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Gyrokinetic projection of the divertor heat-flux width from present tokamaks to ITER

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Outline

- **Introduction**
- **Validation on DIII-D, C-Mod and NSTX (US Milestone)**
  - **Attached divertor regime to study the minimal heat-flux width**
  - **Measure heat-flux footprint at entrance to Debye Sheath**
    - **Then, obtain λ_q in terms of outboard midplane distance**
  - NSTX and DIII-D are in the drift-dominant λ_q regime
  - C-Mod at cross-over from drift to turbulent λ_q
- **Prediction for ITER: blobby turbulence dominated**
  - $\lambda_q \approx 5.6\text{mm} >> 0.63\ B_{pol}^{-1.19}$
- **Conclusion and discussion**

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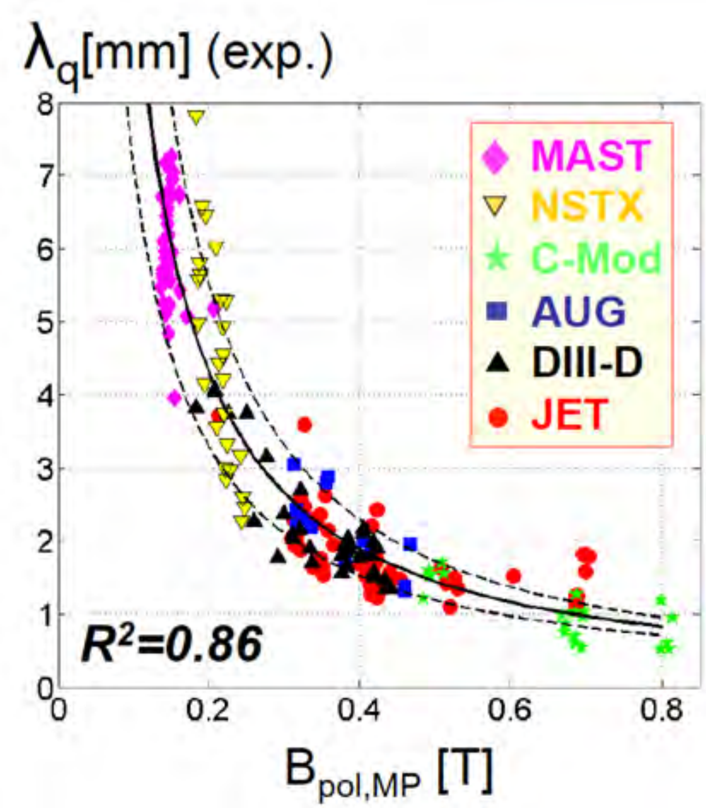
+ First Author acknowledges helpful discussions with R. Goldston.

Introduction

- Neoclassical, turbulence, and neutral particle physics are **all** important
- Neoclassical dominant models, by XGC0 [‘10 US JRT] and Goldston, gave

  $\lambda_q \propto 1/B_p^{\gamma}$, γ~1

  – Appears to be working for the present-day tokamaks. But, high B_p cases?
- Will this be true in large ITER? Use XGC1 with electrostatic blobby turbulence
- XGC1 validation must be performed
- Edge plasma is in non-equilibrium kinetic state: non-Maxwellian, non-diffusive
  – Requires a full-f kinetic ion & electron simulation for high-fidelity predictability



T. Eich et al., NF 2013; PRL 107, 215001 (2011)

→ **Extreme scale computing**: We use 90% Titan (~300K cores + 19K GPUs, spending 10M core hours/day) for 3 days for 1 ITER case

5D Total-f XGC Family Codes

Code	GK, DK	Solver Dimension	3D	X-point	MC neutrals recycling
XGC1 hybrid (E&M)	GK ions hybrid electrons	3D (r, θ, ζ) Turbulence		Yes	Built-in
XGC1 kinetic	**GK ions** + **DK electrons** or GK electrons	3D (r, θ, ζ) Turbulence		Yes	**Built-in, H^0 born away from divertor plates**
XGCa (NESAP**)	GK ions, DK electrons	2D (r, θ), GK Neoclassical & Kinegtic transport modeling	RMP	Yes	Built-in, H^0 born at plates
XGC0	DK ions & electrons	1D (r), DK Neoclassical & Kinetic transport modeling	RMP	Yes	DEGAS2, H_2^0 at divertor plates

