Recent Developments in Gyrokinetic Understanding of Divertor Heat-Load Width*

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(Acknowledgement: NSTX, DIII-D, C-Mod, JET and ITER collaborators)

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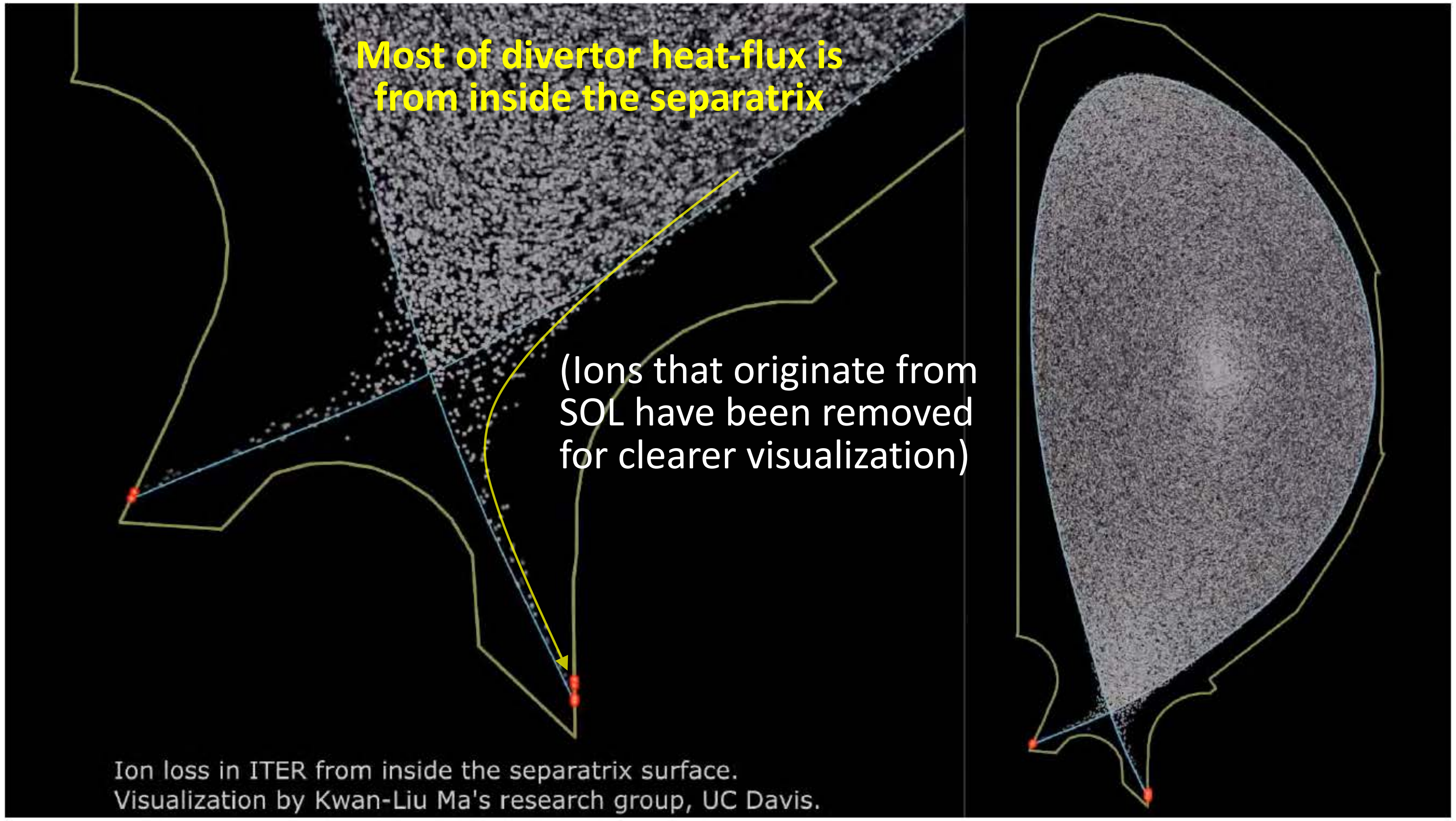
*This work funded by DOE FES and ASCR through the SciDAC Program

*Computing resources provided by OLCF and ALCF via INCITE, and NERSC via DOE SC allocation

The gyrokinetic code XGC tries to simulate plasma particle dynamics as in real experiment, according to Vlasov-Fokker Planck equation, below gyrofrequency

Mission: Use largest computers to perform first-principles-based studies

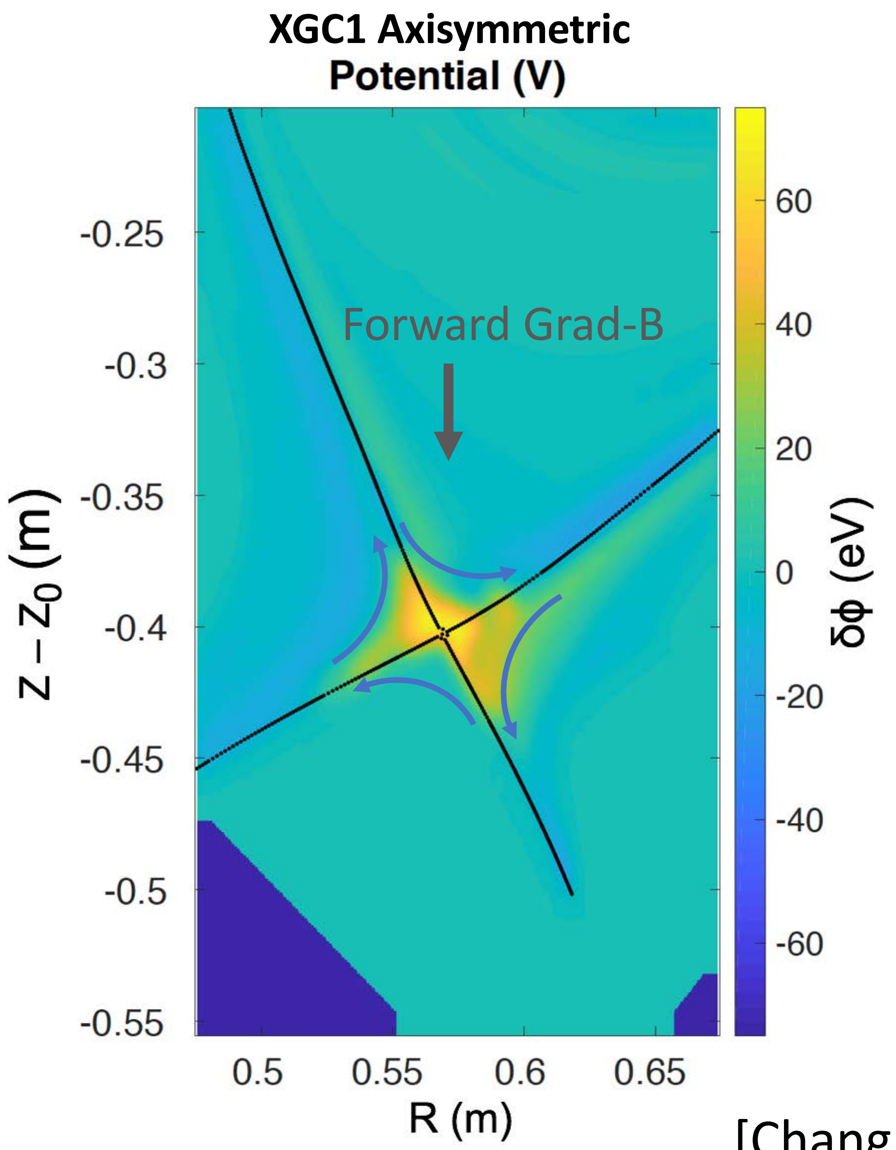
- Total-f particle-in-cell
- Neutral particle recycling with atomic cross-sections
- Logical sheath at material bd
- Non-Maxwellian plasma
- NL Fokker-Planck operator
- Heat, momentum & cooling source/sink
- > Trillion particles: Requires largest computers
- Attached plasma so far, moving toward detachment.



ITER

Free parameter: neutral particle recycling rate (R=0.99) & Φ(limiter)=0.

