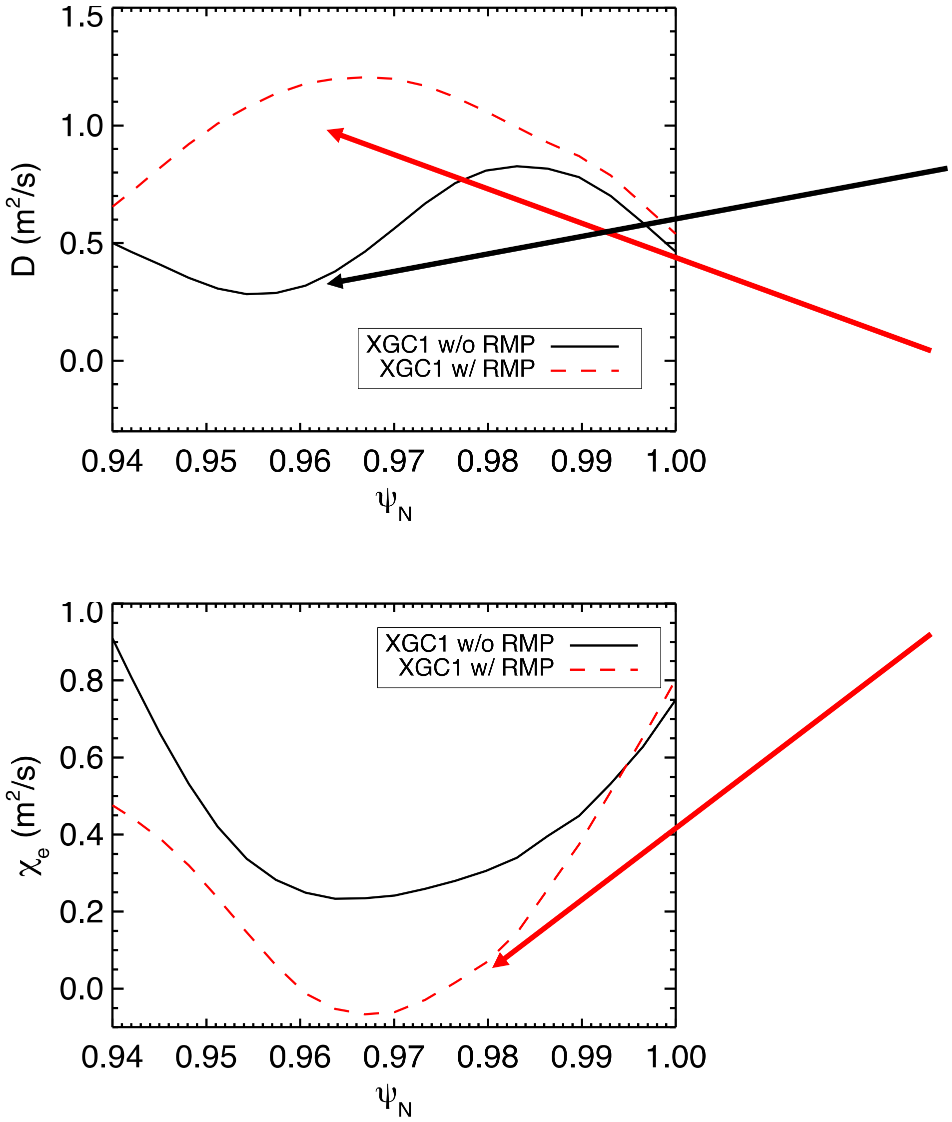
$$\Gamma_{3D} = \frac{\left\langle \int \left[\nabla\psi \cdot (\delta\boldsymbol{B}/|B|)\, v_\parallel \tilde{f} \right] \mathrm{d}^3 v \right\rangle}{\langle |\nabla\psi| \rangle}$$