- Blobs from XGC1: S. Ku, TH/P6-16
- Neutrals on turb.: Stotler, TH/P6-7

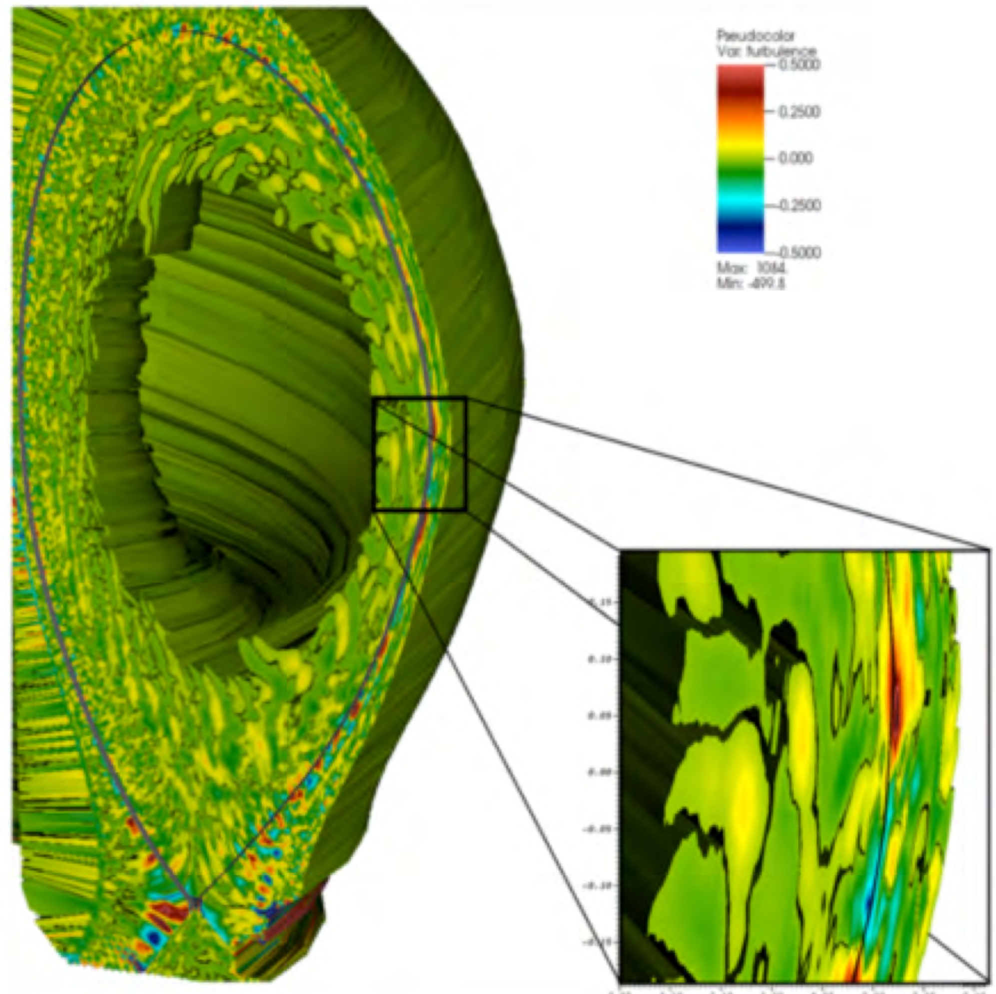
- SOL phys: Churchill, TH/P6-10
- Edge boostrap: Hager, TH/P2-27

Ability for "blobby" edge turbulence + orbit dynamics is a pre-requisite for heat-flux width study

