Infuse Workshop, 11/9/2023

XGC Predictions of Scrape of Layer Width in Present and Future High Field Spherical Tokamaks*

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*Funding provided by US DOE via INFUSE program and computing resources provided by NERSC

XGC-ST40 INFUSE Collaboration Status 1

- Approved in FY2021
- CRADA signed in FY2022
- Simulation of a lower current (0.5MA) ST40 discharge was performed in FY2022
  - After several trials, it was concluded that the plasma profile was too far from gyrokinetic equilibrium: below the turbulence criticality; λ_q not enhanced
- Tokamak Energy decided to identify a higher current, better diagnosed discharge
  - A new 1 MA plasma profile (#ST10014) was given to PPPL in CY2023
  - Multiscale electrostatic simulation was performed with a fruitful result
    - Result reported here
    - Neoclassical, electrostatic turbulence, neutral particle recycle in realistic diverted geometry
- #ST10014 discharge, however, still did not have an experimental measurement of divertor heat-load footprint

XGC-ST40 INFUSE Collaboration Status 2

- At 2023 IAEA-FEC London, Tokamak Energy and XGC teams had a meeting
  - Tokamak Energy can now measure divertor heat-load footprint
  - XGC team may not want to proceed with EM simulation of #ST10014 since this shot does not have experimental measurement of heat-load footprint
  - Tokamak Energy will give the XGC team, by Dec. 2023, a new plasma discharge input that has experimental measurement of divertor heat-load footprint
    - ST40 sees a highly peaked electron heat-load right on the outer divertor leg cross-section for an unknown reason: XGC also sees this.
    - Thus, cannot use Eich's fitting formula
  - PPPL will wait for the new discharge input parameters
    - perform EM simulation for validation and physics understanding
  - CRADA no-cost extension (till April 26, 2024) has been submitted to DOE, accordingly
- A computing time proposal has been submitted to ORNL/OLCF specifically for XGC's public-private collaboration simulation

The edge-optimized gyrokinetic code XGC

Realistic divertor geometry

Whole volume w/o artificial inner bd
Logical sheath outer boundary

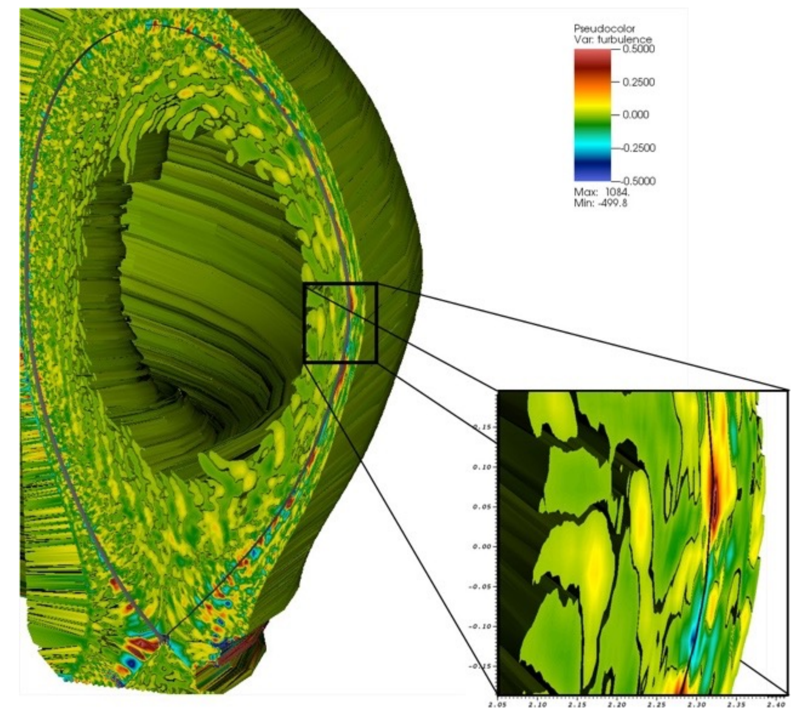
Non-Maxwellian particles with nonlinear
Fokker-Planck collision operator

