Effects of RMP on DIII-D Pedestal Top Transport During ELM Suppression

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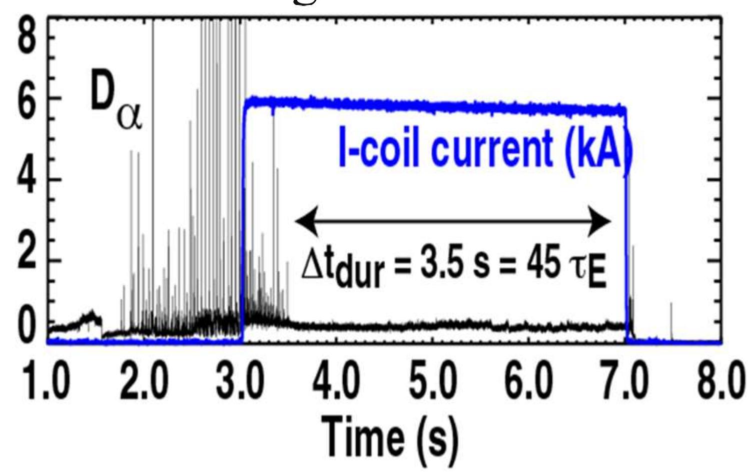
GTC Team & SciDAC ISEP Center

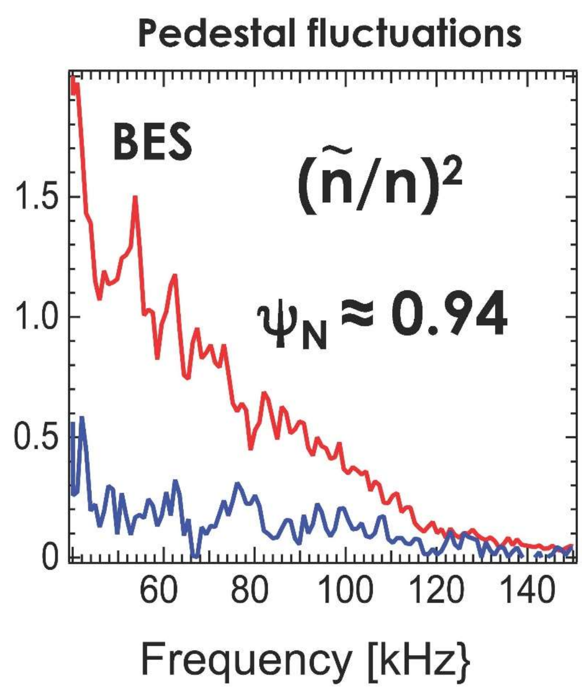
RMP Effects on Edge Turbulence & Transport

- Resonant magnetic perturbation (RMP) is applied to control edge-localized mode (ELM) in tokamak H-mode plasmas [*Evans et al, NP2006*]
- DIII-D n=2 RMP significantly increases microturbulence in outer regions, and leads to particle pump out & change in toroidal rotation [*McKee et al, NF2013*]
- ELM control by RMP planned in ITER; need to understand how RMP affects microturbulence?
  - ► Direct effects of RMP 3D fields on microturbulence & neoclassical transport?
  - ► Indirect effects via plasma profile changes induced by RMP [*Nazikian et al; C. Paz-Soldan et al, PRL2015*]?
- Require gyrokinetic turbulence simulation in 3D equilibrium with magnetic islands

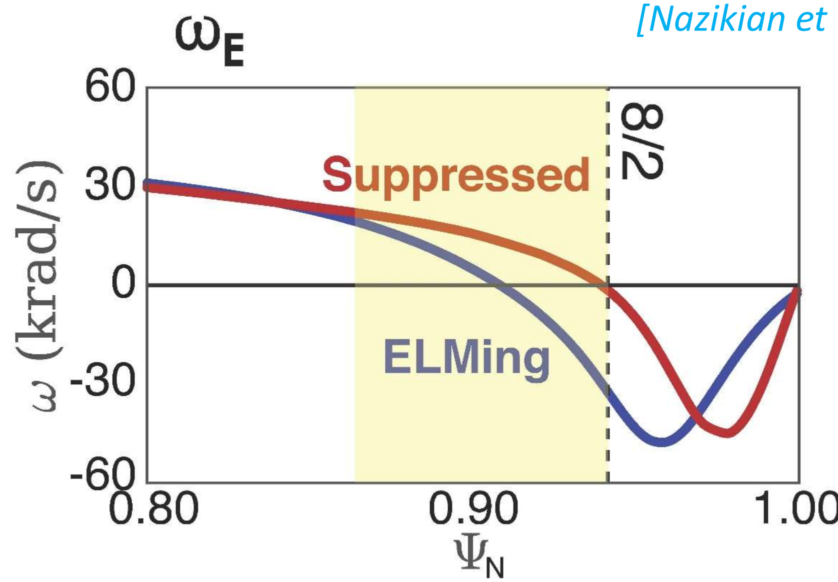


Wade, et al., IAEA 2012

Increase In Turbulent Fluctuations Also Seen At Onset of ELM Suppression With Reduction of ExB Shear



[Nazikian et al, PRL2015]



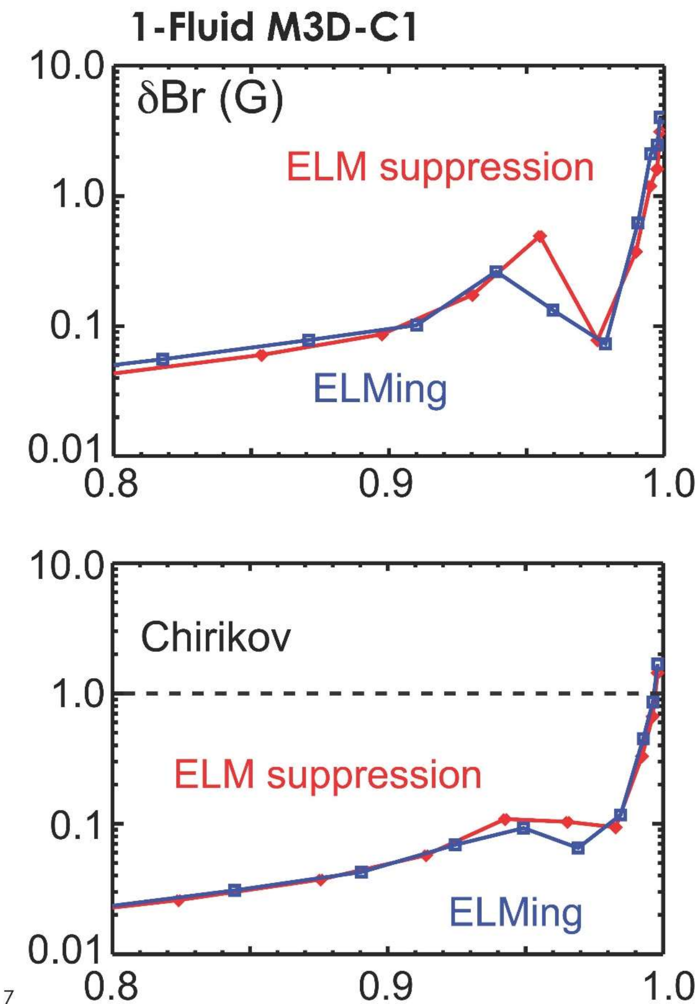
- **What is the role of turbulence in pedestal transport ?**

Latest Linear M3D-C1 Modeling Shows Resonant Magnetic Field Well Below Stochastic Level

- Top of pedestal resonant field ~ 0.6 G

- Maximum applied $\delta B \approx 6 \times 10^{-4}$

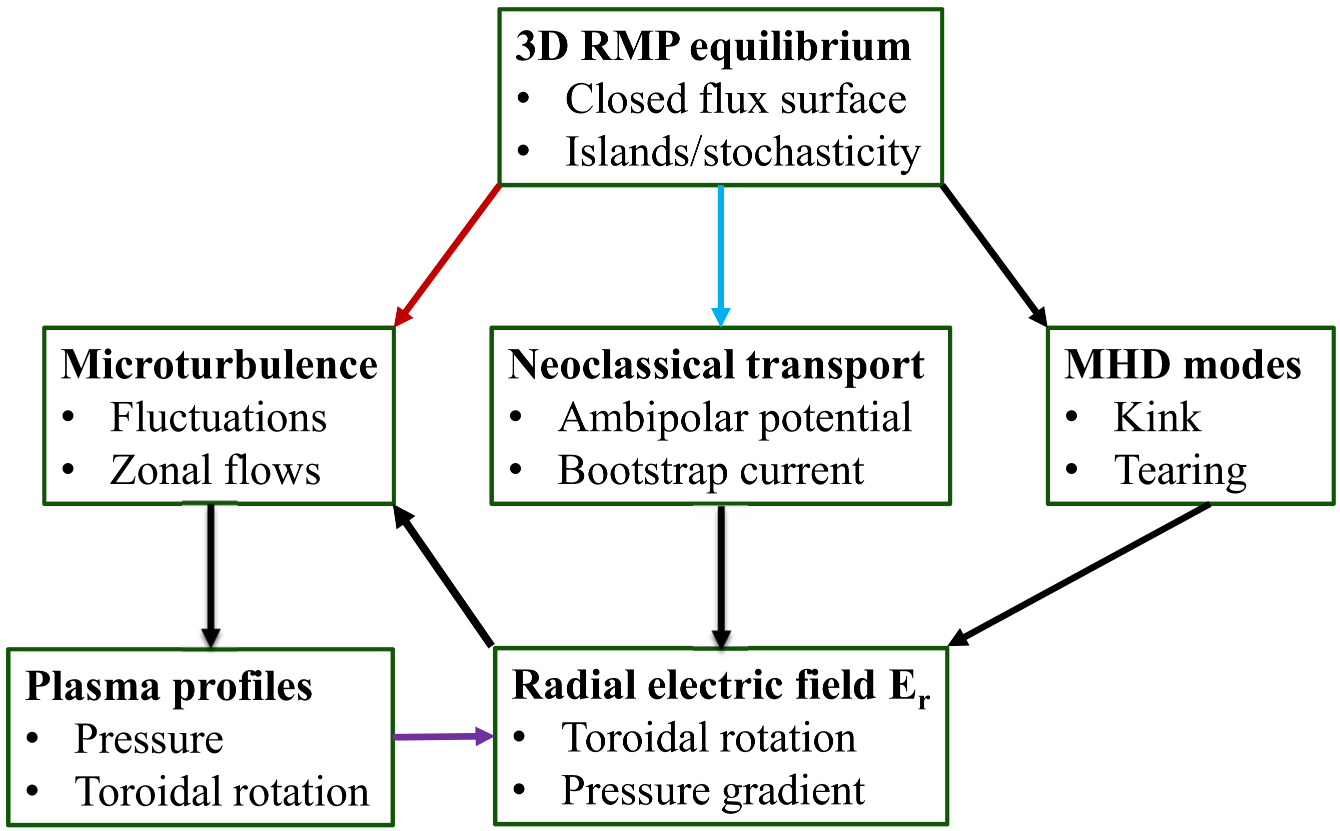
- Stochasticity limited to separatrix ~ 1 % of flux



