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

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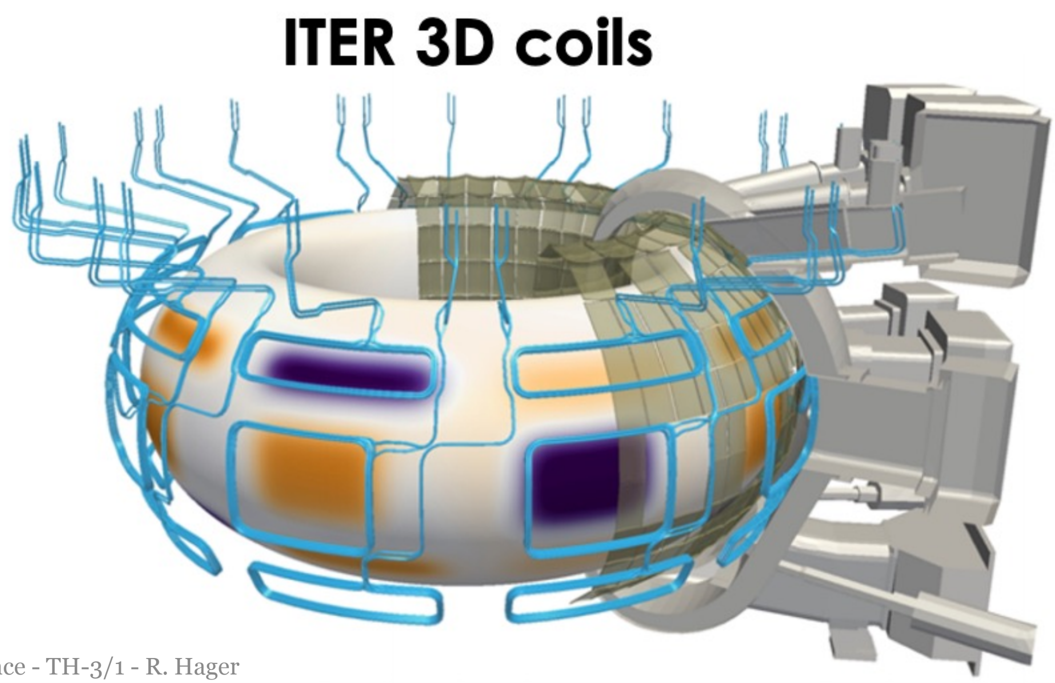
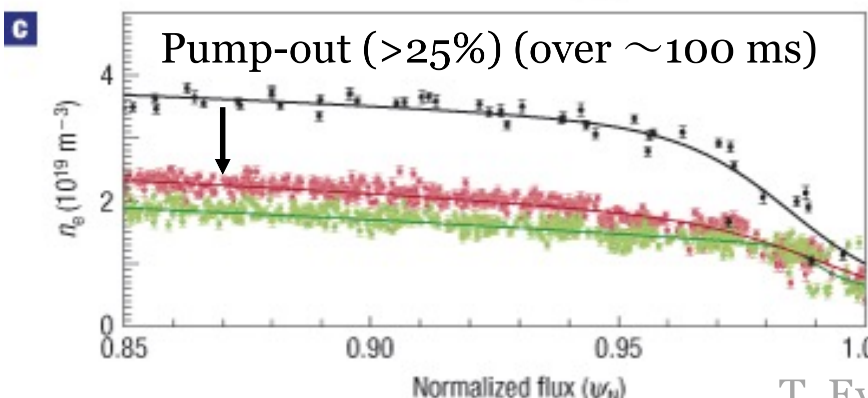
Outline

- Introduction
- Numerical Approach
- Using DIII-D and KSTAR plasmas
  - Change of turbulence properties by RMPs
  - Change of transport by RMPs
- Conclusions and Discussion

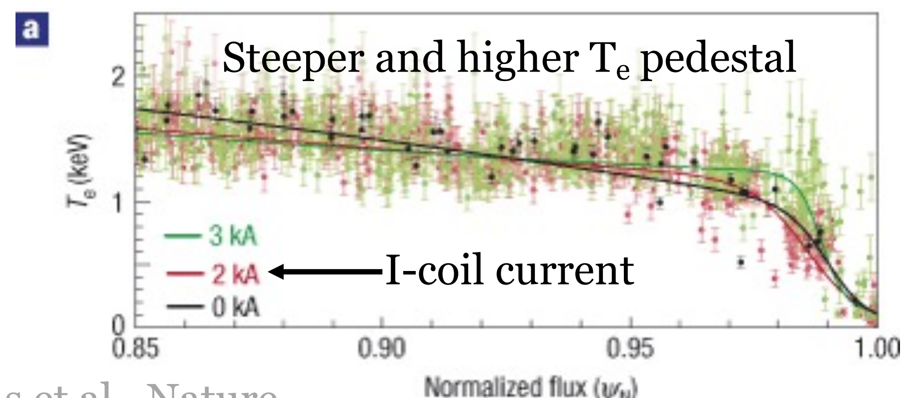


- ITER plans to use 3D fields, **R**esonant **M**agnetic **P**erturbations (RMP), for ELM suppression

What is the physics behind the density pump-out?



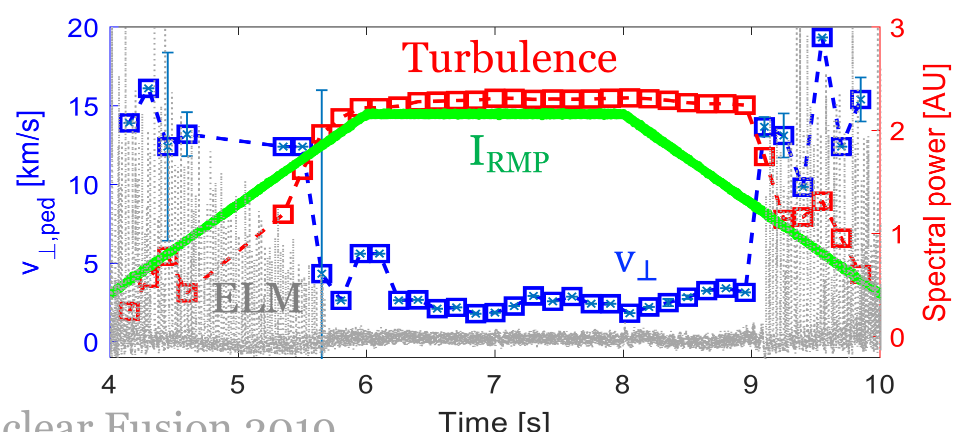
Why is electron heat still confined?



T. Evans et al., Nature 2006

Why is turbulence intensity higher with RMPs?

Apparent correlation between I-coil current, turbulence intensity, $v_\perp$ and ELM intensity