2013-2014 INCITE, using 90% (16,384 nodes~25pF) of maximal heterogeneous Titan

- Relevant region for the λ_q study: $0.98 \lesssim \Psi_N \lesssim 1.02$
- Attached plasma
- For a minimal 1st-principles based study, a GK simulation should have
  - electrostatic blobs with kinetic electrons
    [D'Ippolito et al., (2011)]
  - neoclassical orbit dynamics
  - ExB dynamics
  - $E_{||}$ solution
  - neutral recycling for steady state
  - nonlinear collisions

  across magnetic separatrix



Blobs from XGC1: S. Ku, THP-6/16

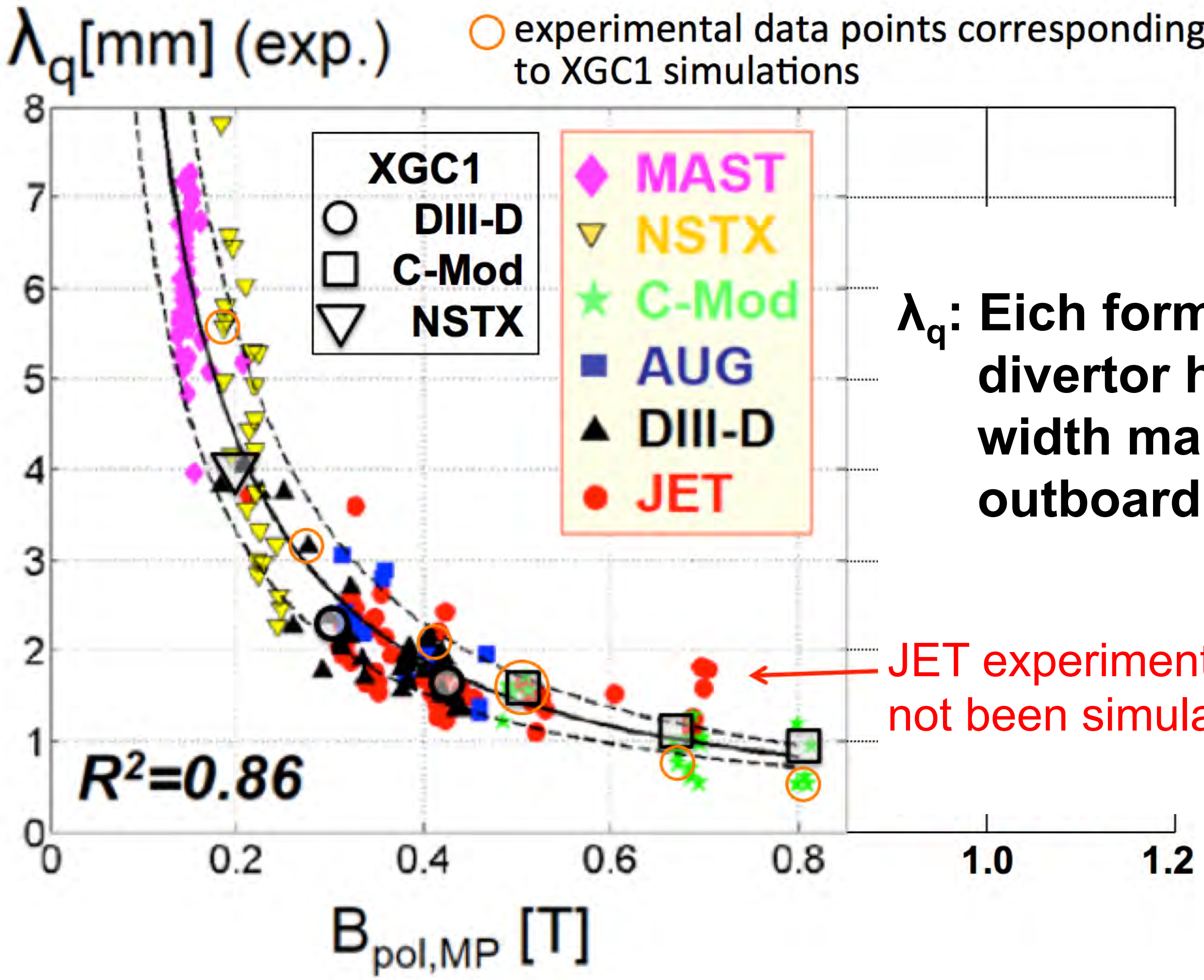
Simulation by S. Ku, Visualization by D. Pugmire