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

Turbulent-neoclassical RMP Transport



- Effective particle diffusitity without RMP is low (D<0.5 m^2/s) at $\psi_{N\sim}$0.95-0.97
- Turbulent+neoclassical particle diffusivity with RMP is higher than without RMP

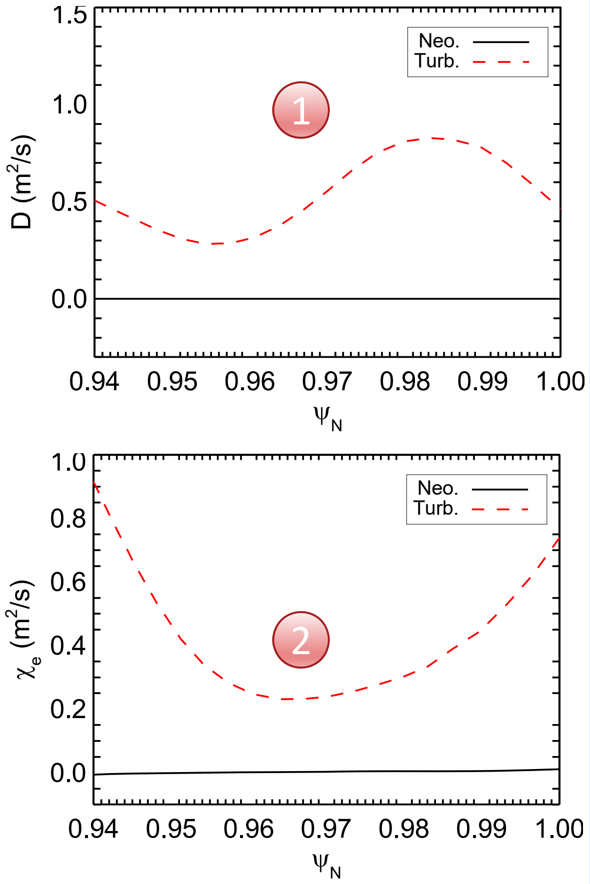
  → **Density pumpout**

- Turbulent+neoclassical electron thermal diffusivity is suppressed between 0.96$\lesssim\psi_N\lesssim$0.98

  → **Electron thermal barrier**

RMP Transport

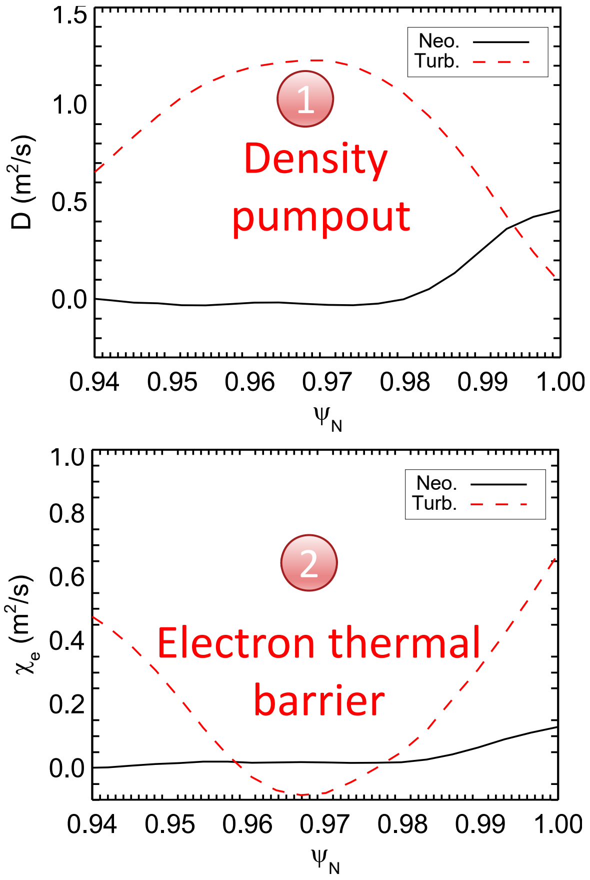
Without RMP



① Turbulent particle flux is higher in the pedestal region ψ_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**).