XGC outputs all the drift motions, including ExB around X-point

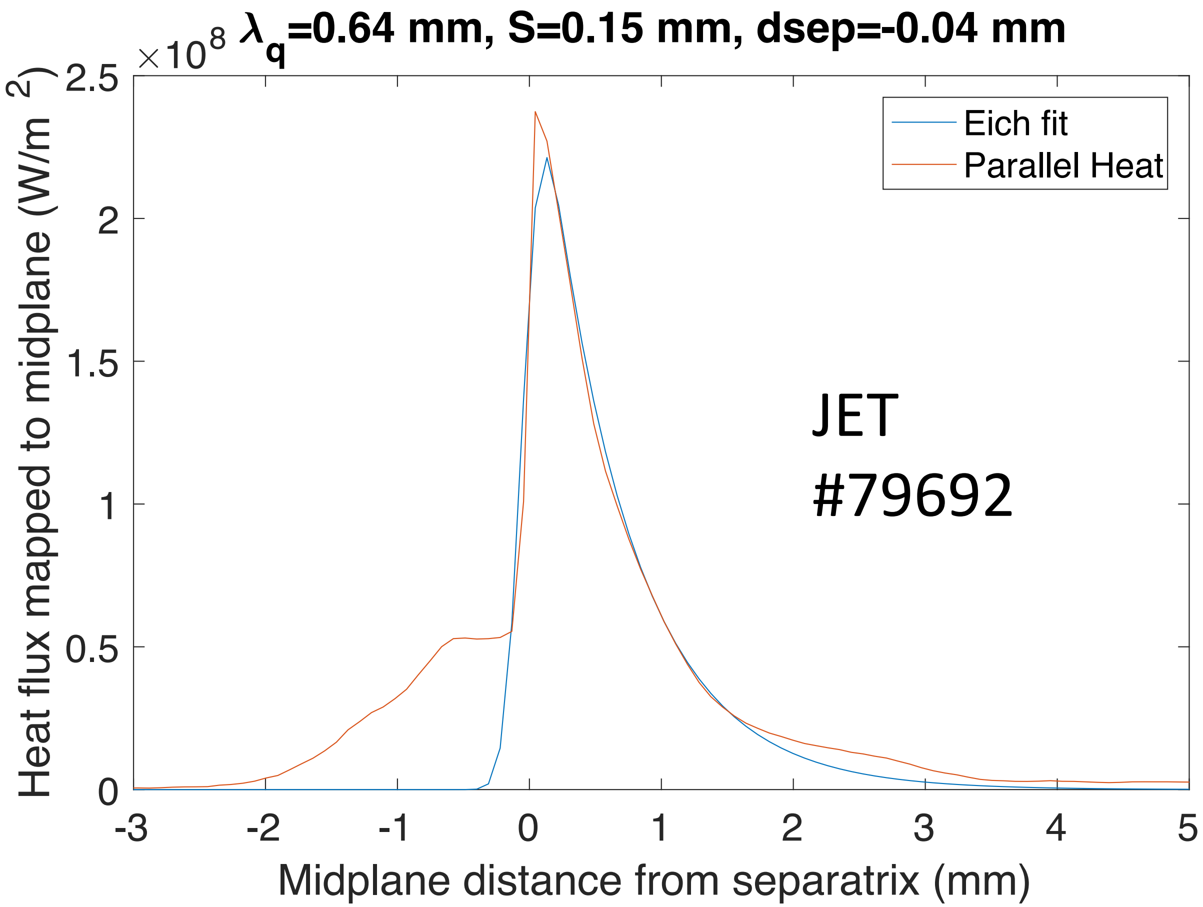


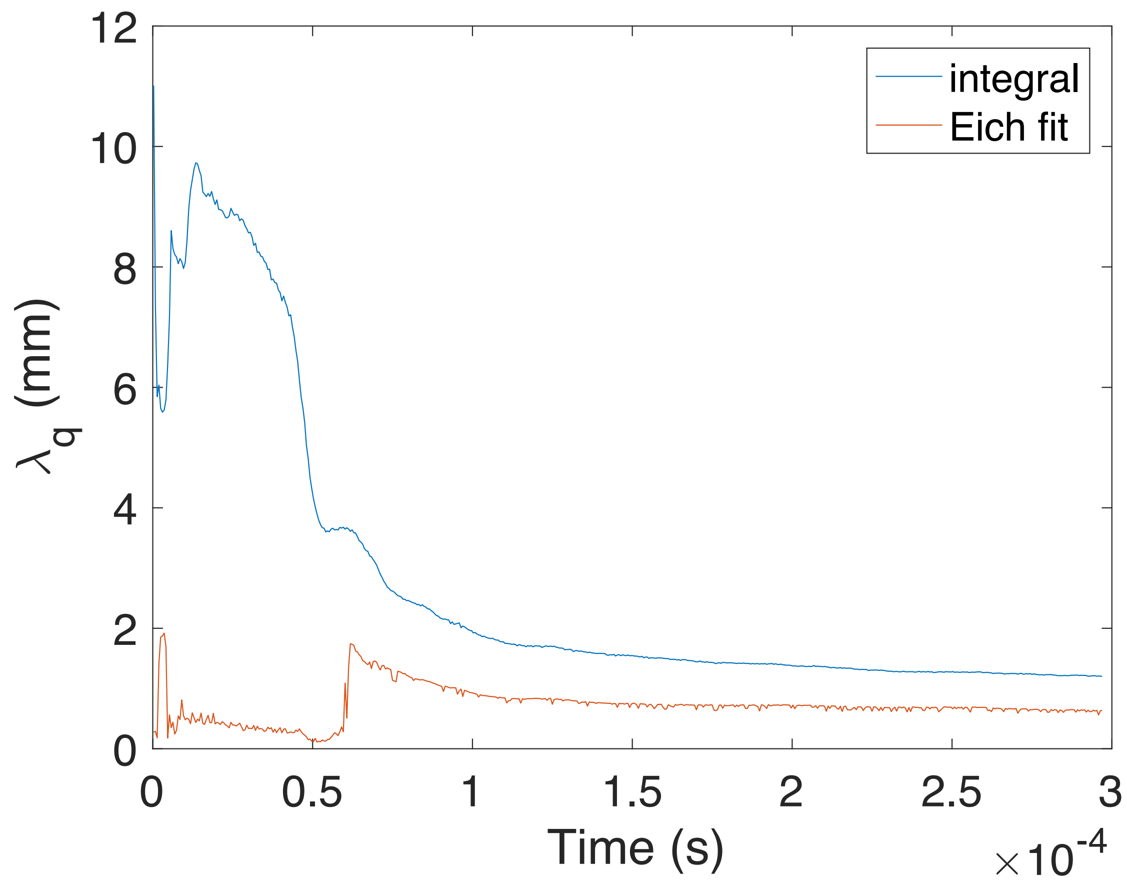
a C-Mod, H-mode plasma

[Chang et al., PoP 2019]

- Forward Grad-B:
  - Potential hill with higher plasma density around X-point
  - Lower T_e around X-point (pressure equilibration)
  - Impurity particles from SOL tend to enter into core through the high-field side near X-point
- Backward Grad-B reverses the ExB drift direction

XGC automatically outputs the gyrokinetic heat-flux footprint consistently with neoclassical, turbulent and neutrals physics