DIII-D NATIONAL FUSION FACILITY

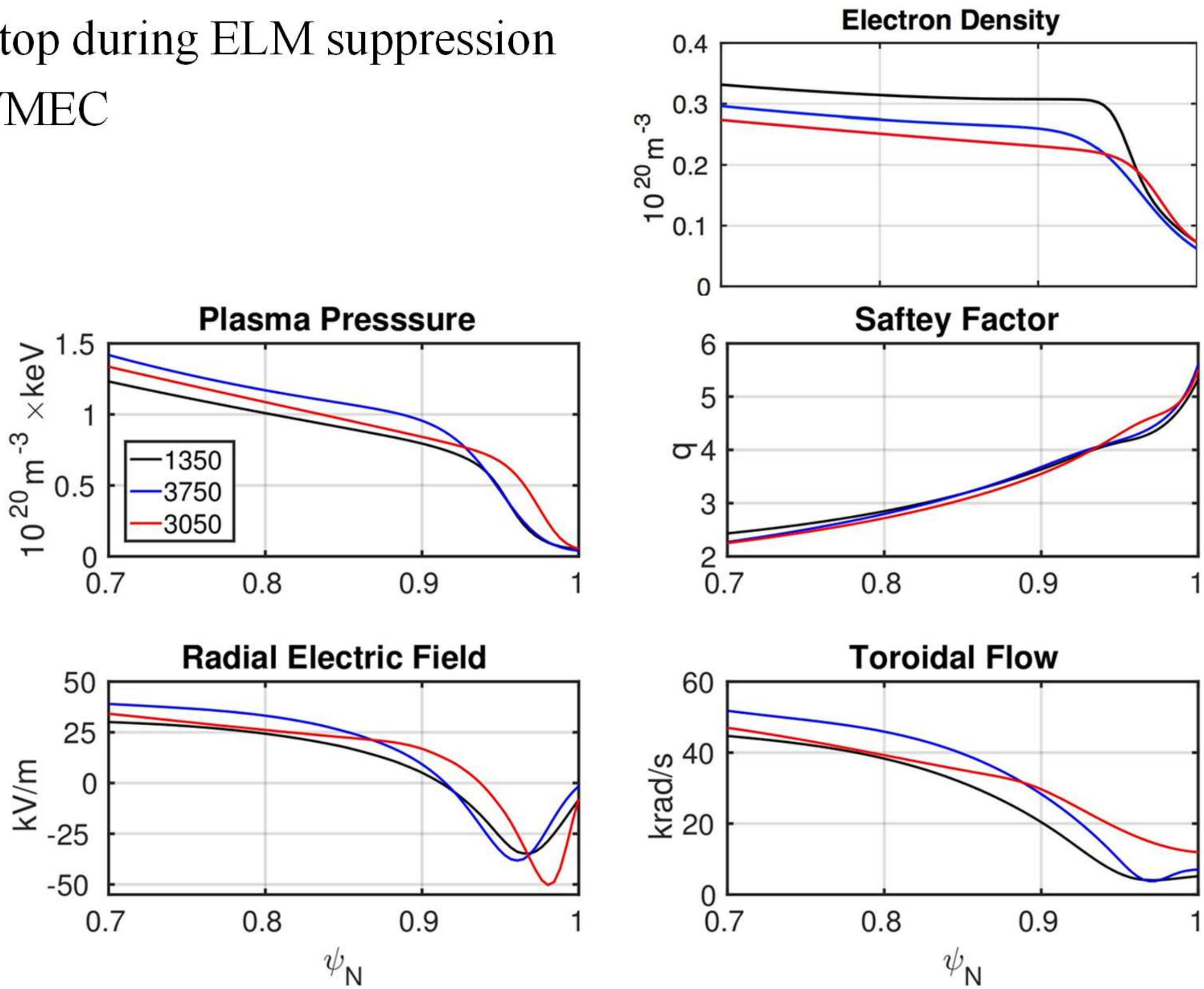
Effects of 3D RMP on Tokamak Edge Transport

- Can 3D fields with closed flux surfaces enhance turbulent transport?
- Role of magnetic islands and stochastic fields?
- Indirect effects on microturbulence, e.g., radial electric field shear?



Plasma Profile Changes by n=2 RMP

- Weaker ExB shear on pedestal top during ELM suppression
- Three DIII-D equilibria from VMEC
  - ✓ 158104.1350: ELMing w/o RMP
  - ✓ 158103.3750: ELMing w/ RMP
  - ✓ 158103.3050: ELM suppression