H. K. Park et al., Nuclear Fusion 2019

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

M3D-C1 calculates:
Perturbed MHD equilibrium in presence of RMPs

→

XGC calculates:
Gyrokinetic plasma transport in 3D magnetic equilibrium

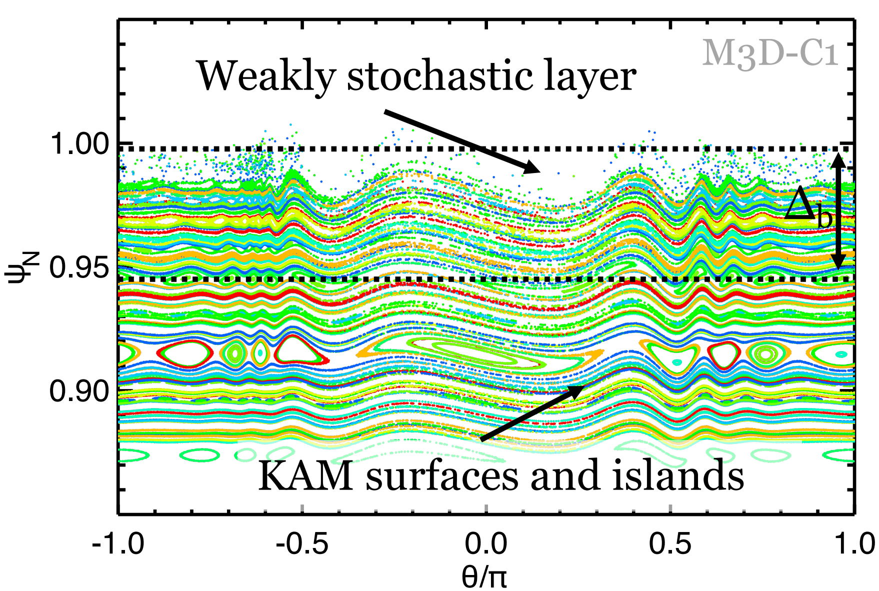
- M3D-C1 is a two-fluid extended-MHD code
  - Domain includes plasma, SOL, and surrounding vacuum region.
  - Uses Spitzer resistivity and realistic transport coefficients ($\sim 1\,\frac{\mathrm{m}^2}{\mathrm{s}}$)
  - Perturbed equilibrium includes small magnetic islands and localized regions of stochasticity

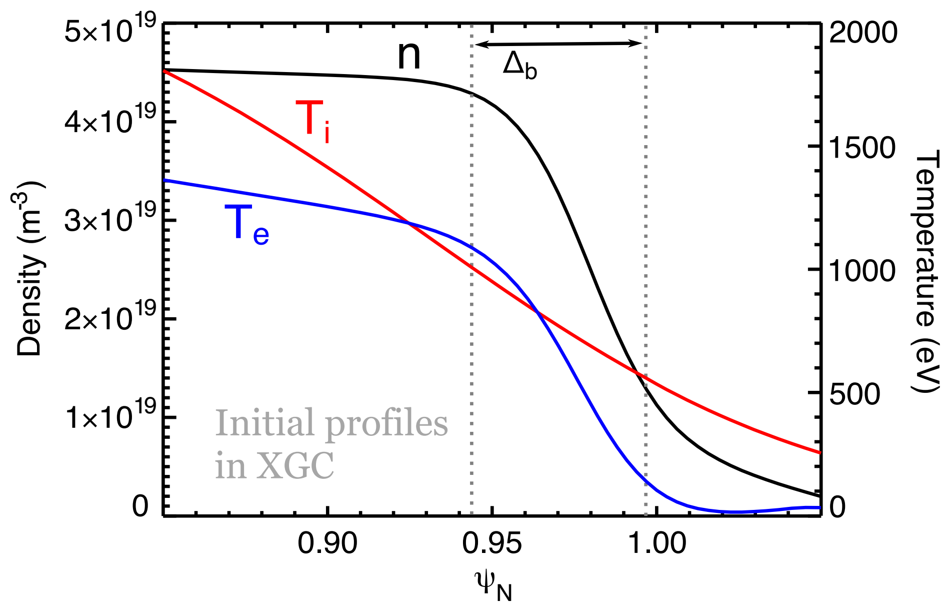
- XGC is a **global 5D gyrokinetic**, total-f particle-in-cell code
  - Whole volume simulation including SOL, separatrix, and magnetic axis
  - Self-consistent 3D background and turbulent electric field
  - Nonlinear Fokker-Planck-Landau collision operator
  - Neutral particle recycling

M3D-C1 is not Sufficient to Understand Transport → Need to Study Kinetic Physics

- DIII-D H-mode discharge #157308 → M3D-C1 yields perturbed field with good KAM surfaces at $\psi_N \leq 0.98$
- Thin, weakly stochastic layer close to the separatrix ($\psi_N \geq 0.98$)
- δB is strong enough to affect trapped particle dynamics
- Pedestal width comparable to ion banana orbit width Δ_b

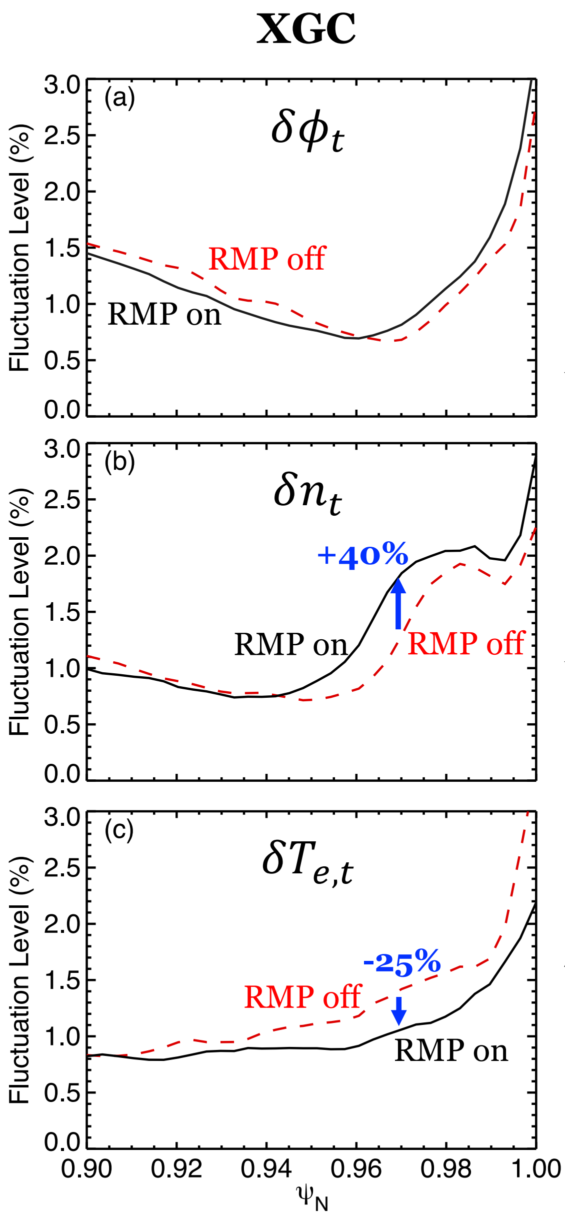
→ Need to study kinetic physics to understand transport!





