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

Robert Hager[a)], C. S. Chang[a)], N. M. Ferraro[a)], A. Kleiner[a)], J. Lee[b)], R. Nazikian[a)]

28th IAEA FEC, May 2021

[a)]Princeton Plasma Physics Laboratory, [b)]Korea Institute of Fusion Energy

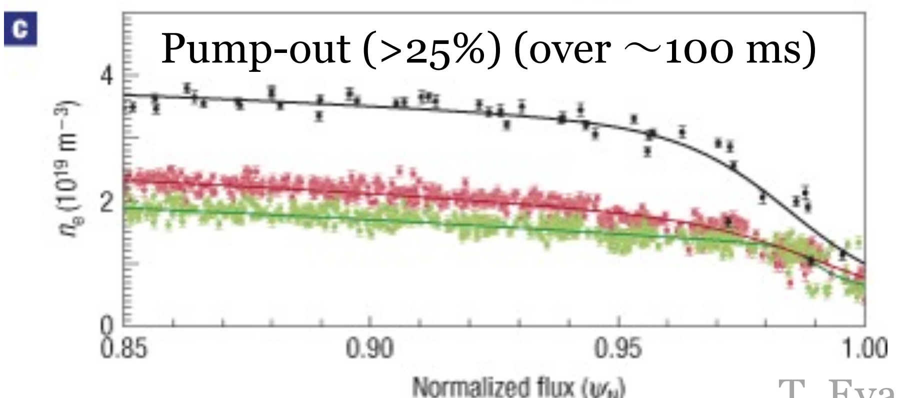
Thanks to:
Qiming Hu, Brian Grierson, Won-Ha Ko, the XGC team, the DIII-D Team, and the KSTAR team

Outline

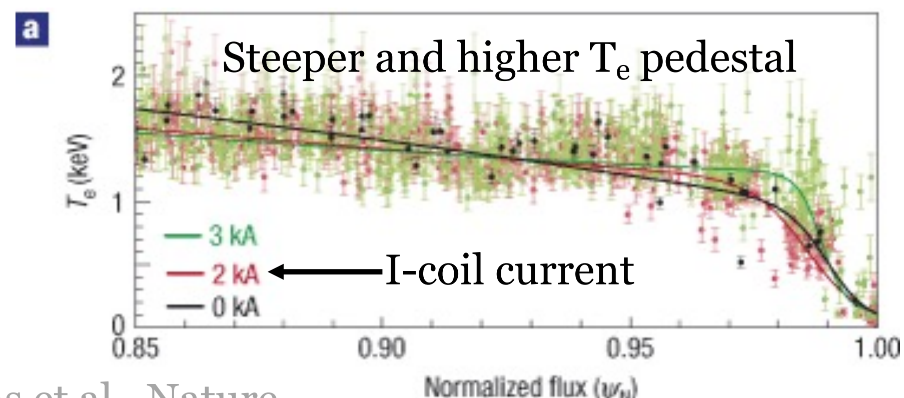
- Introduction
- Numerical Approach
- RMP-induced transport in DIII-D and KSTAR
  - Density pump-out
  - Electron heat confinement
- Conclusions and Discussion

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

What are the physics behind the density pump-out?



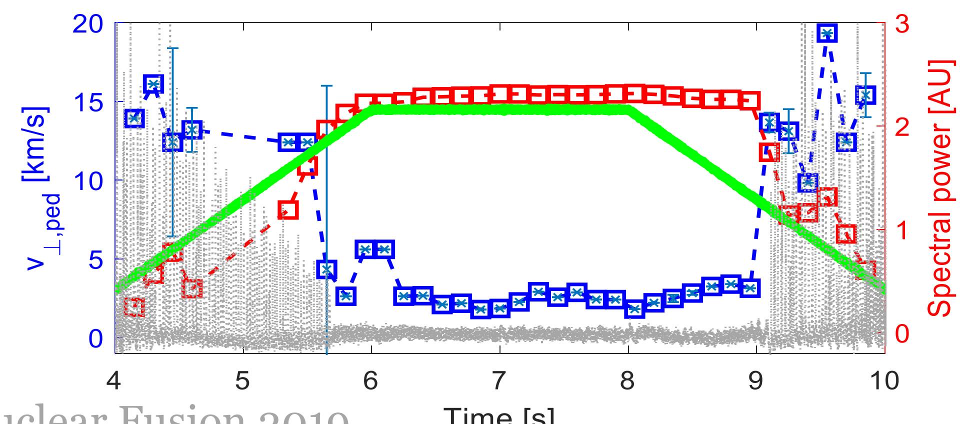
Why is electron heat still confined?



T. Evans et al., Nature 2006

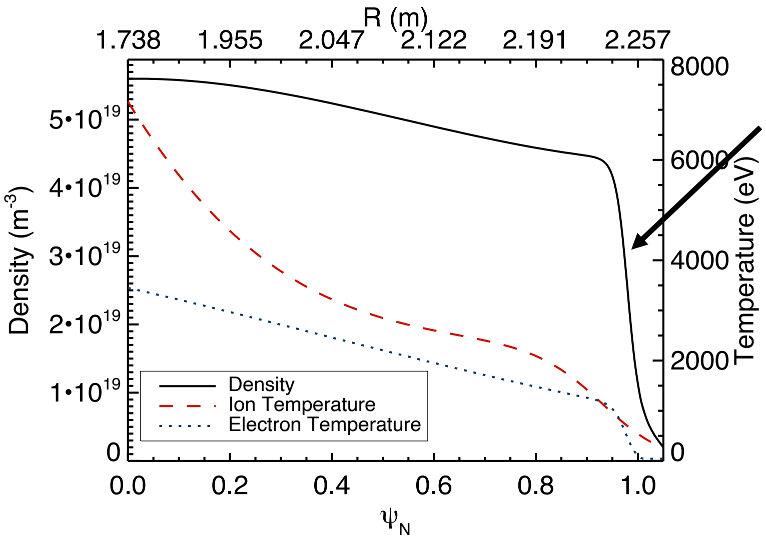
Apparent correlation between
- I-coil current
- Turbulence intensity and
- ELM intensity

What are the physics behind RMP ELM-suppression?