3D RMP Equilibrium with Closed Flux Surfaces

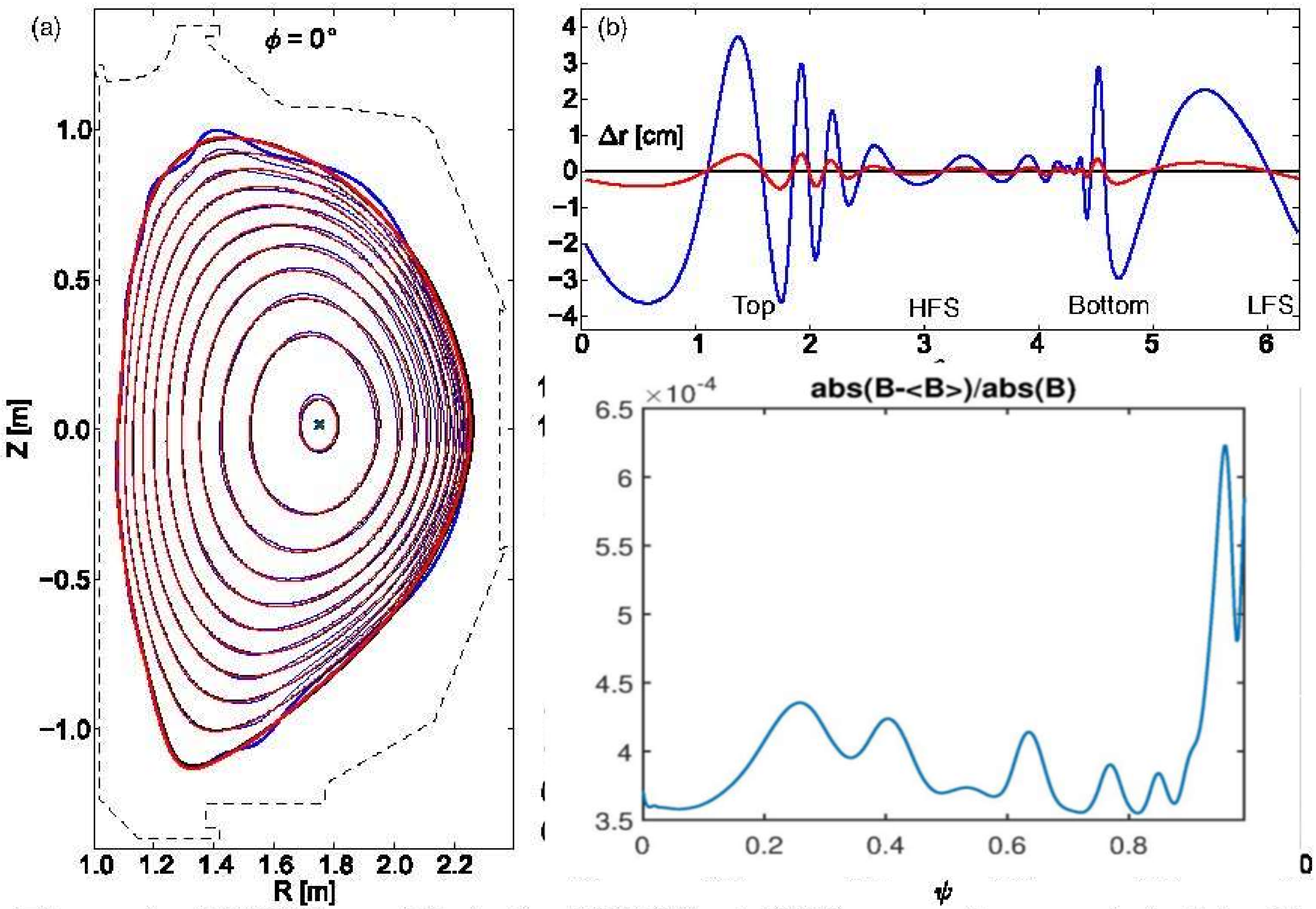
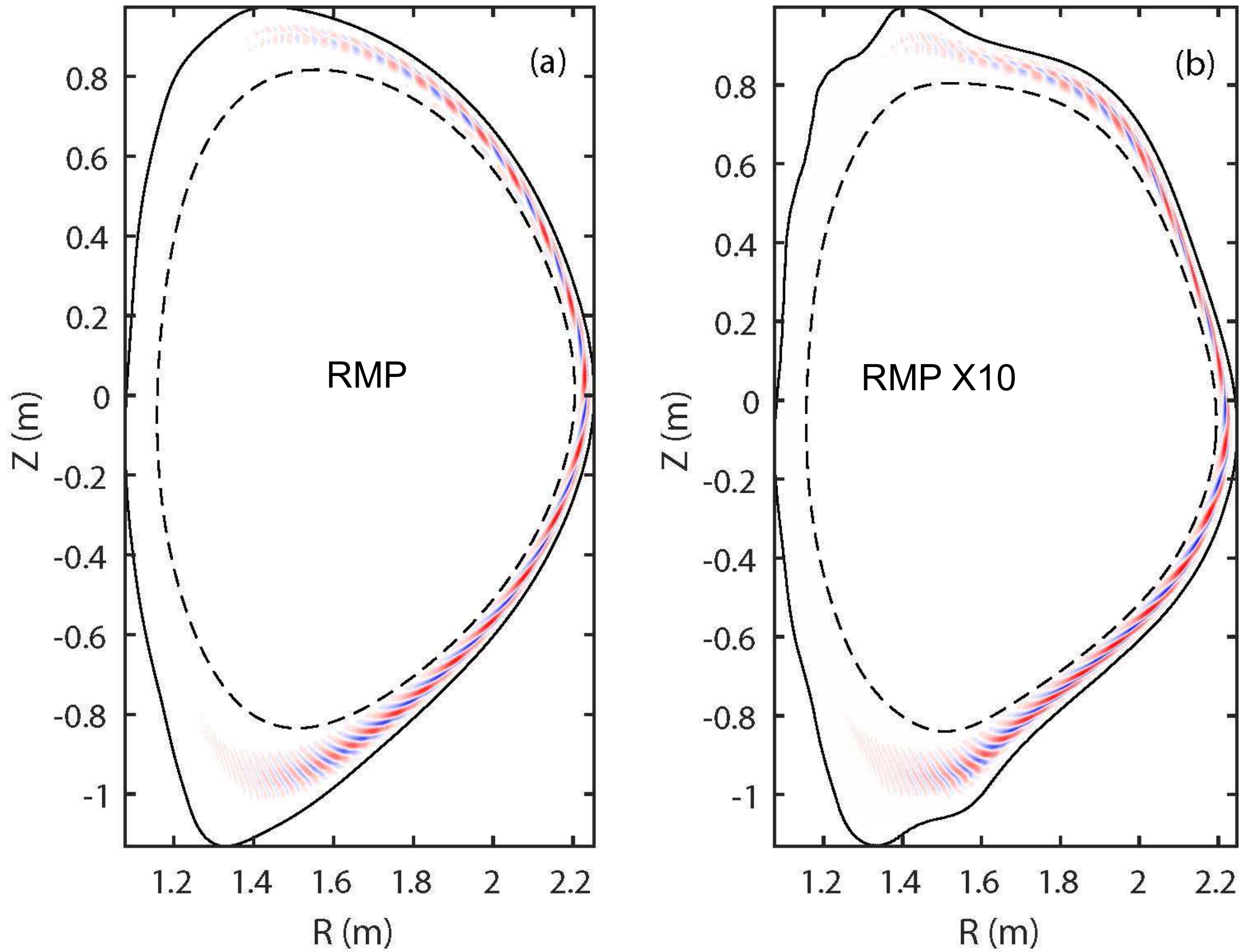


Figure 1: VMEC equilibria for 158103 at 3050 ms: axisymmetric (black), RMP (red), RMPx10 (blue). (a) Cross-section at toroidal angle 0. (b)

KBM Mode Structure from GTC simulations

- ITG unstable in pedestal region
- KBM neat marginal stability
- Use larger pressure gradient to excite KBM



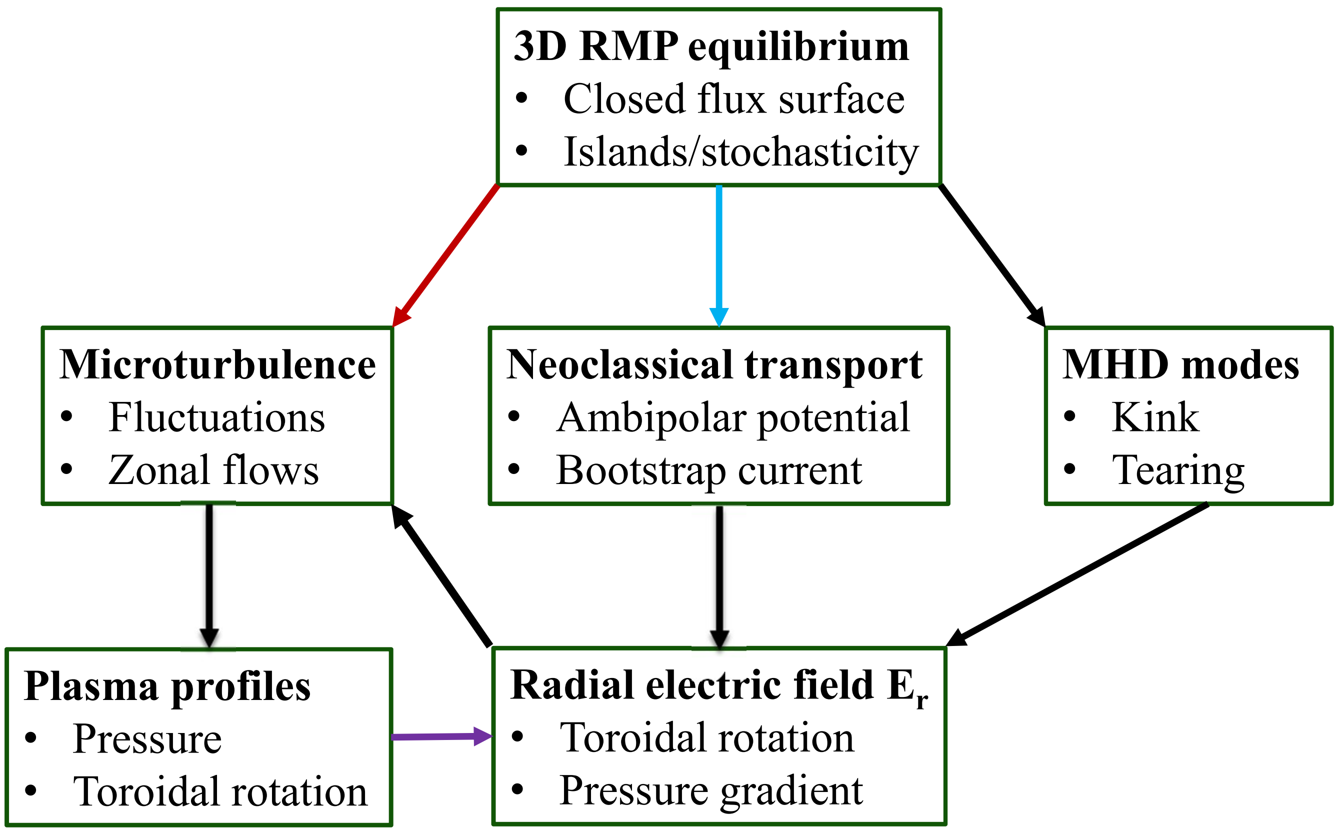
GTC Simulations of KBM & ITG in n=2 RMP Equilibrium

- No increase of growth rates for electromagnetic kinetic-ballooning mode (KBM) in the presence of RMP
  - ✓ GTC simulation results do not support local (flux-tube) theory predicting enhanced KBM instability due to local magnetic shear modulation *[Bird & Hegna, PoP2014]*
- No significant increase in turbulent transport in electrostatic ion temperature gradient (ITG) turbulence
- Effects of 3D fields on zonal flow damping is insignificant to modify turbulent transport in electrostatic driftwave turbulence
  - ✓ GTC simulations do not support conjecture that zonal flow damping by RMP increase microturbulence *[Leconte et al, NF2014]*

Effects of Resonant Magnetic Perturbations on Microturbulence in DIII-D Pedestal, I. Holod, Z. Lin, S. Taimourzadeh, R. Nazikian, D. Spong, and A. Wingen, Nuclear Fusion ***57****, 016005 (2017)*

Effects of 3D RMP on Tokamak Edge Transport

- Can 3D fields with closed flux surfaces enhance turbulent transport?
- Role of magnetic islands and stochastic fields?
- Indirect effects on microturbulence, e.g., radial electric field shear?