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

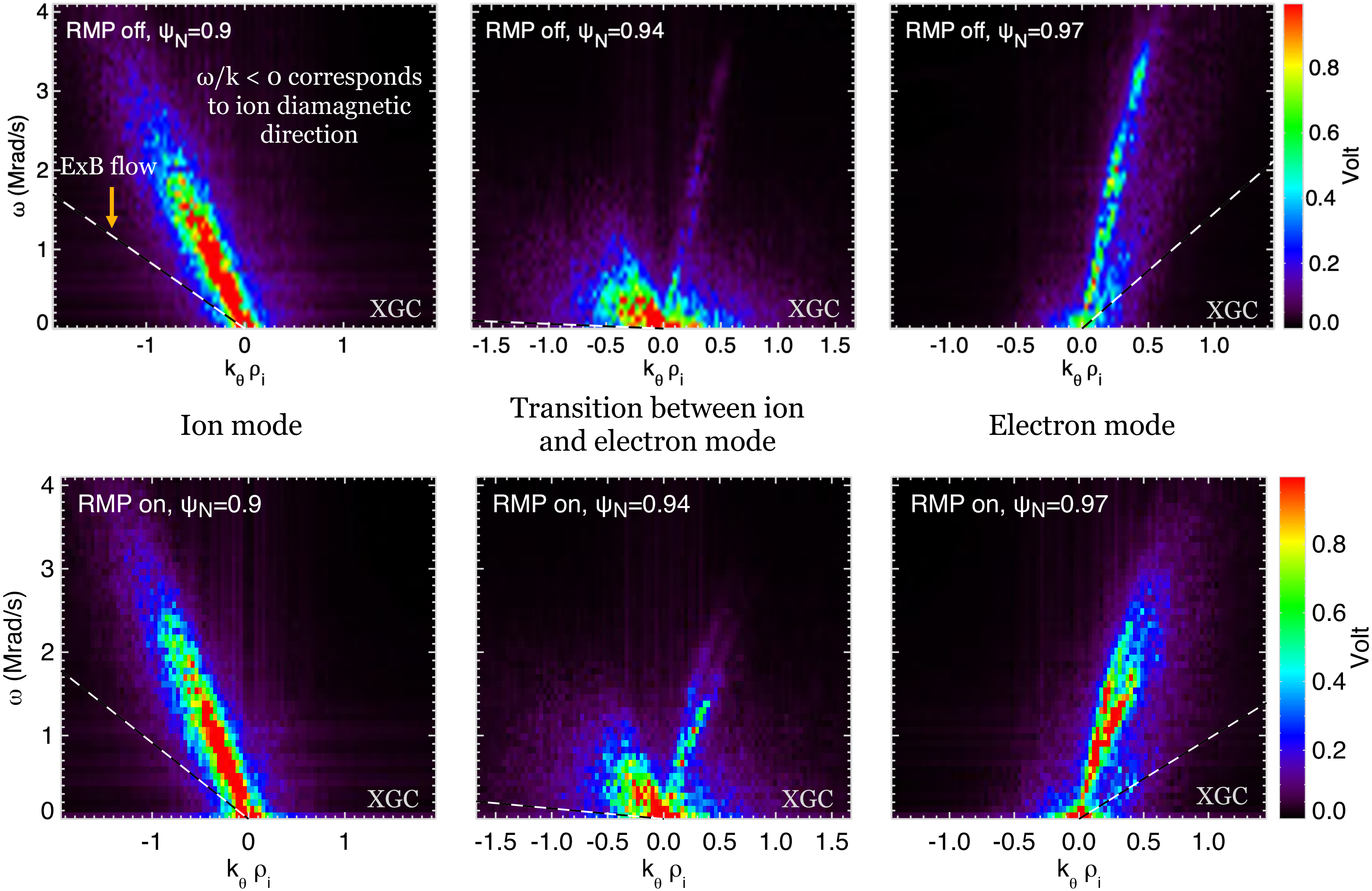
RMPs Increase Density Fluctuations and Decrease Temperature Fluctuations in the Pedestal



- n=3 mode (RMP) is removed to study changes in relative RMS turbulence fluctuation levels
- Potential fluctuations change only by ~10%.
- Density fluctuations increase with RMP.
- Electron temperature fluctuations decrease with RMPs.
- These changes are correlated with changes in the transport fluxes.
- δp_e is minimized by restricting δT_e.

R. Hager et al., Physics of Plasmas (2020)

Spectra suggest enhanced TEM in pedestal slope. ITG deeper inside does not change as much (at t~0.2 ms)



R. Hager et al., Physics of Plasmas (2020)

There are three main transport channels:

- **Neoclassical flux** $$\Gamma_D = \frac{\langle \int \left[\nabla\psi \cdot (\boldsymbol{v}_D + \overline{\boldsymbol{v}}_{ExB})\, \overline{f}\, \right] \mathrm{d}^3 v \rangle}{\langle |\nabla\psi| \rangle}$$
- **Flutter transport** $$\Gamma_{3D} = \frac{\left\langle \int \left[\nabla\psi \cdot (\delta\boldsymbol{B}/|B|)\, v_\| \tilde{f} \right] \mathrm{d}^3 v \right\rangle}{\langle |\nabla\psi| \rangle}$$
- **Turbulent ExB flux** $$\Gamma_{turb} = \frac{\left\langle \int \left[\nabla\psi \cdot \tilde{\boldsymbol{v}}_{ExB} \tilde{f} \right] \mathrm{d}^3 v \right\rangle}{\langle |\nabla\psi| \rangle}$$

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

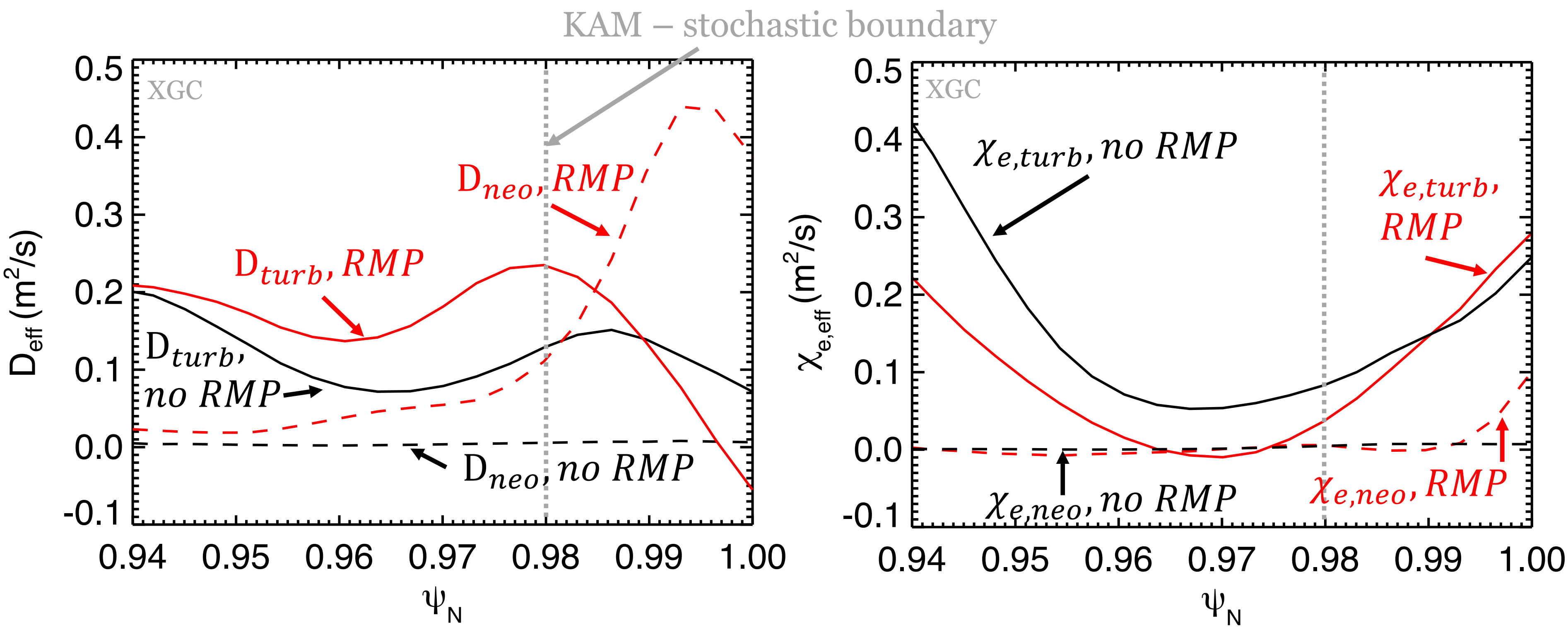
$\overline{(\dots)} \rightarrow$ toroidal average