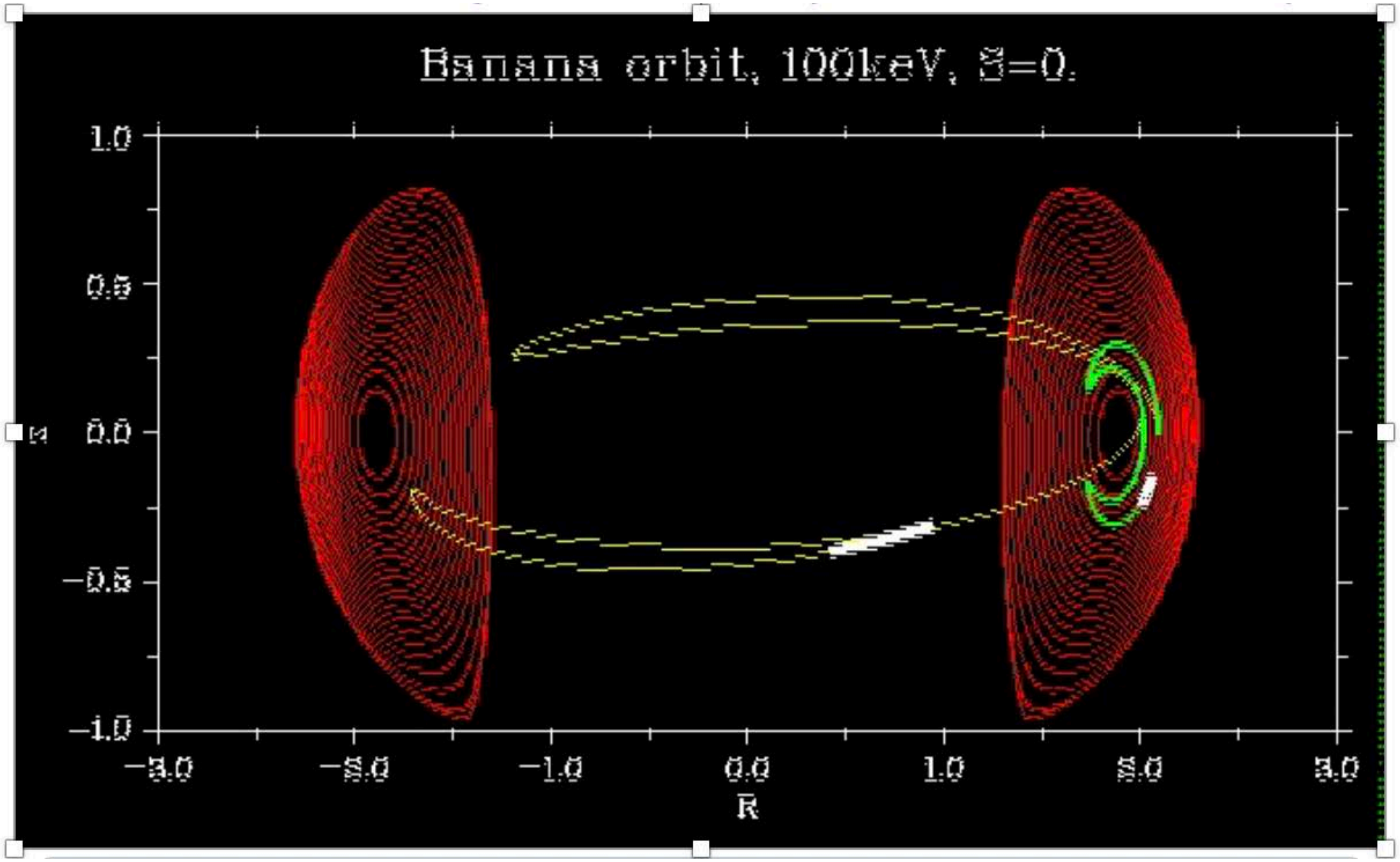
Outline/Summary

The edge gyrokinetic code XGC says

- Today's conventional tokamaks and 5MA-ITER:
  - Transport in pedestal is at ion neoclassical level
  - Transport across separatrix is also at ion neoclassical level despite the "blobby" turbulence.

  → λ_q ~$0.63/B_{pol}^{1.19}$ [Eich (~Goldston)]
- 15MA-ITER: Transport in pedestal and near-SOL is dominated by kinetic micro-turbulence
  - Weak neoclassical ExB shearing due to small $\rho_{i,pol}/a$ cannot suppress turbulence [Kotchenreuther, Chang 2017]
  - This also includes the weak neoclassical X-point orbit-loss driven ExB shearing rate [Chang 2002, 2017]
  - XGC finds that λ_q^{XGC} is spread by kinetic trapped-electron turbulence by >6x λ_q^{Eich}
- Machine Learning and Regression reveal a hidden parameter $a/\rho_{i,pol}$
  - Consistently with the neoclassical ExB shearing physics
- A simple correction to Eich formula is identified (preliminary)
  - A manufactured JET plasma at higher I_p and ITER plasma at I_p~12MA are needed to refine the formula
- To validate the XGC findings – trapped-electron turbulence – on today's tokamaks, a turbulence-dominant wide pedestal with high T_e(sep) may be used: $\rho_{i,pol}/L_{ped}<<1$ and weak ν_e at separatrix
  - QH mode with edge ECH/LHH could be a good candidate?
  - λ_q measurements from EAST with edge LHH shows a significant λ_q broadening?

Kinetic effect: Neoclassical ion orbit excursion generates radial electric field



- Banana width $\sim \rho_{ip} \propto 1/B_{pol}$
- Ion/electron banana width ratio is $(m_i/m_e)^{1/2}$ >>1

→ Radial charge separation

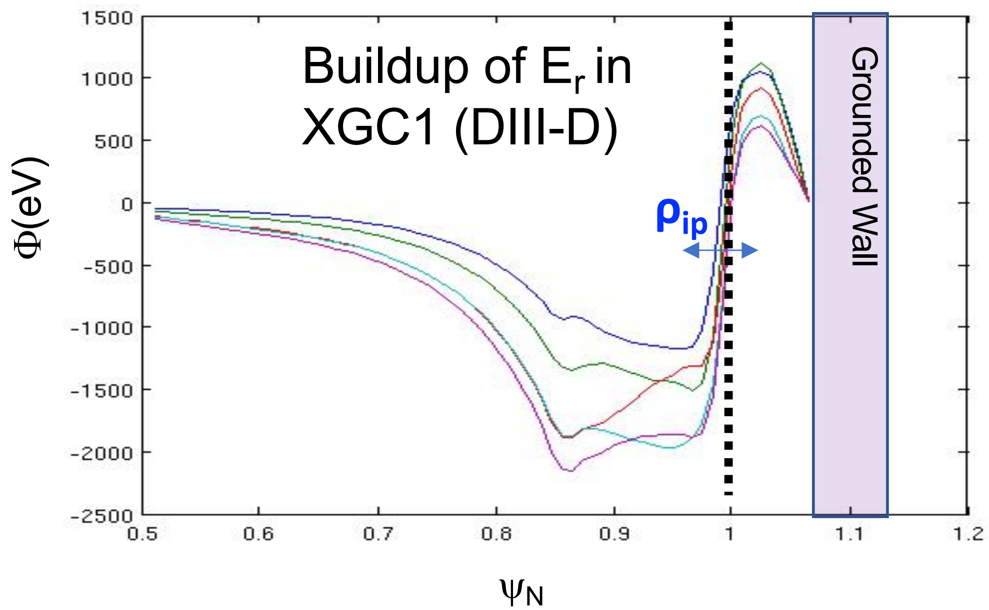
→ (Sheared) radial electric field generation
[Chang, PoP2004]

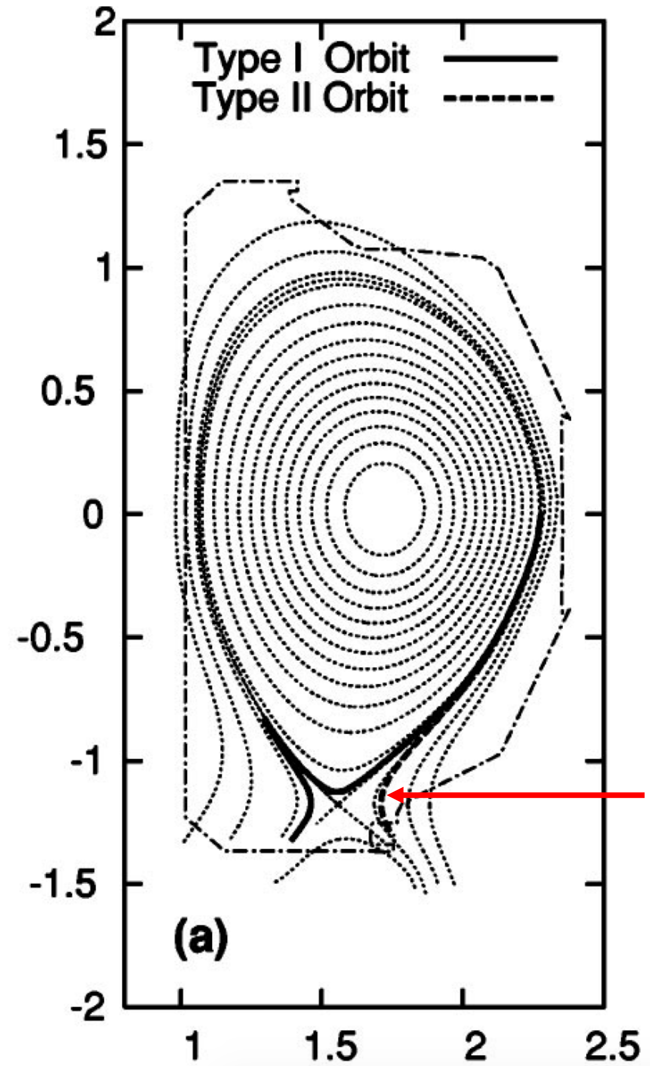
→ Suppresses turbulence

- If $\rho_{ip}/L \rightarrow 0$, neoclassical $E_r \rightarrow 0$

Kinetic effect: Neoclassical X-point orbit loss generates E_r-layer and toroidal rotation in the edge, from ion orbit drift ($1/B_{pol}$)

- B_P=0 at magnetic X-point and is small around it.
  - Weak poloidal ion rotation
  - Confinement is lost → ion orbit loss
  - Negative charge within ion banana width Δ_b inside separatrix → strong E_r<0 in Δ_b layer
- Strong E_r or toroidal rotation creates steep ∇p (force balance, electrostatic confinement) → pedestal

