KSTAR Conference, Feb. 21-23, 2018, Muju Resort, Korea

High-Fidelity Physics for KSTAR

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*Funding by DOE FES and ASCR
**Computing resources provided by OLCF, ALCF, and NERSC

Outline

- **Necessity for a "high-fidelity" or "first-principles-based" simulation**
  - The highest-fidelity method possible on today's HPCs is gyrokinetics.
- **Candidates for impactful high-fidelity physics for KSTAR**
  - L-H transition physics
  - Divertor heat-load width physics
  - 3D physics: RMP, neoclassical tearing modes
  - Pedestal structure and onset of edge localized modes
  - Edge-core interaction
  - Impurity physics
  - Onset of Sawtooth instability
  - Density limit
  - Onset of plasma disruption
- **Discussions**

What is a first-principles-based simulation?

[Wikipedia] "In physics, a calculation is said to be from **first principles, or *ab initio***, if it starts directly **at the level of established laws of physics and does not make assumptions such as empirical model and fitting parameters.**
For example, calculation of electronic structure using Schroedinger's equation within a set of (justifiable) approximations that do not include fitting the model to experimental data (or parameters) is an *ab initio* approach."

→ No free parameters or fitting formula, except for experimental conditions.

- In plasma physics, 6D Vlasov eq. is the most *ab initio* equation.
  - 5D gyrokinetic eq. is the next high-fidelity *ab initio* equation within the justifiable approximation ($\partial/\partial t << \Omega_B$), and keeps the Landau resonance.
- **Fluid equations** ($\nu_c >> v/L$ for $^{\forall}v\&L$) use unjustifiable closure approximations or fitting models for weakly collisional or non-Maxwellian plasmas → not *ab initio.*
  - *E.g.,* $D_{\perp,||}$ *and* $\chi_{\perp,||}$, *banana transport, orbit loss physics, SOL transport, etc*
  - **Gyro-fluid** equations use a **fitting model for Landau resonance**

Understanding and predicting L-H transition for ITER

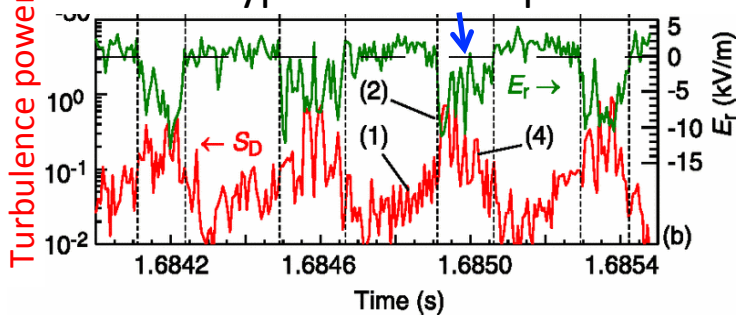
ITER relies on L-H transition in the Q=10 scenario.

1. Will ITER achieve L-H transition at a reasonable aux. heating power?
   - Affected by machine dependence?: 3D B-perturbation?, divertor geometry and X-point geometry?, neutral recycling?, wall material?
2. Different machines have reported different basics of bifurcation.
   - DIII-D and C-Mod: Conservative Reynolds work from the turbulence-drivn ExB shearing [Tynan, Ziegler, Diamond, Kim, Hahm,…]
   - JFT-2M, ASDEX-U, NSTX: Neoclassical mean ExB shearing & dissipation, driven by orbit-loss and/or ∇p force-balance [Kobayashi, Cavedon, Shaing-Lee, Biglari-Diamond, …]
   - Different bifurcation t-duration: fast bifurcation type or slow limit-cycle-oscillation type
   - How are these affected by "machines."
3. We first need to obtain a high-fidelity understanding before predicting ITER.
   - First GK understanding has been reported [CS Chang, PRL 2017]

Experimental L-H bifurcation time scale: fast type or slow-LCO type

- When $P_{heat} \approx P_{LH}$, the bifurcation is observed to be slow undergoing many limit cycle oscillations (I-phase) [Schmitz PRL12, Conway PRL11, and others]

LCO type GAMs in I-phase

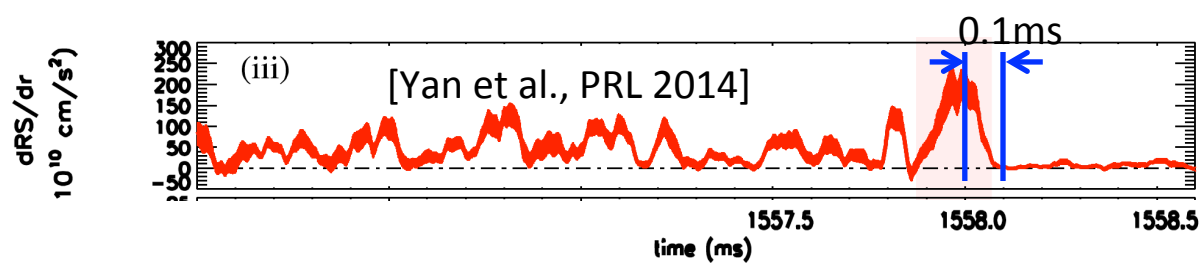


GAMs can be part of the bifurcation physics:
Non-LCO GAMs in L-phase, and
LCO GAMs in I-phase.

[Conway, PRL 2011, ASDEX-U]

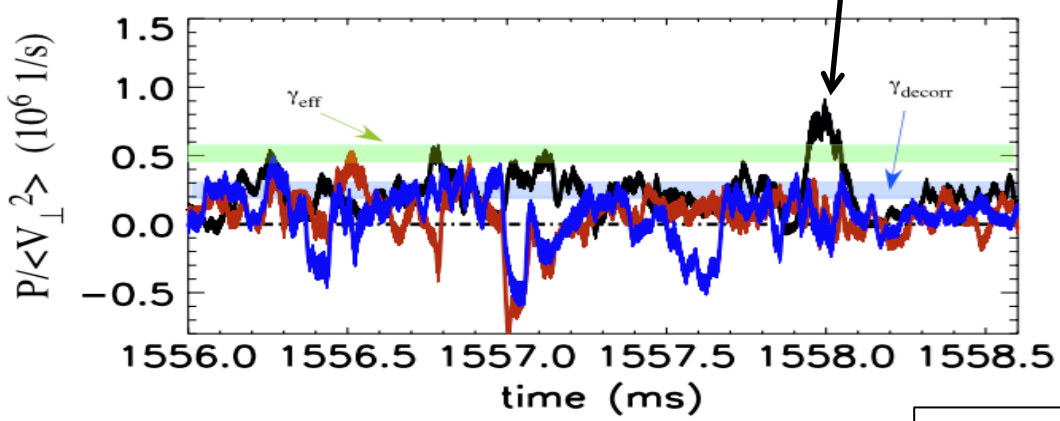
- When $P_{heat} > P_{LH}$, the bifurcation is **fast ($\lesssim$ 0.1 ms)** with an abbreviated I-phase [Yan PRL14, DIII-D, and others]

$$F_{\theta,Reynolds} = -d\langle\delta V_r \delta V_\theta\rangle/dr$$



Evidence for zonal Reynolds-work just before L-H bifurcation

The zonal, turbulence-driven, Reynolds consumption rate
$P=\langle\tilde{v}_r\tilde{v}_\theta\rangle V_E' / (\gamma_{eff}\tilde{v}_\perp^2/2)$ becomes >1 momentarily (Δt ~0.1ms).