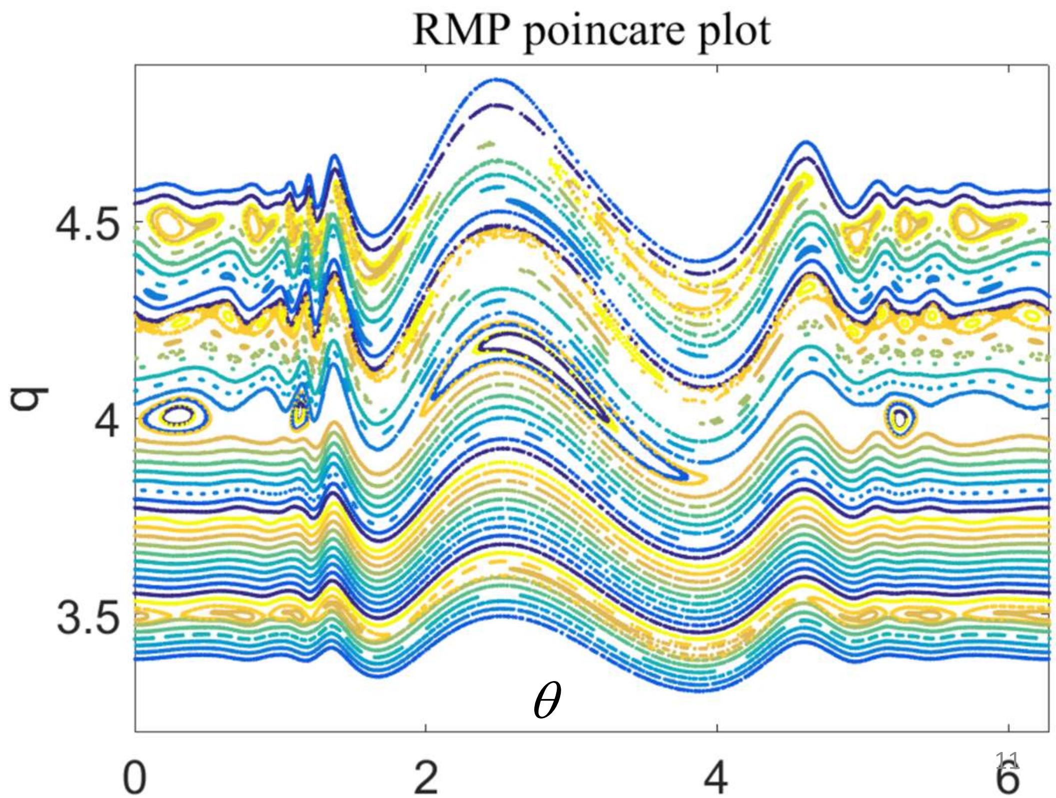
Effects of Islands/Stochastic Fields on Microturbulence

- GTC simulations finds RMP islands (from M3D-C1 equilibrium data) have little effects on microturbulence with adiabatic electrons
- Developed new simulation model for accurately treating zonal flow using kinetic electrons in RMP islands and stochastic fields

Conjecture:

► Electron adiabatic response to zonal flows in the presence of magnetic islands and stochastic fields can drastically increase zonal flow dielectric constant for long wavelength fluctuations.

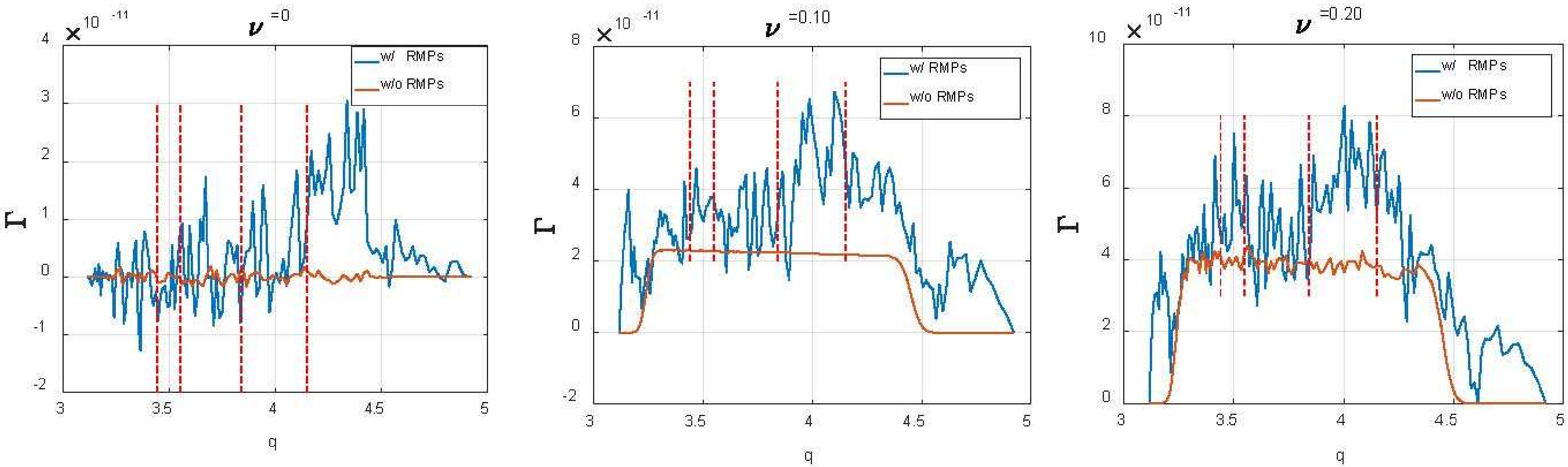
► Zonal flow generation can then be reduced and the microturbulence can be enhanced greatly



Effects of Islands/Stochastic Fields on Neoclassical Transport

- Electron particle flux due to RMP flutter transport is comparable to axisymmetric neoclassical particle flux
  - ▶ GTC simulation results do not support conjecture that magnetic flutter transport responsible for density pumpout *[Callen et al, NF2013]*
- RMP flutter transport localizes near rational surface
- RMP flutter transport causes little density pump out, but could induce changes in radial electric field, especially near q=4 surface

[J. Y. Fu, 2018]