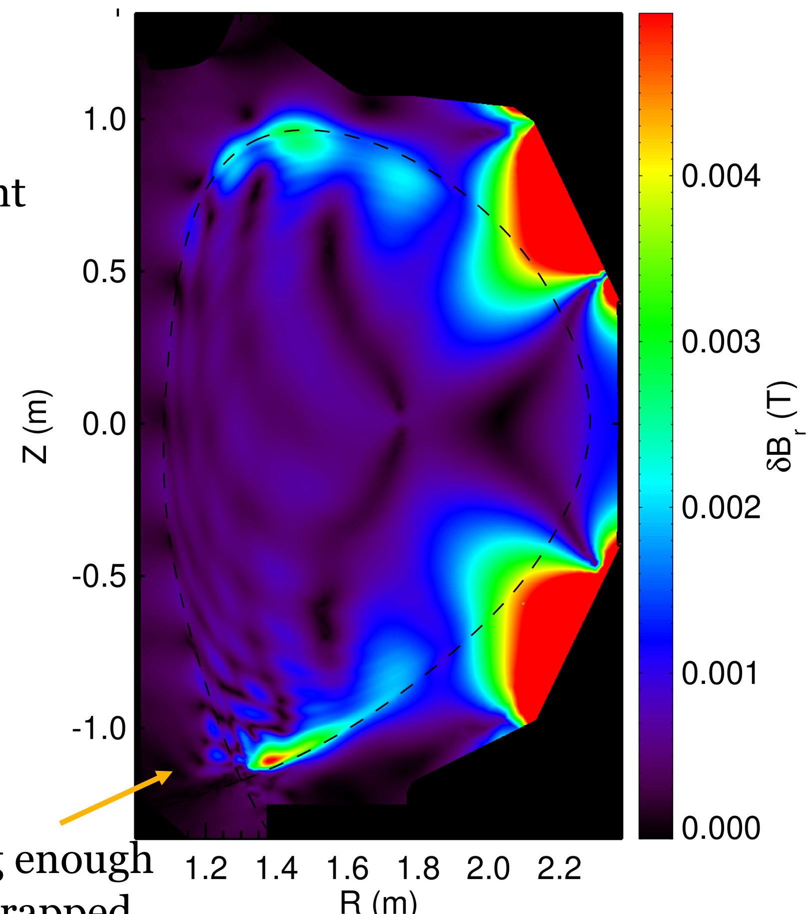
KSTAR, J. Lee et al., Nuclear Fusion 2019

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



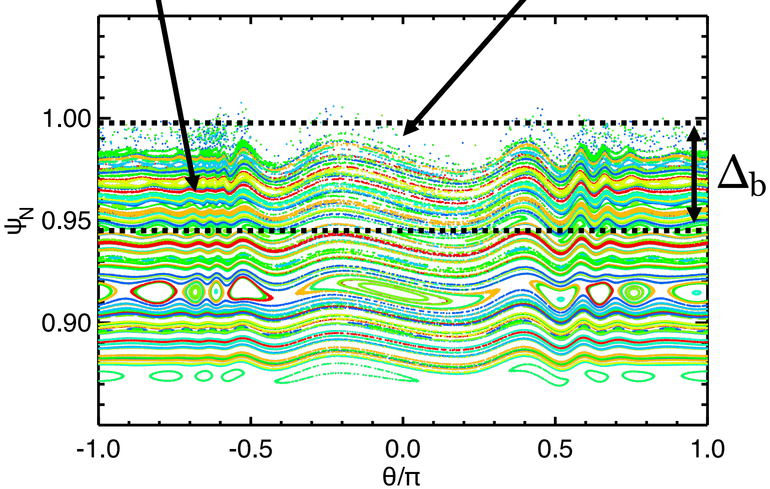
Thermal ion banana orbit width is comparable to pedestal width and spans multiple resonant surfaces

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 $\psi_N \gtrsim 0.98$

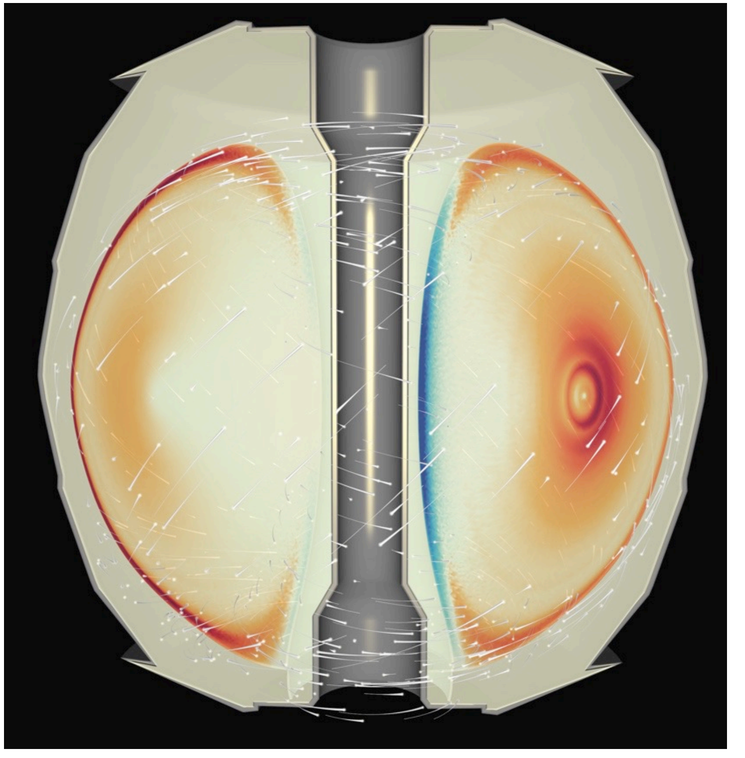


δB strong enough to affect trapped particle dynamics

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

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
  - 3D electric field and plasma profile solutions consistently with gyrokinetic physics and magnetic equilibrium
  - 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:

- 3D equilibrium magnetic field using fluid plasma response → **screened RMP field**

(planned)

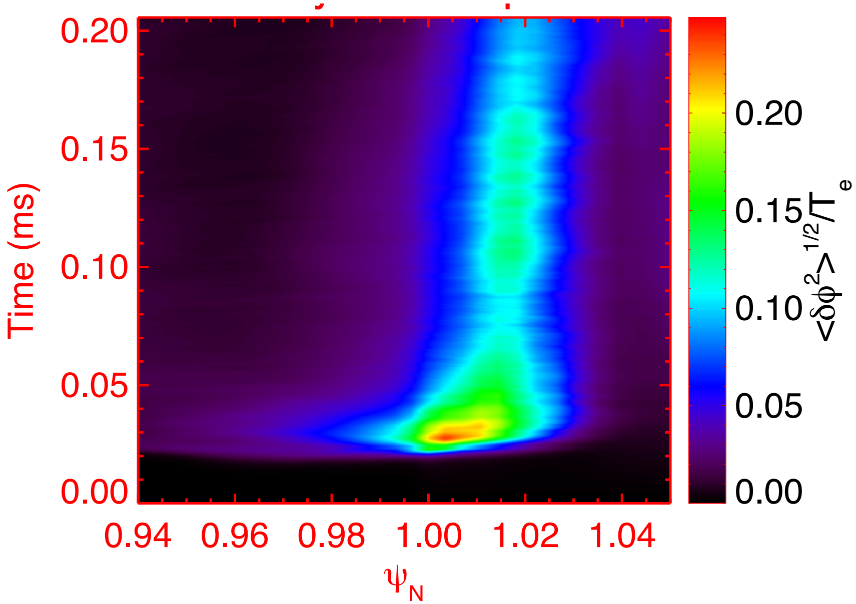
XGC:

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

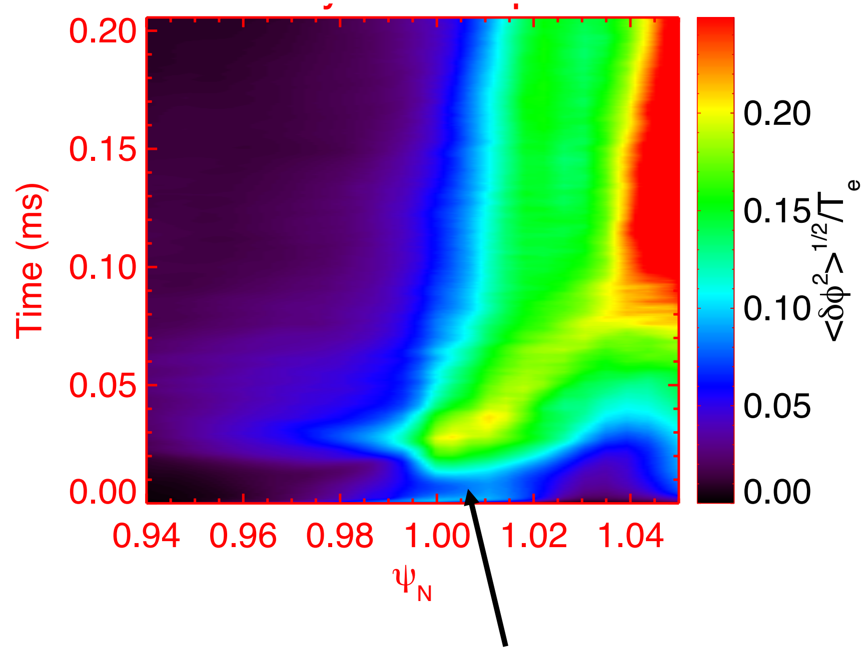
- M3D-C1 provides perturbed 3D magnetic equilibrium
- XGC computes plasma transport
- Planned extensions
  - Updated plasma profiles, effective transport coefficients, kinetic response currents, etc. can be returned to M3D-C1 for longer time-scale coupled simulation (to be done soon)
  - Self-consistent RMP penetration in XGC
  - Use electromagnetic version of XGC (mixed-variable formulation)