$$\boldsymbol{\Gamma_{neo} \stackrel{def}{=} \Gamma_D + \Gamma_{3D}}$$

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

Increased turbulent+neoclassical particle diffusivity with RMPs

Lower effective electron heat conductivity

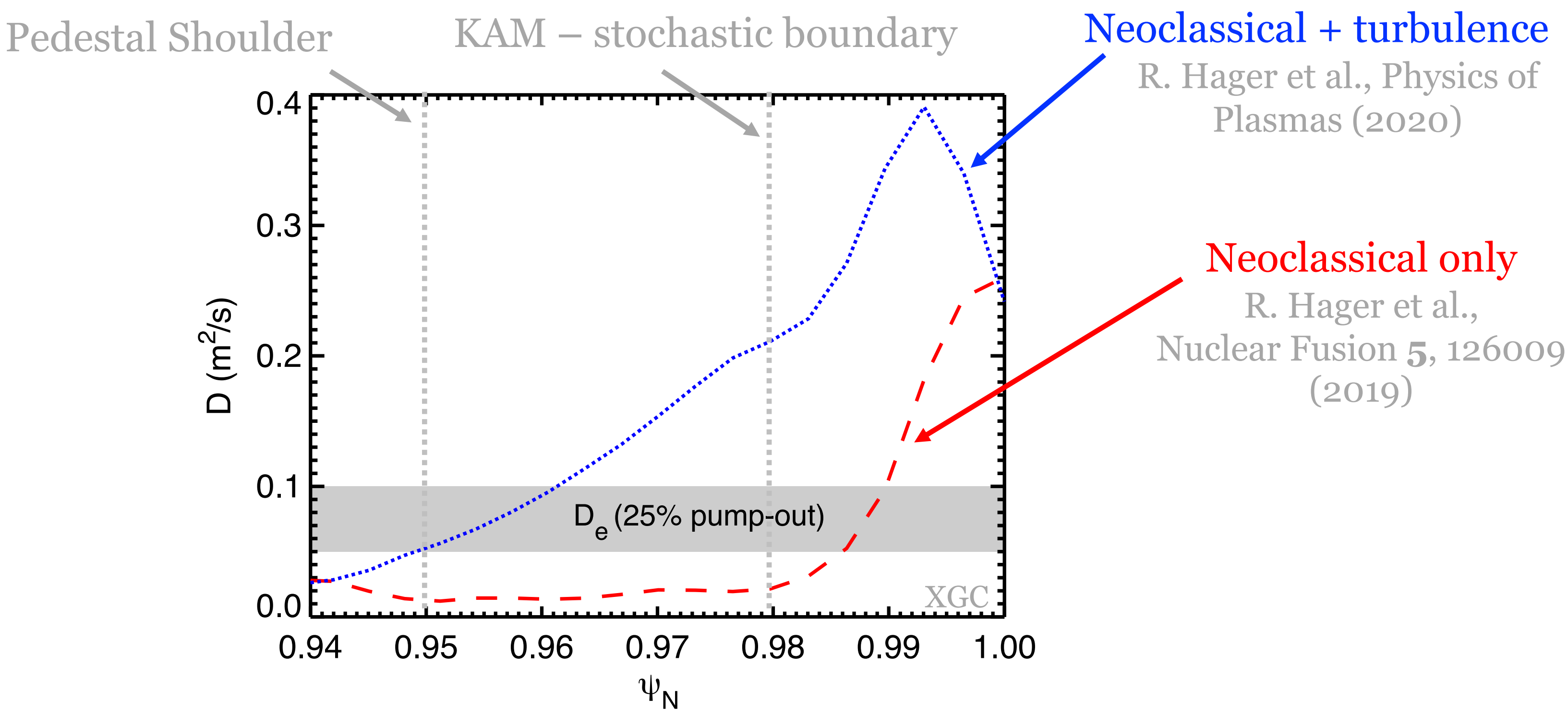


→ Electron thermal transport barrier in the steep pedestal region survives

R. Hager et al., Physics of Plasmas (2020)

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



→ 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: $S_{AB} = \left\langle \hat{A}\,(\psi_N, m, \varphi)\hat{B}^*(\psi_N, m, \varphi)\right\rangle_{tor}$

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:

$$\Gamma_t(\psi_N, m) = \alpha(\psi_N) P_{vn} \cos(\delta\zeta_{vn})$$

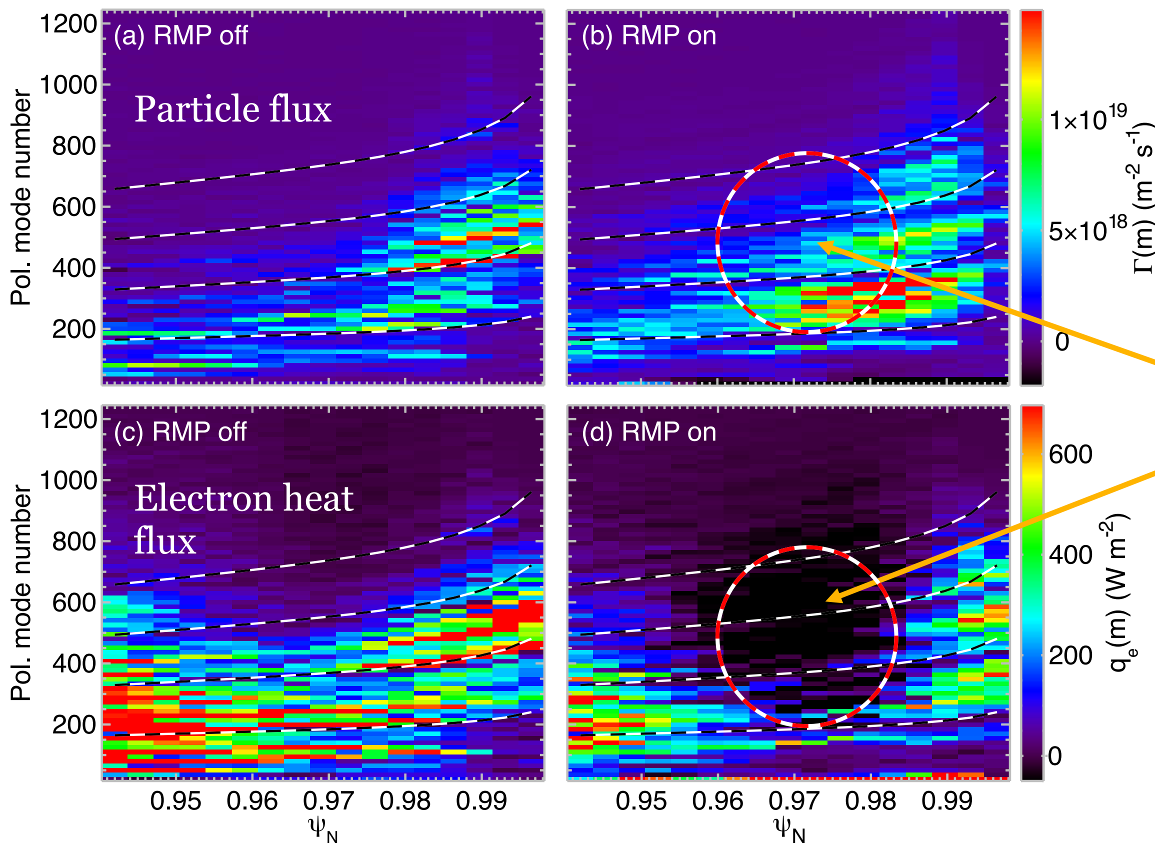
$$Q_t(\psi_N, m) = \alpha(\psi_N)\,\frac{3}{2}\,k_B\,[\langle n\rangle P_{vT}\cos(\delta\zeta_{vT}) + \langle T\rangle P_{vn}\cos(\delta\zeta_{nT})]$$

$$q_t(\psi_N, m) = Q_t - \frac{5}{2} k_B\,\langle T\rangle \Gamma_t$$

(α is a geometric factor from the flux-surface average.)