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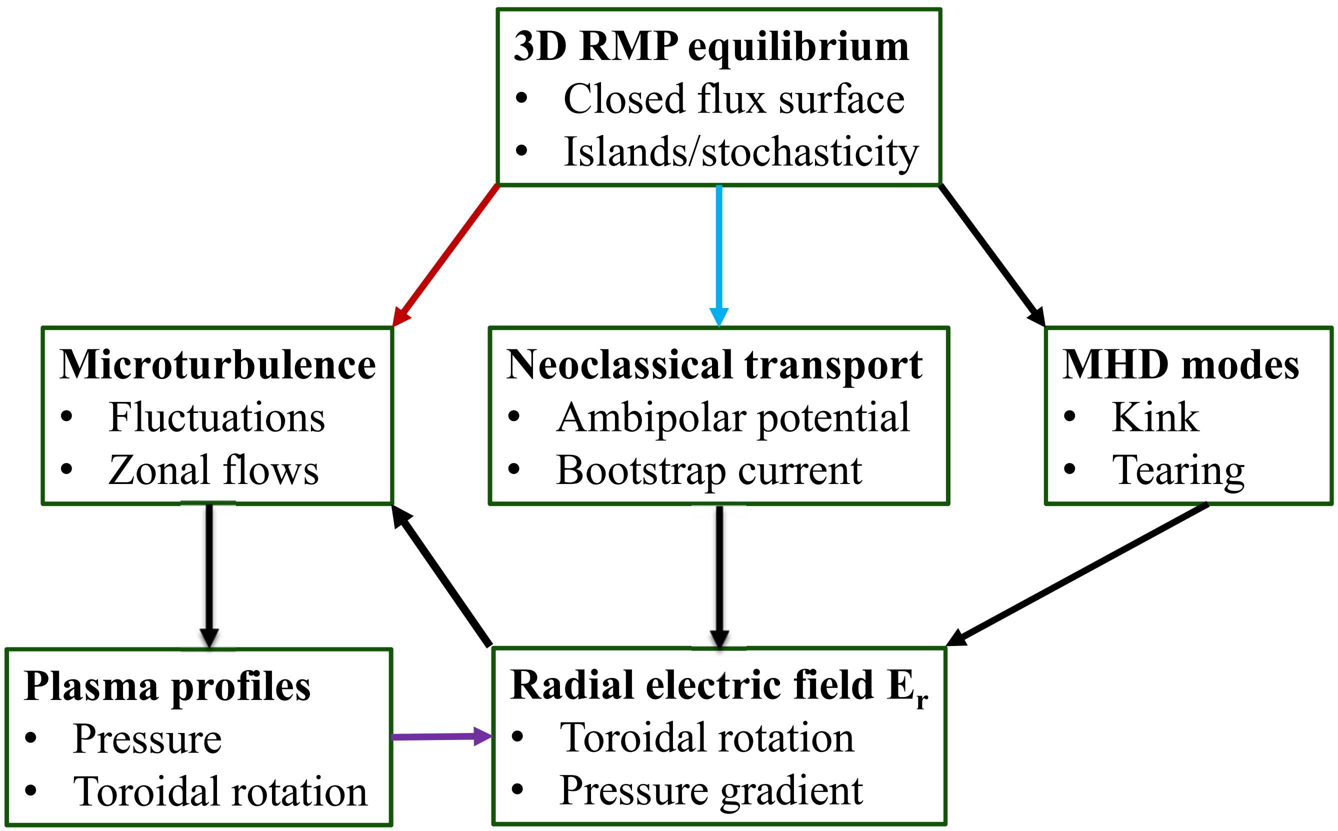
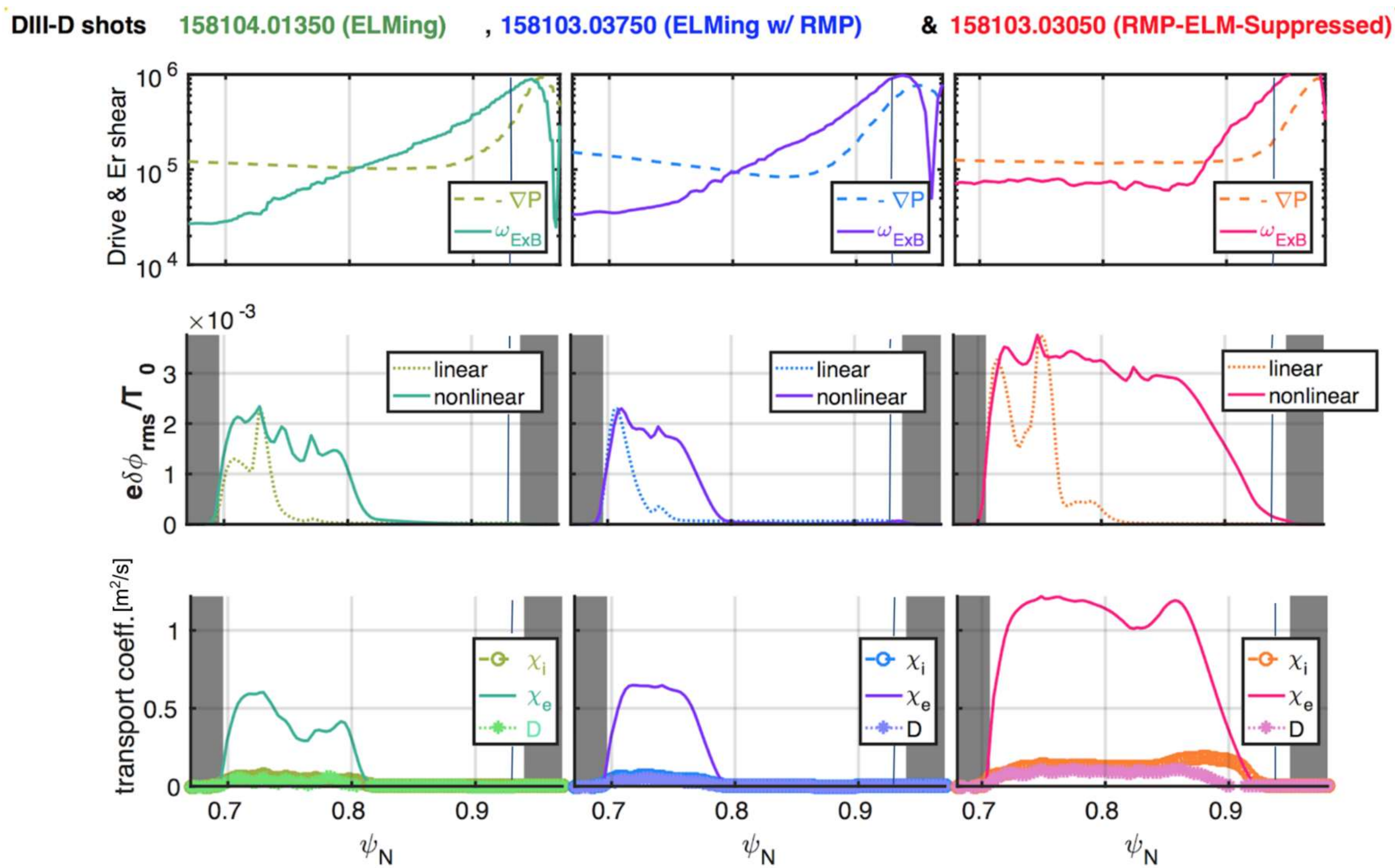
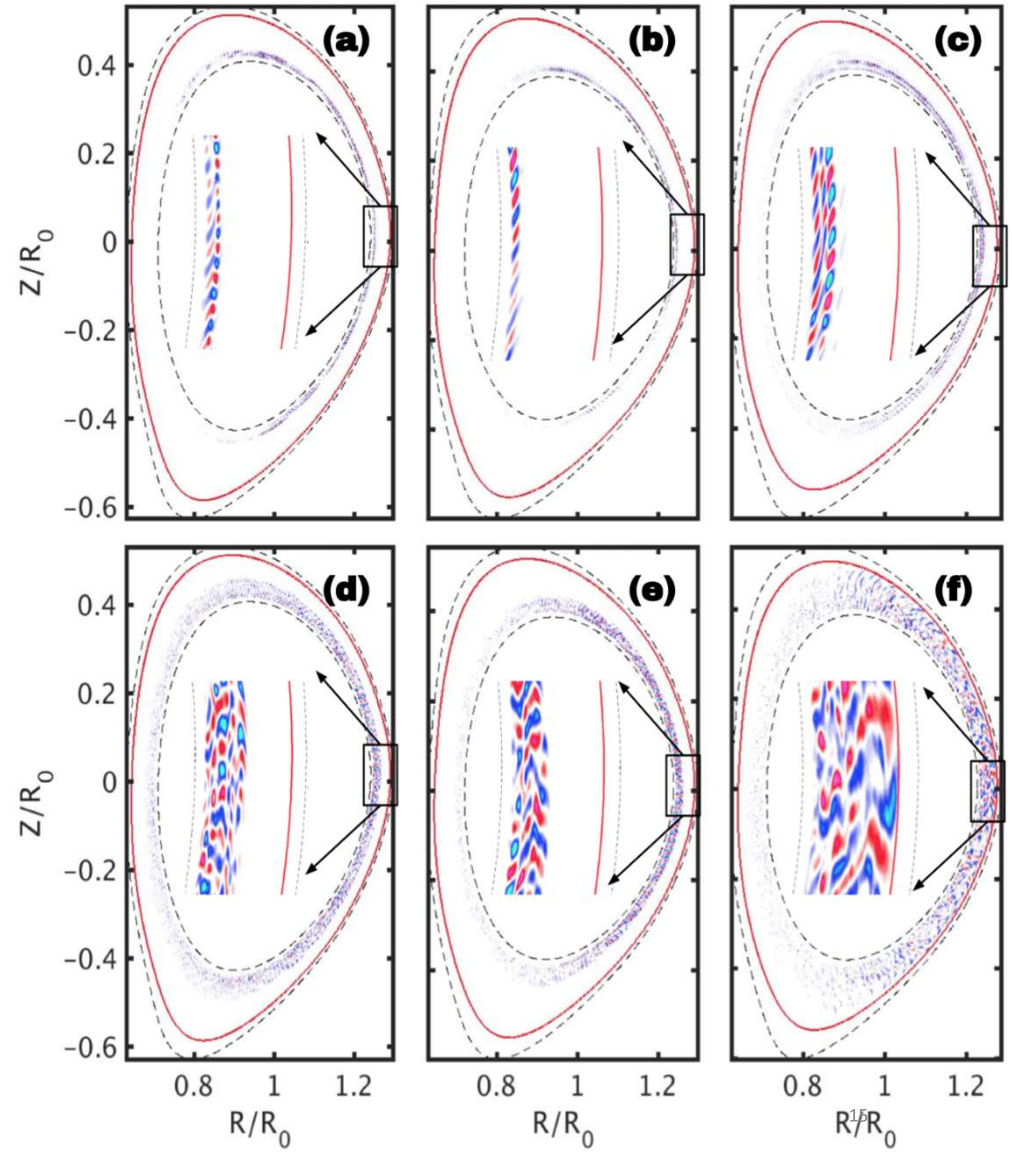


GTC Simulations Find Stronger Driftwave Instability in Outer Edge & Turbulence Spreading due to Weaker ExB Shear During ELM-Suppression



Radial Range of Turbulence is Much Larger During ELM-Suppressions

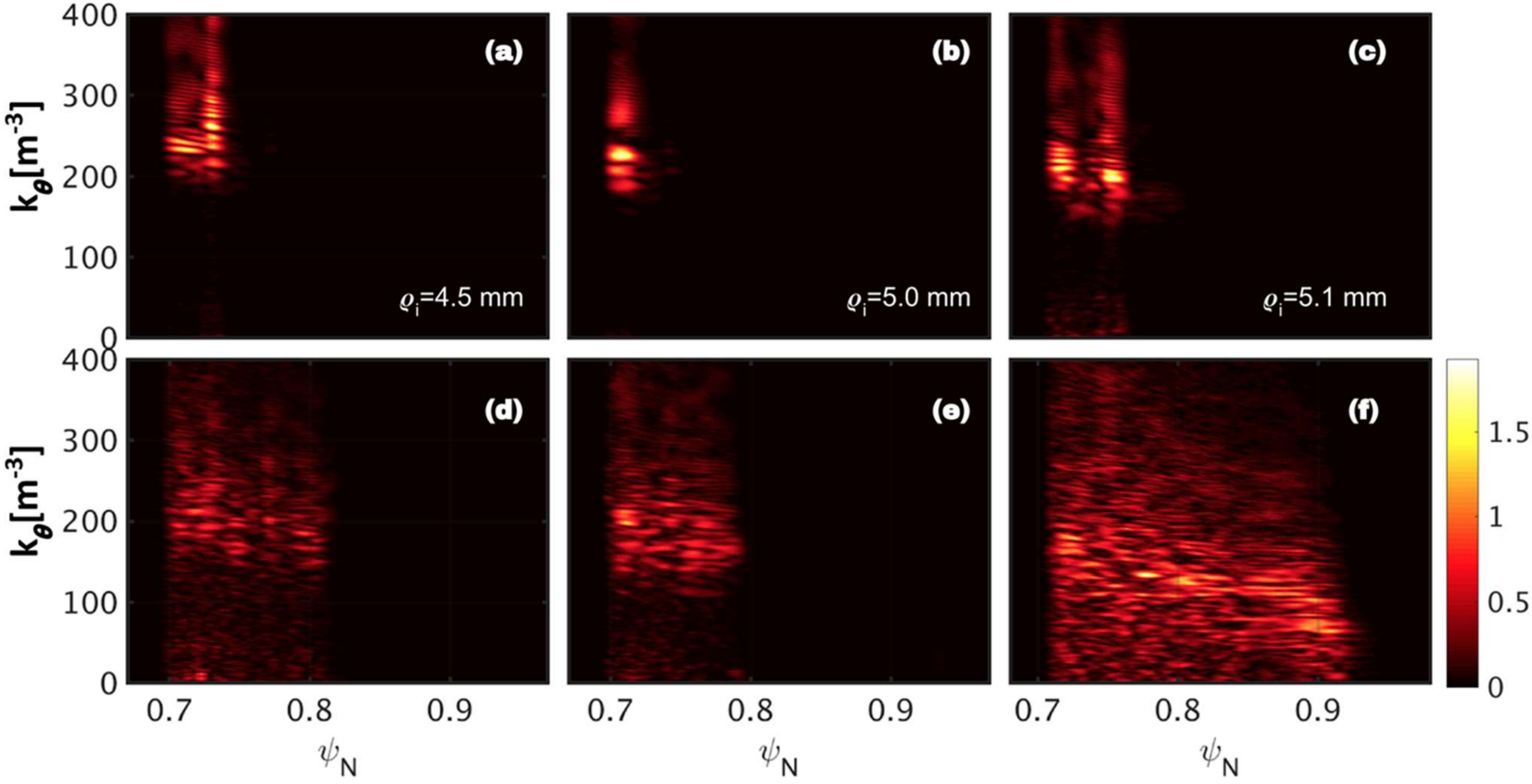
- Linear structures form inside of ped top
- Turbulence spreads up to q = 4 surface ($\psi_{pol,N}$=0.93) during ELM suppression
- q = 4 surfaces are in red color