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

Without RMPs

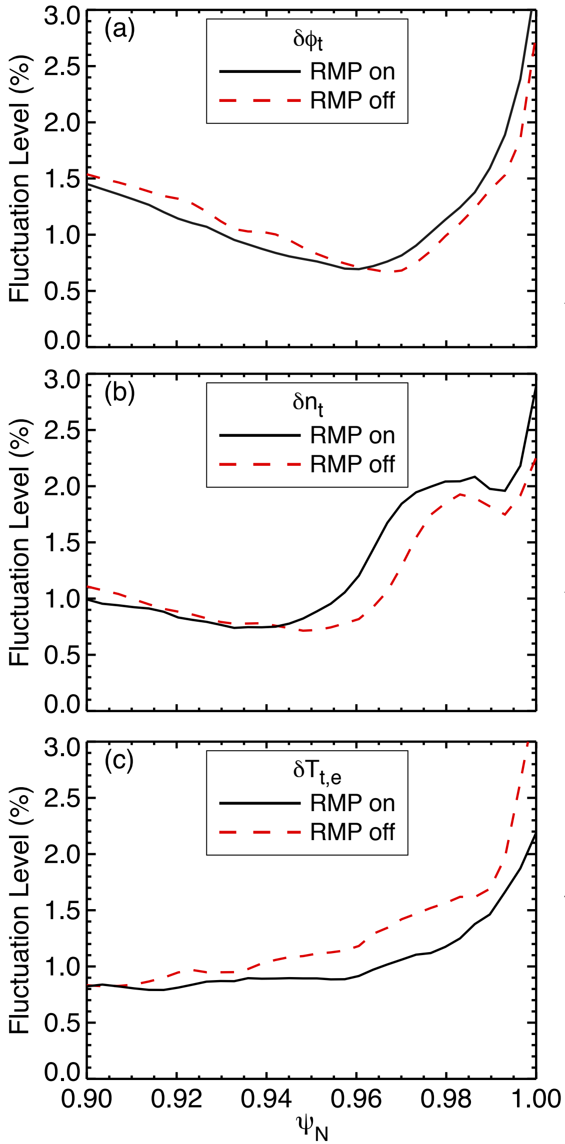


With RMPs



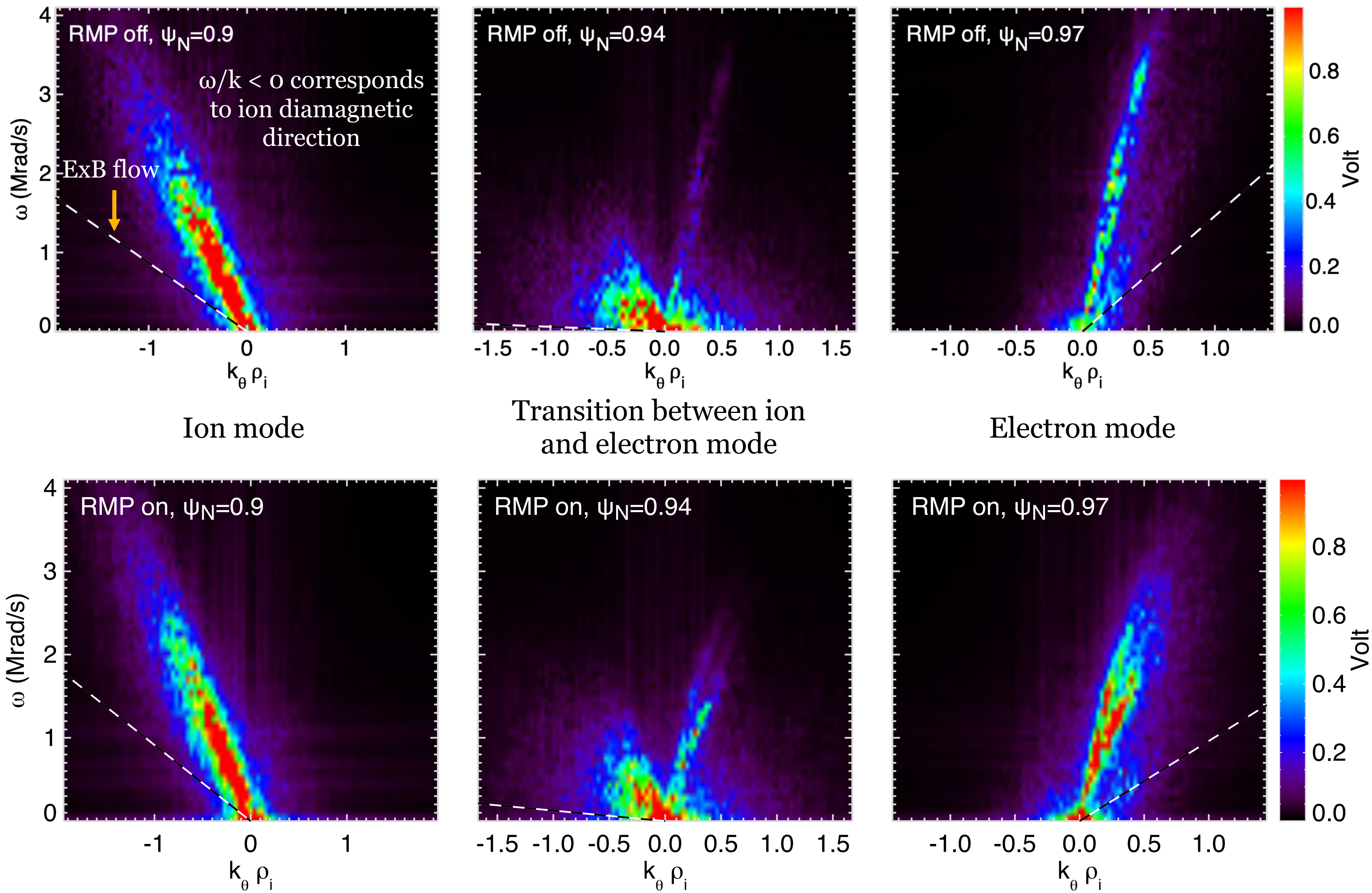
Immediate (electron transit timescale) n=3 response to RMP field before turbulence sets in

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 (by up to 40% at $\psi_N \approx 0.97$).
- Electron temperature fluctuations decrease with RMPs (by ~25% at $\psi_N \approx 0.97$).
- These changes are correlated with changes in the transport fluxes.
- δp_e is minimized by restricting δT_e.

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

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

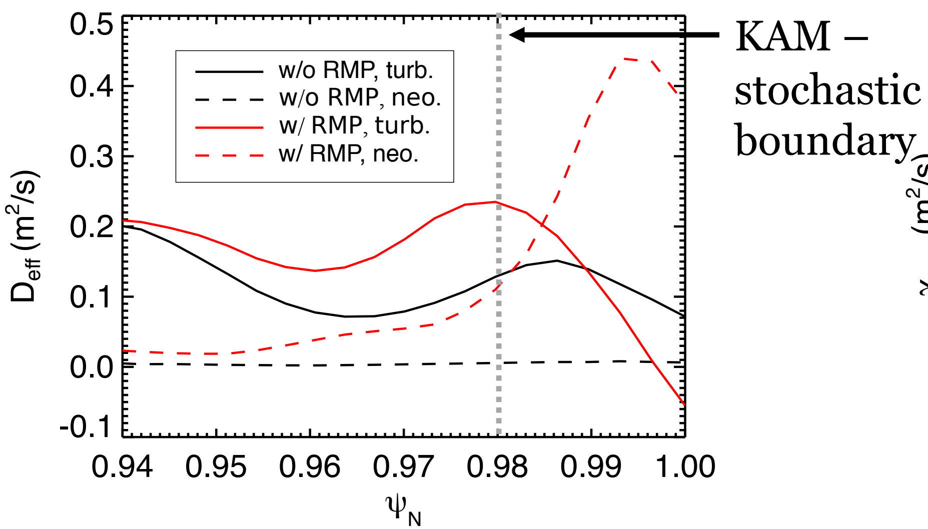
$\overline{(\dots)} \rightarrow$ toroidal average

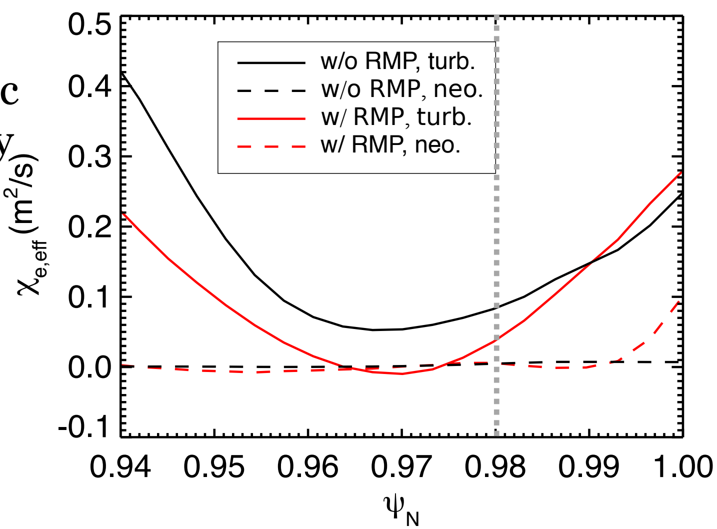
$$\boldsymbol{\Gamma_{neo} = \Gamma_D + \Gamma_{3D}}$$

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 RMPs
→ $\Delta D=(D_{neo}+D_{turb})^{(RMP)} - (D_{neo}+D_{turb})^{(no\ RMP)}$ 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