Increased Particle Flux Density from m≳200 at ψ_N~0.97

XGC cross-spectrum analysis



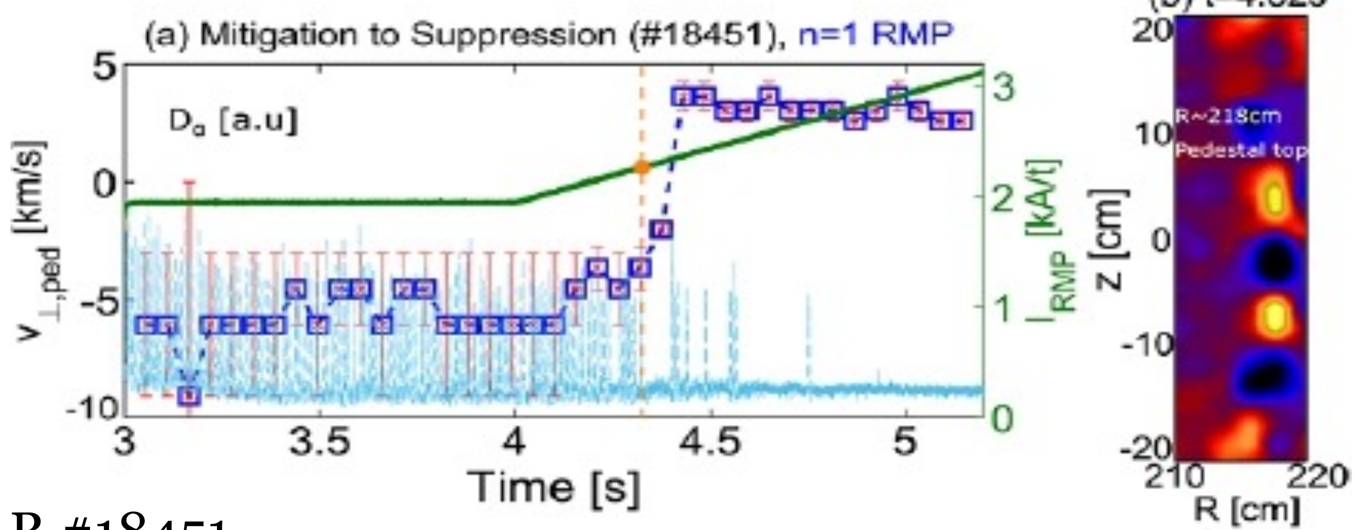
R. Hager et al., Physics of Plasmas (2020)

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

→ Electron energy transport is convective, riding the particle flux, which does not alter the T_e gradient much.

Study Correlation between I_{RMP} and Turbulence Intensity in KSTAR discharge 18451 with n=1 RMPs

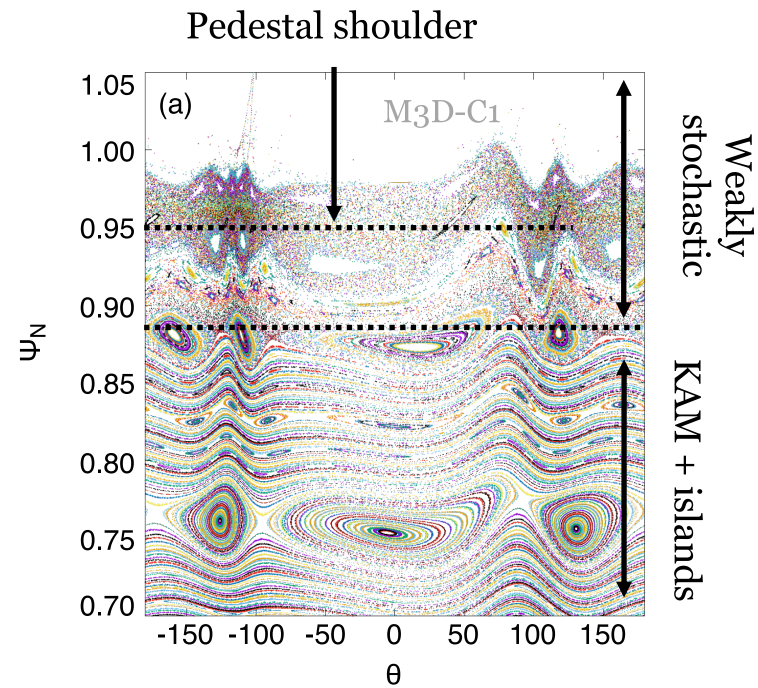
Y. In et al 2019 Nucl. Fusion 59 056009

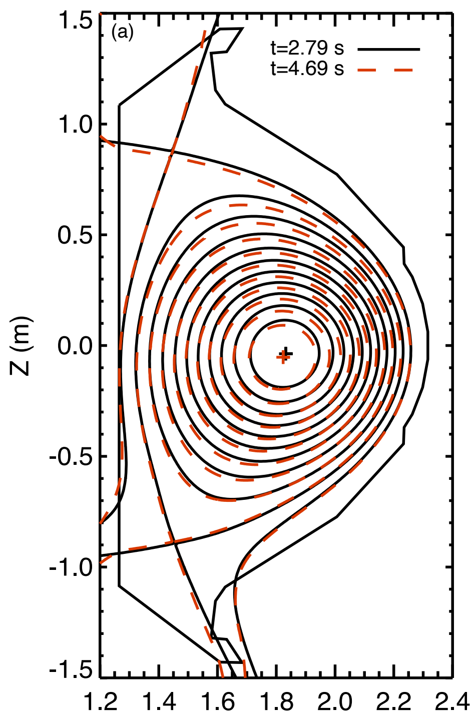


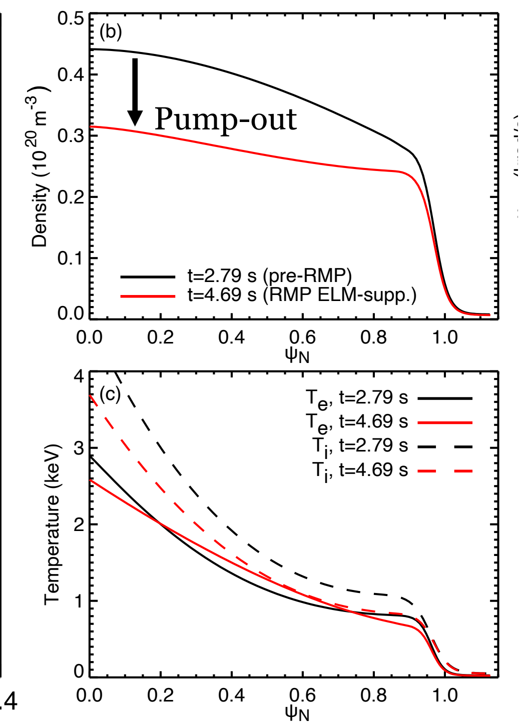
- KSTAR #18451
  - ELMing H-mode at t=2.79 s before RMP application
  - ELM mitigation at I_{RMP}=2 kA/t
  - ELMs suppressed at $t \geq 4.4$ s
- Study two time slices with M3D-C1+XGC
  - t=2.79 s, I_{RMP}=0 kA/t → Before RMP application
  - t=4.69 s, I_{RMP}=2.69 kA/t → ELM suppression

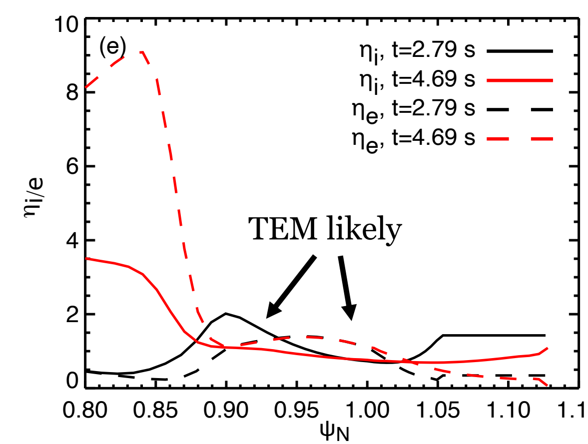
Pedestal ($\psi_N \geq 0.9$) is Weakly Stochastic → Expect Stronger Role of Neoclassical Transport

- Plasma shapes and safety factor profile are very similar at t=2.79 s and t=4.69 s
- Pump-out: central density reduced by ~25%
- Perturbed magnetic field weakly stochastic in the pedestal (from the q=4 surface outwards)
- Low η_i and η_e → Trapped electron mode (TEM) likely unstable