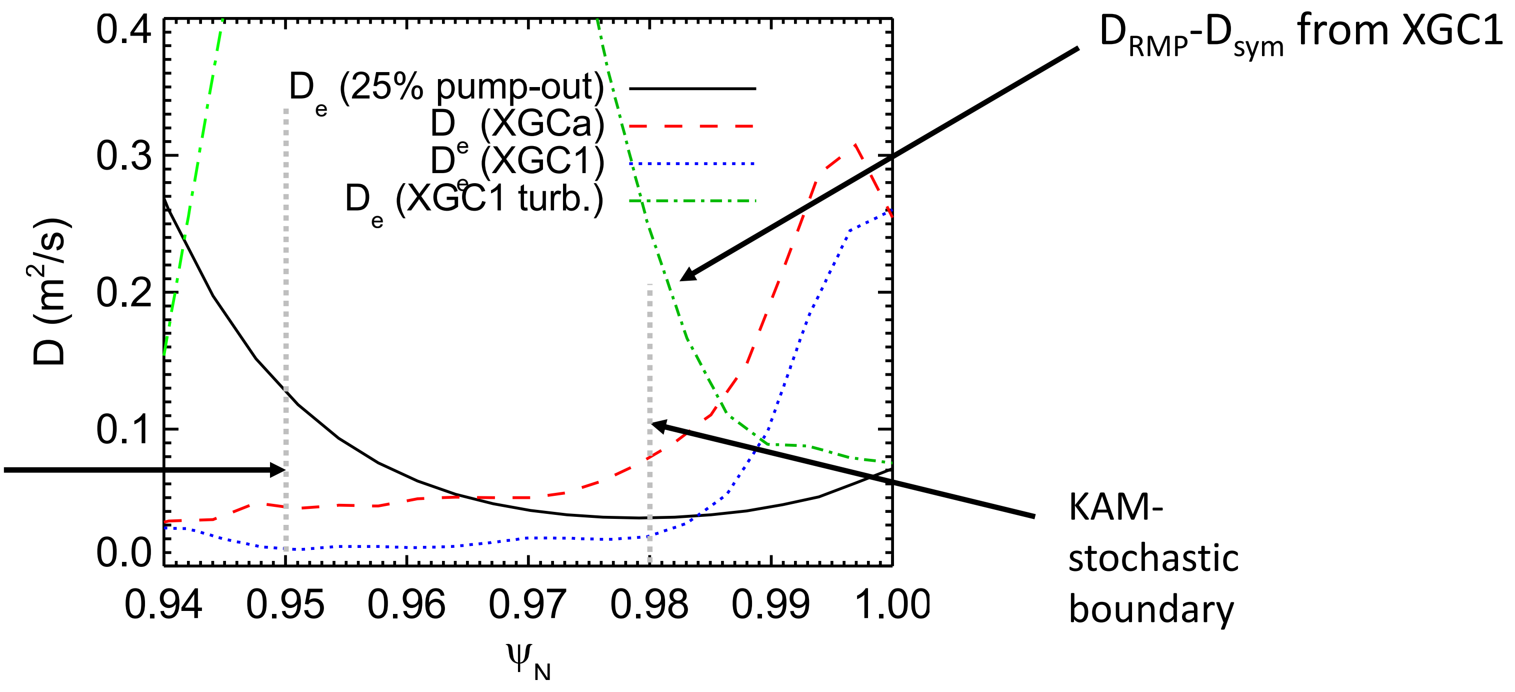
② As in the pure neoclassical simulation, the electron heat flux is reduced around $\psi_N \sim$ 0.97.