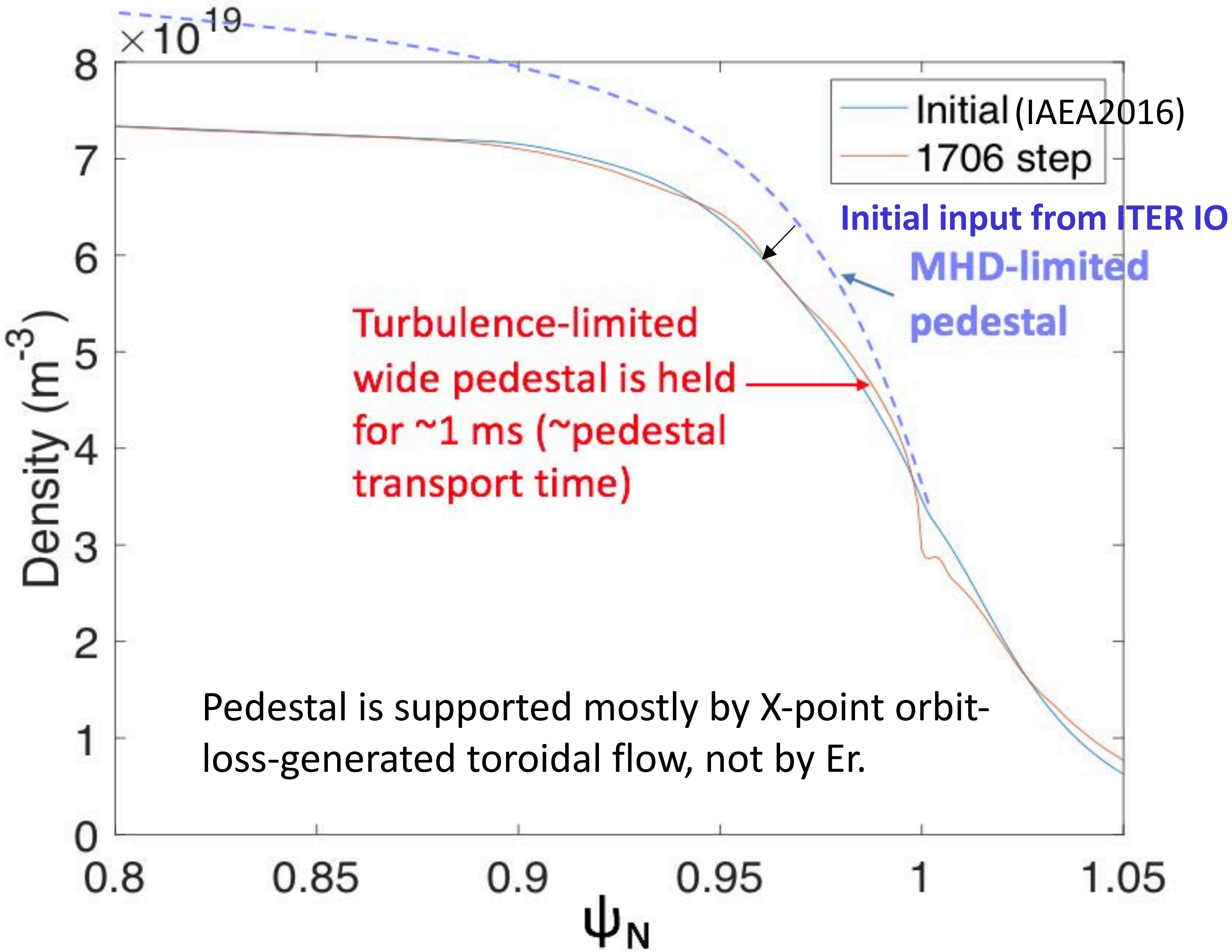




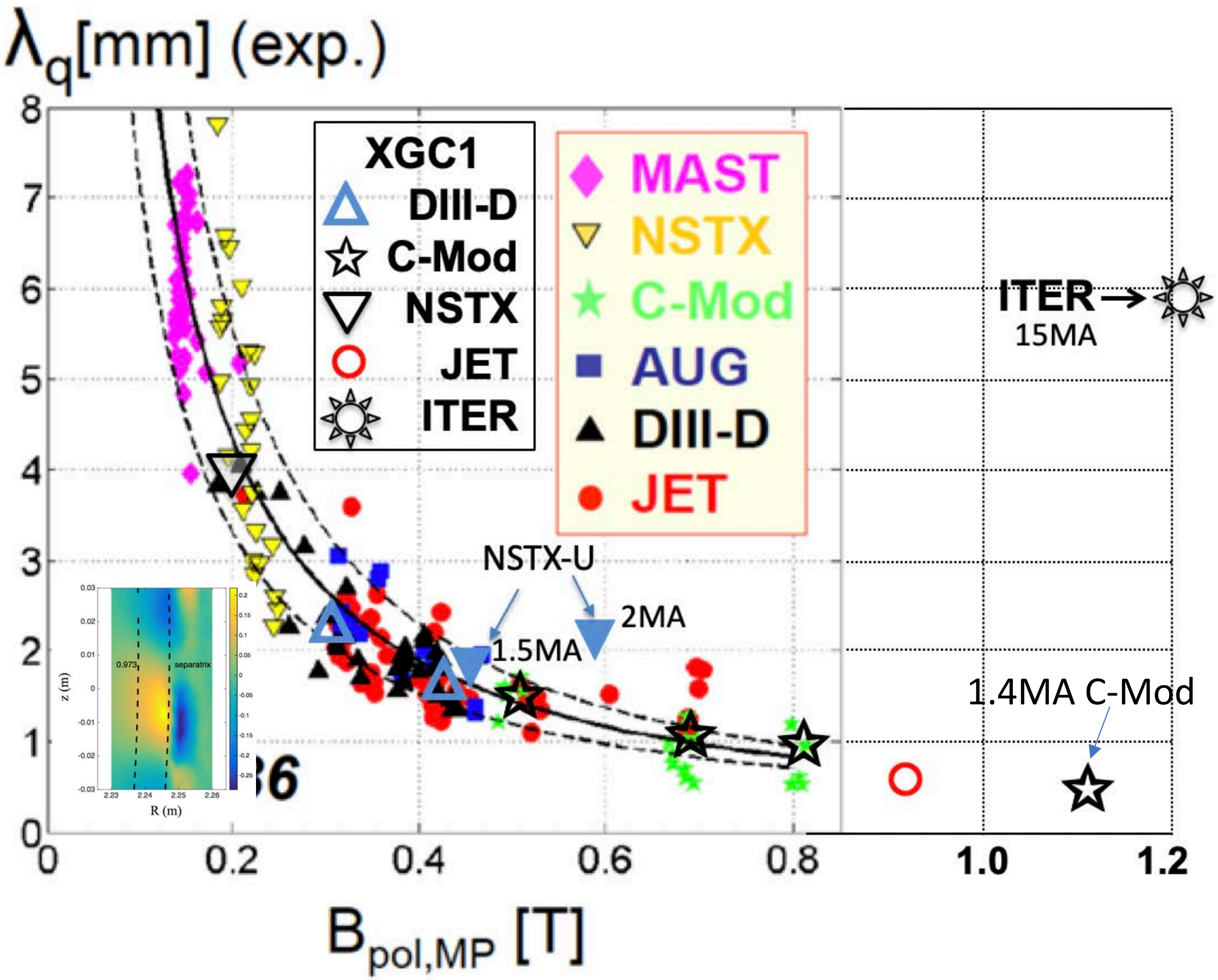
Typical ion X-point loss orbits (XGC)

XGC says: with $a/\rho_{i,pol}$ becoming very large, hence the neoclassical ExB shearing rate becoming weak, the 15MA ITER pedestal becomes turbulence-dominant

- A new turbulence-dominant pedestal profile is established in XGC1 in the pedestal-turbulence self-organization time (~1ms): but only a “wiggly” energy balance has been achieved yet.
  - n_e pedestal is ~2x milder than the MHD-limited profile.
- ITER at full-current may achieve a significant H-mode pedestal height that
  - Is only 10% lower than the operation design value,
  - But, mild enough not to provoke the usual ELMs from peeling-ballooning modes.
- More simulations will be performed on world #1 Summit, to confirm this important result further.