Turbulence dynamics

Neoclassical particle dynamics
with X-point orbit loss

MC neutral particle recycling and
atomic physics dynamics

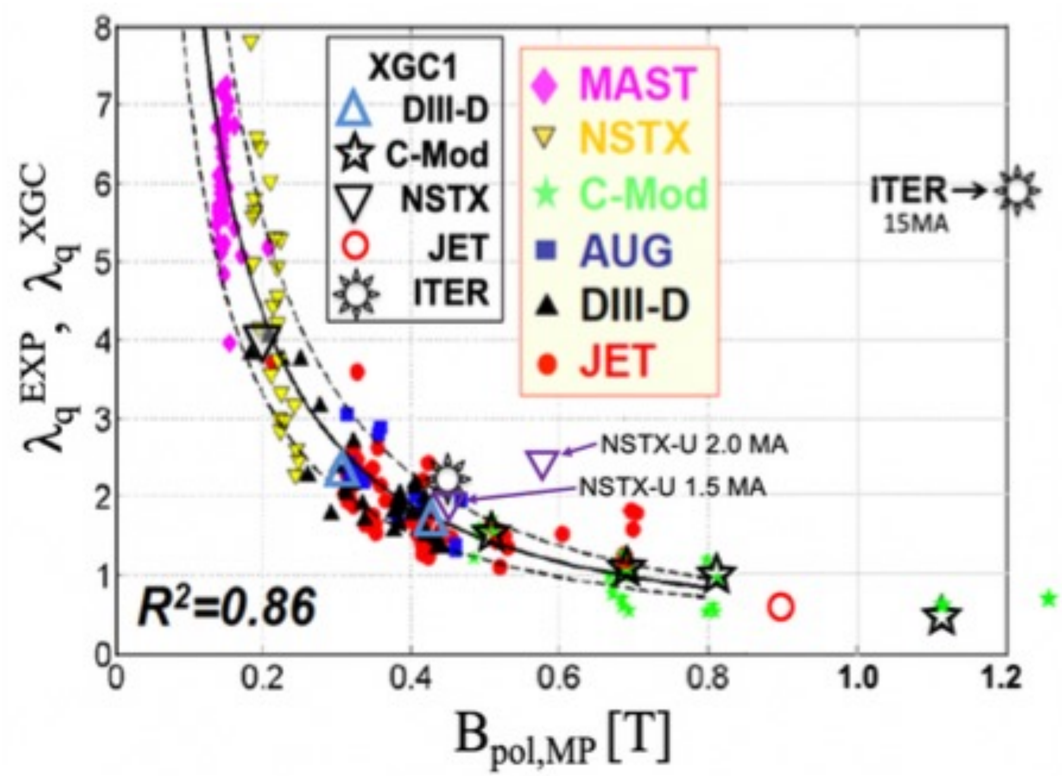
Heat/torque/cooling sources



A typical edge electrostatic turbulence in a tokamak plasma simulated by XGC. Sheared streamer and blobby turbulence structures around the magnetic separatrix surface can be seen. [Visualization is by D. Pugmire of ORNL]

Motivation

- Smaller divertor surface area in a ST reactors raises deeper concern regarding the divertor heat exhaust density
- How will the baseline divertor heat-load width in a high-current ST plasma compare against Eich's data regression values?
  - In terms of λ_q, which is the heat-load width measured on outer divertor plates mapped to outer midplane