Black Ψ_N= 0.98
Red 0.96
Blue 0.93

"zonal"

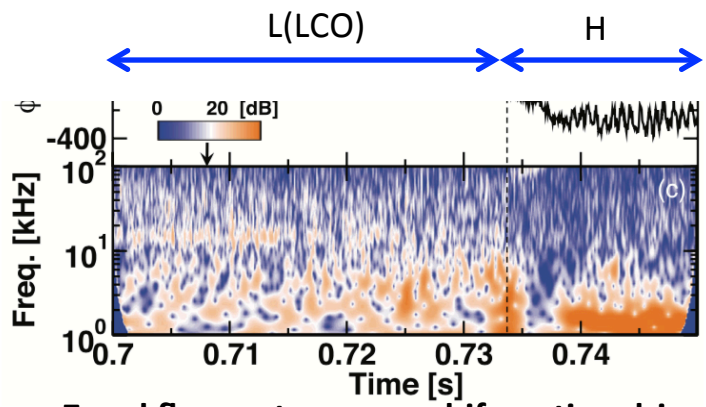
[Yan et al, PRL 2014, DIII-D]

γ_{eff}=turbulence recovery rate
~ linear growth rate of the strongest mode

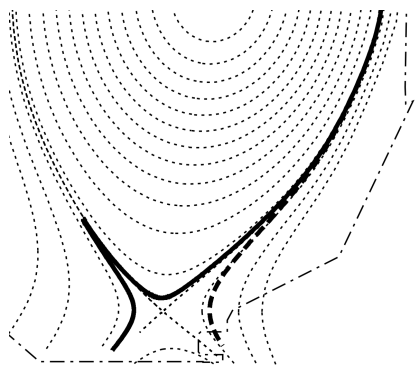
No-time for development of a strong enough ∇p (Moyer had an explicit measurement). What is then keeping the turbulence suppressed?

Evidence for the non-existence of zonal flow also claimed

- V'_{ExB} is driven by ∇p [Cavedon et al., NF2017, ASDEX-U], zonal flow not seen.
- V'_{ExB} is claimed to be X-point orbit-loss-driven *[Kobayashi et al., PRL2013]*
- NSTX found Reynolds work is irrelevant [Diallo17]. Instead, $P_{L\text{-}H}$ is strongly correlated with orbit-loss V'_{ExB} [Kaye, NF2011; Battaglia, NF2013]

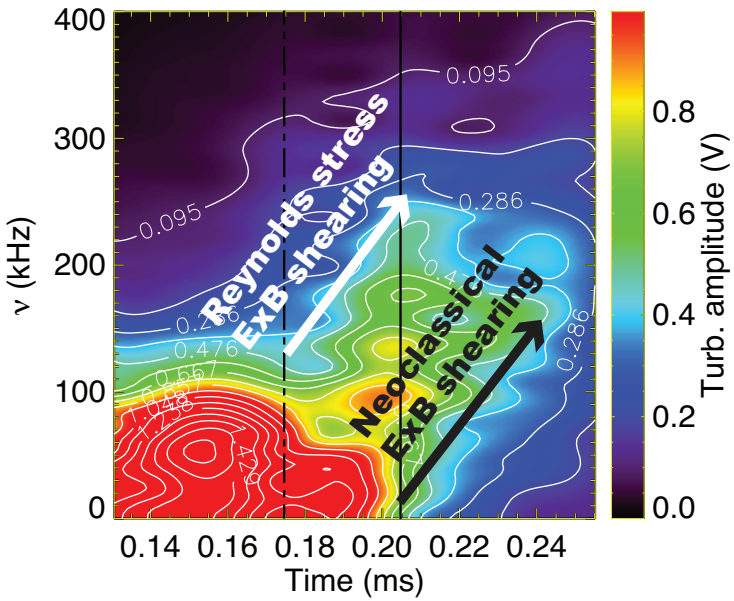


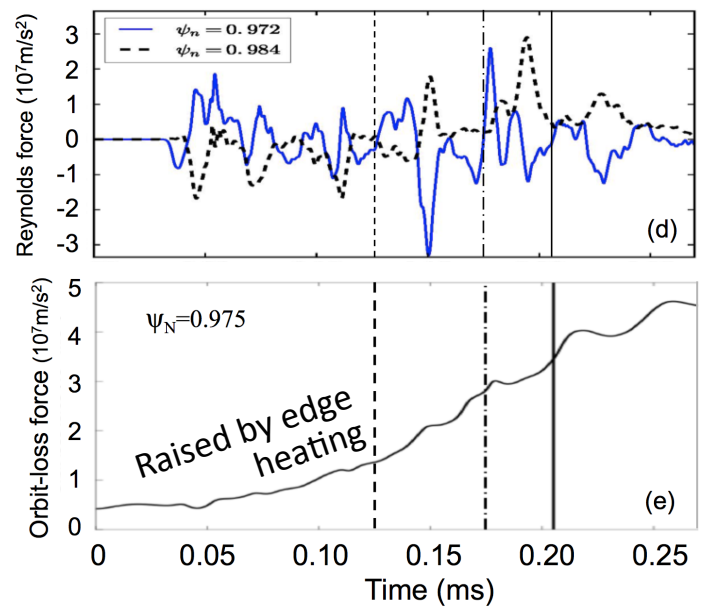
Zonal flow not seen as a bifurcation driver?
[Kobayashi NF 2017, JFT-2M]



Ion X-point orbit-loss to divertor
[S. Ku-C.S. Chang, PoP 2004],
(as a special case to K.C. Shaing's general orbit loss story).

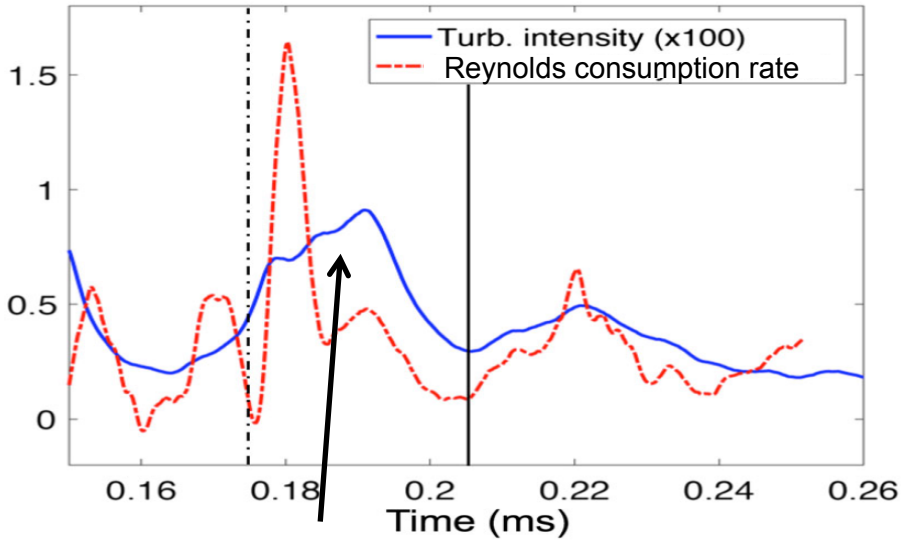
XGC1 gyrokinetic simulation shows both mechanisms work together

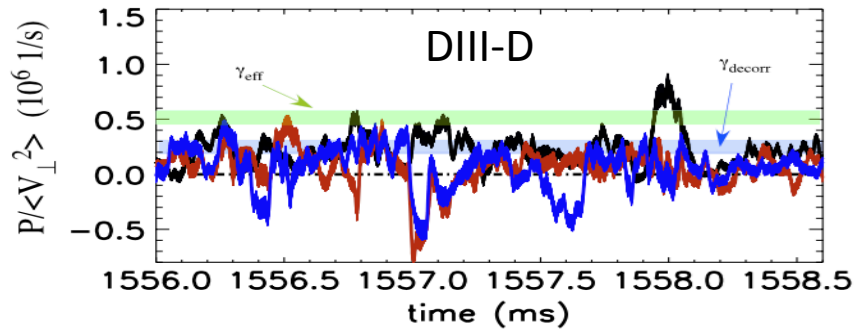




- The conservative Reynolds-ExB-shearing starts the turbulence suppression and the dissipative mean-ExB shearing completes the L-H bifurcation.
- Between the two events, turbulence and ExB shearing undergoes LCO at ~ $\boldsymbol{\nu}_{GAM}$ (I-phase)
- If P_{heat} is not enough, LCO may last for a long time. ∇p may rise in I-phase leading to mean V_E'

We see that the turbulent Reynolds consumption rate $P=\langle\tilde{v}_r\tilde{v}_\theta\rangle V_E' / (\tilde{v}_\perp^2/2)$ becomes $>\gamma_{eff}$ transiently to trigger I-phase