Effects of RMP-Induced Changes of Radial Electric Fields on Microturbulence in DIII-D Pedestal Top, S. Taimourzadeh, L. Shi, Z. Lin, R. Nazikian, I. Holod, D. Spong, 2018

GTC Simulations Finds that Long Wavelength Modes Nonlinearly Spread to Pedestal Top During ELM Suppression

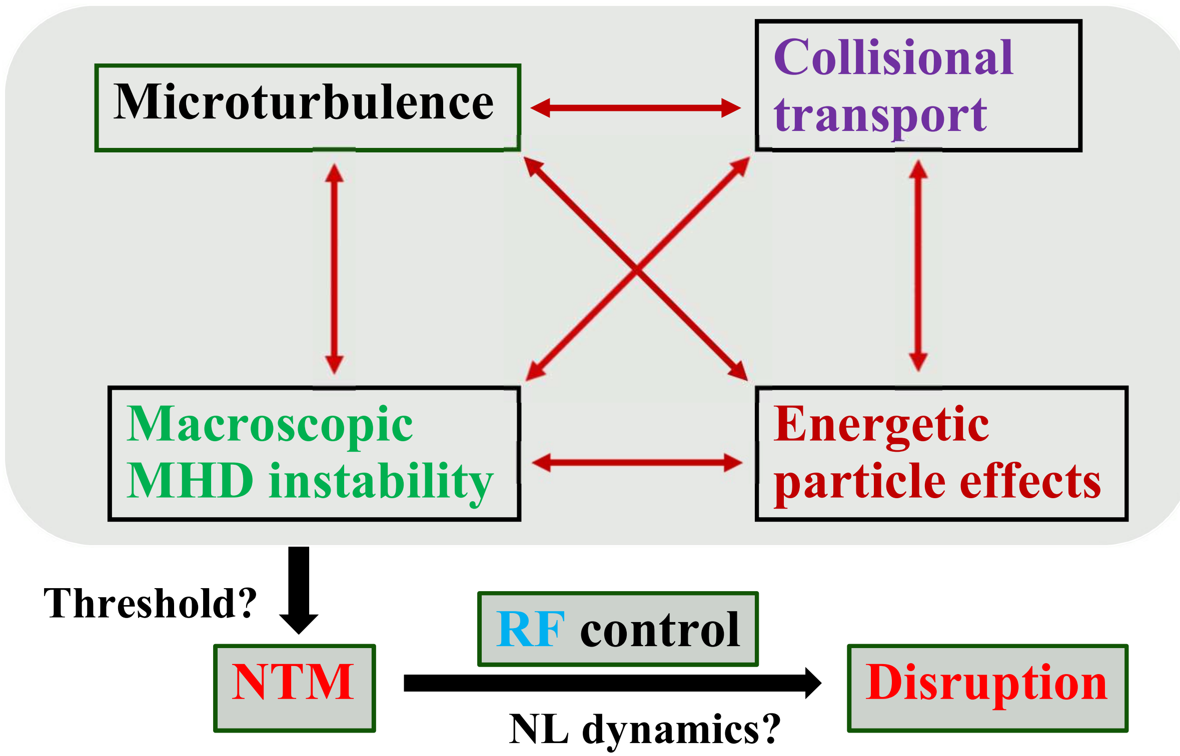
- In DIII-D, long wavelength fluctuations observed near pedestal top during ELM suppression



<u>Summary on n=2 RMP Effects on Pedestal Top Transport</u>

- **Can 3D fields with closed flux surfaces enhance turbulent transport?**
  - ✓ GTC simulations find no increase of ITG/KBM growth rates, damping of zonal flow insignificant to modify turbulent transport [*Holod et al, NF2017*]
- **Role of magnetic islands and stochastic fields?**
  - ✓ GTC finds that electron flutter transport due to RMP islands is not large enough to directly provide measured enhancement in transport, but may contribute to observed change in radial electric field
  - ✓ RMP islands have little effects on microturbulence with adiabatic electrons; Developed new simulation model for RMP islands
  - ► RMP-induced stochastic fields could suppress zonal flow generation due to increase of zonal flow dielectric constant by electron adiabatic response to ZF?
- **Indirect effects on microturbulence?**
  - ✓ GTC finds that reduction in radial electric field shear due to RMP leads to a much stronger driftwave instability in the outer edge and an outward turbulence spreading, resulting in a larger turbulent transport on pedestal top during ELM suppression [*Taimourzadeh et al, 2018*]
  - ► Mechanism for changes in radial electric field, i.e., causality? [*R. Nazikian, 2018*]
  - ► Universality of indirect effects? ELM suppression with an n = 3 RMP [*Moyer, PoP2017*]

Integrated Simulation Needed to Study Nonlinear Interactions of Multiple Kinetic-MHD Processes



- Neoclassical tearing mode (NTM) is the most likely instability leading to disruption
- NTM excitation depends on nonlinear interaction of magnetohydrodynamic (MHD) instability, microturbulence, collisional (neoclassical) transport, and energetic particle (EP) effects. NTM control requires radio frequency (RF) waves

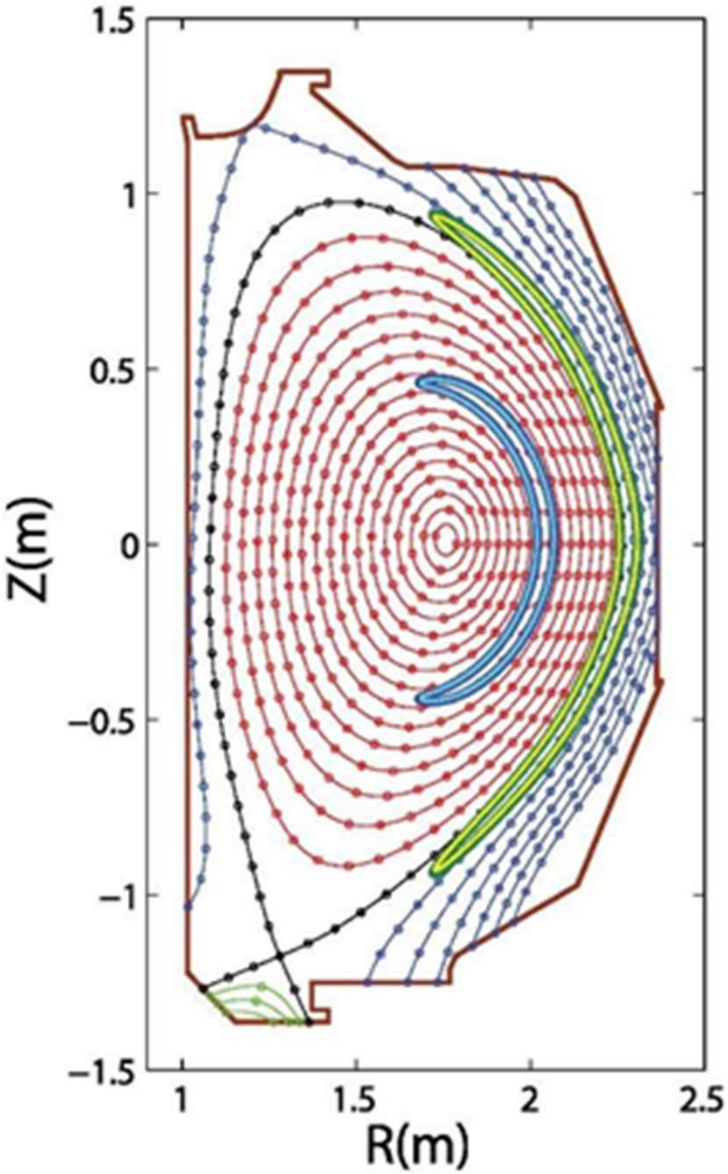
Gyrokinetic Toroidal Code (GTC)