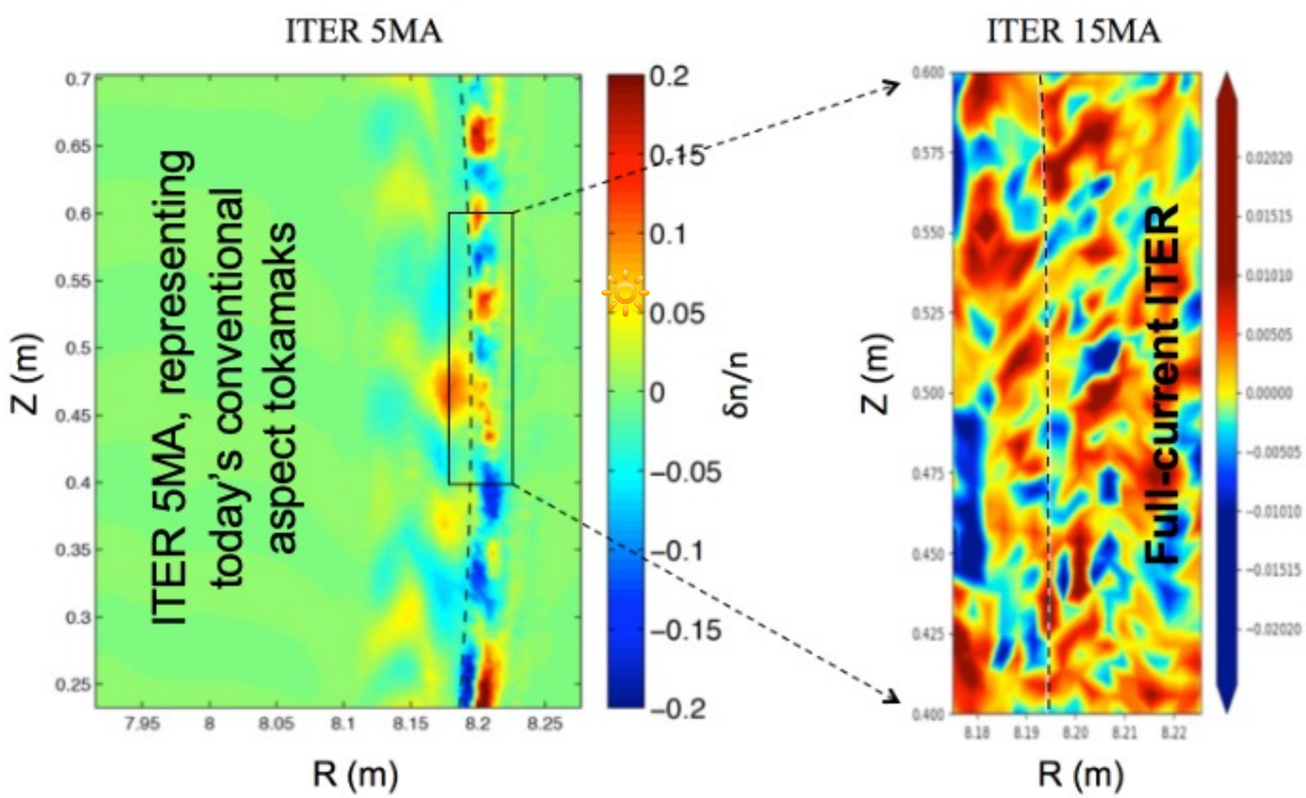


- Electrostatic XGC prediction agreed with λ_q data from all the existing tokamaks or Eich regression values λ_q^{Eich}
- Also agreed with λ_q^{Eich} on 5MA Pre-Fusion ITER
- The same code, however, predicted ~12X wider λ_q for FPO 15MA ITER *[C.S. Chang, NF 2017]*
- XGC's results for 1MA NSTX and 1.5MA NSTX-U agreed with Eich's regression values
- XGC then produced ~2X wider λ_q for 2.0MA NSTX-U