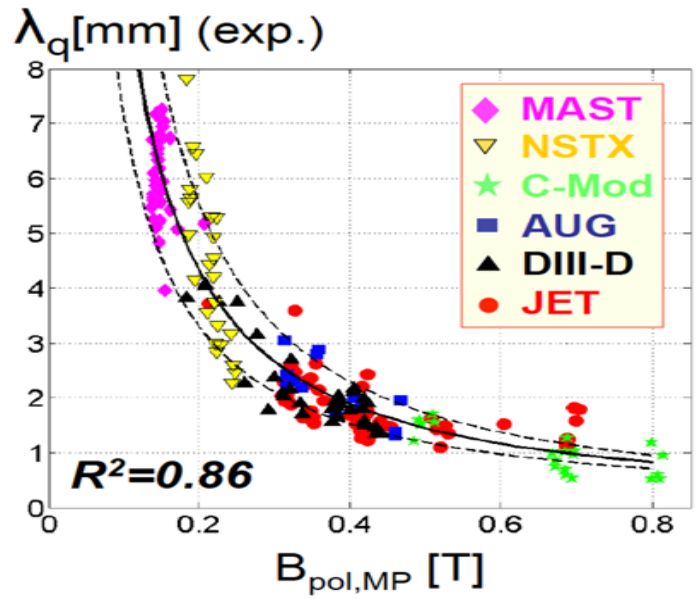
[Yan, PRL 2014, DIII-d] and [Ziegler, PPCF 2014, C-Mod] reported a transient Reynolds consumption at L-H transition.

Can KSTAR and GK code collaborate to predict L-H bifurcation dynamics that are relevant to ITER?

- **Can KSTAR measure the turbulence spectrum evolution at high enough resolution: Δt~0.01ms, $\Delta\Psi_N$~0.01?**
- **Can KSTAR measure the main species edge profiles (including the T_i profile), together with impurity species profiles?**
- **Several mechanisms may deserve considerations for the ITER H-mode operation: Combination of the Reynolds-stress-driven and orbit-loss-driven ExB shearing rates may get affected by**
  - **Error-field and RMPs**
  - **Isotope effect**
  - **X-point location (geometry)**
  - **High-Z + low-Z impurity particles**
  - Neutral particle recycling from W wall: kinetic energy and recycling rate
  - $\rho_*=\rho/a$ → XGC1 result indicate that ITER may have long "I-phase."

If the heat-load width in ITER is as narrow as prediction by the present experimental data, its operation will be difficult.

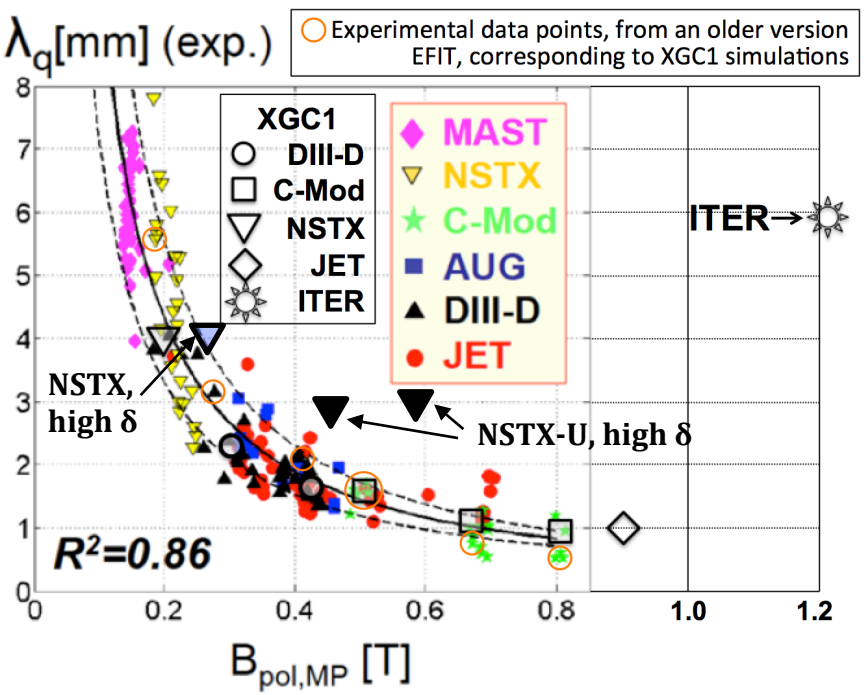
- Regression analysis by Eich *et al.* yields
  $\lambda_q \propto 1/B_p^{\gamma}$, $\gamma \sim 1.19$
  - Explained via neoclassical orbit excursion physics: $\gamma=1$ [XGC0, US JRT 2010; Goldston, NF 2012; XGC1, NF 2017]
- Will ITER -- with smaller $\rho_* = \rho_i/a$ → weaker neoclassical effect -- obey the same physics?
- Neoclassical + blob turbulence + neutral recycling (multi-physics) must be considered together in non-equilibrium condition
  → extreme scale GK simulation



T. Eich et al., NF 2013; PRL 2011

- We used 90% Titan (~300K cores + 19K GPUs = 27PF, spending 10M core hours/ day) for 3 days for 1 ITER case → Korea will have this capability soon.

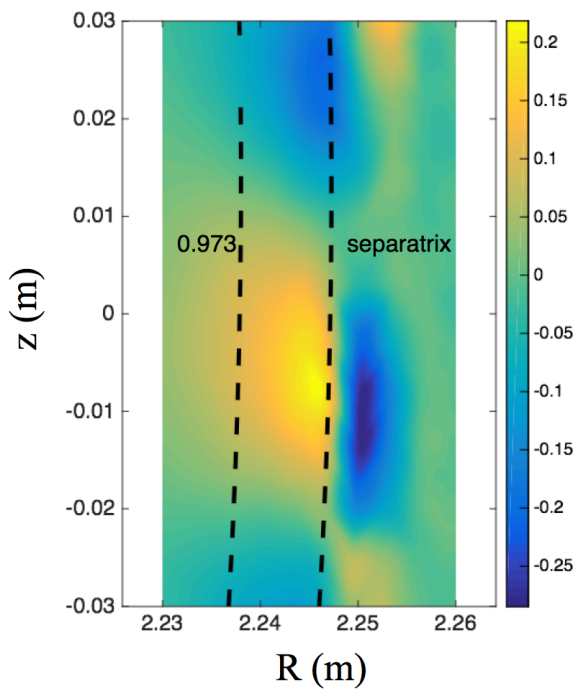
XGC1 agrees with the experimental Eich scaling in all the existing tokamaks: NSTX, DIII-D, C-Mod and JET.

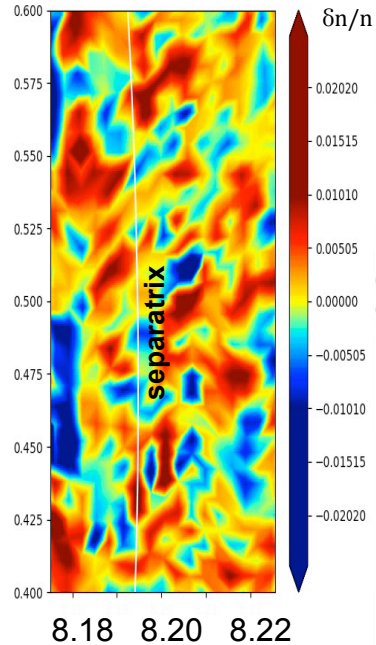


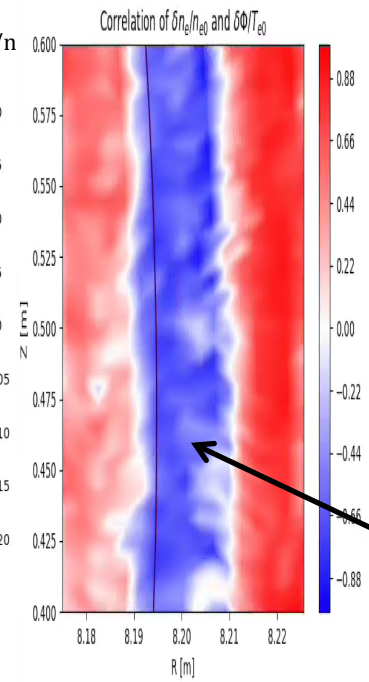
- However, XGC1 shows $\lambda_q \approx 6$mm in ITER, instead of <1mm.
  - Turned out to be from dominance of **turbulent transport in the weak neoclassical regime** ($\rho_* <<< 1$)

  → **much easier operation of ITER**
- In the high-triangularity NSTX-U model plasmas (1.5 and 2MA), λ_q is 2-3X greater than Eich.
  - Could be from a **geometry effect?**
  - Relation to ITER phyiscs/operation?
  - **Can KSTAR study the triangularity effect on λ_q?**

In the modeled ITER edge plasma, turbulence self-organizes to accommodate the weak neoclassical loss across the separatrix.