With RMP



The Difference in the Particle Diffusivity between XGC1 with and without RMP is Sufficient for Density Pump-Out

- Assume 25% density pump-out as before
- From XGC1 use: D_{RMP}-D_{sym}



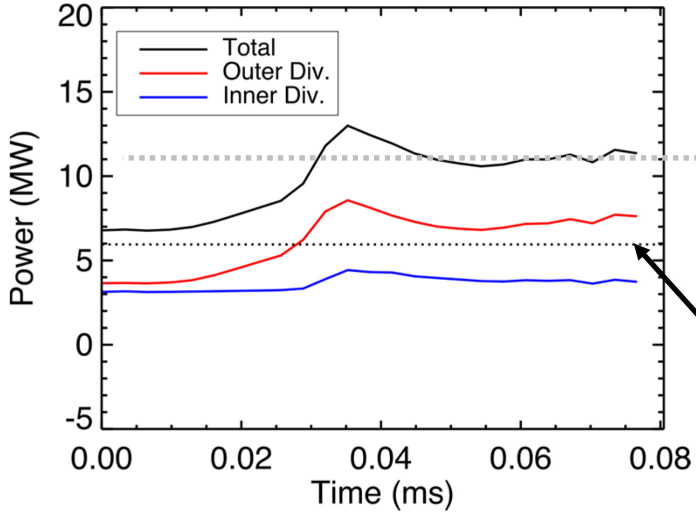
D_{RMP}-D_{sym} from XGC1

Pedestal Shoulder

KAM-stochastic boundary

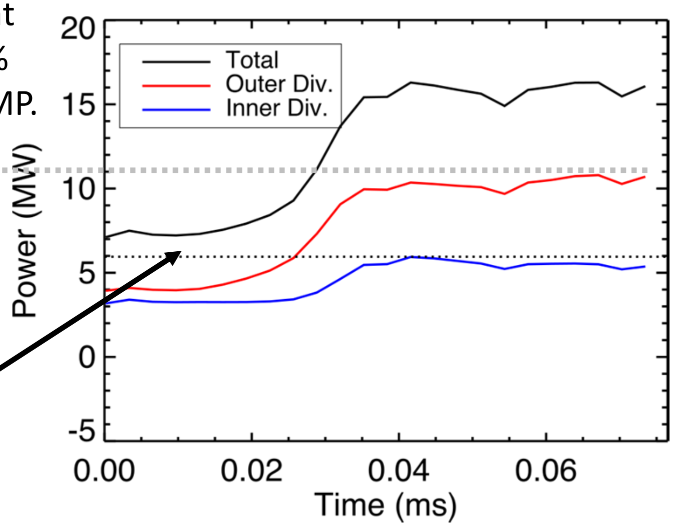
Divertor Heat Load

Without RMP

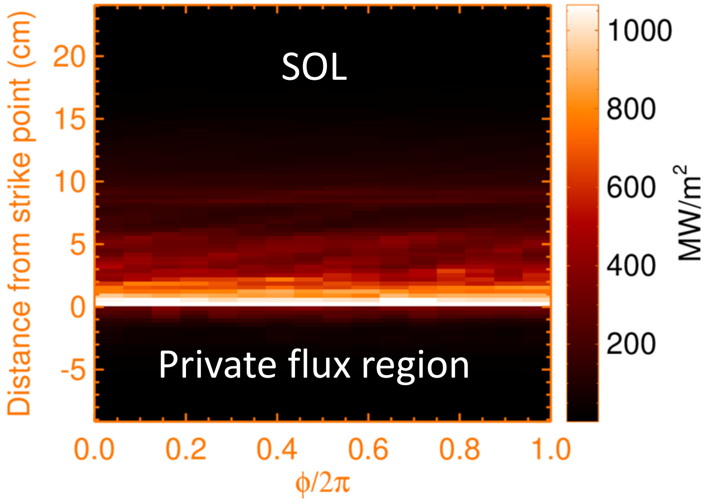


Both cases are not in power balance yet. Divertor heat load is ~50% larger with RMP.