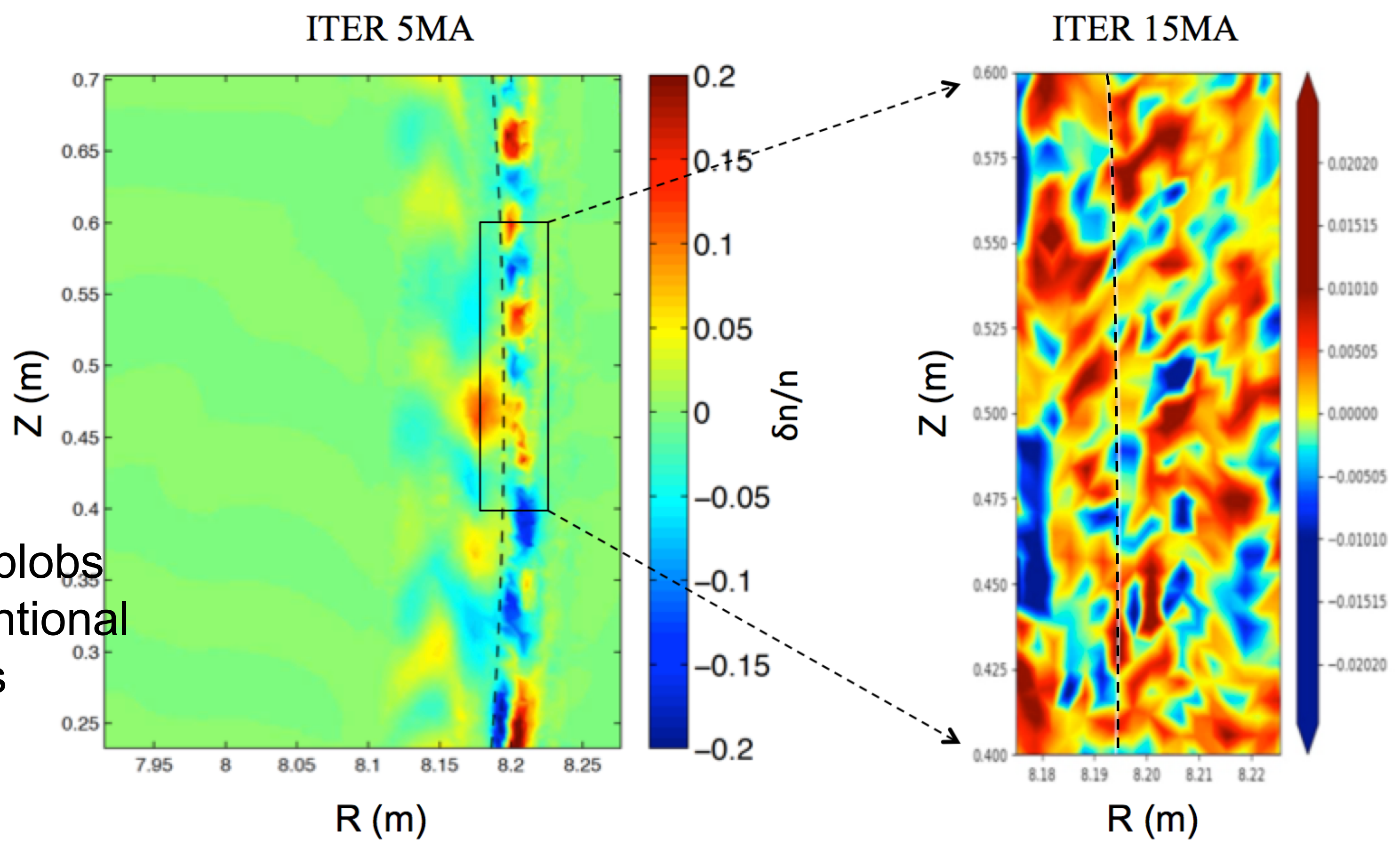
Predictions from gyrokinetic XGC agree with λ_q^{14}(Eich) on existing tokamaks, but not on 15MA ITER.



- Ion drift-motion dominant $\propto 1/B_{pol}$
- But, the same code predicts λ_q(XGC) >6λ_q(Eich) for 15MA ITER
  - Confirmed via multiple attempts
- High-current C-Mod experiments have B_{pol} similar to 15MA ITER
  - Both experiment and XGC showed $\lambda_q \sim \lambda_q^{14}$(Eich): Is this a bifurcation?
  - Hidden parameters, or something is wrong: simulation has been confirmed multiple times
- XGC on NSTX-U at 2MA also produced a wider λ_q
  - But, not at 1.5MA
  - Hidden parameters, again?

XGC: Electron heat-spread by kinetic trapped electron modes is the suspect

- Fact: $\rho_{ip}/a \rightarrow 0$ in 15MA ITER yields little neoclassical ExB shearing,
- Fact: $(2a/R)^{1/2} \rightarrow 1$ in NSTX-U with warm T_e yields TEM turbulence



XGC: Similar to blobs in today's conventional aspect tokamaks

TEM streamers are the suspect. ITGs do not penetrated into SOL [Chang, 2009].

- XGC found a mixed TEM-blob turbulence structure on 2MA NSTX-U

Isolated "**blobby**" turbulence (with **strong sheared-ExB** flow across separatrix)

Connected "**streamer**"-type turbulence (with **weak sheared-ExB** flow across separatrix)

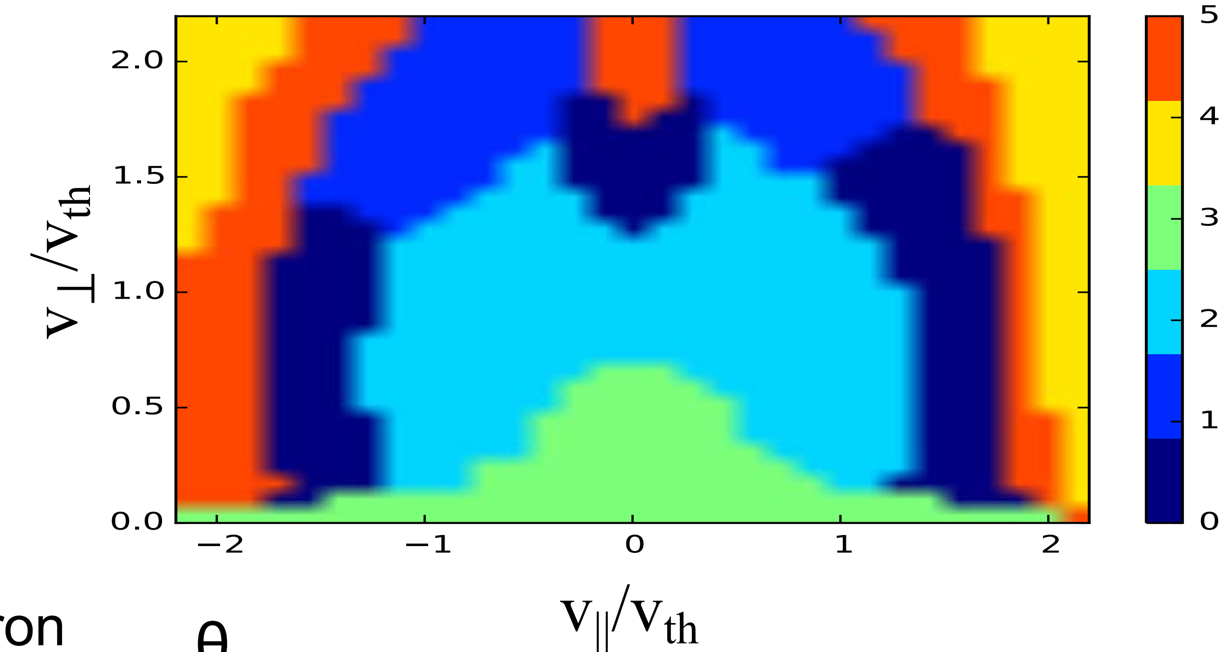
Machine learning reveals trapped electron interaction with turbulence in the 15MA ITER edge (R.M. Churchill)

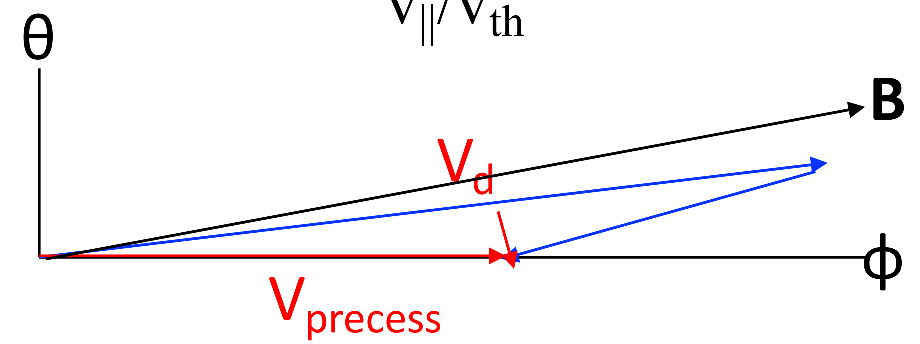
(Summit data, NERSC)

A strong non-adiabatic electron response found across the separatrix: characteristics of TEMs.

- K-means clustering, with K=6
- At a higher energy band, trapped electrons show correlated response to turbulence
  - Another sign of CTEM turbulence
- Because of the high $\omega_* \sim v(\rho/L)$ around the separatrix, q needs to be high for precession resonance by trapped electrons: $V_{precess} \sim v(\rho/R)(B/B_P)$