~3X compressed scale for ITER than DIII-D

→ ~3X longer radial streamer size in ITER than the radial blob size in DIII-D.

Strong anti-correlation between δn and δΦ across the separatrix surface

(Left) Blob-type turbulence in the existing tokamaks that obey the Eich scaling

(Right) Streamer-type turbulence in ITER edge that spreads the heat-load on divertor plates.

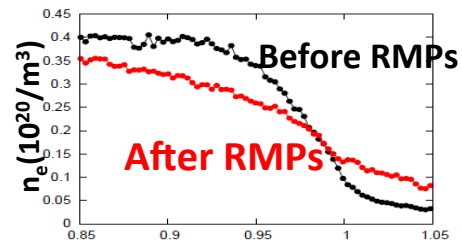
How can a gyrokinetic simulation improve the RMP physics?

- 3D RMPs are one of few control methods against ELMs in ITER.
  - RMP penetration/transport has mostly been studied via **MHD/fluid**.
- RMP physics can be improved by considering **interaction of the plasma kinetics and turbulence with the stochastic/island magnetic structures**
  - RMP penetration and distribution
  - Edge profile evolution
  - Modification of the edge localized mode onset
  - Momentum transport
  - Impurity transport
  - Divertor heat-flux footprint
  - Core density and temperature
  - …
- All of these can be relevant to KSTAR's research emphases

Kinetic RMP simulation examples

1. **RMP penetration** study on a model DIII-D 126006 plasma, n=3

   [Gunyoung Park and C.S. Chang]



   - Use the **drift-kinetic** neoclassical code XGC0
   - ITER-like low collisionality (~0.1), H-mode
   - 6 MW of heat and 4 N-m of torque at inner boundary (ψ_N=0.8)
   - A fixed turbulent radial transport is assumed, $D \approx \chi_e \approx \chi_i \approx \chi_\phi \approx 0.2$ m^2/s (<< RMP-driven neoclassical transport)
   - Vacuum RMP boundary condition at $\psi_N \approx 1.06$

2. **RMP transport** study using the 3D B-field evaluated by M3D-C1

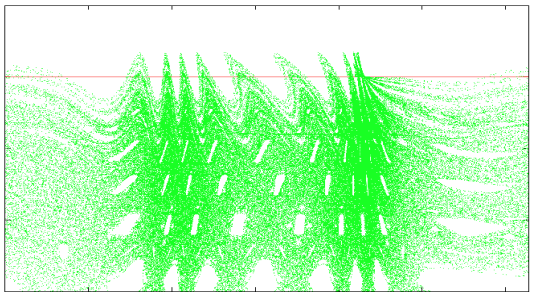
   [R. Hager, N. Ferraro, R. Nazikian, C.S. Chang et al., IAEA 2018]

   - Use the **gyrokinetic** neoclassical code XGCa: XGCa--M3D-C1 coupling
   - To be enhanced for self-consitent RMP penetration.

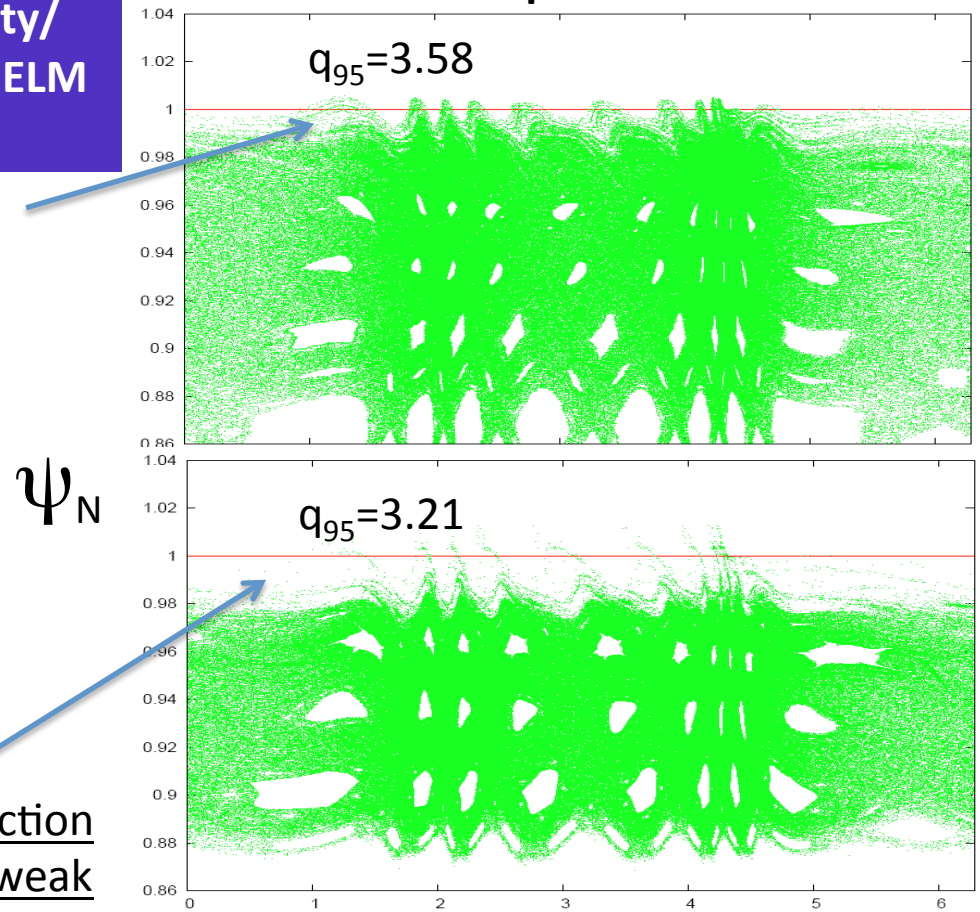
Field line puncture plot, starting from ψ_N=0.96, shows that robust vacuum B-stochasticity/ islands remain closer to separatrix in the ELM suppression window

XGC0 responded RMPs

Inside the q_{95} window: Field line connection between plasma and wall is stronger