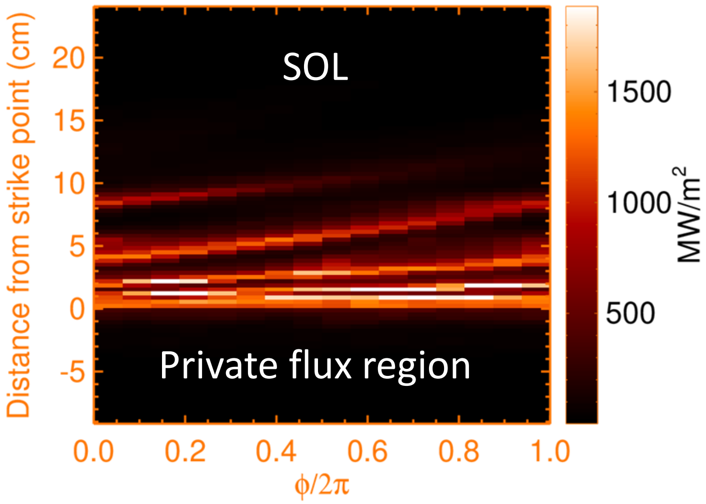
With RMP



Heating Power

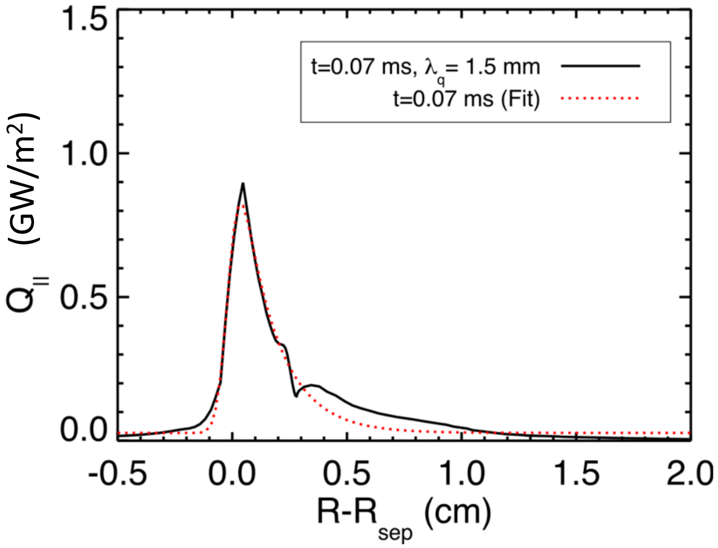


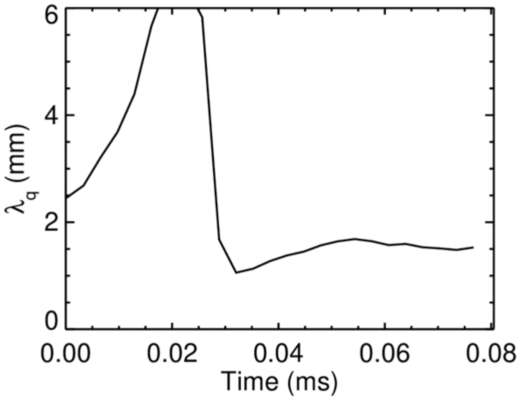
Parallel energy flux at divertor plates exhibits n=3 striations with RMP field turned on.



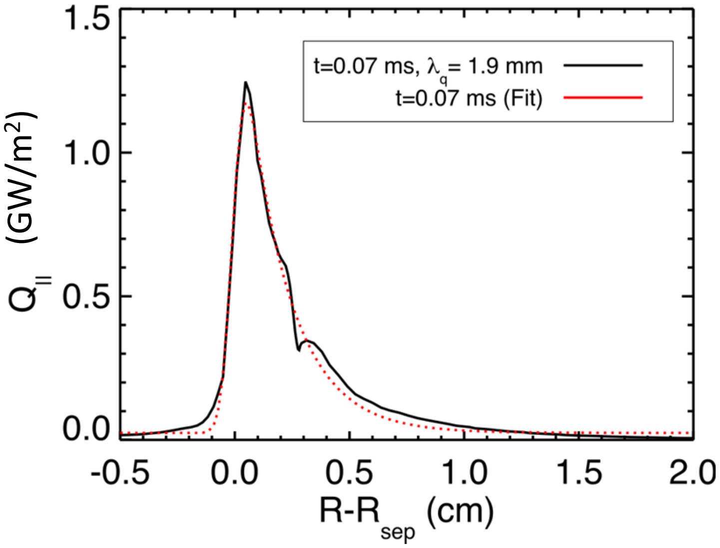
Divertor Heat Load Width is already saturating: The RMP case is wider by ~30%

