TH/2-3

Gyrokinetic simulation of blob transport and divertor heat-load

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SciDAC-3 Center for Edge Physics Study

EPSi Edge Physics Simulation

Outline

- Introduction of the problem
- Introduction to XGC1
- Gyrokinetic edge blobs
- Divertor heat-load footprint and I_P scaling from XGC1
- Status of the XGC1 development
- Conclusion and discussion

Core Gyrokinetic Turbulence Code

GEM (U of Colorado) models PBM and KBM in DIII-D H-mode pedestal (Wan PRL 2012) and nonlinear ELM (Wan PoP 2013)

Edge Gyrokinetic Turbulence Code

XGC1 - full x-point, neutrals

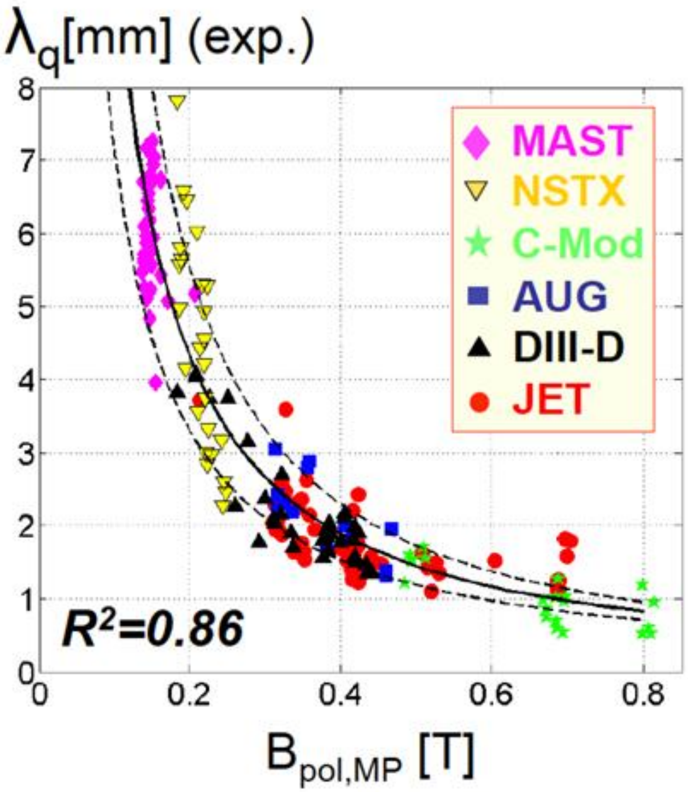
!

EPSi

Edge Physics Simulation

Divertor heat-load width is a serious issue for ITER and future tokamak reactors

- If extrapolated from the present-day trend ($\propto 1/I_P$),
  - ✧ Divertor heat-load width in ITER would be $\lambda_q \approx 1$mm when mapped back to the outboard midplane, and
  - ✧ The localized heat-load would far exceed the material tolerance limit.
- Unanswered critical questions:
  - ✧ Will the $1/I_P$ trend hold for ITER?
  - ✧ How can we control λ_q?
- Physics understanding is needed for reliable and predictive answers.
- Scrape-off plasma is in non-equilibrium kinetic state
  - ✧ Kinetic neoclassical + turbulence simulation is needed
  - ✧ Difficult to simulate!



T. Eich et al., NF 2013

Total-f Gyrokineic code XGC1 in diverted geometry

XGC1: X-point included Gyrokinetic Code 1

- **Edge plasma is in a non-thermal equilibrium state and requires a non-perturbative kinetic simulation**
    - Heat and momentum (and particle) flux from the core
    - Losses to material wall with neutral recycling, radiative loss, wall-sheath
    - Magnetic separatrix geometry: Orbit loss and X-point transport
    - Steep pedestal, with the gradient-width being ~ ion banana width
    - Blobs: $(\delta n_{max} - \delta n_{min})/\langle n \rangle = \mathcal{O}(1)$
    - Non-Maxwellian, requiring nonlinear Fokker-Planck collisions.
- **Nonlocal self-organization and overlapping multi-scale physics**
    - Neoclassical, turbulence, (logical) sheath, and neutral particles with atomics physics (and wall) self-organize together non-locally
    - Core-edge self-organization: artificial core-edge boundary is undesirable.