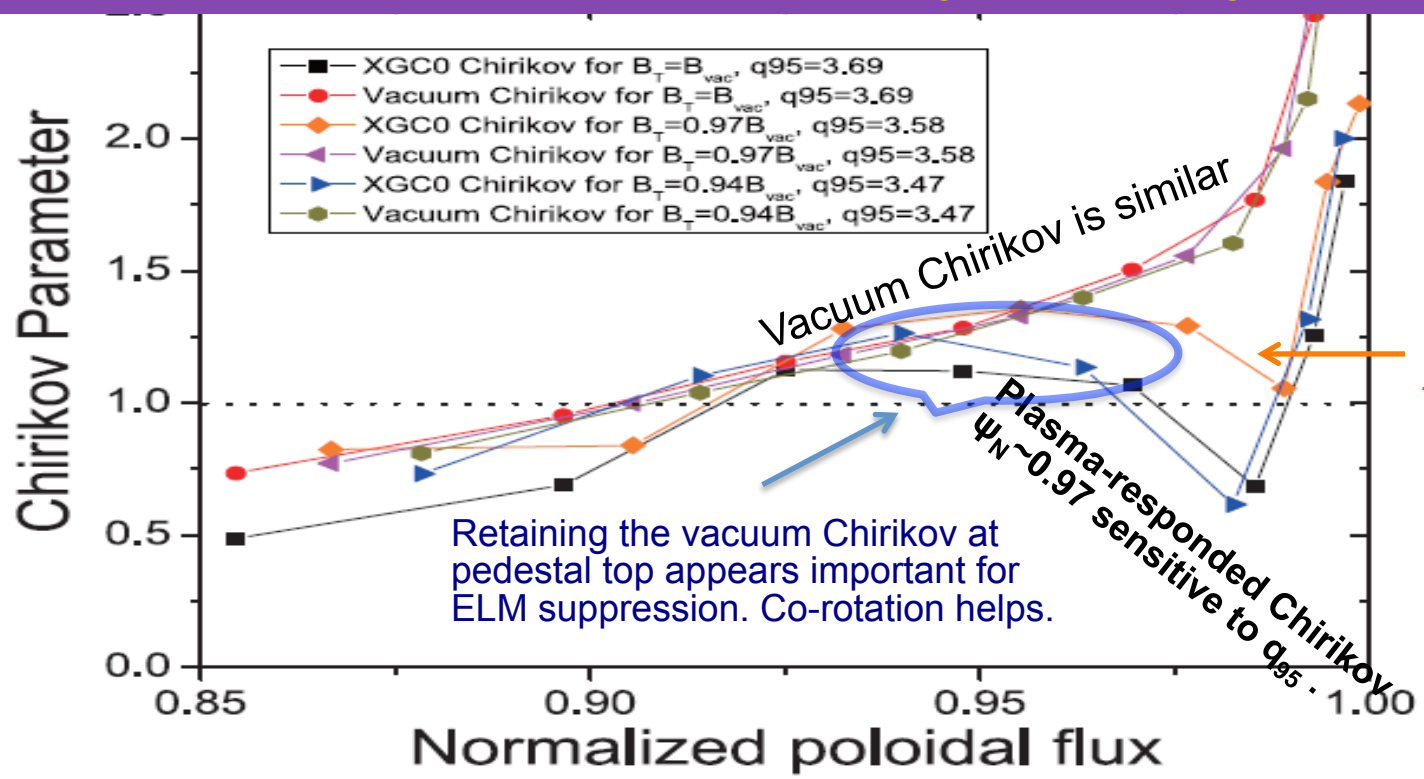


Vacuum RMPs with
B_T =1X $B_{T,EQDSK}$, q_{95}=3.69



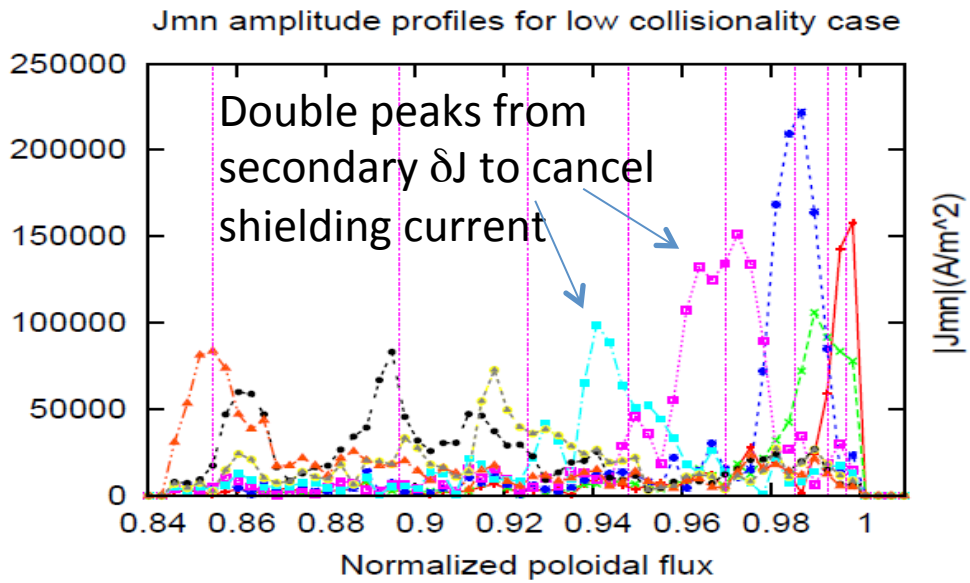
Out-of-window: Field connection between plasma and wall is weak

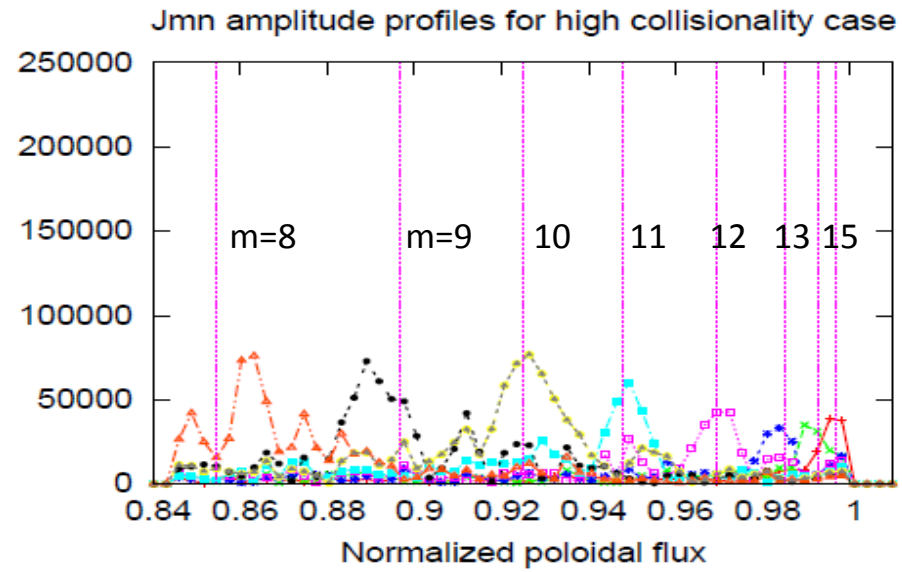
Vacuum Chirikov is similar, but the plasma-responded Chirikov is a sensitive function of q_{95} around 3.58.
Near q_{95} =3.58, Chirikov ≥1 everywhere. Outside the ELM suppression window, Chirikov<1 just inside the separatrix surface ψ_N~0.97.
→ "Vacuum Chirikov>1 is only a necessary condition."



DIII-D indeed saw jump in the electron loss to divertor plates when q_{95} is inside the window [Watkins 2007]

Kinetic Effect: broadening of $\delta J_{||}$, strong interaction between currents, secondary $\delta J_{||}$, and collisional $j_{||}$ damping





Low collisionality

Strong shielding currents at m≥13 suppresses local RMPs and stochasticity as soon as the RMPs meet the pedestal.

Secondary currents tend to cancel the primary shielding current effect at m≤12, leading to the recovery of RMPs and stochasticity at inner radii.

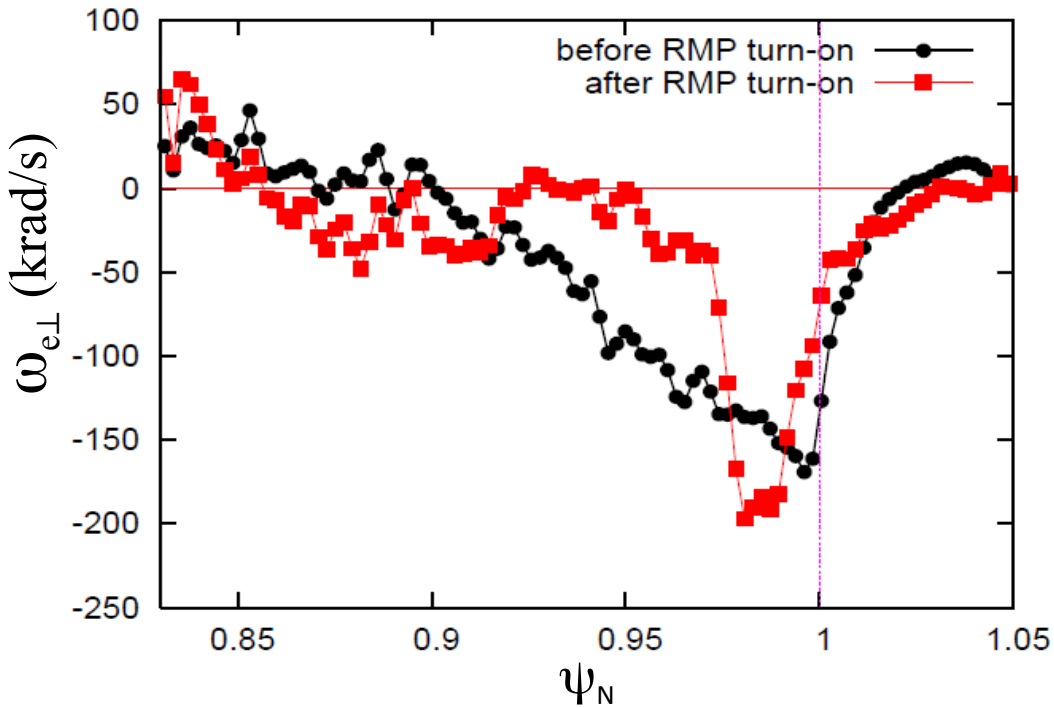
High collisionality

Primary shielding currents are weak and does not generate strong secondary currents (collisional dissipation).