Experimental validation cases studied by XGC1

B-field, first wall, plasma profiles and the heat source are imported from eqdsk files.

Shot	Time (ms)	B_T (T)	I_P (MA)	$B_{pol,OM}$ (T)
NSTX 132368	360	0.4	0.7	0.20
DIII-D 144977	3103	2.1	1.0	0.30
DIII-D 144981	3175	2.1	1.5	0.42
C-Mod 1100223026	1091	5.4	0.5	0.50
C-Mod 1100223012	1149	5.4	0.8	0.67
C-Mod 1100223023	1236	5.4	0.9	0.81

Successful validation of the XGC1 heat-flux widths λ_q against all three US tokamak data

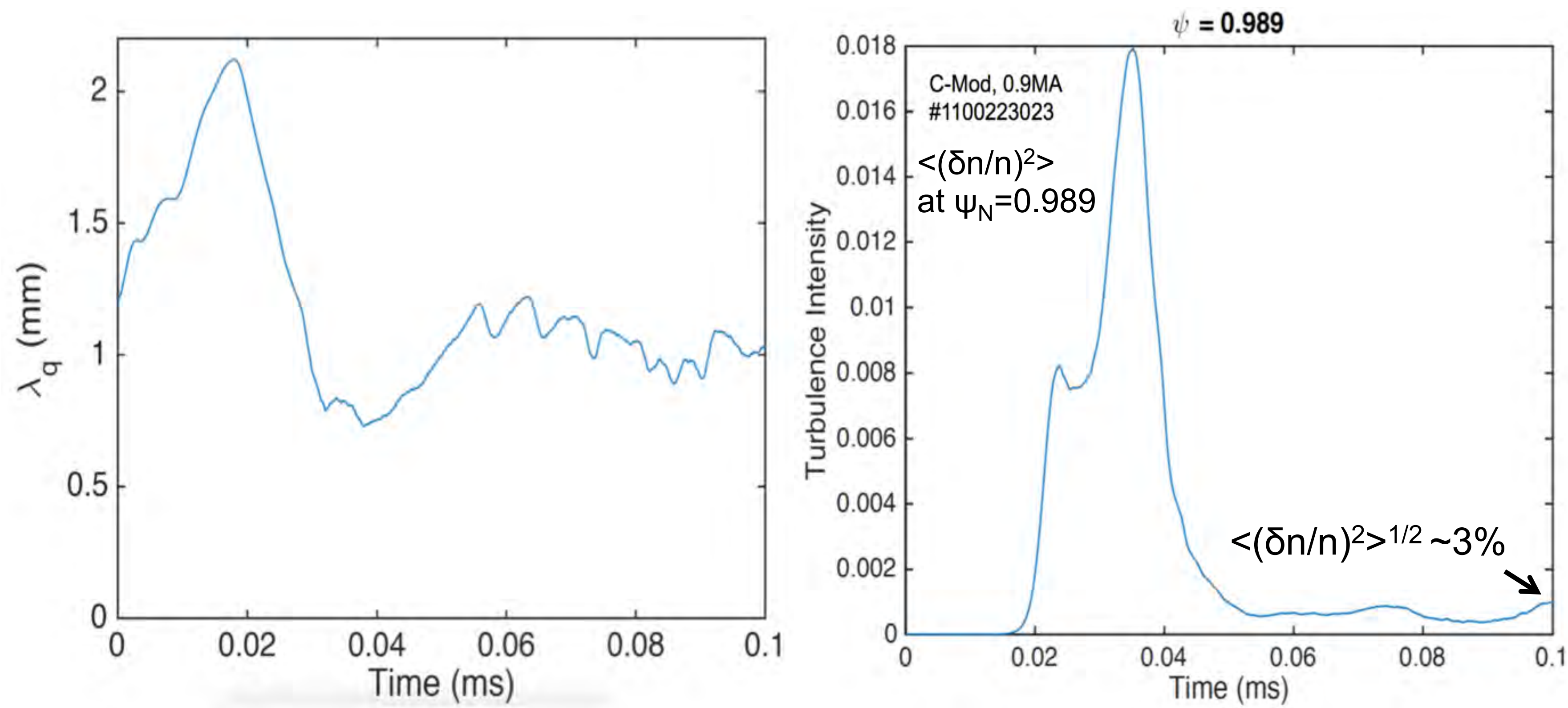


λ_q: Eich formula fit for divertor heat-flux width mapped to outboard midplane

JET experiments have not been simulated, yet.

Example time behavior: C-Mod, 0.9MA

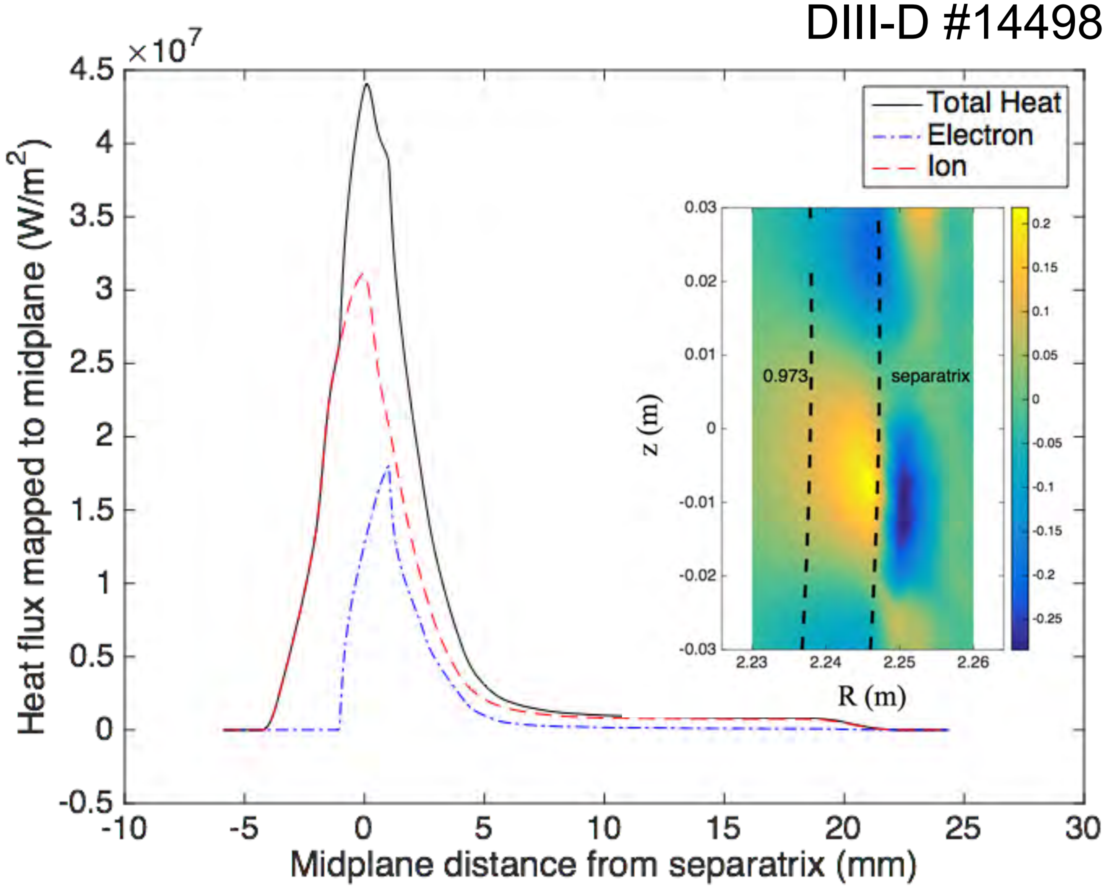
We execute the simulation until λ_q and edge tubulence saturate.