XGC1 is designed to study such plasmas

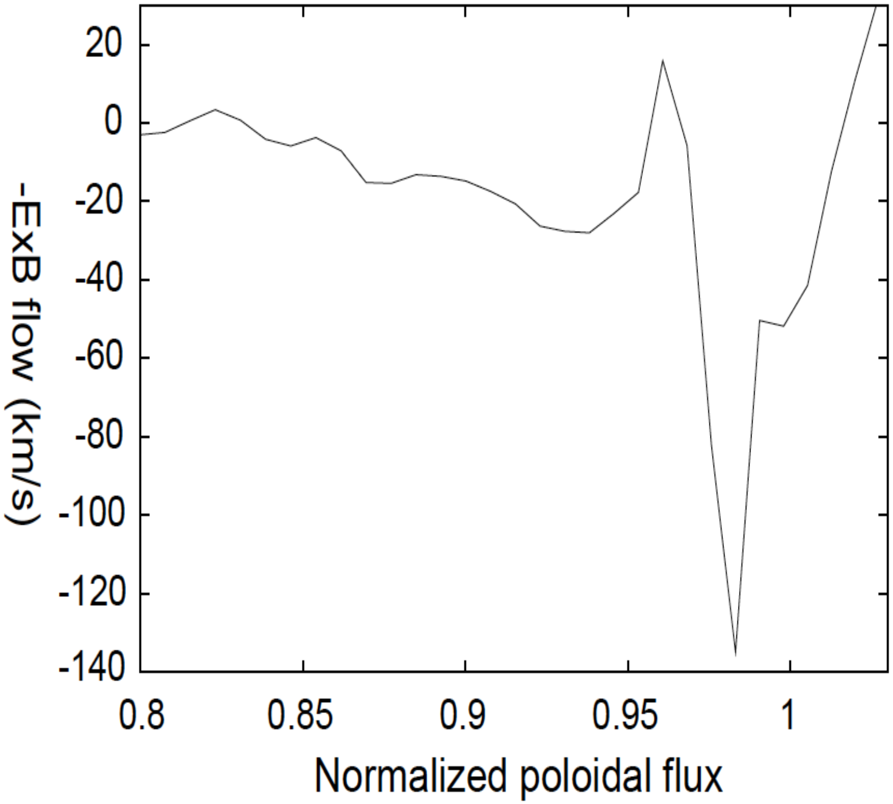
-- Requires **extreme scale computing (2014 total award ~300M hrs)**

-- Efficient scalability to extreme scale (maximal Titan/Mira/Edison)

XGC1 determines the E_r profile automatically, from the multiscale physics of orbit loss, neoclassical, turbulence, neutral particles and (logical) wall-sheath.

Equilibrium E_r evolution and feedback is important in the edge, while being more passive in the core.

→ E_r in edge needs to be "determined," instead of being calculated from given plasma n, T, V profiles using force balance, as usually done in core.