- GTC: first-principles, integrated simulation capability for nonlinear interactions of multiple kinetic-MHD processes
- Current capability in a single version:
  - ✓ Global 3D toroidal geometry & experimental profiles
  - ✓ Microturbulence: 5D gyrokinetic ions & electrons, electromagnetic fluctuations (including compressional perturbations, tearing & non-tearing parity)
  - ✓ MHD and energetic particle (EP): Alfven eigenmodes, kink, tearing modes
  - ✓ Neoclassical transport: Fokker-Planck operators
  - ✓ Radio frequency (RF) waves: 6D Vlasov ions

[Lin et al, Science1998]

Phoenix.ps.uci.edu/GTC

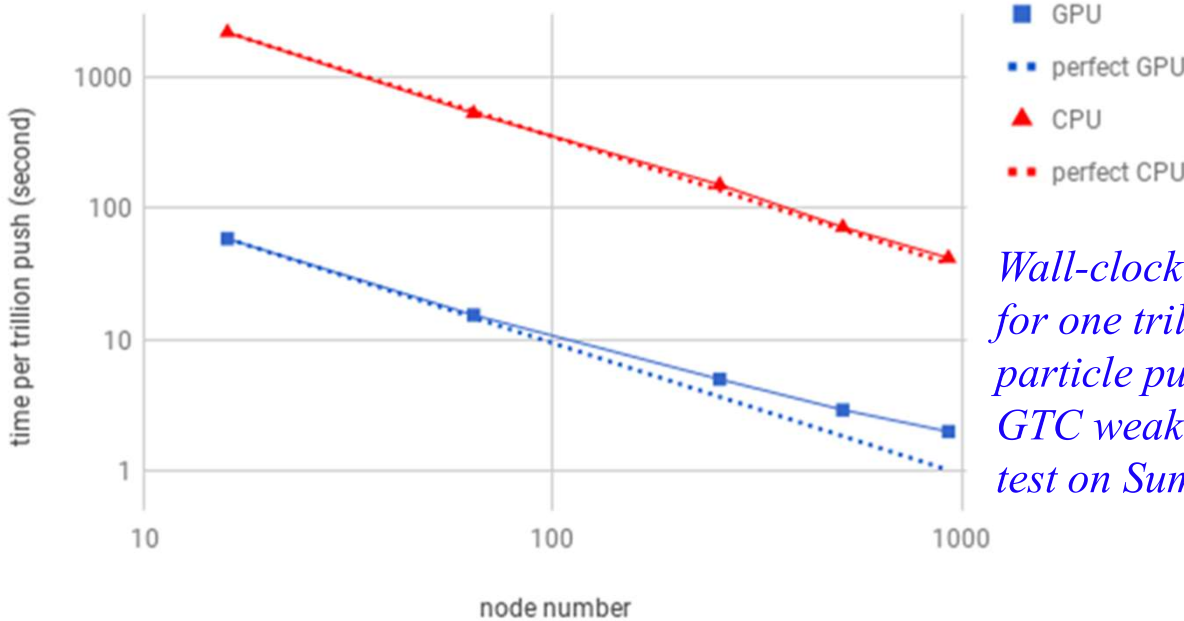
A conservative scheme of drift kinetic electrons for gyrokinetic simulation of kinetic-MHD processes in toroidal plasmas,
J. Bao, D. Liu, Z. Lin, Phys. Plasmas ***24****, 102516 (2017)*



Optimizing GTC for Exascale Computing

- GTC being developed as energetic particle module in fusion whole device modeling (WDM) by SciDAC ISEP (Integrated Simulation of Energetic Particles in Burning Plasmas) collaborations: UCI, GA, PPPL, ORNL, LBNL, LLNL
- GTC speeds up 20X from CPU to GPU on SUMMIT (world's fastest computer) by CAAR (Center for Accelerated Application Readiness) project: UCI, PU, ORNL, NVIDIA, IBM
- GTC recently selected by NVIDIA as one of Top 15 App Worldwide

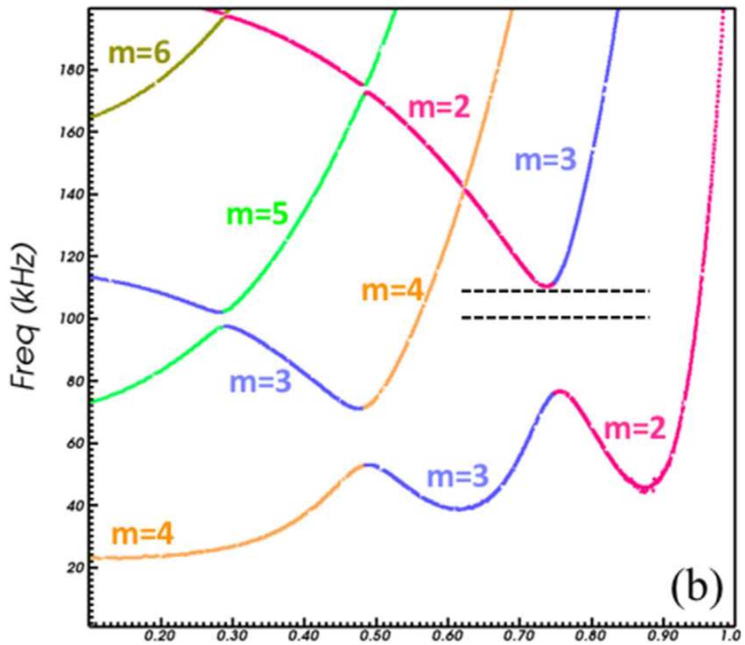
PPPL Theory seminar, Friday (7/13)

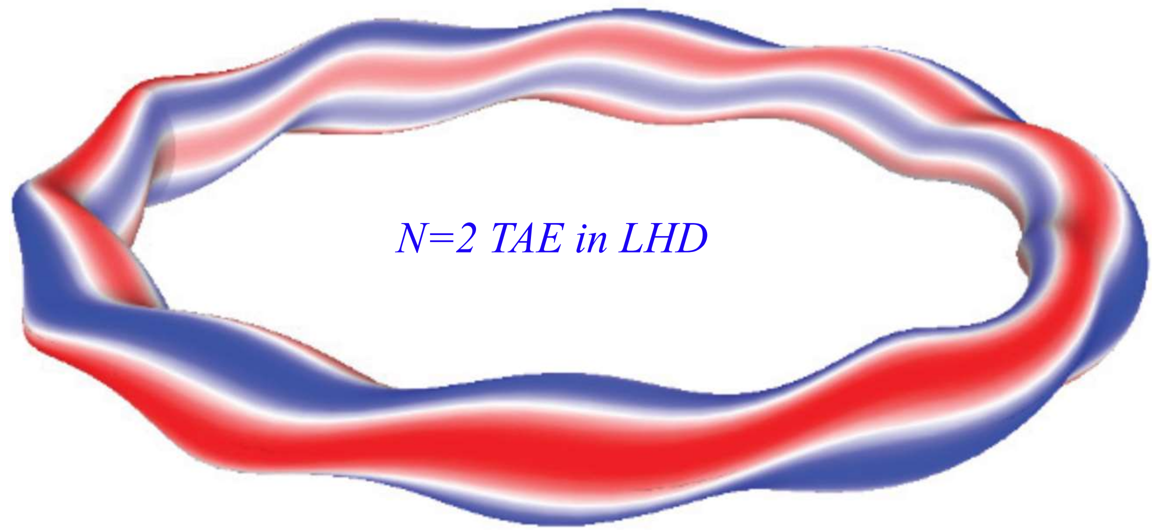


Wall-clock time for one trillion particle pushes in GTC weak scaling test on Summit

GTC Simulations of TAE in LHD Stellarator

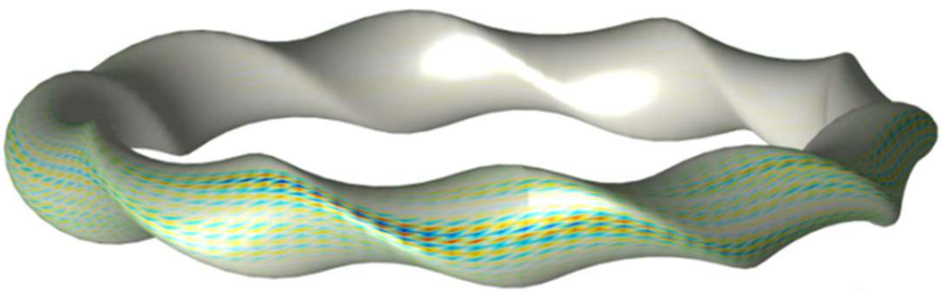
- What are the properties of turbulent transport and energetic particle confinement in stellarators optimized for neoclassical transport?
- Require global gyrokinetic simulations
- GTC linear simulations of TAE in LHD carried out; Nonlinear simulations ongoing

