A New Predictive Scaling Formula for ITER's Divertor Heat-Load Width Informed by Gyrokinetic Simulation and AI/ML

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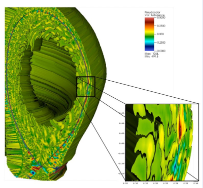
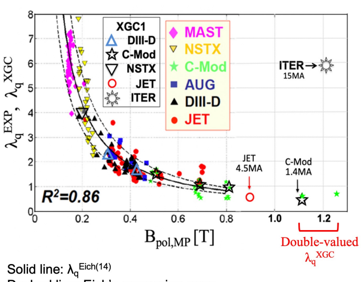
Introduction

- **Understanding the heat-flux width in attached divertor condition is essential since**
  - It sets the baseline for heat-load with in semi-detached/detached divertors
  - Divertor plasma gets accidentally attached: could burn the divertor plates
- **The edge gyrokinetic code XGC**: specialized in the edge simulation across the separatrix to wall
  - Study non-equilibrium plasma (non-Maxwellian)→ total-f
  - Heat, momentum and particle sources
  - Monte-Carlo neutral particle recycling with atomic data
  - Fully nonlinear Fokker-Planck collision operator → AI/ML operator
  - Complicated edge geometry: unstructured triangular mesh
  - X-point orbit loss is critically important for edge physics
  - XGC is a SciDAC + ECP code
  - In all three early-science programs: Frontier CAAR, Aurora ECP, Perlmutter NESAP
- Now, electromagnetic (not a subject of this talk)
  - Micro-turbulence, fluid-type instabilities, neoclassical, neutral, atomic physics



XGC that predicted λ_q^{XGC} values in agreement with experiments in all three US tokamaks and JET also predicted λ_q^{XGC}=12 $\lambda_q^{Eich(14)}$ in full-current ITER plasma



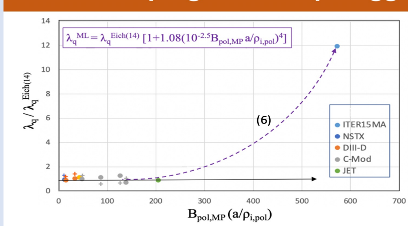
Solid line: $\lambda_q^{Eich(14)}$
Dashed line: Eich's regression error

There is always an unknown uncertainty in the extrapolation.

- λ_q solution from XGC is double-valued around 1.2MA
- Hidden parameter that was not included in Eich's regression?
  - The important kinetic parameter ρ_i/a is missing in Eich's parameter set.
- How can we verify if ρ_i/a can resolve the double valuedness?

→ Simulation-anchored Machine Learning

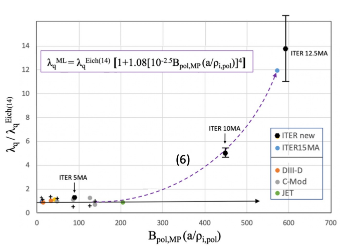
The AI program Eureqa suggested simple formulas



Which one should be taken?

λ_q^{ML}=0.63$B_{pol,MP}^{-1.19}$ [1.0 + 1.08x10^{-10} ($B_{pol,MP}$ a/$\rho_{i,pol}$)^4] with RMS error=18.7% (6)
=0.63$B_{pol,MP}^{-1.19}$ [1.0 + 1.961x10^{-16} (a/$\rho_{i,pol}$)^6], RMSE=17.9% (7)
=0.63$B_{pol,MP}^{-1.19}$ [1.0 + 1.68x10^{-18} $B_{pol,MP}$ (a/$\rho_{i,pol}$)^7], RMSE=17.0% (8)
=0.63$B_{pol,MP}^{-1.19}$ [1.0 + 1.91x10^{-13} ($B_{pol,MP}$ a/$\rho_{i,pol}$)^5], RMSE=17.0% (9)
=0.63$B_{pol,MP}^{-1.19}$ [1.0 + 3.46x10^{-4}[4.04x10^{-5} $B_{pol,MP}$ (a/$\rho_{i,pol}$)^3]^{Bpol,MP}, RMSE=16.1%. (10)

We tested the formulas with three more ITER simulations. The simplest formula works the best.



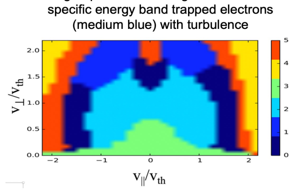
Formula No.	λ_q^{ML} from various formulas	Ratio to λ_q^{XGC}=2.65mm
Eq. (6)	2.77 mm	1.05
Eq. (7)	0.86 mm	0.32
Eq. (8)	1.79 mm	0.68
Eq. (9)	2.30 mm	0.87
Eq. (10)	2.24 mm	0.84

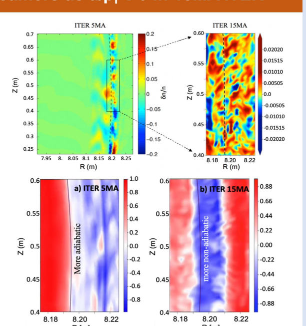
- What could be the new physics?
- Is a/ρ_i really different between ITER and the present-day tokamaks and the ExB shearing rate really dependent on a/ρ_i?