E_rxB solution from XGC1 in a DIII-D H-mode plasma with ITG turbulence

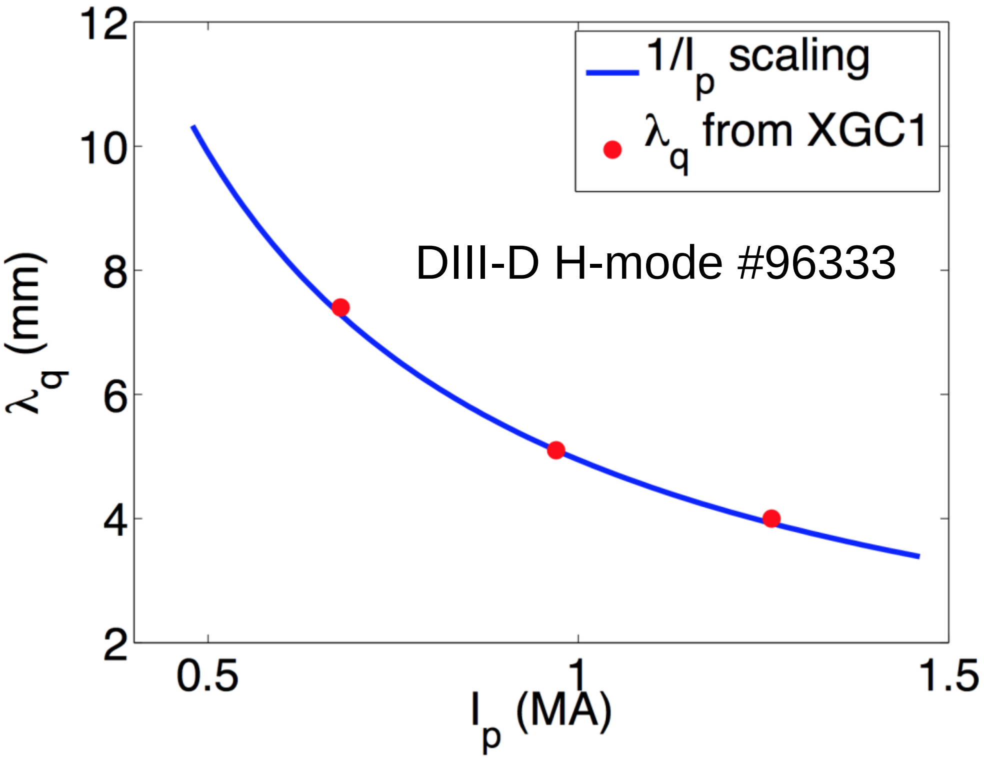
λ_q versus I_p

- λ_q: Divertor heat-load width mapped back to outboard midplane
- Three calculated λ_q points approximately line up with the $1/I_p$ curve
- The I_P= 0.68 & 1.26 MA cases are manufactured from the 0.97MA case by multiplying a uniform constant to B_P, while keeping the plasma profiles and the flux surface shape unchanged.

- Agrees with the neoclassical scaling found for DIII-D, NSTX and C-Mod from XGC0 in 2010 [2010 DOE JRT Report]

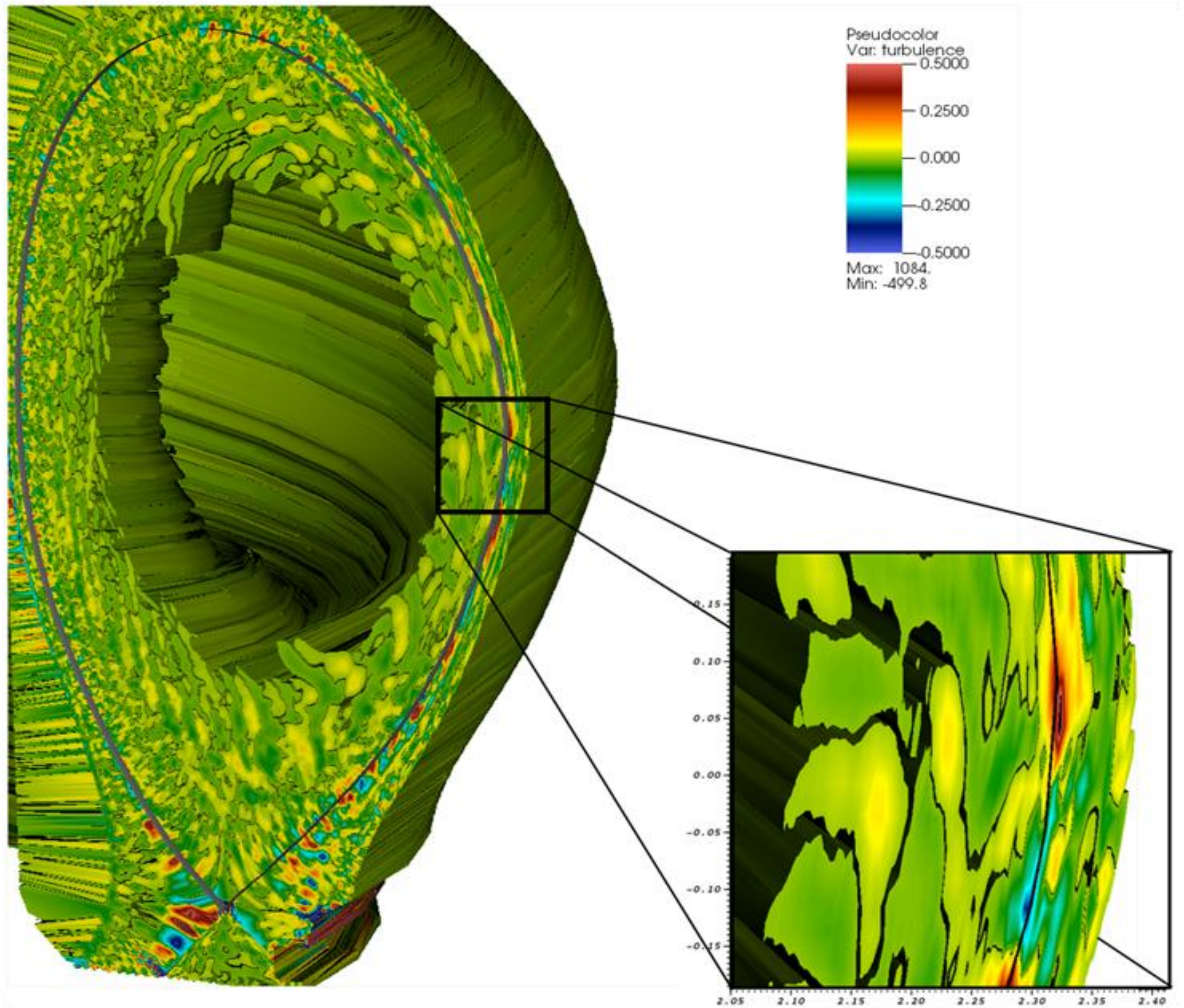
- Agrees with the simple heuristic neoclassical argument by R. Goldston [Nucl.Fusion, 2012]