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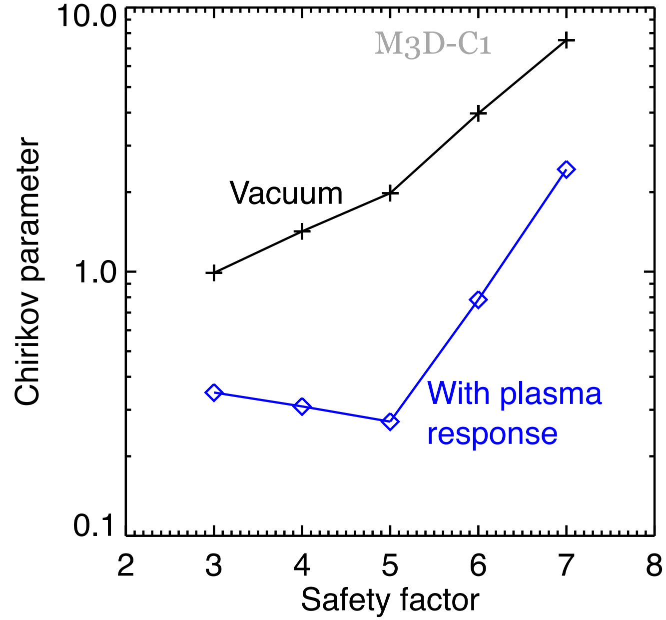
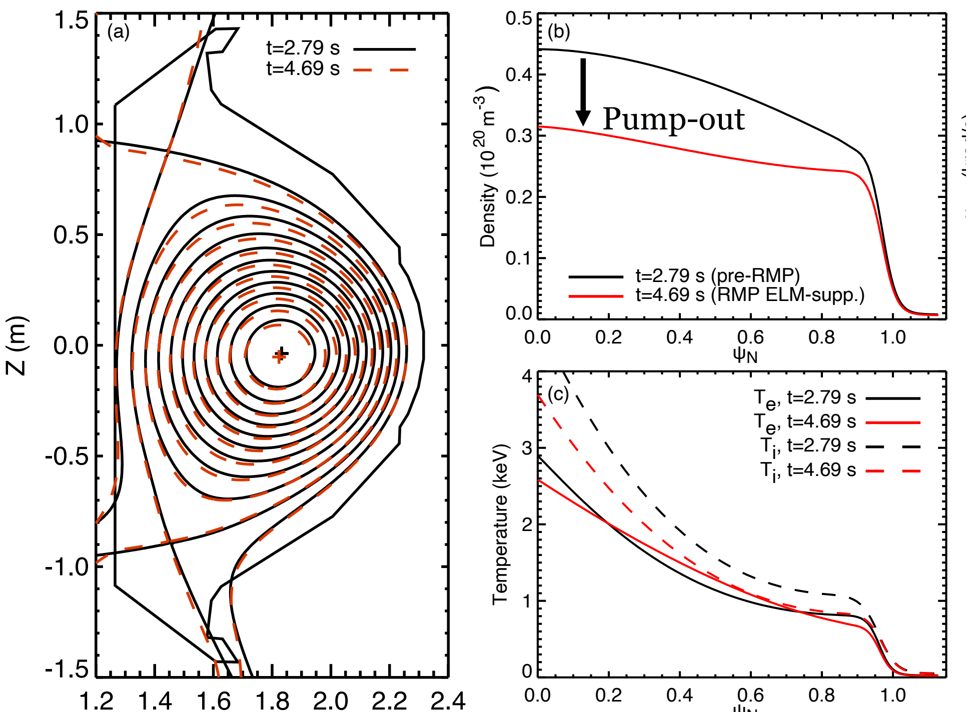
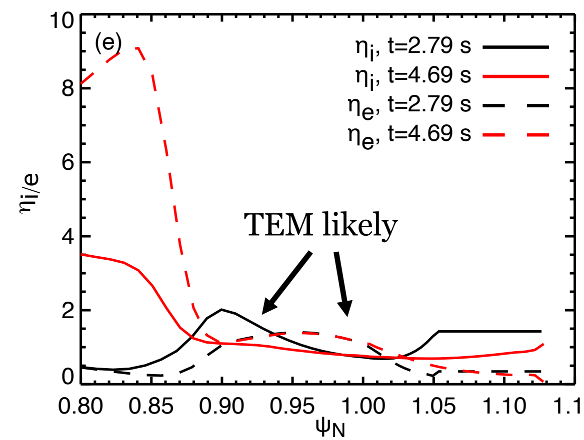
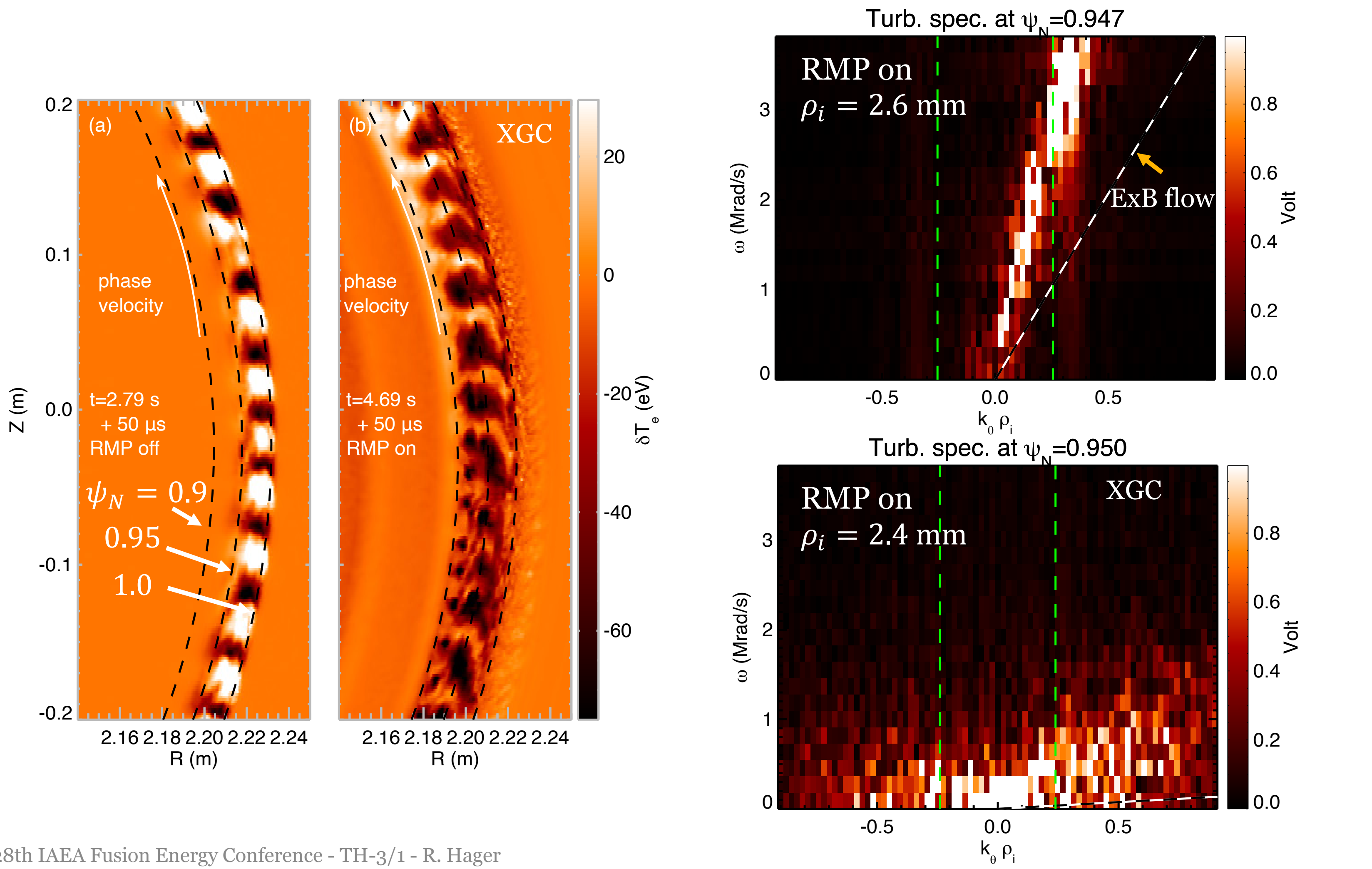