Saturation of λ_q (left) and turbulence intensity $(\delta n/n)^2$ (right). Turbulence intensity is plotted at $\Psi_N \approx 0.99$ near the birth of the blobs ($\Psi_N \approx 0.98$).

XGC1 prediction:
λ_q dominated by warm ions in DIII-D and NSTX plasmas.

DIII-D #144981, I_P=1.5MA

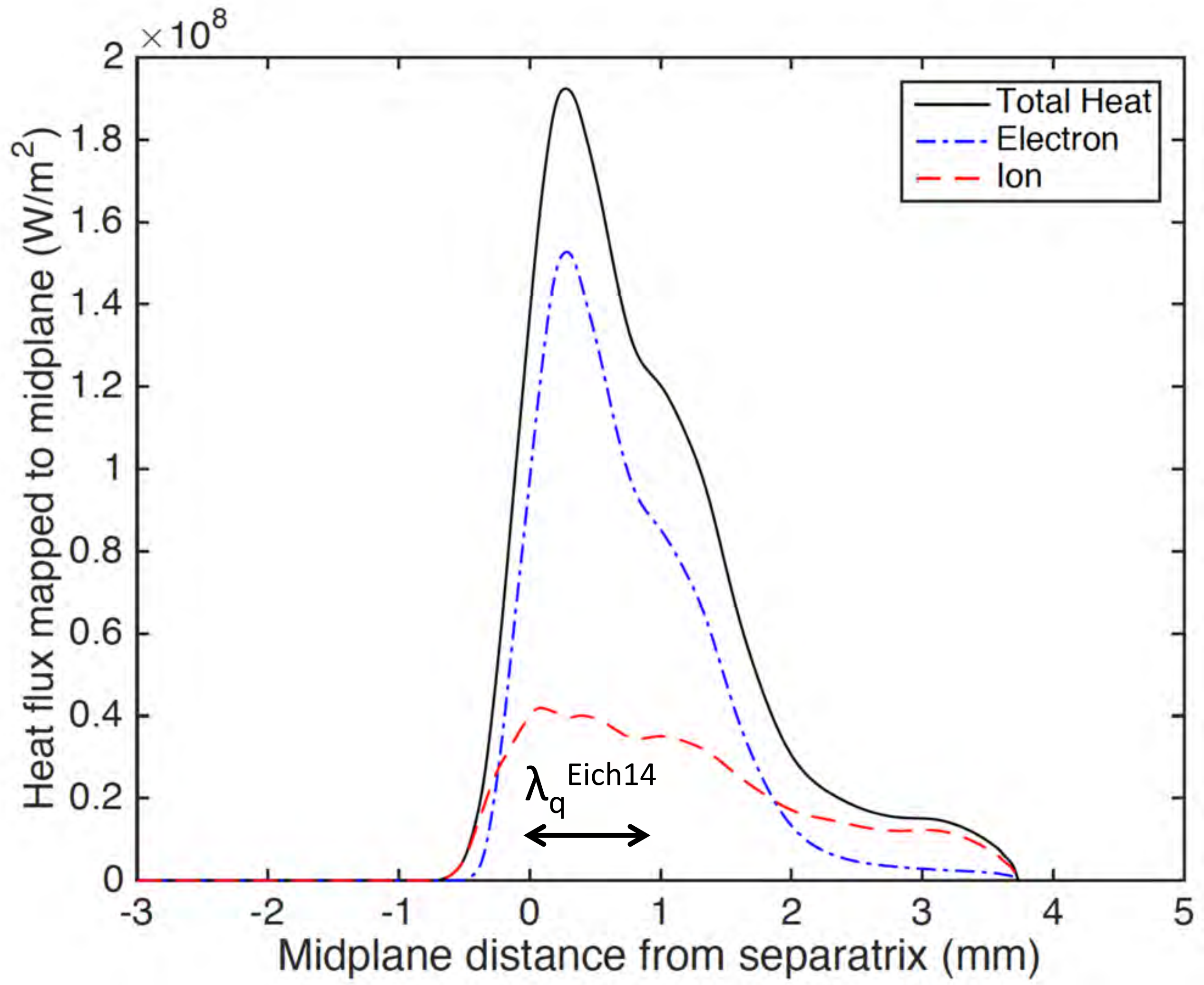


Intentional reduction of neutral atomic physics effect in front of divertor pates allows us to study the ion and electron components in the heat-flux footprint: DIII-D, 1.5MA.