  → A hint that a higher–B ST could yield wider λ_q

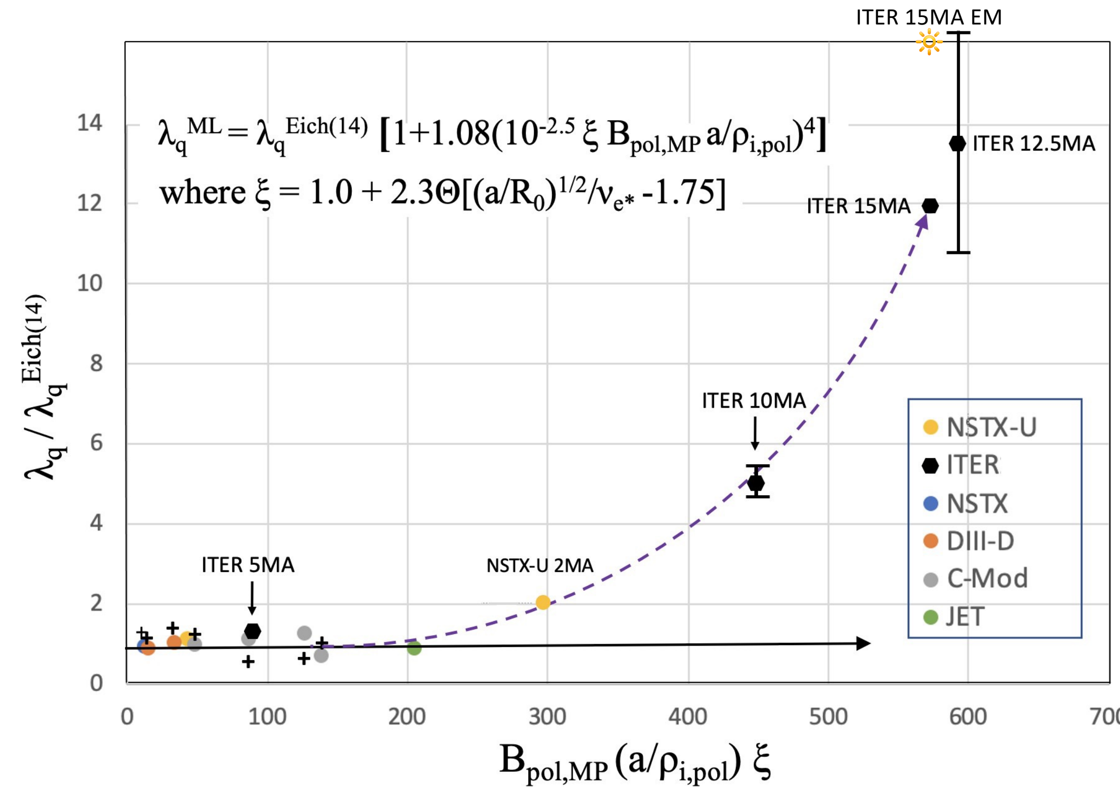
Science *[C.S. Chang, PoP 2021]*

- It is found that streamers from dissipative trapped-electron modes spread the heat-load footprint
  - ITER: DTEMs are unsuppressed due to lack of ExB shearing rate from extremely small $\rho_{i,P}/a$
  - NSTX-U: Strong DTEMs are driven by large trapped population and strong toroidicity



Blobs at edge of 5MA ITER or existing tokamaks

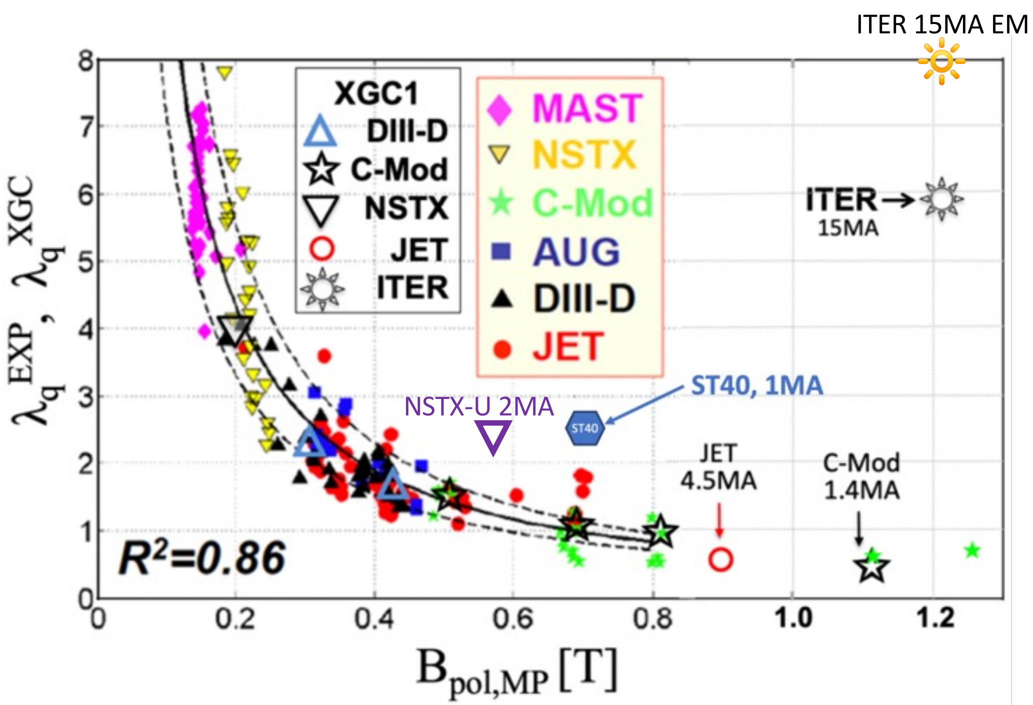
TEM streamers at edge of 15MA ITER or 2MA NSTX-U