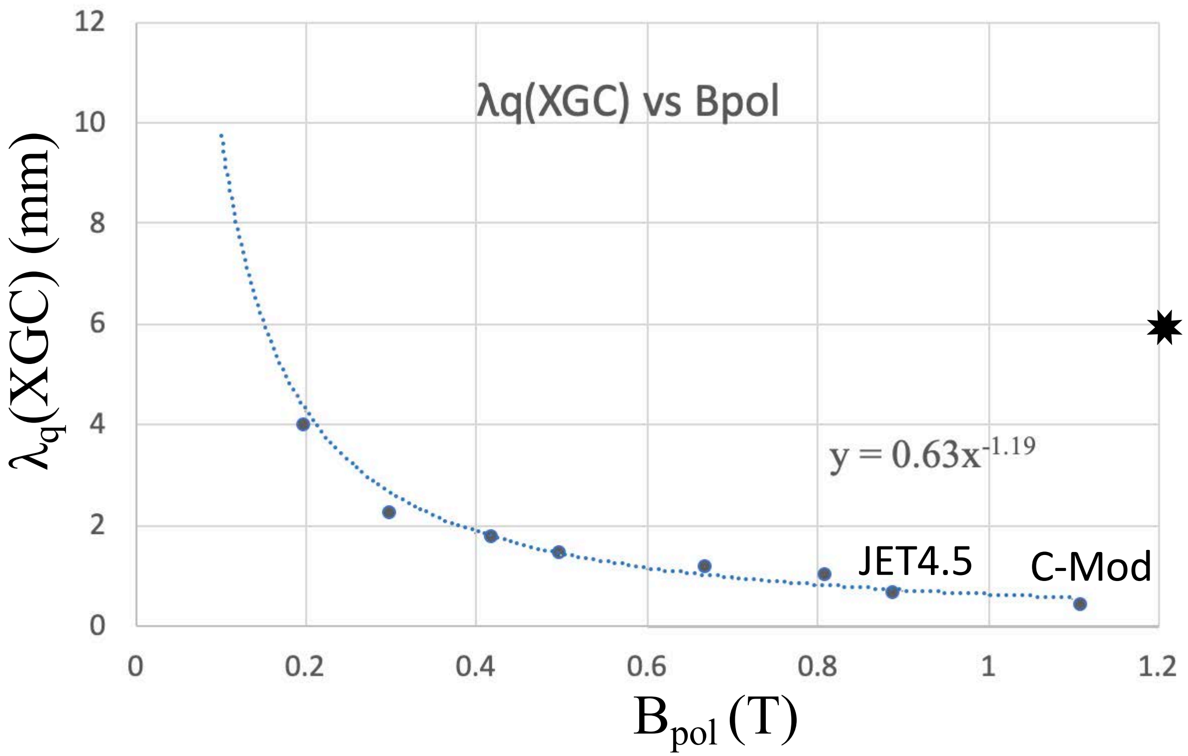
→ easier excitation of Collisionless trapped electron modes (CTEMs) just inside the separatrix, ψ_N=0.98-1, where ∇P_e is high.

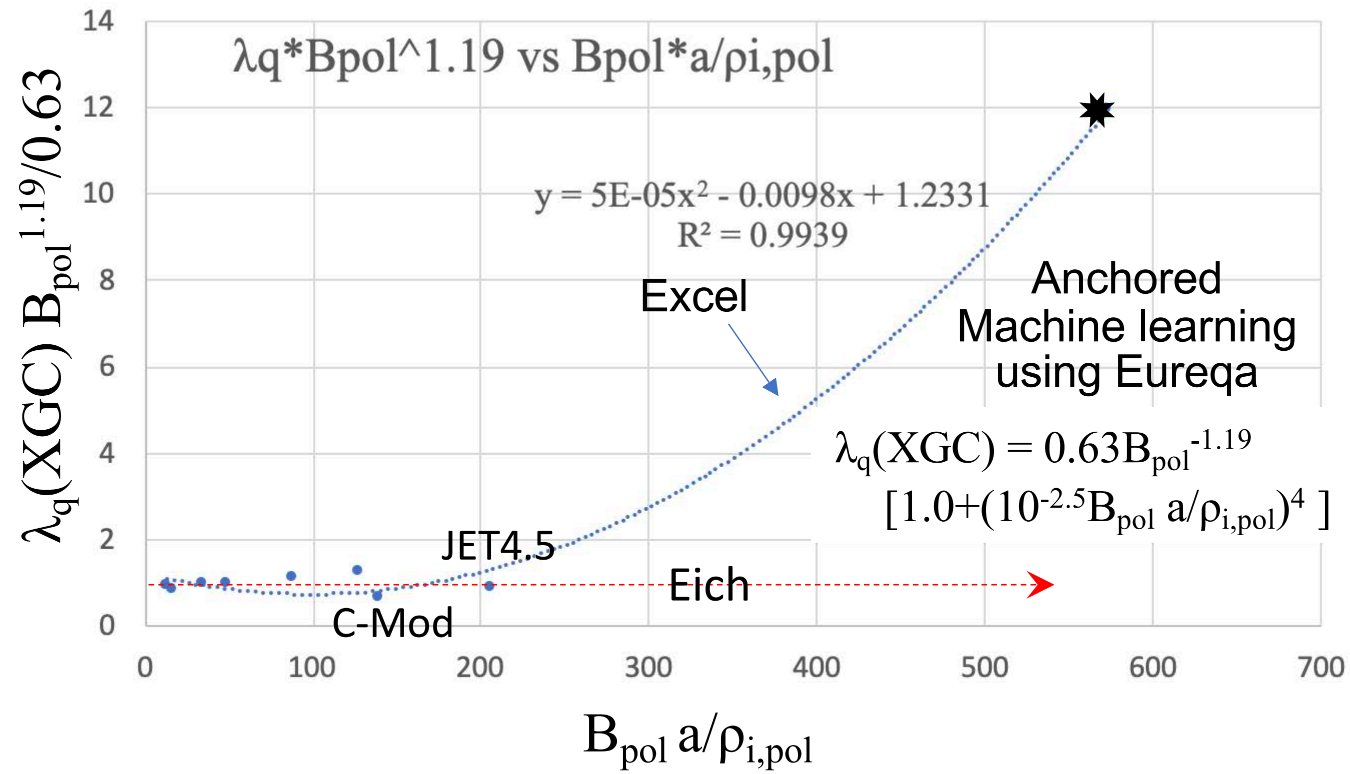




Looking for hidden parameters from CTEM physics understanding

- Large $a/\rho_{i,pol}$ weakens the neoclassical ExB shearing rate → stronger TEM



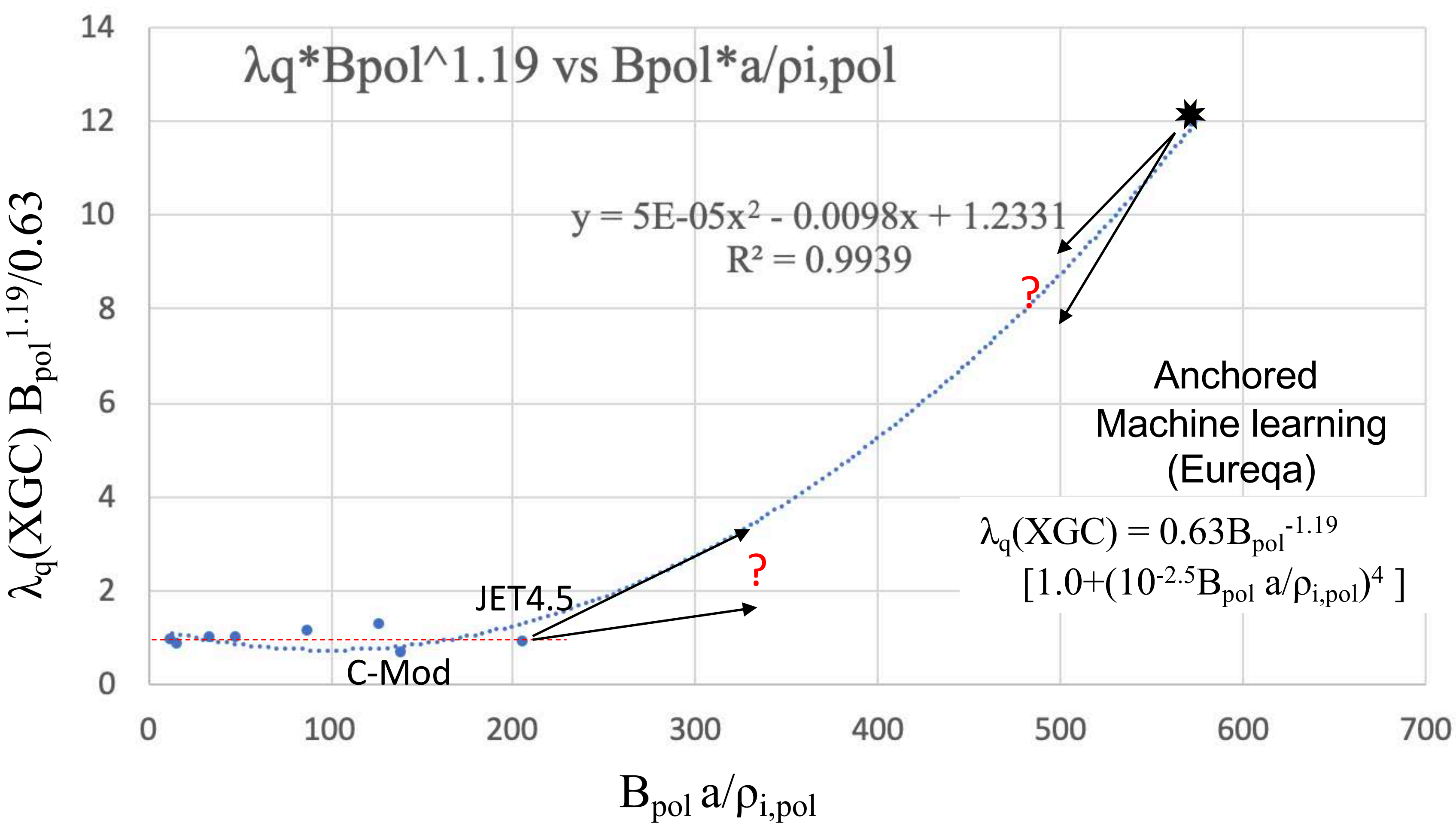


- In the present conventional aspect-ratio tokamaks, λ_q(XGC) follows λ_q(Eich).
- However, **λ_q(XGC) shows a discontinuity (of multiple solutions) between high-Ip C-Mod and 15MA ITER.**