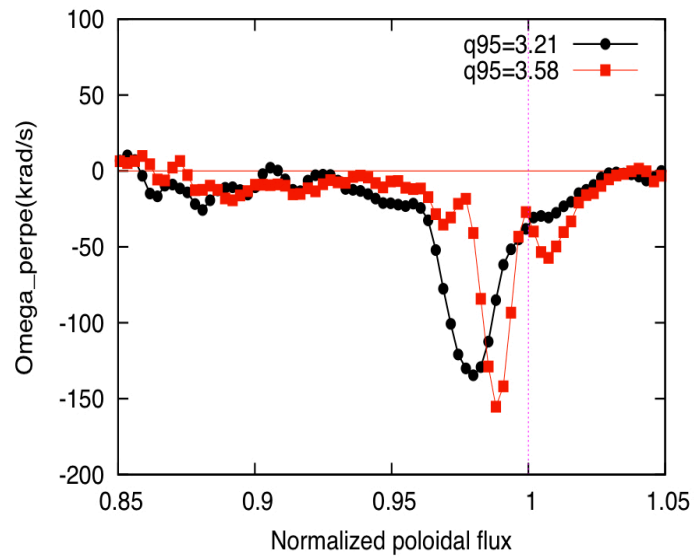
Primary shielding currents accumulate toward inner radii and **still shields** RMPs.

XGC0 finds RMPs make $V_{e\perp} = V_{e*} + V_{ExB} \approx 0$ at pedestal top

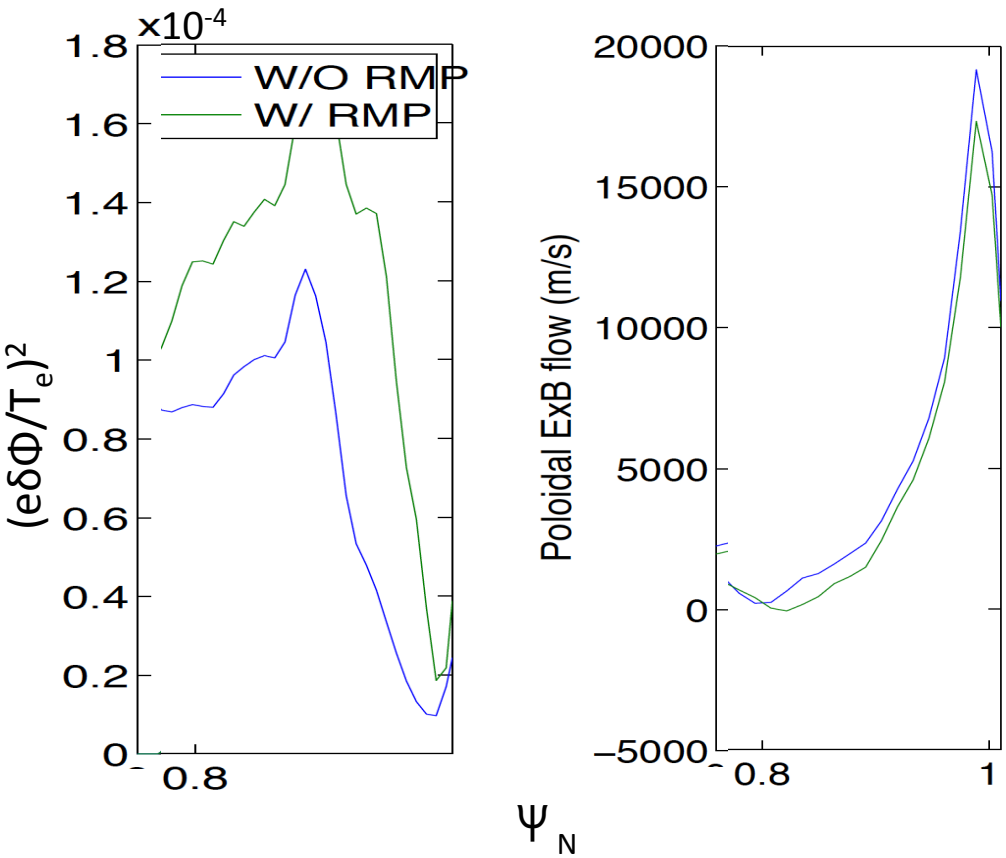
Large negative $V_{e\perp}$ ψ_N=0.98-0.99 is supported by the robust X-point orbit-loss effect.



When q_{95} is inside the suppression window, the $V_e \approx 0$ region moves outward into pedestal top



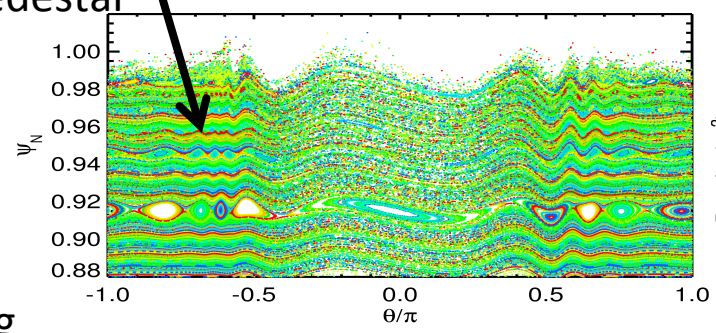
The XGC0-responded RMPs enhance the edge ITG turbulence



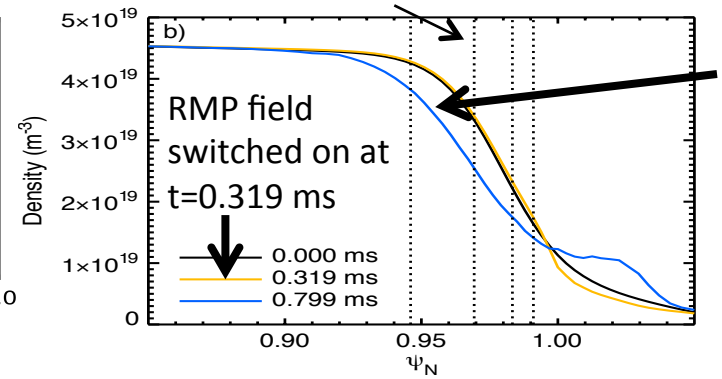
- The XGC0-responded RMPs are imported into XGC1
  - XGC0: drift-kinetic i + e and neutral recycling
  - XGC1: adiabatic electrons (plus n_0) to study the pure RMP effect
- Reduction in the mean V_{ExB} by RMPs is ~10%, while the $|\delta\Phi|$ enhancement is ~15%.
  - This effect will be enhanced by kinetic electrons
- This is only beginning of the study. Study will be extend to include kinetic electrons and other turbulence modes in XGC1.

XGCa Gyrokinetic Study (Hager): begins to pump out plasma density despite the good KAM surfaces in the M3D-C1 calculated RMPs.