→ Electron thermal transport barrier in the steep pedestal region survives

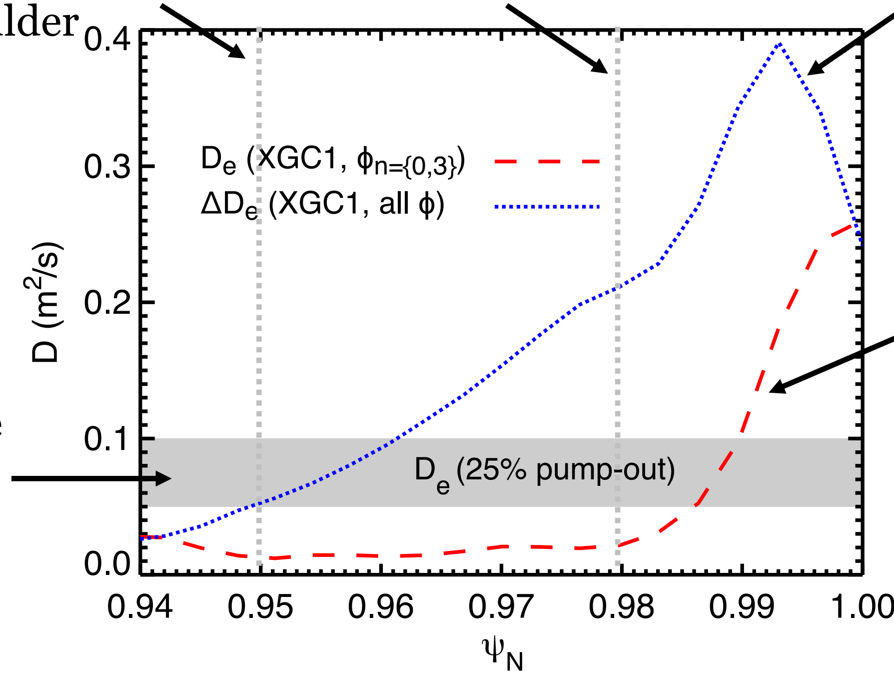
RMP-Driven Particle Diffusivity (Turbulence+Neoclassical) is Sufficient for Density Pump-Out

- 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 [R. Hager et al., Nuclear Fusion **5**, 126009 (2019)]

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

→ 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:

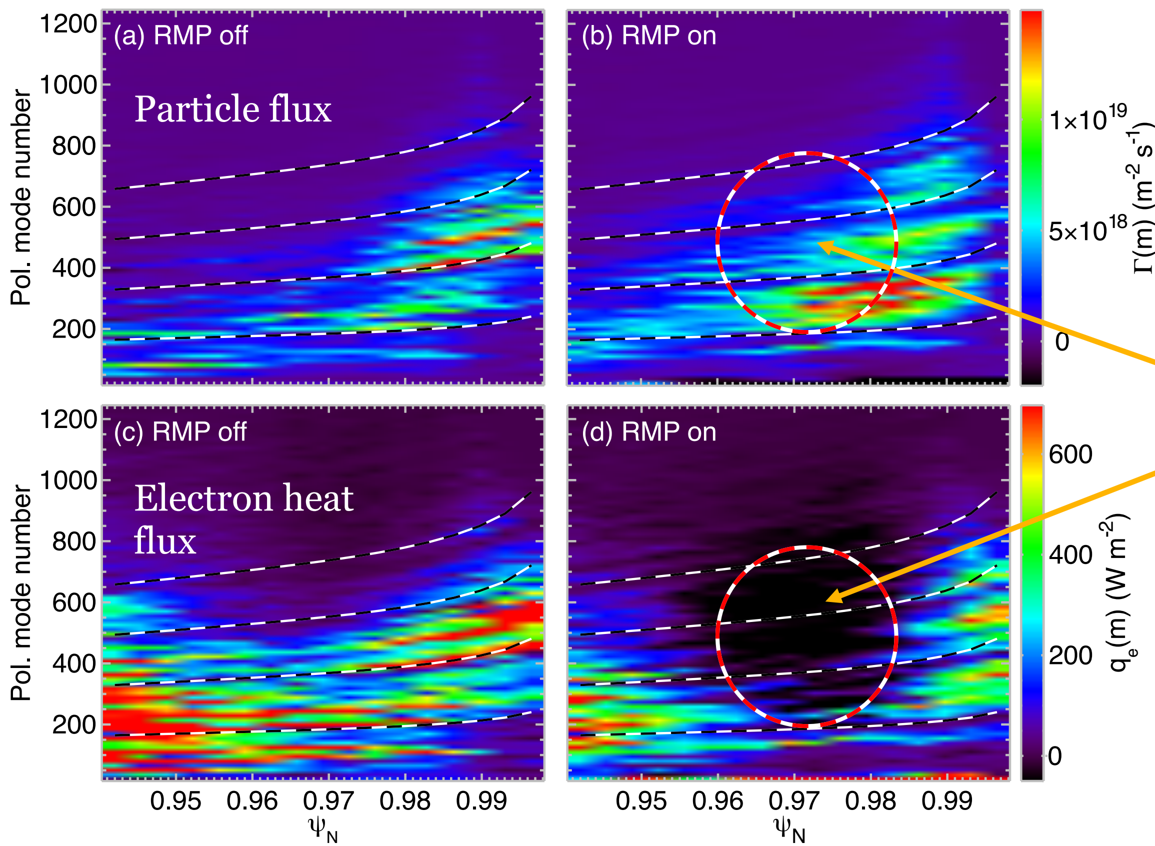
$$\Gamma_t(\psi_N, m) = \alpha(\psi_N)P_{vn}\cos(\delta\zeta_{vn})$$

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

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

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

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

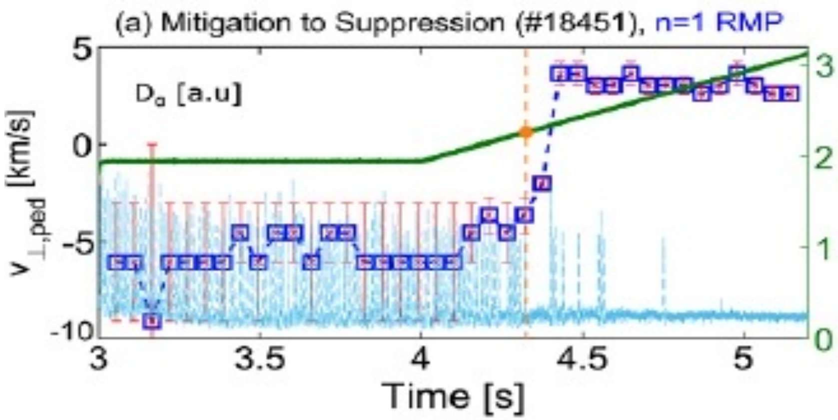


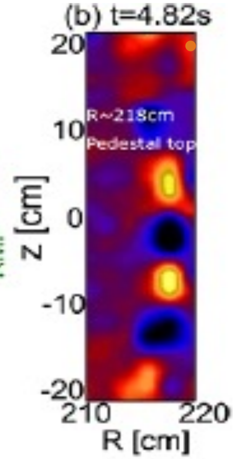
RMPs increase particle flux and decrease electron heat flux density around ψ_N~0.97 at higher poloidal mode numbers m≳200 ($k_\theta\rho_i$ ≳0.2-0.3).