Ip (MA)	λq (mm)
0.68	7.4
0.97	5.1
1.26	4



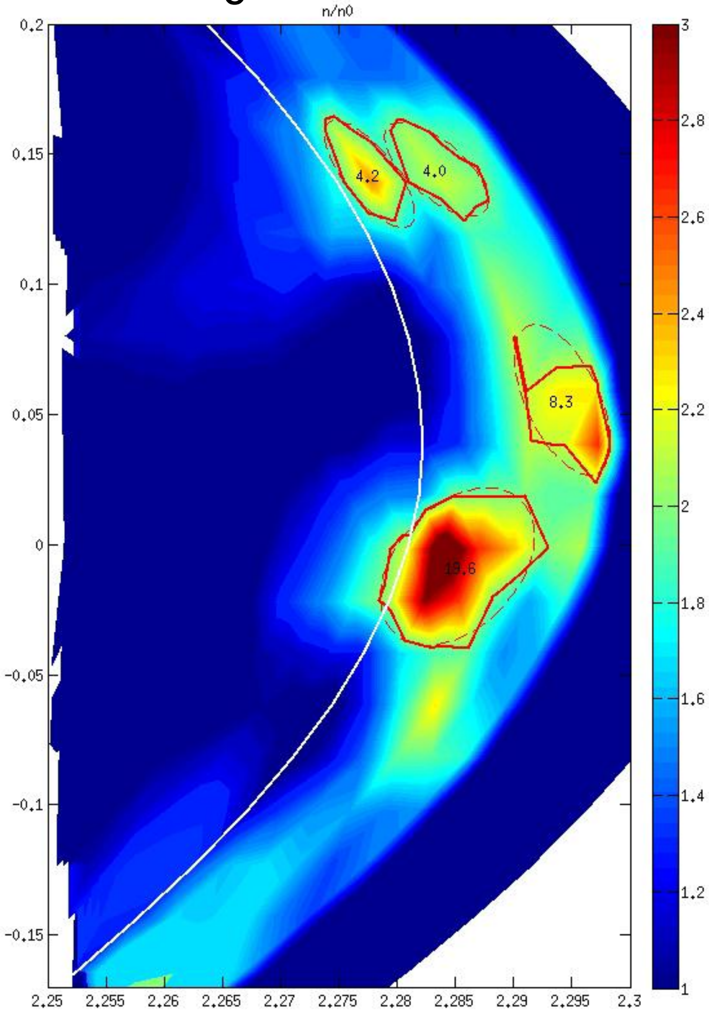
As soon as the drift-kinetic electrons were added to the gyrokinetic ions, the edge blobs appeared.

- DIII-D H-mode 96333
- The simulation ended at ~ 1ms.
- No core-edge boundary used
- Birth and life of the edge blobs being studied.
  - ✧Birth of blobs through ExB shearing can be seen.