- Heat-load spreading by electrons (blobby spread) is ~2X narrower than that by ions (neoclassical $V_{d,magnetic}$)
- Radial blob size ~5mm (see insert)
- $T_i > T_e$ in scrape-off
- Ions (electrons) gain (lose) kinetic energy in the pre-sheath potential, elevating the ion effect.
- Neutral particle effect is only ~10% in this model.

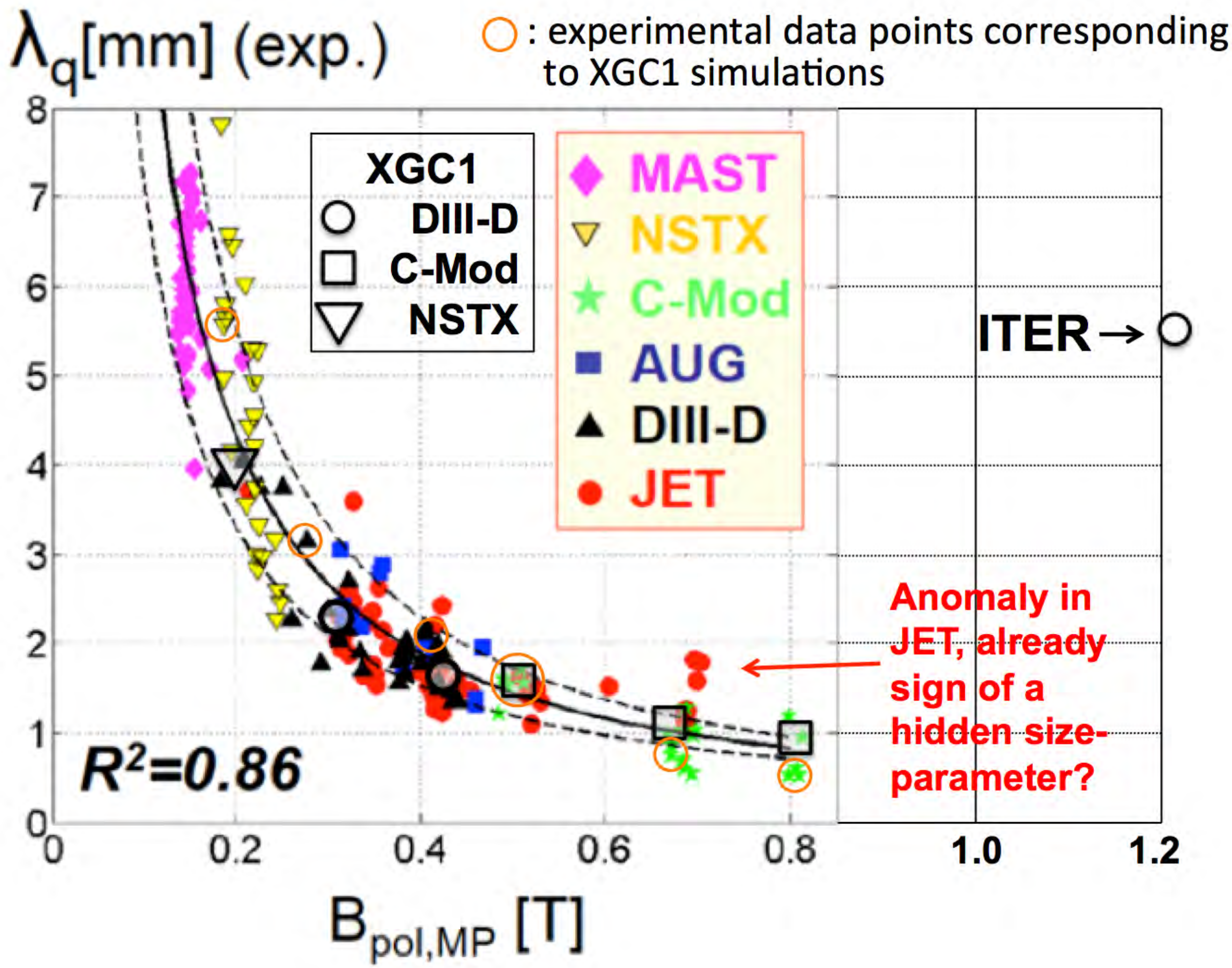
XGC1: In high current (0.9MA) C-Mod, electrons dominate the heat-flux magnitude.