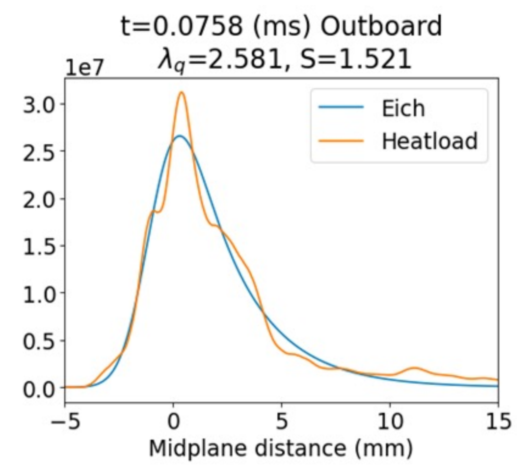
A simulation-anchored AI produced a simple surrogate model as a correction to $\lambda_q^{Eich(14)}$. ST40 can provide **validated** data to rase the accuracy of the surrogate model. EM effect?

λ_q^{XGC} on ST40 (#ST10014)

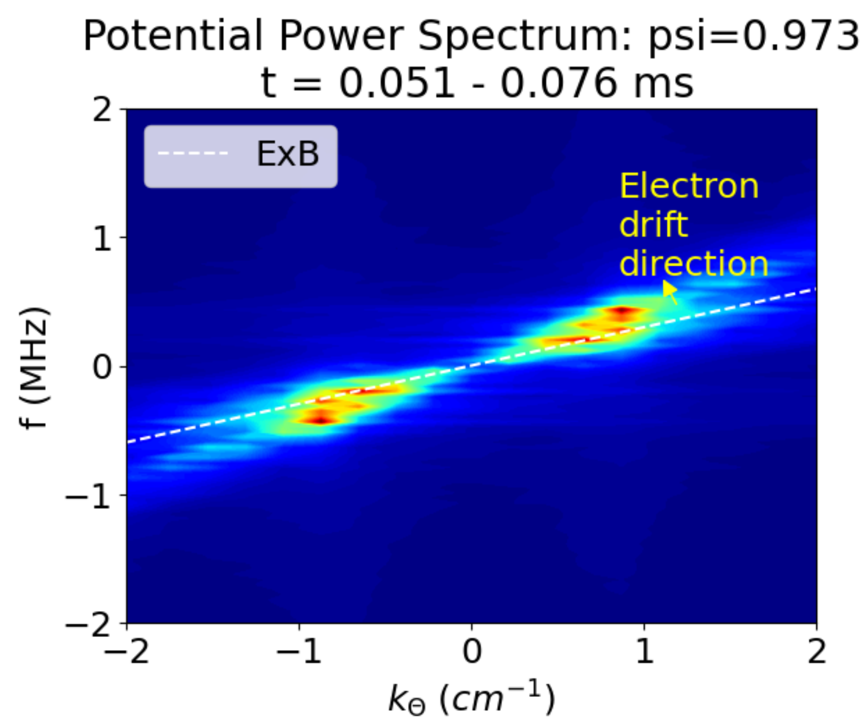
- λ_q^{XGC} for 1MA ST40 #10014 is found to be ~2.5X wider than $\lambda_q^{Eich(14)}$.
- Consistently with findings from 15MA ITER and 2MA NSTX-U, DTEMs become dominant at edge



ST40 at a higher B-field shows a greater λ_q^{XGC} enhancement over a lower B-field NSTX-U. Why? Smaller ρ_i/a → weaker ExB shearing.



Peaked electron heat flux at outer divertor leg.