XGC Simulation: Unstable Trapped-electron Modes (TEMs) extends to pedestal top, covering $0.9 \le \psi_N \le 1$

- Mode structure propagates in elec. diamagnetic direction in ExB frame → TEM
- Turbulence grows faster around pedestal top with RMPs.
- Need synthetic diagnostic for better comparison with experiment



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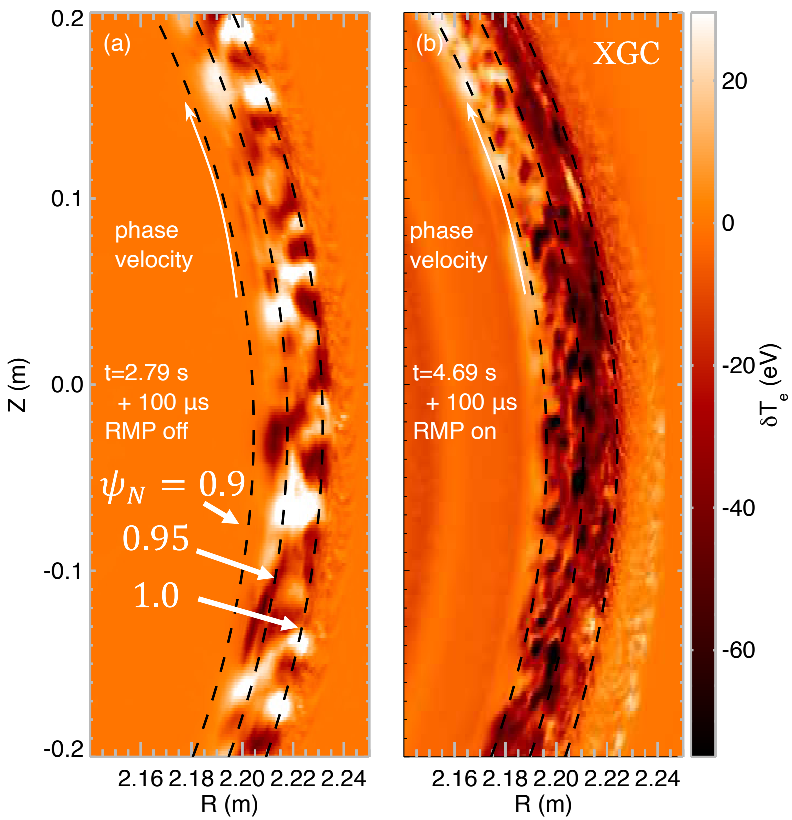