→ 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 H-mode discharge 18451

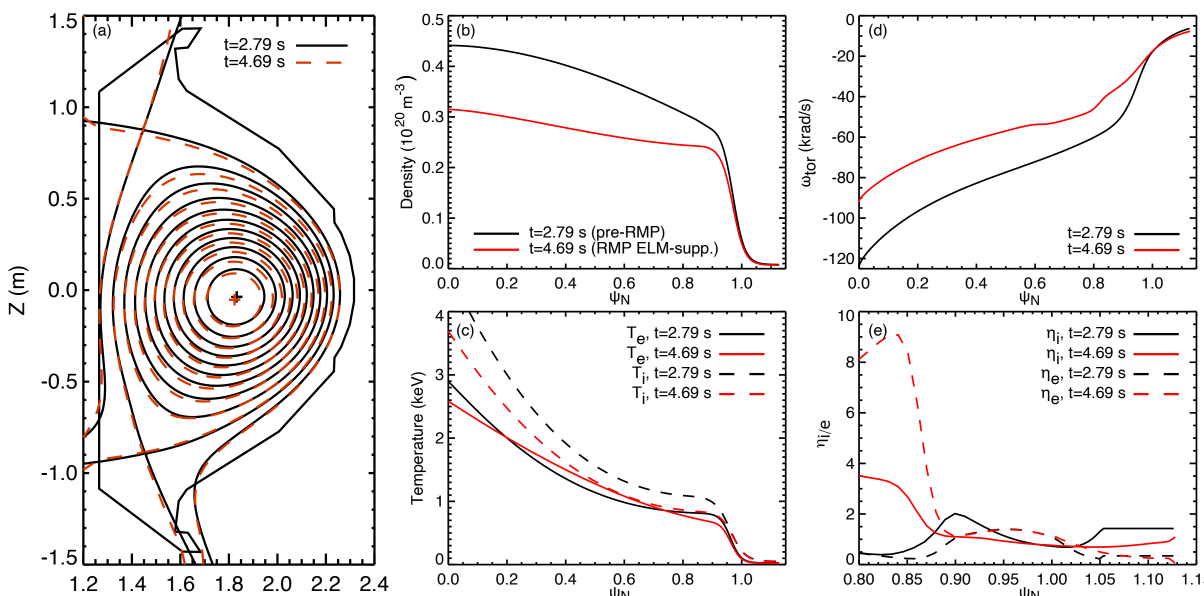
Y. In et al 2019 Nucl. Fusion 59 056009



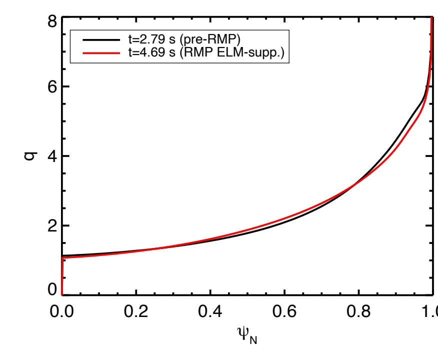


KSTAR #18451

- t=2.79 s, I_{RMP}=0 kA/t → Before RMP application
- t=3.39 s, I_{RMP}=2 kA/t → ELM mitigation
- t=4.69 s, I_{RMP}=2.69 kA/t → ELM suppression



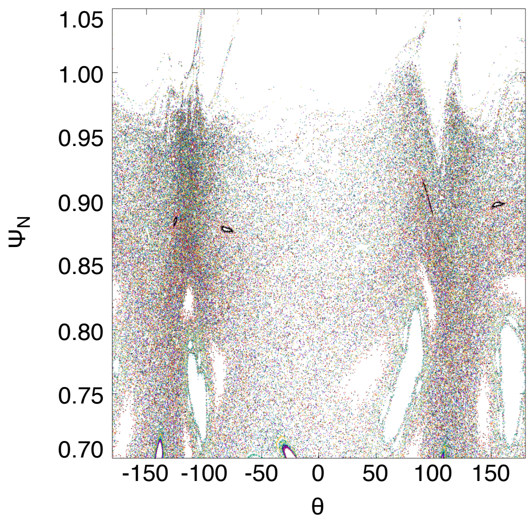
Equilibrium data →
t=2.79 s: kinetic EFIT
t=4.69 s: M3D-C1 based on kinetic EFIT



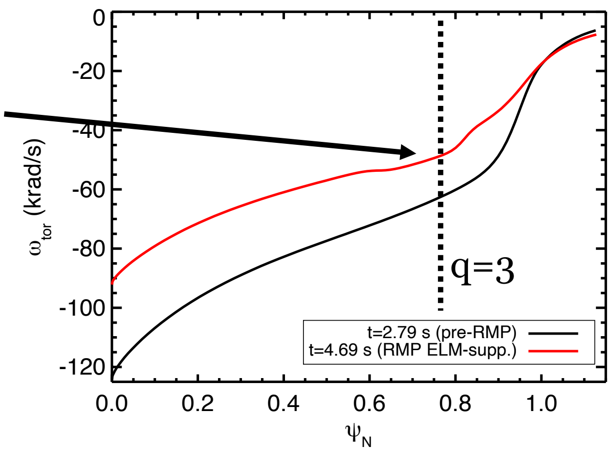
RMP Calculation with M3D-C1 is Very Sensitive to the Toroidal Rotation