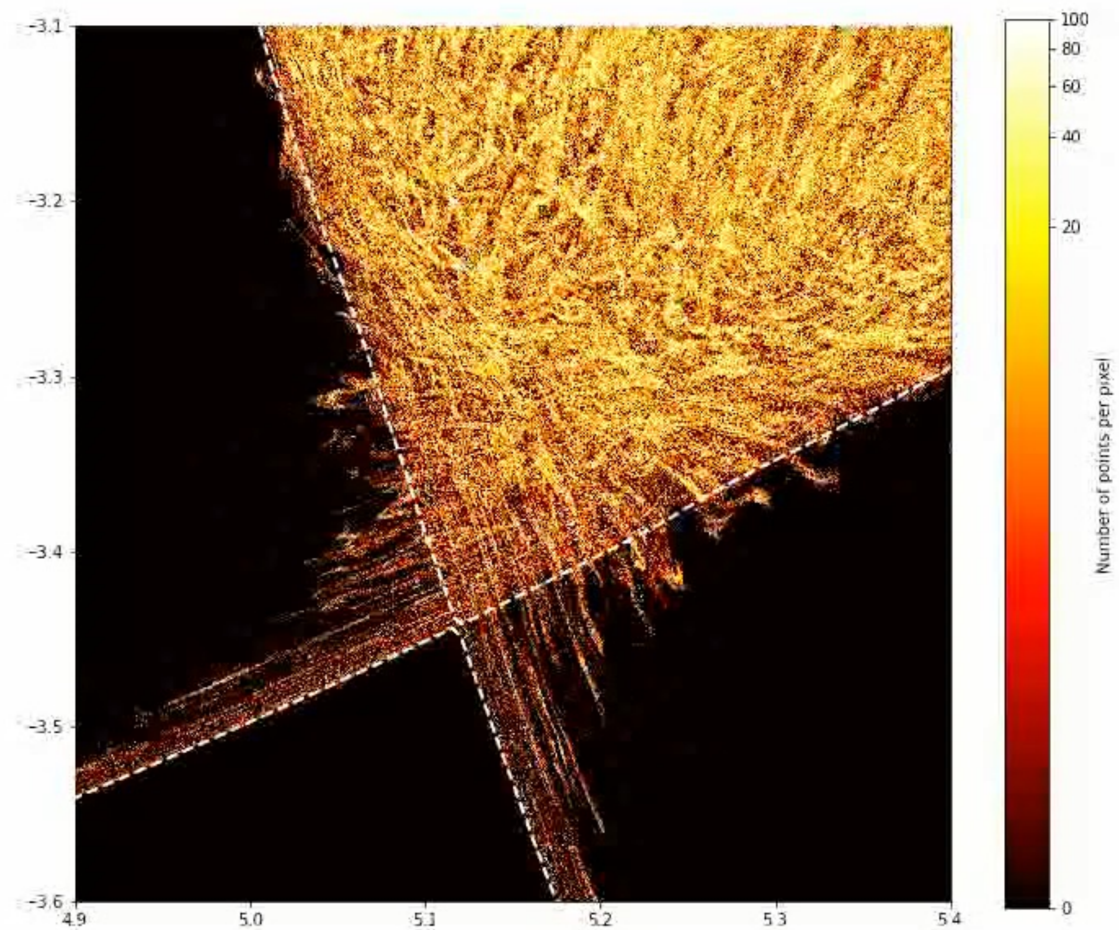


Electrostatic XGC shows TEM dominant turbulence in the edge pedestal near the magnetic separatrix

Plans for the remainder of current INFUSE cycle (till 4/2024)

- Upgrade the XGC simulation to electromagnetic
- Study how the electromagnetic effect will modify the exhaust heat-load footprint
  - e.g., Turbulent homoclinic tangle effect
  - Compare against experiment
- Provide physics understanding
  - e.g., Strong electron heat-exhaust along the outer divertor?
  - Why ST sees wider λ_q^{XGC} more easily than a conventional tokamak does?
  - The only place we saw the λ_q enhancement on conventional tokamaks was in a turbulence dominant QH mode w/o EHO
- Write a joint paper including a validate surrogate model λ_q for STs

Turbulent homoclinic tangle in 15MA ITER edge, making stochastic connection between pedestal and divertor



2nd INFUSE phase?

- Raise the accuracy of the simple surrogate formula for $\lambda_q^{predictive}$
  - That can be utilized for ST40 upgrades and reactor designs
  - By studying more ST40 discharges and and validating the simulation results
- Will ST follow the same λ_q path as conventional high-B tokamaks?
- How will impurity particles, gas injection and shaping change heat exhaust and λ_q in ST?
  - Part of validation process
  - Use XGC-DEGAS2 for a more accurate atomic physics validation