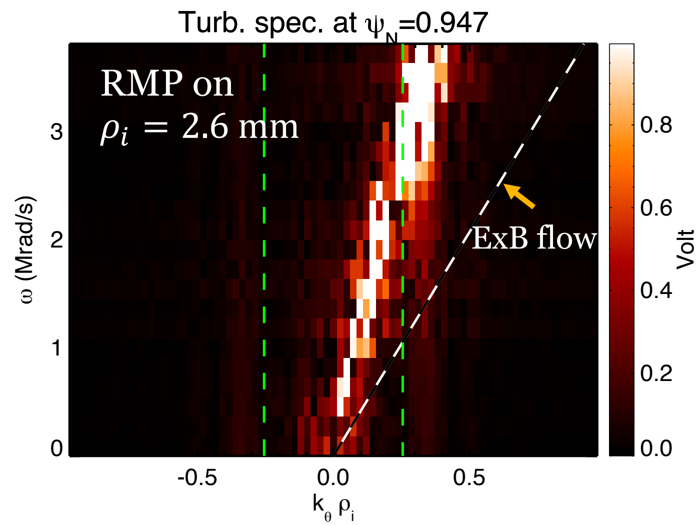

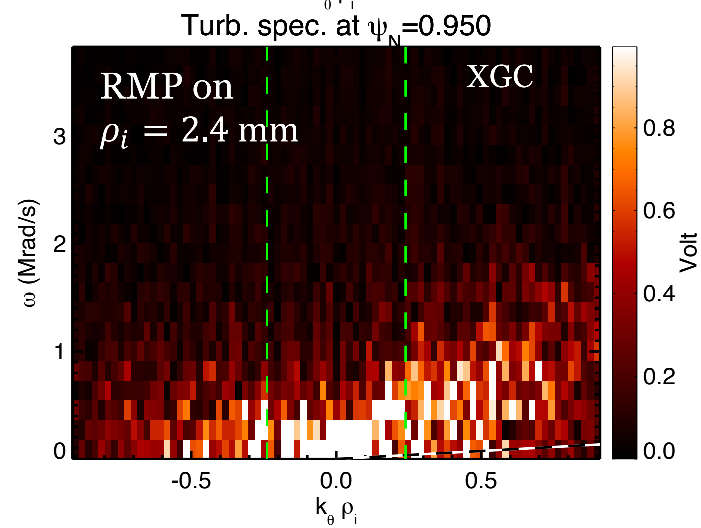

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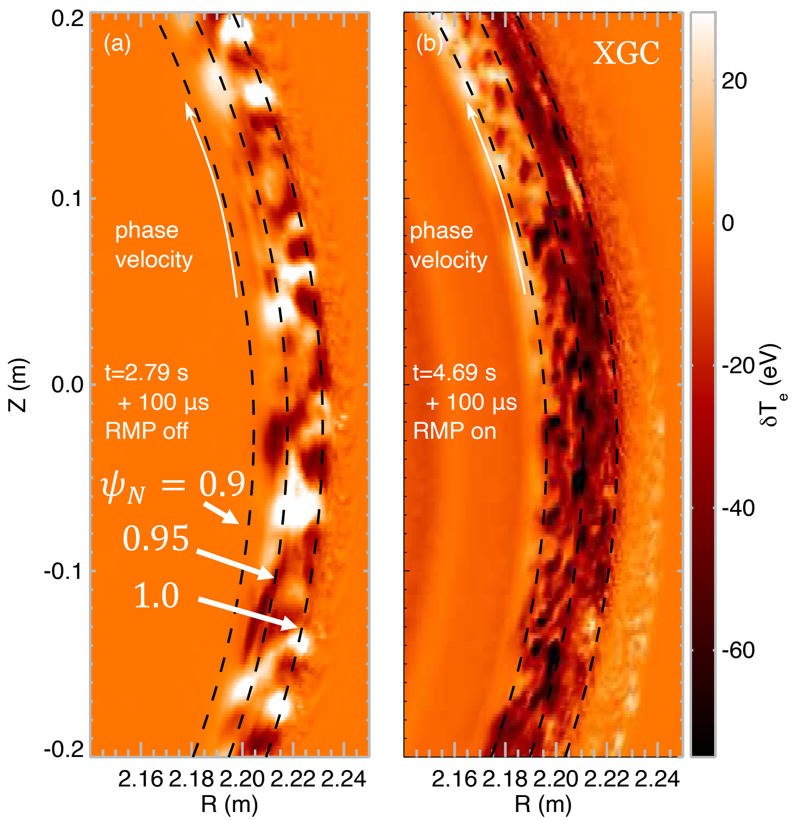
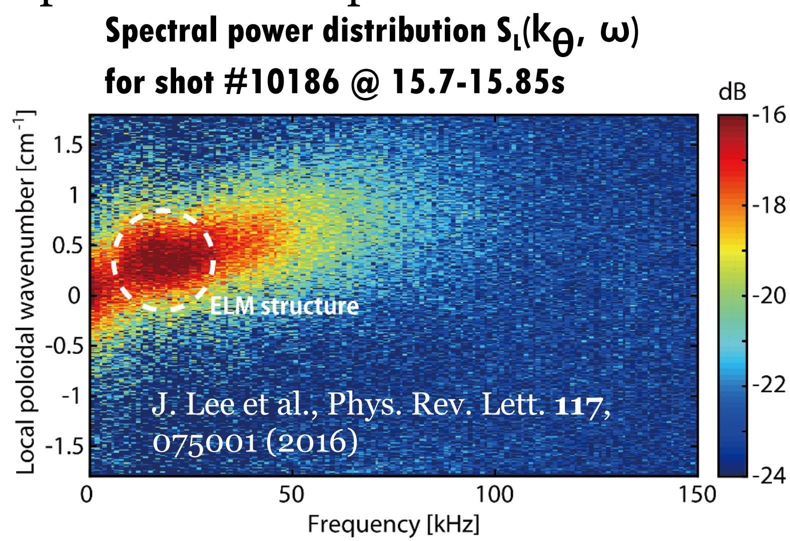
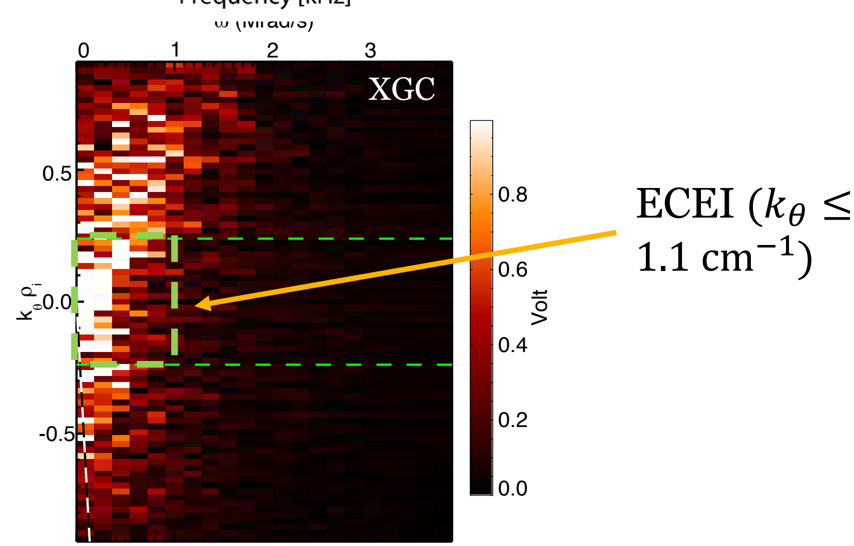
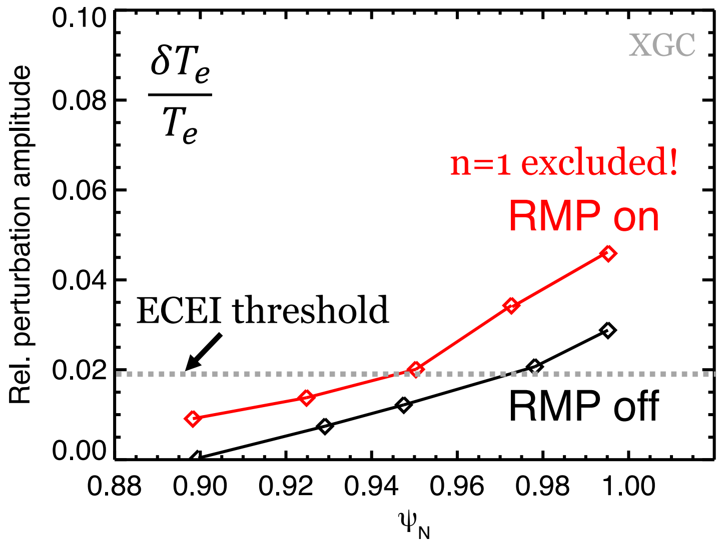


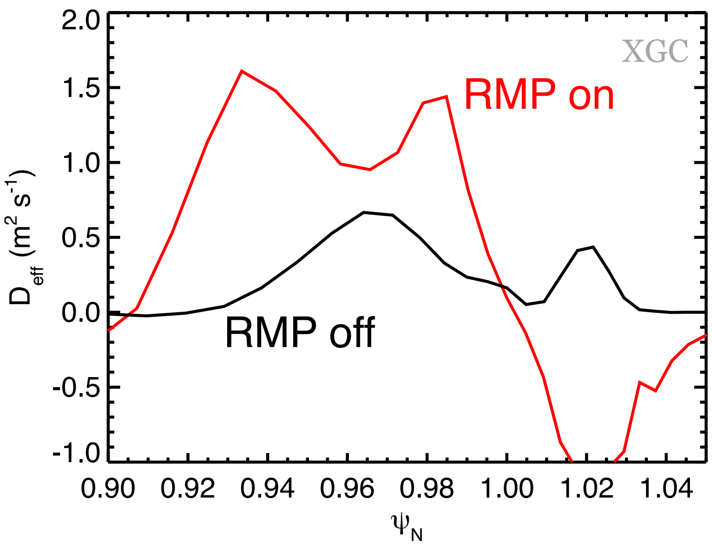


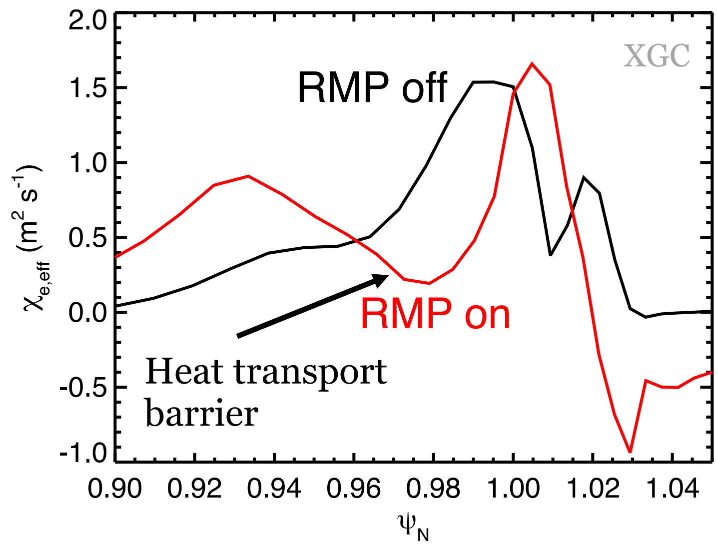


XGC Simulation Exhibits Similarities to KSTAR, but Electromagnetic Turbulence may be Missing



- Relative perturbation amplitudes $\frac{\delta\phi}{T_e}, \frac{\delta n}{n}, \frac{\delta T_e}{T_e}$ are $\gtrsim$ 2x higher (experiment: 4x)
- Particle flux is enhanced in the pedestal with contribution from turbulence.
- High neoclassical electron heat flux, but heat barrier at ψ_N~0.98





Conclusions

- Simulations of DIII-D (n_{RMP}=3) and KSTAR (n_{RMP}=1) exhibit
  - Higher particle flux in the pedestal → **density pump-out**
  - Electron heat transport barrier in the pedestal → **maintains steep T_e gradient**
  - TEM turbulence at $\psi_N \geq 0.94$ (DIII-D) and $\psi_N \geq 0.90$ (KSTAR) are affected by RMPs
  - KSTAR shows higher degree of stochasticity than DIII-D
  - Fundamental result is similar between n=1 (KSTAR) and n=3 (DIII-D)
- XGC simulations of KSTAR n=1 RMP discharge find
  - ~2x higher fluctuation amplitudes with RMPs compared to pre-RMP phase
  - Experiment finds ~4x increase → electromagnetic effects might be missing
- Working on self-consistent RMP penetration in XGC → mitigate uncertainty due to experimental plasma and rotation profiles
- Electromagnetic XGC will be used to study effect on ELM-turbulence interaction