- When we use $B_{pol}\, a/\rho_{i,pol}$ as the scaling variable,
  - λ_q(XGC) in the present tokamaks still follows λ_q(Eich)
  - and the discontinuity from high-Ip C-Mod to 15MA ITER disappears

Moving forward for a more accurate λ_q-scaling law towards ITER

Requires a large compute time on Summit



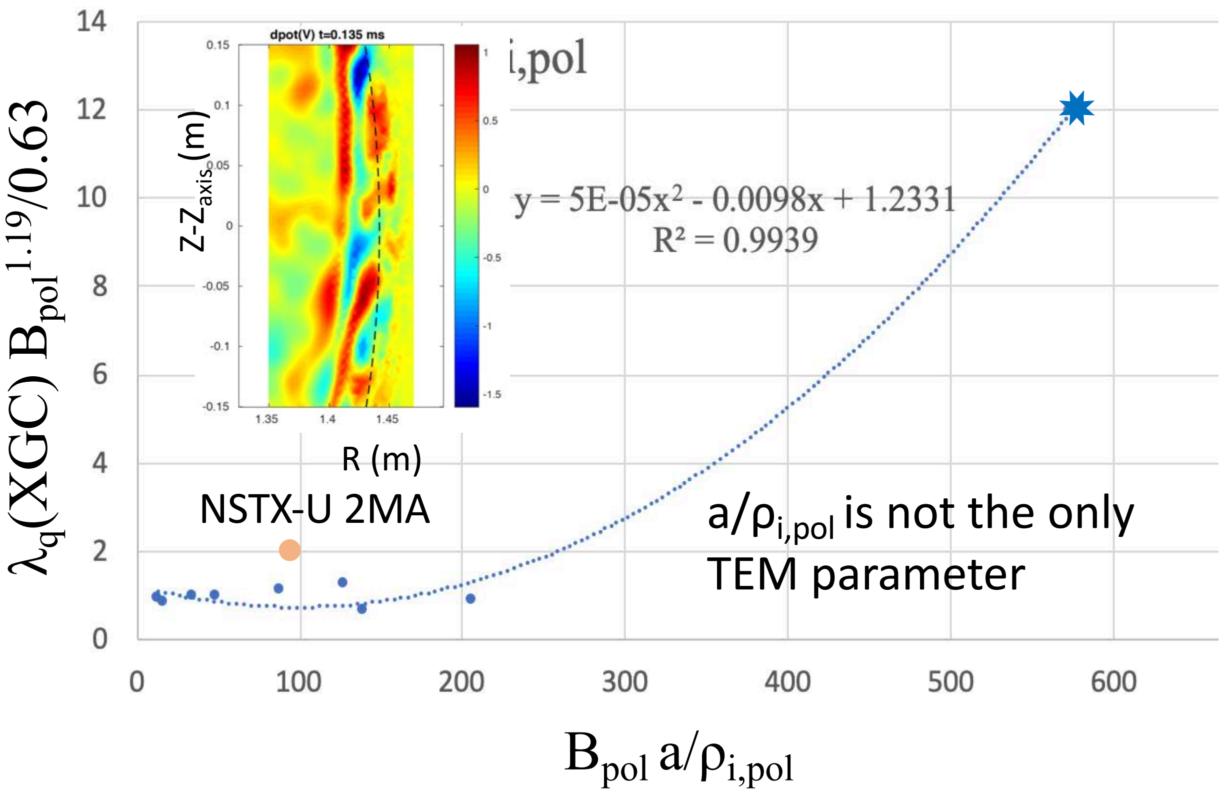
Further refinement using machine learning will be performed after more simulations.

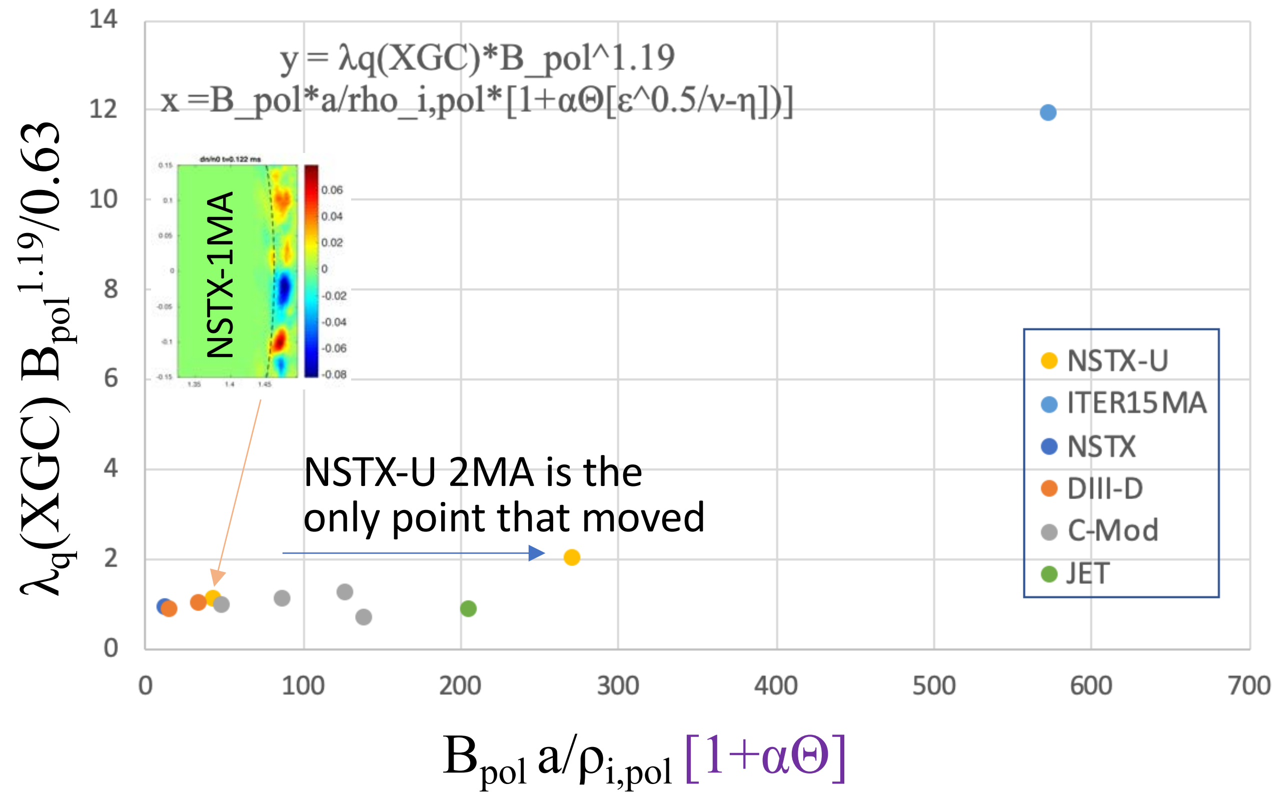
We need at least a couple more data points between the high-Ip JET and the full-B ITER

- Collaboration with JET and ITER teams needed to build some artificial plasma and B equilibriums

How do we validate the TEM broadening of λ_q in existing tokamaks?

Most of the NSTX-U edge electrons are in banana regimes → Strong CTEM drive if $\nu_{e*} \approx \nu_{e^\wedge} < 1$: validated





- λ_q(XGC) for 2MA NSTX-U shows ~2xλ_q(Eich)
- $N_{e*,\wedge}$ <1 at Ψ_N=0.99, most of the electrons are banana trapped
- Edge turbulence across separatrix is mixture of blobs and streamers → TEM

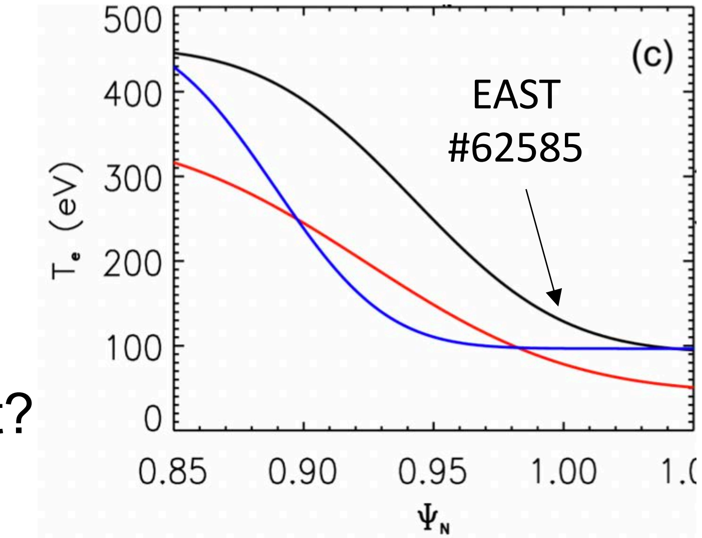
- Θ represents CTEM threshold
- Assume CTEM threshold ~ $(a/R)^{1/2}/\nu_{e*} > \eta$
- Fit α and η to make Θ=1 for NSTX-U 2MA, & 0 for 1.5MA → α=2 and η=1.75 have been chosen