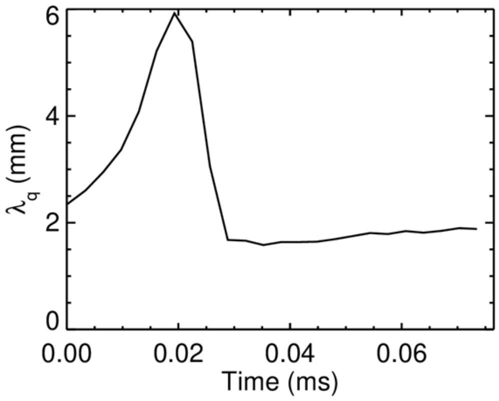
Without RMP





With RMP





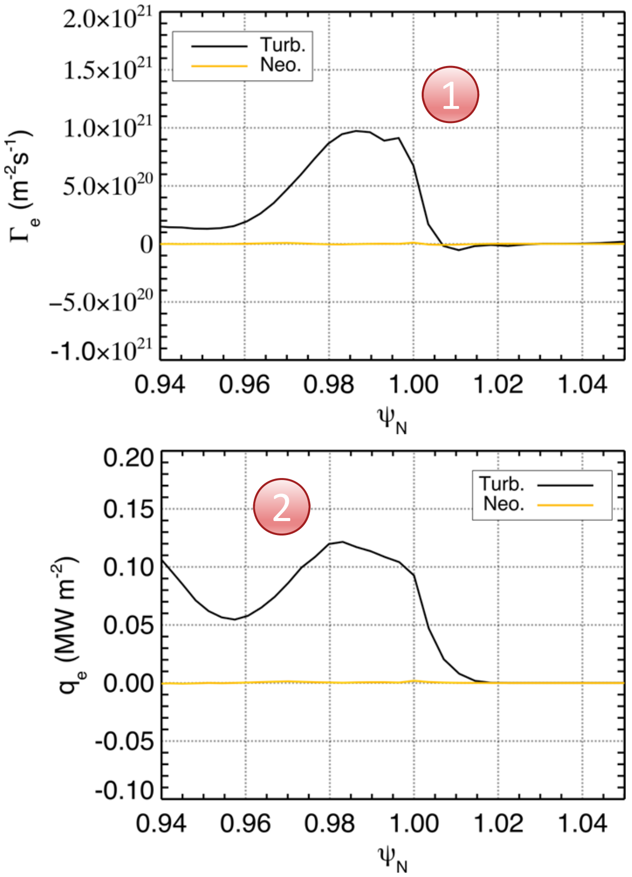
Conclusions

Conclusions

- When using M3D-C1 RMP field in XGC simulations, the combined neoclassical and turbulent transport are needed to explain density pumpout
- An electron thermal barrier exists in the pedestal slope ($\psi_{N\sim}$0.96-0.98) in both
  - pure neoclassical and
  - neoclassical+turbulence cases
- Density pumpout is from turbulence
- Longer turbulence simulations will be run to reduce statistical error
- Use kinetic response currents to compute RMP penetration in XGC
- Electromagnetic simulations are to be performed to study effect on ELM stability

RMP Transport

Without RMP



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② As in the neoclassical simulation, the electron heat flux is reduced around $\psi_N\sim0.97$.

With RMP