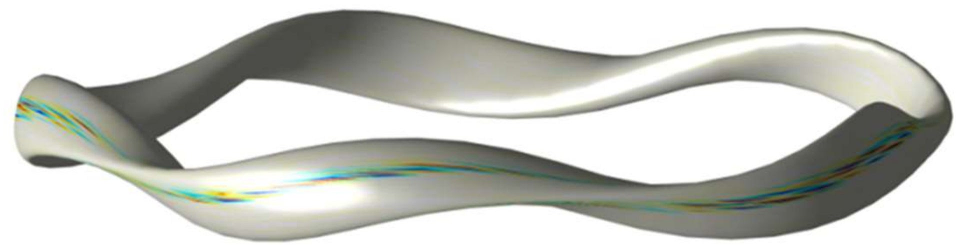


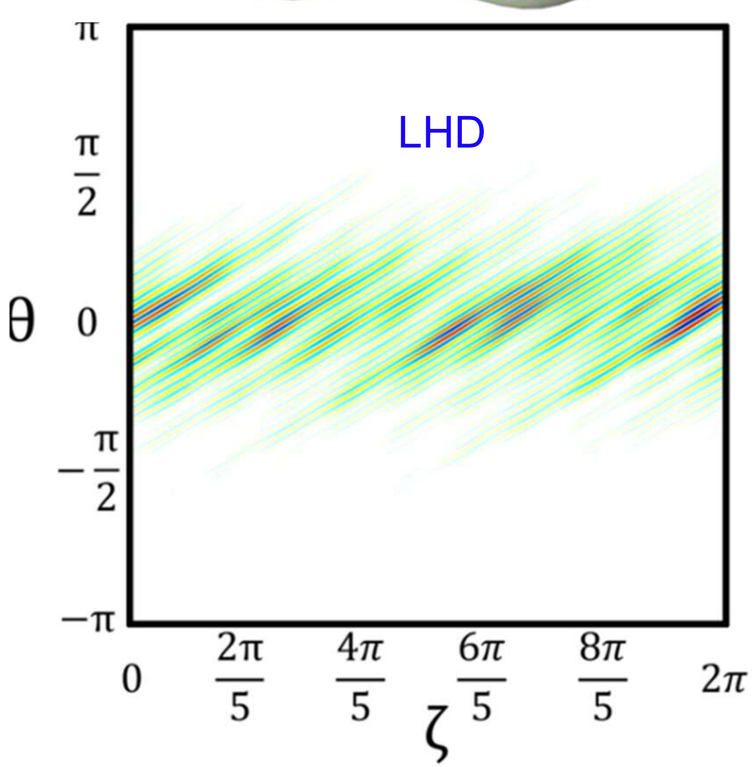


Global linear gyrokinetic simulation of energetic particle- energetic particle-driven instabilities in the LHD stellarator, D.A. Spong, I. Holod, Y. Todo and M. Osakabe, Nuclear Fusion ***57****, 086018 (2017)*

GTC Simulations of ITG in W7-X & LHD Stellarator

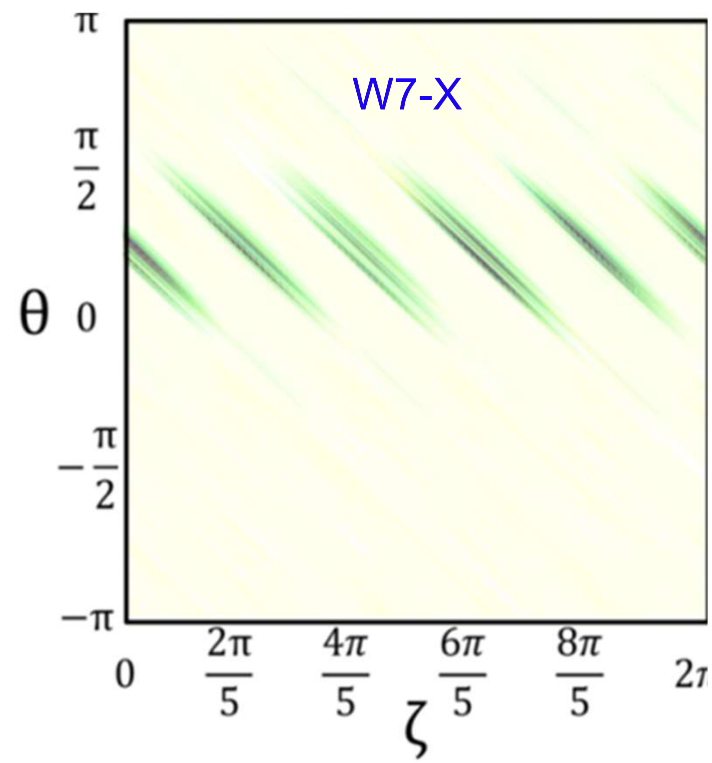






- GTC linear growth rate & frequency agree well with EUTERPE
- Mode structure in W7-X localized, LHD extended in toroidal direction

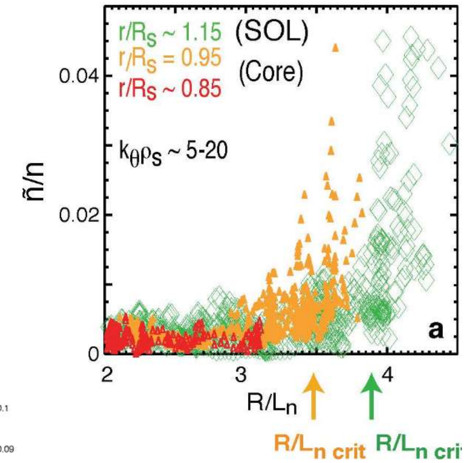
[H. Y. Wang, 2018]

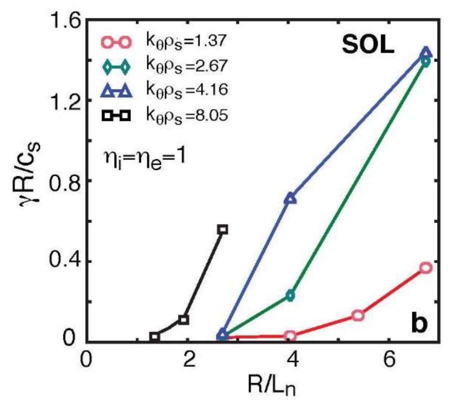


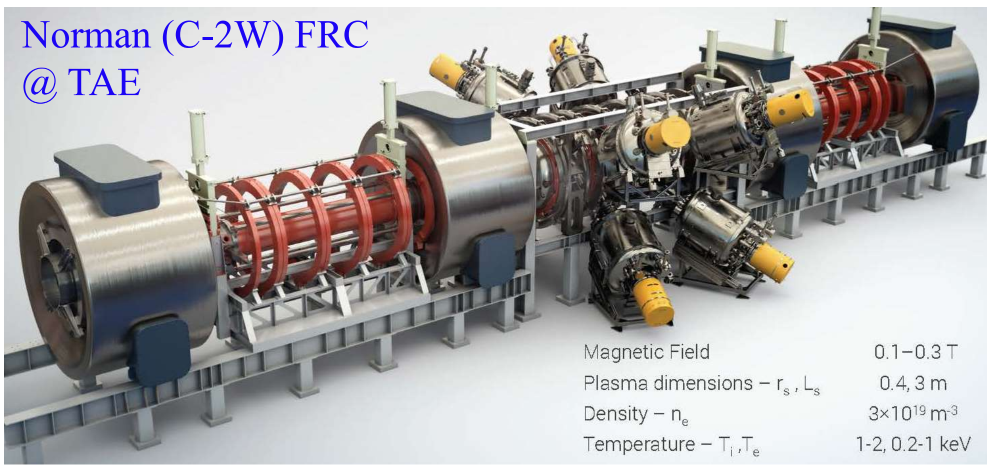
Turbulent Transport in Field Reversed Configuration (FRC)

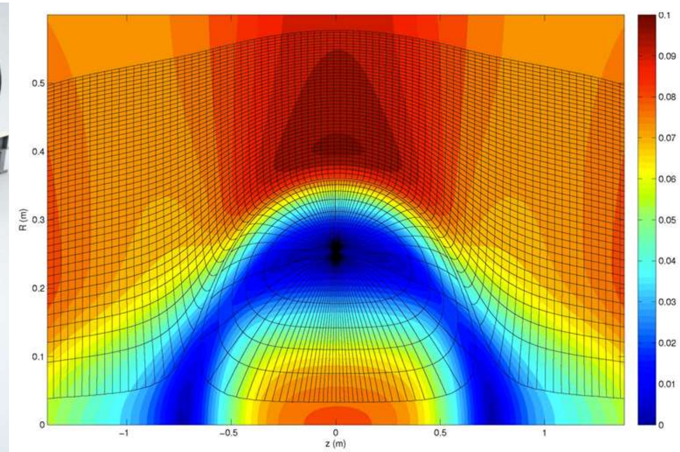
- Stable FRC plasma at TAE Technology as MHD instabilities suppressed by NBI, plasma gun, magnetic mirror plug, electrode biasing
- Can FRC plasma be heated to fusion-relevant temperature?
- Microscopic driftwave is expected to be unstable due to bad curvature, but GTC finds ion-scale modes stable in FRC core
  - ✓ Stabilized by magnetic gradient, large Larmor radius, short field lines
- SOL driftwaves unstable with critical pressure gradient, agree qualitatively with C-2 FRC data; SOL turbulence spreads into core

First Evidence of Suppressed Ion-scale Turbulence in a Hot High-β Plasma, L. *Schmitz et al, Nature Communications,* 2016









POSTDOCTORAL SCHOLAR POSITION
FUSION SIMULATION
UNIVERSITY OF CALIFORNIA, IRVINE

The University of California, Irvine (UCI) invites applications for two Postdoctoral Researcher positions in integrated fusion simulation beginning in September 2018. The fusion simulation group at UCI is led by Professor Zhihong Lin, who directs the Center for Integrated Simulation of Energetic Particles (ISEP), part of US Department of Energy (DOE) Scientific Discovery through Advanced Computing (SciDAC) initiative. The successful candidates will develop advanced simulations on the world's fastest supercomputers to study energetic particle confinement and turbulent transport in fusion experiments including tokamak, stellarator, and field reversed configuration. See http://phoenix.ps.uci.edu/zlin/ for additional information.

The successful applicants will have a Ph.D. degree in plasma physics or fusion energy science; salary will be commensurate with experience and qualifications. Applicants should submit a curriculum vitae, statement of research interests, a list of publications, and three names for letters of recommendation to Professor Zhihong Lin by email zhihongl@uci.edu.