Strong m=3 tearing response with experimental rotation profile

→ no KAM surfaces left at $\psi_N \gtrsim 0.65$

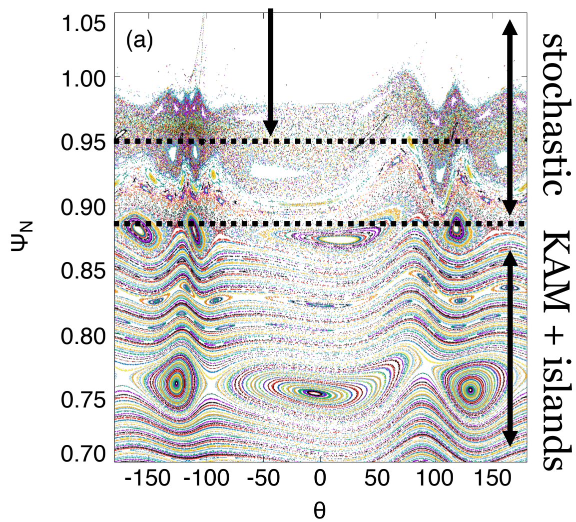


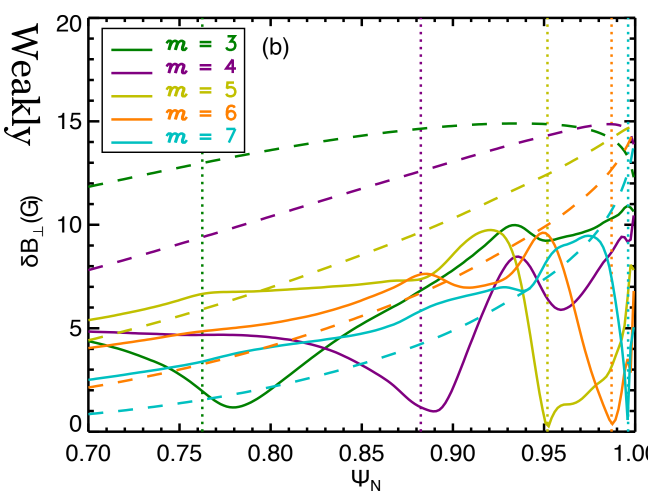
Tweak rotation profile by ~5-10% to avoid m=3 resonance



Modeling decision:
Try to make RMP field more consistent with current understanding of ELM suppression
→ RMPs penetrate pedestal top

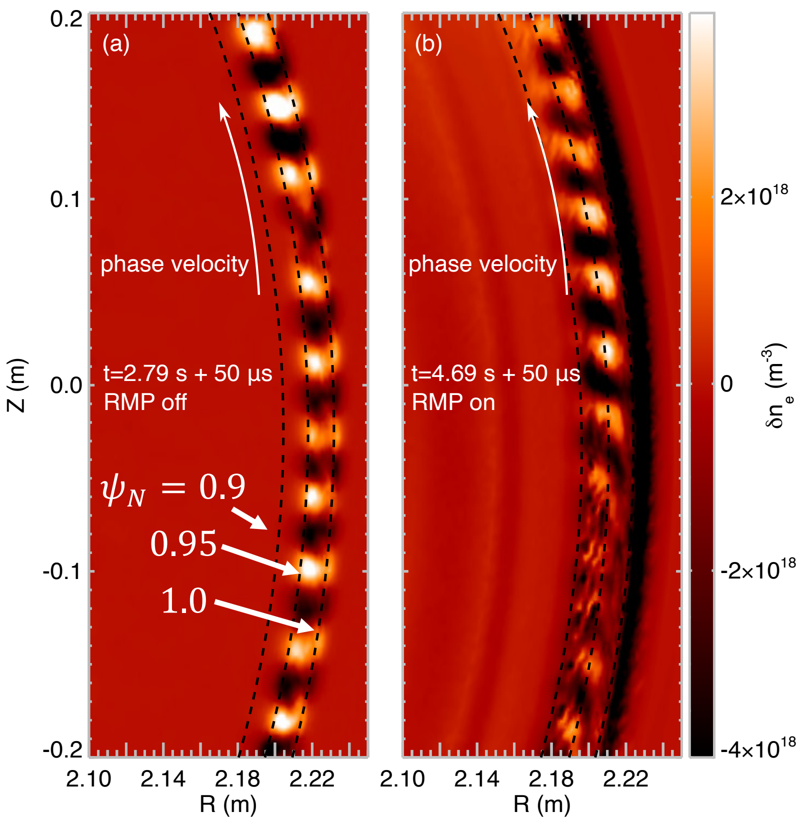
Pedestal shoulder

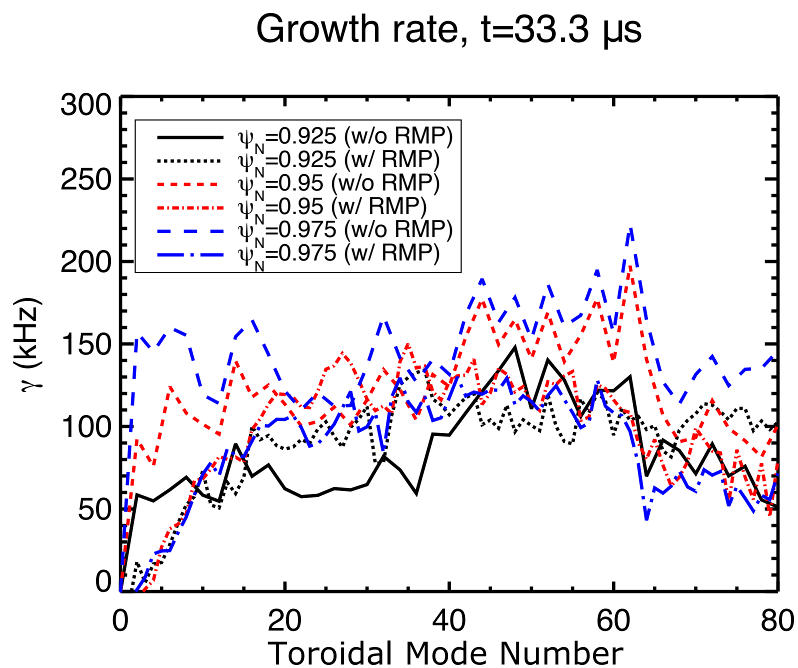




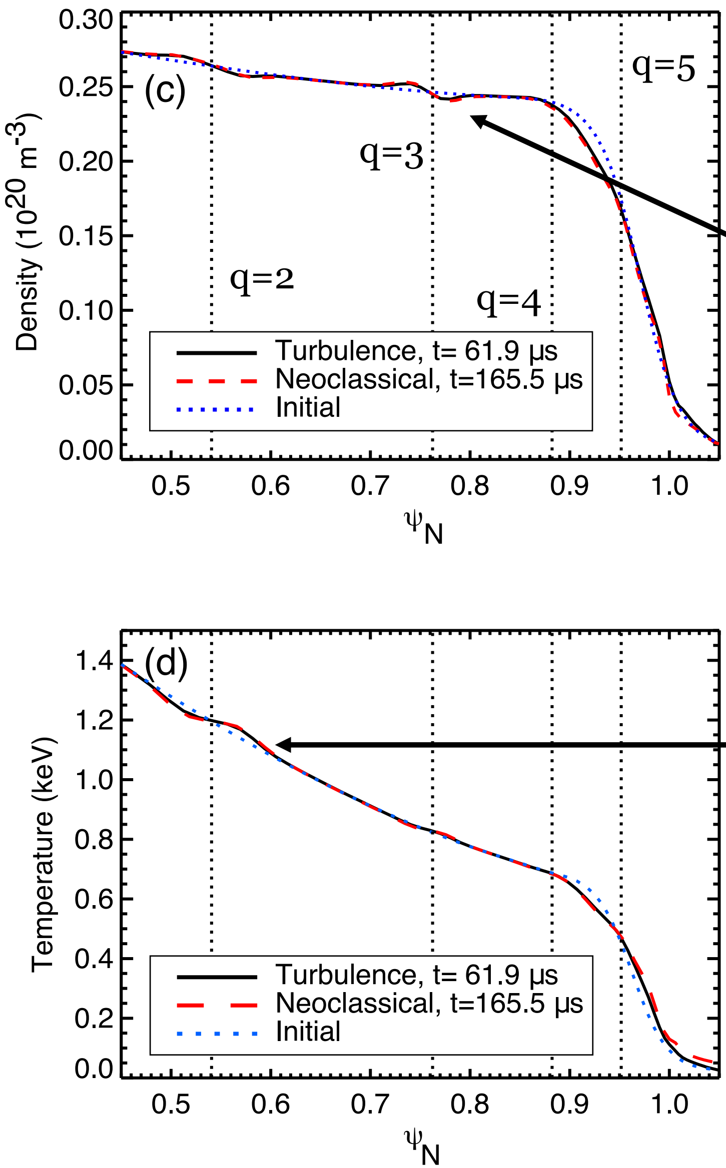
XGC Simulation: Unstable Trapped-electron Modes (TEMs) extends to pedestal top, covering $0.9 \leq \psi_N \leq 1$