It turned out that blobs change to TEM streamers as a/ρ_i →0 in 15MA ITER

At least three evidences exist that the edge turbulence across the magnetic separatrix in 15MA ITER is from the non-adiabatic trapped electrons.

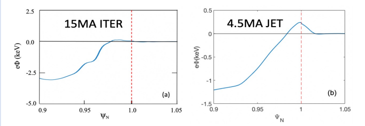
Supervised ML: K-Means Clustering into 6 groups shows strong correlation of specific energy band trapped electrons (medium blue) with turbulence

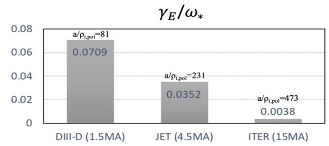




Correlation between δn_e and $\delta\Phi$

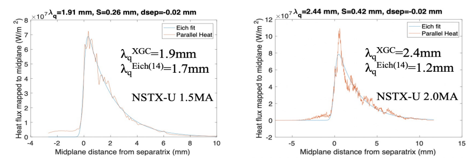
How different is a/ρ_i between present-day tokamaks and full-current ITER, and how it affects ExB shearing rate across separatrix?



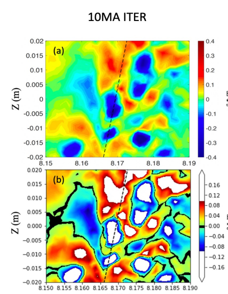


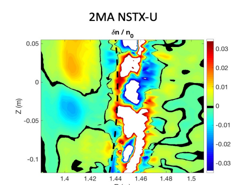
Test: effect of the collisionless TEM (CTEM) turbulence on λ_q using NSTX-U plasma models

- Due to low T_e, it is difficult for today's tokamaks to have CTEM turbulence across separatrix.
  - Dissipative TEM (DTEM) turbulence is subject to ExB-shearing suppression, which is present in today's moderate a/ρ_i tokamaks, while CTEM can be more rubust against moderatate ExB-shearing rate
- Low aspect-ratio tokamaks can have a strong CTEM drive if the edge Te is high enough
  - Most of the edge electrons are magnetically trapped & enhanced effective collisionality does not exist.
- XGC finds that the highest current (2MA) NSTX-U has a high enough edge T_e and yields λ_q^{XGC}≈2 $\lambda_q^{Eich(14)}$, while a lower current (1.5MA) NSTX-U shows λ_q^{XGC}≈$\lambda_q^{Eich(14)}$.



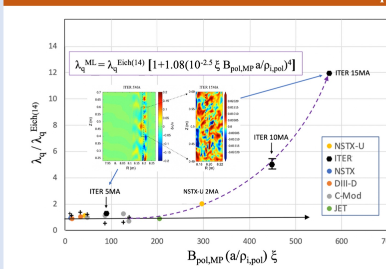
NTX-U shows mixture of blob and streamer type tubulence structures across the separatrix, as 10MA ITER does





- Tops and valleys of the blobs are cut off and colored white.
- NSTX-U shows weaker streamer amplitude than 10MA ITER, indicating that the λ_q-enhancement may be weaker.

A CTEM onset-factor ξ can make the two NSTX-U results agree with the new predictive λ_q^{XGC+ML} formula



ξ=1+ 2.3Θ[$(a/R_0)^{1/2}/\nu_{e*}$ -1.65], where Θ is the heavy-side step function.

For a tight aspect-ratio tokamak, $\nu_{e*} = \hat{\nu}_e$.

We need more simulation/experimental data to confirm and refine the CTEM onset criterion ξ.

Summary

- Previous results [C.S. Chang et al., NF 2017 & PoP 2021]
  - The edge gyrokinetic code XGC predicts λ_q^{XGC} that agrees with the Eich's #14 all-machine formula $\lambda_q^{Eich(14)}$, including the highest current C-Mod results, but also finds λ_q^{XGC} ≈ 12 $\lambda_q^{Eich(14)}$ for 15MA ITER
  - A simple modification to the Eich's formula has been found using a machine learning program with the input data from experimental and XGC simulation data
    - New physics is in the kinetic paramter a/ρ_i, which was missing in the Eich regression set.
    - Collisionless TEM (CTEM) streamers spread λ_q^{XGC}
  - The new formula has been successfully tested against three new ITER simulations.
- Present work
  - NSTX-U plasmas are used as the strongest candidate for testing the CTEM turbulence effect on λ_q^{XGC}
  - A highest performing NSTX-U plasma model at 2MA indeed shows λ_q^{XGC}≈2 $\lambda_q^{Eich(14)}$, with a mixed turbulence structure between blobs and streamers
- Designing new experiments in the existing tokamaks, or finding from existing data-base, that show deviation from Eich formula is important for validation of the new formula
  - Wide-pedestal QH mode with ECH heating at edge?
- Hopefully, we can use the new formula for ITER scenario development and fusion reactor designs
- Future work: λ_q study in detached plasmas and examination of the magnetic fluctuation effect.

ACKNOWLEDGEMENTS

- Work supported by US DOE through SciDAC HBPS
- Computing resources provided by OLCF and ALCF through INCITE award