Good KAM surfaces in the pedestal

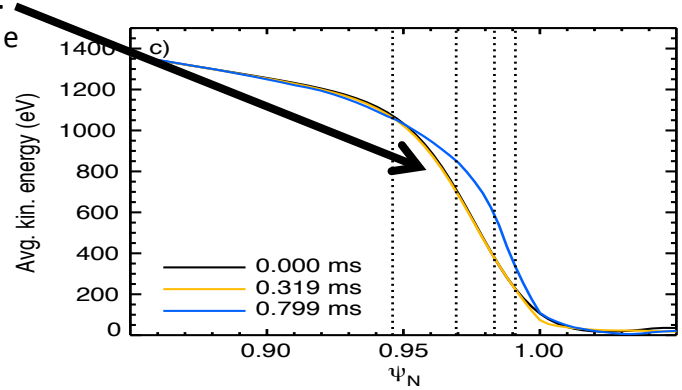


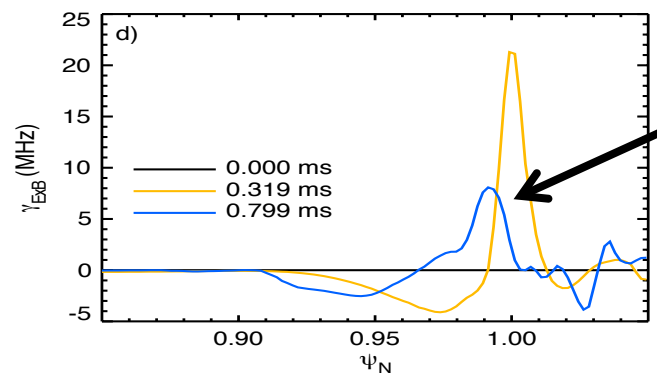
Rational surfaces:
10/3, 11/3, 12/3, 13/3



Density reduction begins via pumpout

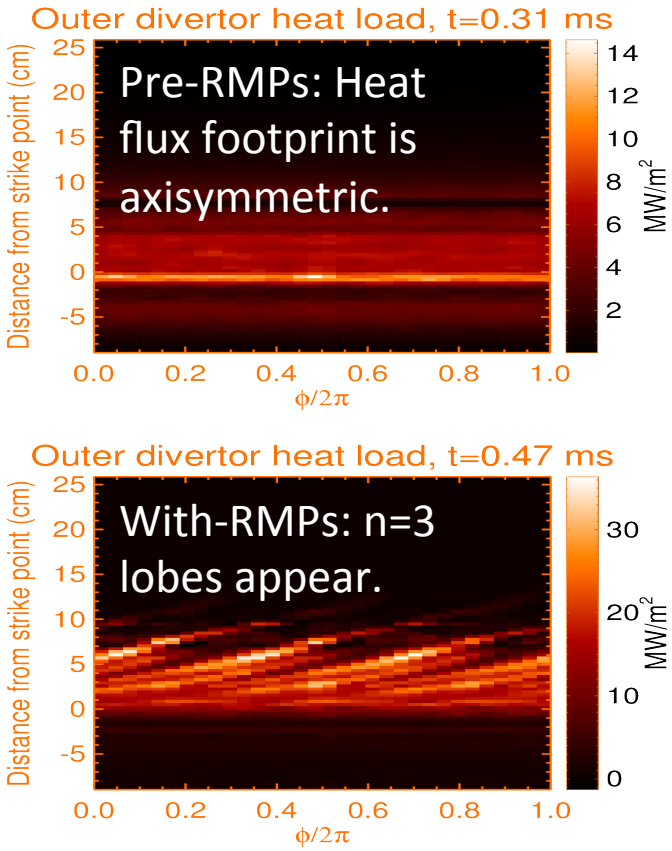
Steepening of Grad-T_e





Reduction of ExB shearing rate by RMPs around separatrix

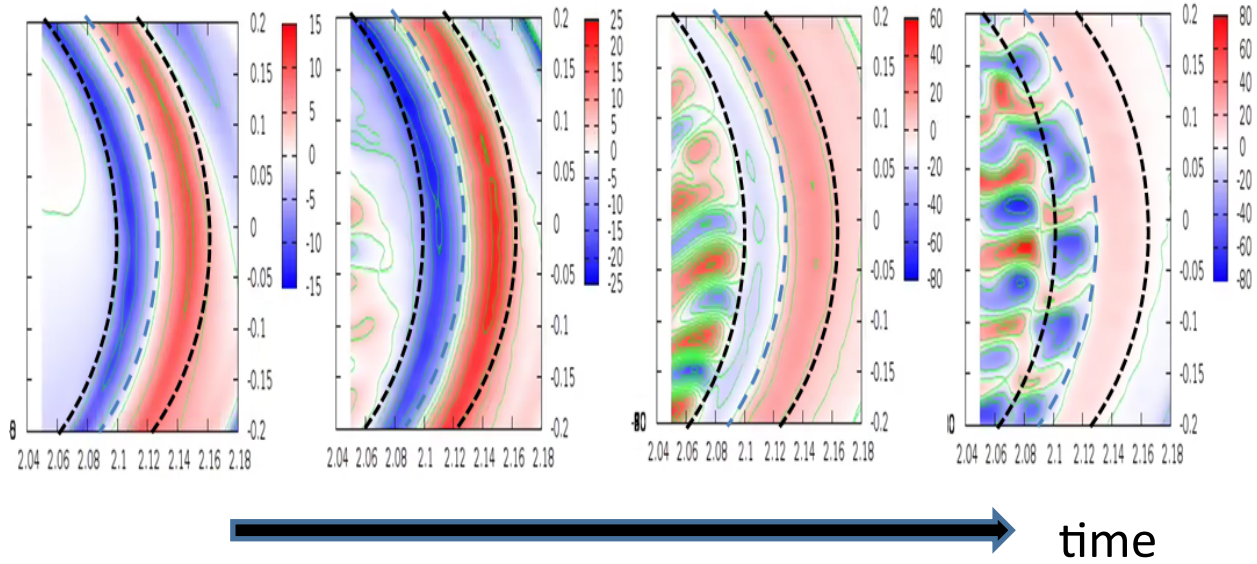
XGCa also calculates the RMP-modified divertor heat flux footprint



- Will improve physics fidelity further in XGCa and XGC1 by utilizing
  - Turbulence
  - XGC's internal Ampére's law solver to compute gyrokinetic RMP penetration consistently with RMP-driven transport: in progress by R. Hager

Interaction of microturbulence and neoclasscial physics around magnetic island: GK ions + DK electrons [J.M. Kwon]

TEM turbulence-spreading into island is blocked by island around O-point

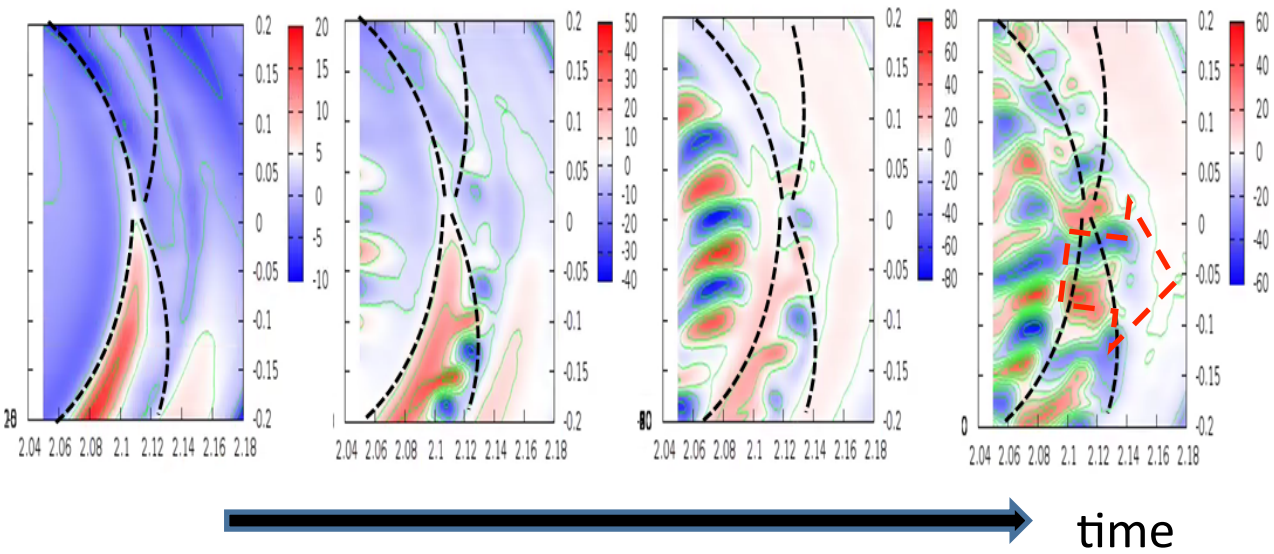


- Black dashed line → Island boundary; Blue dashed line → Radial island center
- Turbulence is confined: spreads into the island, but blocked at the island center