- Available simulation too short to study saturated edge turbulence
- Study exponential growth phase instead (”quasi-linear”)
- Initially unstable mode propagate in electron diamagnetic direction in ExB frame → TEM
- Growth rates in the steep-gradient region are largely similar between pre-RMP and RMP ELM-suppressed phase, but extend to pedestal top with RMPs.





Fast Neoclassical Profile Evolution is Observed around Magnetic Islands and in Stochastic Layer

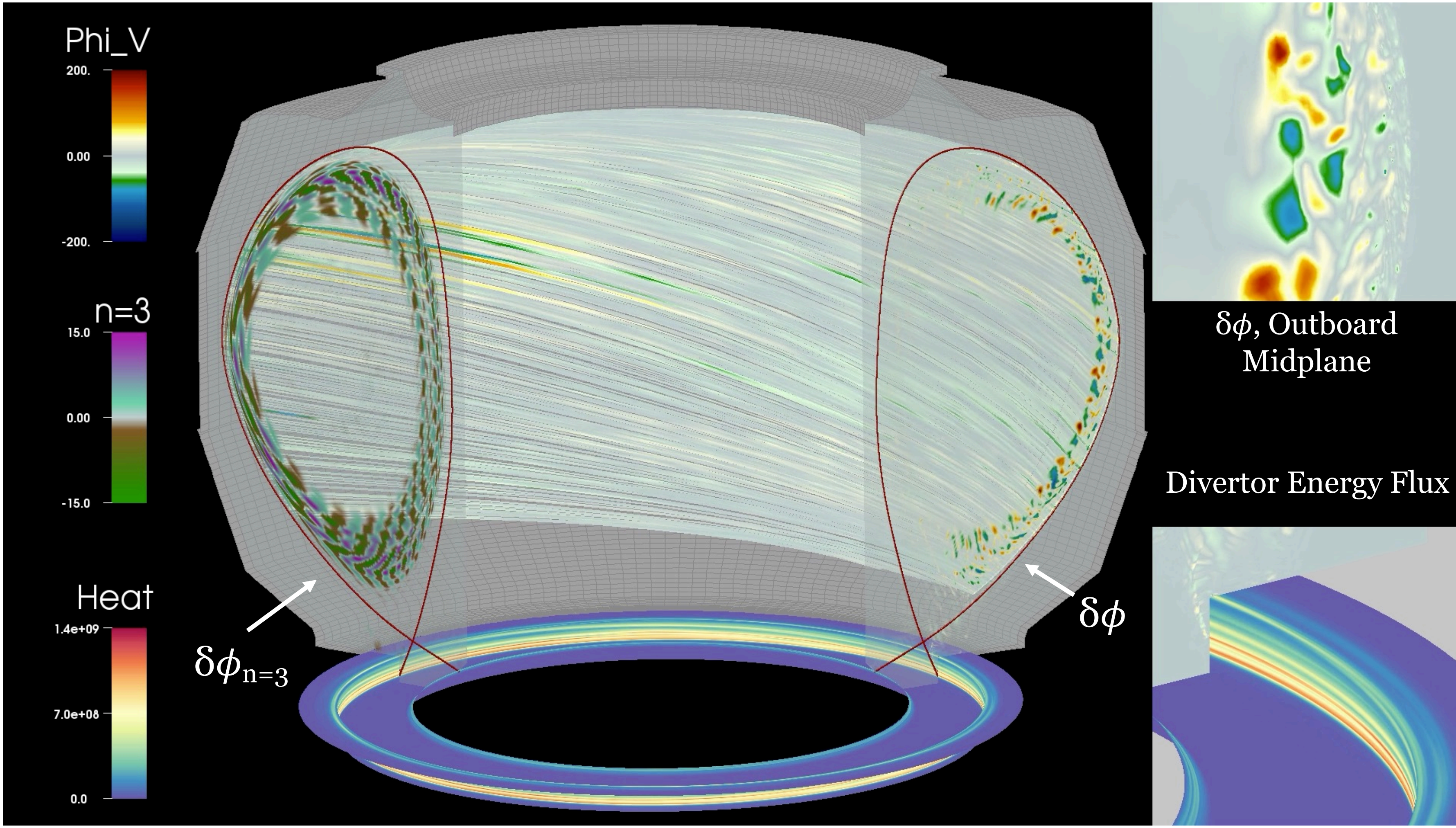


- Neoclassical particle transport (including parallel transport along the perturbed field) is inward around the m=2 and m=3 islands
  → counter-intuitive (similar to J. Kwon et al., Physics of Plasmas 2018)
- Electron temperature flattens across magnetic islands
  → as expected
- This fast evolution is due to turbulence (confirmed with neoclassical simulations)

Conclusions

- Electrostatic XGC (neoclassical+turbulence) with M3D-C1 n=3 RMP field simulations of DIII-D 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 → **maintains steep T_e gradient**
- XGC simulations of KSTAR n=1 RMP discharge exhibit
  - Unstable TEMs extend from the steep-gradient region to the pedestal top ($0.9 \leq \psi_N \leq 1$) during ELM-suppression.
  - Waiting for longer simulation to study saturated edge turbulence
- Working on self-consistent RMP penetration in XGC → mitigate uncertainty due to toroidal rotation
- 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