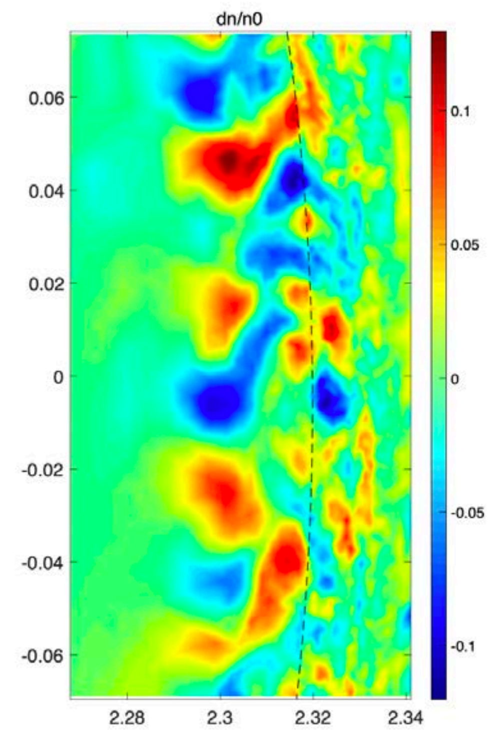
How do we validate the TEM broadening of λ_q in existing tokamaks?

- Look for experiments with “ITER-similar” edge condition
  - Turbulence-limited pedestal: large L/ρ_{pol}
  - Low ν_e^* <1 around the magnetic separatrix (using q_{95})
  - Low torque input

  → Can we study the QH mode edge plasma with low torque input?
  - Edge ECH/LHH can be helpful to reduce ν_e^*<1, given the experimental observations that the pedestal T_i increases more than T_e does in QH.

- Could the broader λ_q observed in EAST [Wan2016, Zhang 2016; Deng2018], with Lower Hybrid Heating in edge, be an example for the kinetic trapped-electron-mode broadening?
  - T_e(sep)~150eV, n_e(sep)~1x$10^{19}m^{-3}$ → ν_e^*<1
  - λ_q^{XGC}~1.7 λ_q^{Eich} : qualitatively agrees with experimental observation
  - Such a broadening was not seen without edge RF heating



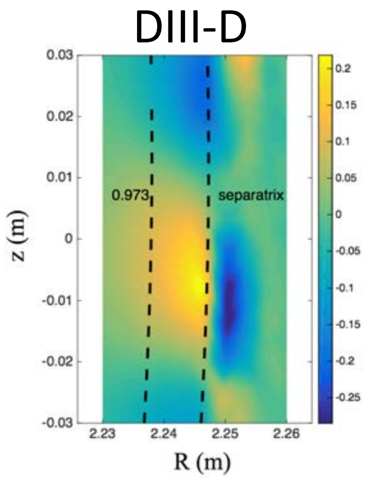


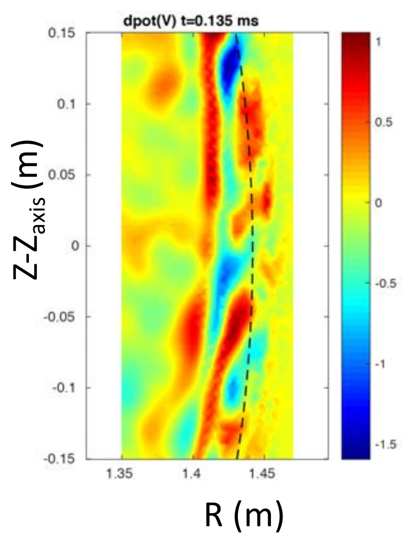
EAST
#62585

geqdsk
provided by
X. Xu

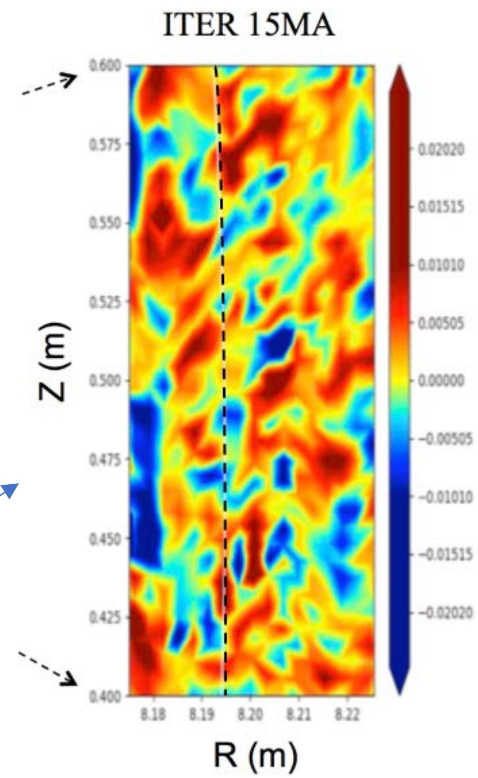
XGC suggests that the wide λ_q ITER is not from a turbulence bifurcation, but a gradual transition: supported by experimental measurement on EAST?

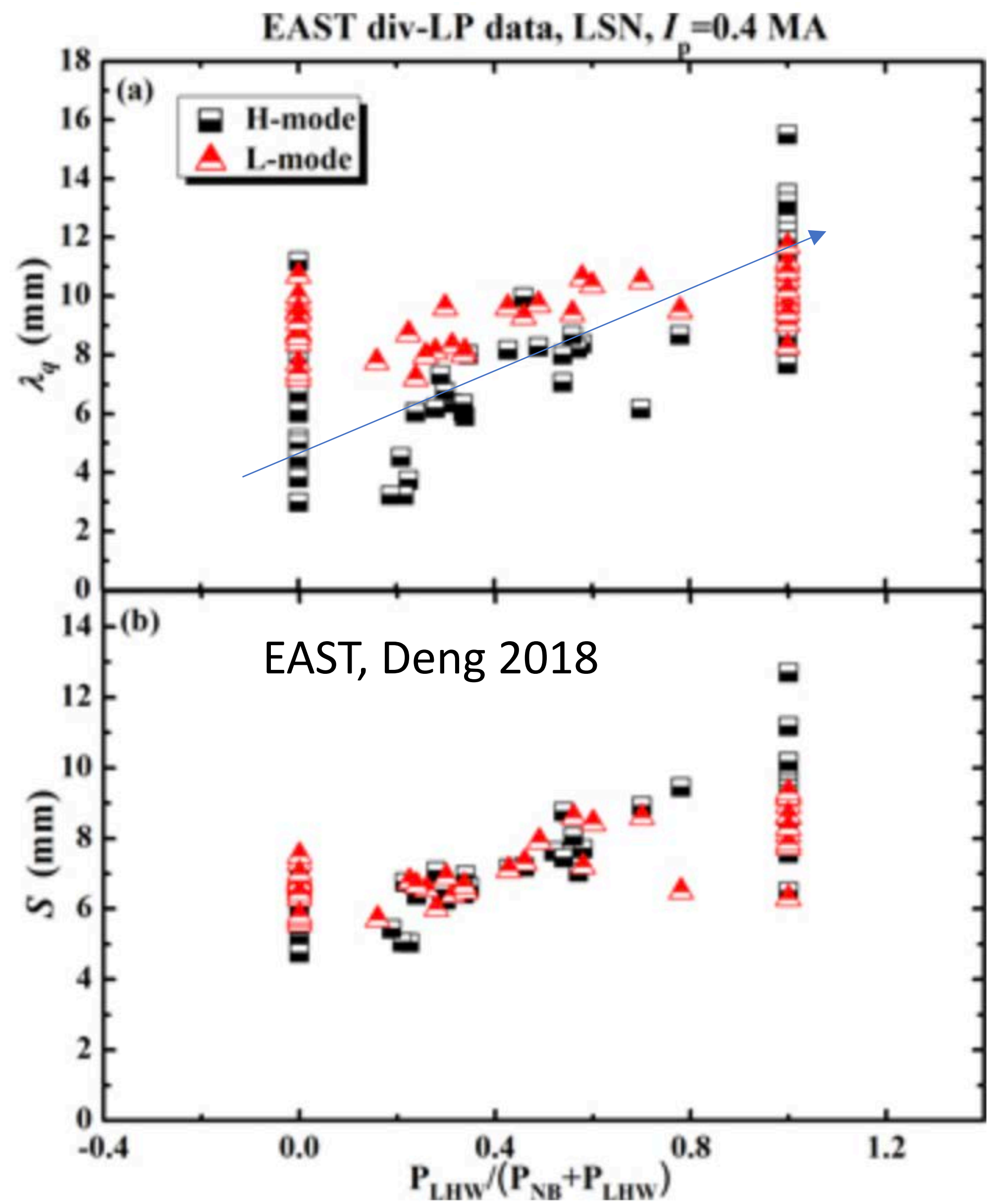
(XGC: Figures not to scale)





2MA NSTX-U, or
EAST with edge LHH





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