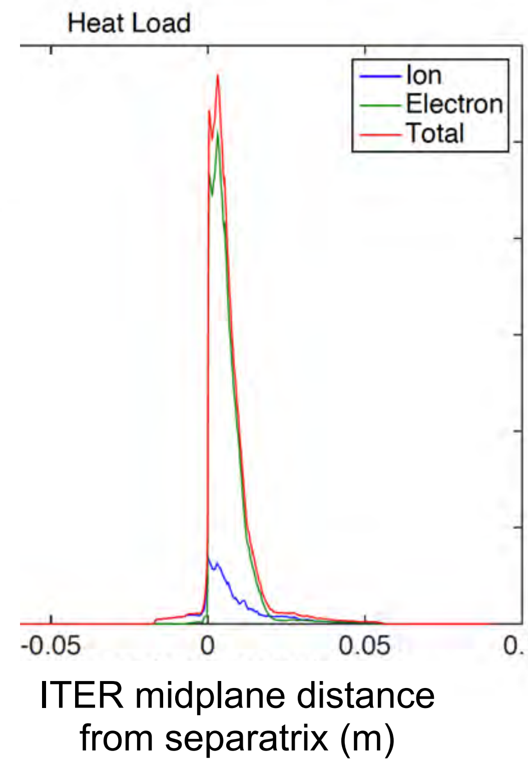
Electron width (blobby spread) is still < ion width (neoclassical)



Prediction for ITER

- The same code that reproduces three US tokamak experimental results predicts $\lambda_q \approx$ 5.6mm, instead of <1mm, using a model edge profile
  - But, λ_q is not very sensitive to details of the edge profile.
- ITER λ_q is completely blob-dominant in both magnitude and width





Conclusion and discussion

- Prediction from gyrokinetic XGC1 simulations on the 3 US tokamaks have been validated against the experimental scaling $\lambda_q \propto 1/B_P^{1.19}$.
- For DIII-D and NSTX, heat-flux width is completely dominated by the ion magnetic drift physics → Similar to Goldston scale, but by warm ions
- For C-Mod (small size) that has high B_p and small magnetic drift, λ_q is at cross-over between magnetic-drift and blobby spreads.
  - Heat-flux magnitude is dominated by electrons, but the ion width is still wider
- The same code that reproduces the experimental results on three US tokamaks shows ~ $\lambda_q \approx 5.6$mm for ITER (large size): blob dominated

  → Much easier operation of ITER
- It appears that there is a size scaling missing in the existing formula.
- JET at higher B_P could shed brighter light on the size scaling parameter.
- More computing time could nail down this problem.