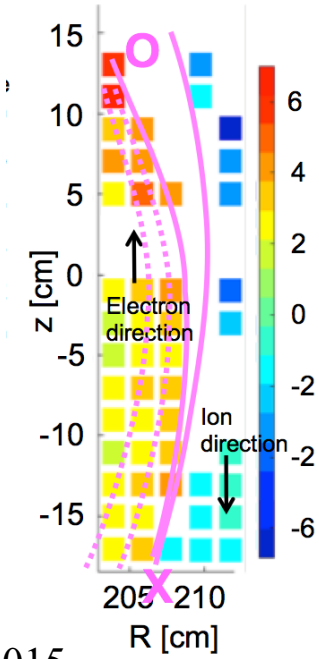
Turbulence is unconstrained near X-point

- Experiment: Turbulence stronger near the X-point
- XGC1: Turbulence is unconstrained around the X-point.

TEM turbulence simulation in XGC1 for the KSTAR plasma



- Experiment: Turbulence direction changes across island.
- XGC1: TEM → ITG

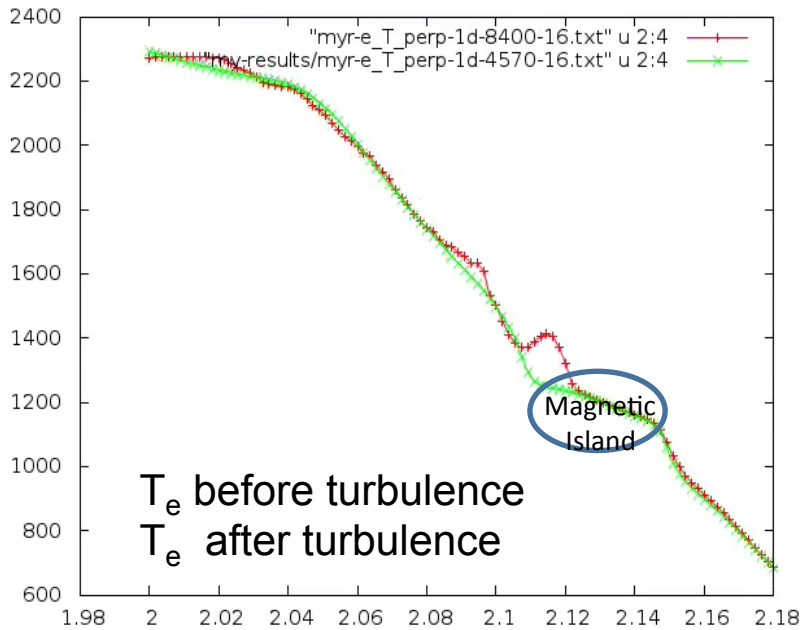


Could be related to exp. observation by K. Ida, www.nature.com/ScientificReports, 2015

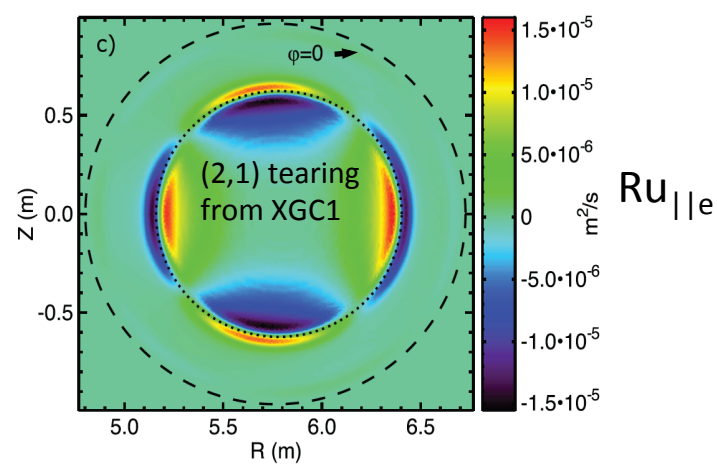
3D GK simulation says that

- **p_e is not flat in an magnetic island even in a neoclassical equilibrium.**
- **Turbulence-spreading sends electron heat into the island and adds to ∇p.**

Radial T_e profile across the O-point

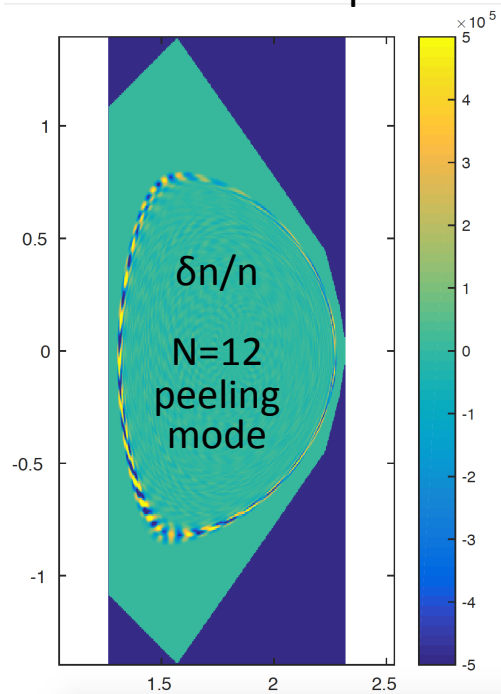


- Microturbulence, MHD modes, and neoclassial physics need to be simulated together in 3D for a more complete understanding of the island/ neoclassical tearing mode physics.



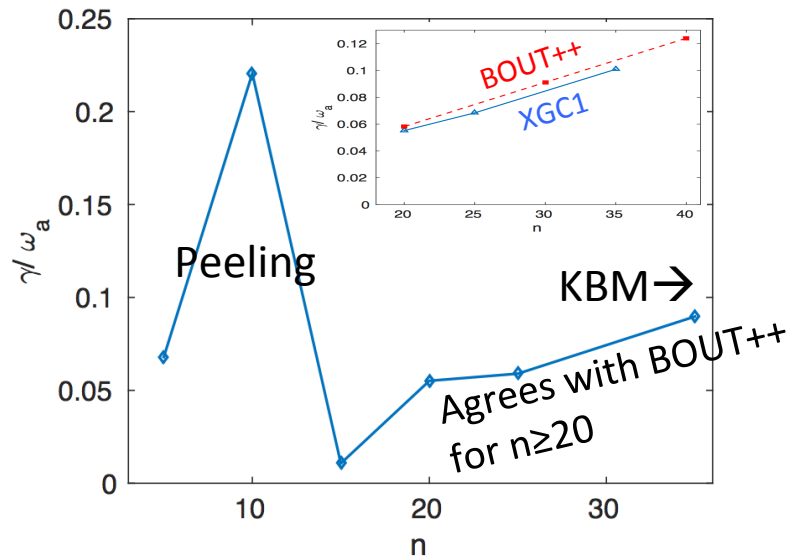
Gyrokinetic edge localized modes in XGC1 [S. Ku]

A KSTAR H-mode plasma



Amplitude at inboard is about the same as at outboard→ slab type modes. Fux expansion the detailed mode structure stand out at inboard.

DIII-D discharge #144981



GK ELM includes ω_r, ρ_i, banana orbits, poloidal-asymmetry, ExB shearing, etc.

Discussion

- **High-fidelity simulation can be available for focussed topical areas**
  - Number of topics and depth of study are limited by manpower
  - Fidelity goes up with computing power
  - KISTI at Korea is soon to have >20PF computer
  - 200PF DOE computer can be available through collaboration
- **Candidates for impactful high-fidelity physics on KSTAR**
  - L-H transition physics
  - Divertor heat-load width physics
  - 3D physics: RMP, sawtooth, NTM and island physics
  - Pedestal structure and onset of edge localized modes
  - Edge-core interaction
  - Impurity physics
  - Onset of Sawtooth instability
  - Density limit
  - Onset of plasma disruption