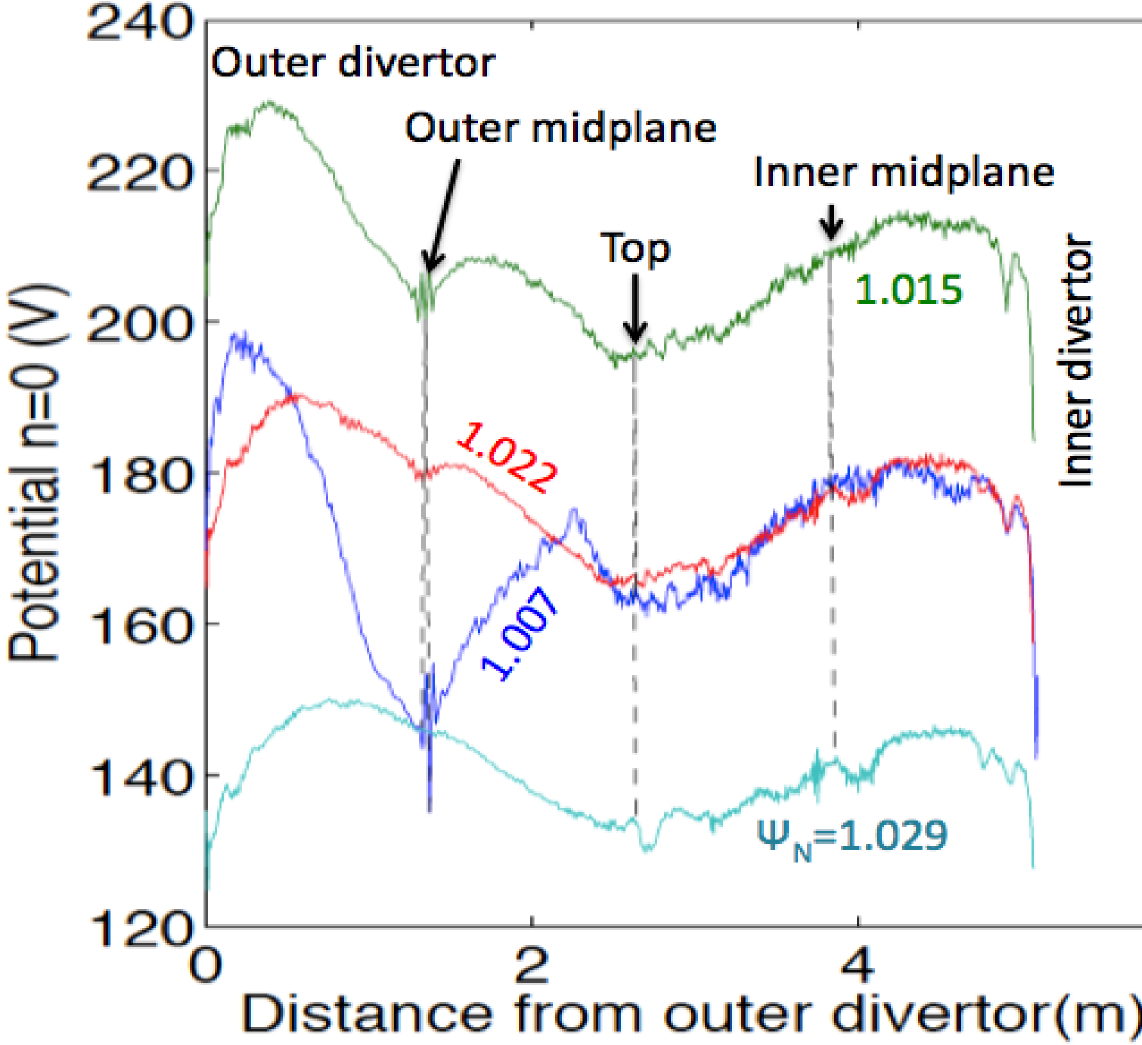
Synthetic diagnostics

n/n_0 from XGC1



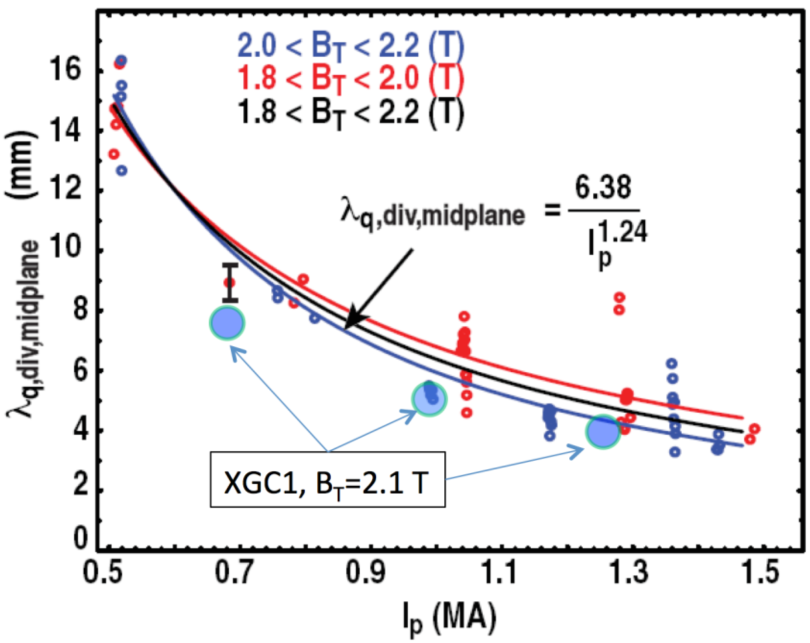
- Synthetic blob detection/analysis software has been developed (J. Lang and M. Churchill)
    - ✧ Blobs are found to carry not only the mass, energy, and momentum but also the vorticity that could affect the L-H and H-L transitions.
- Data from an extreme scale XGC1 simulation is too big for I/O.
    - ✧ We are placing the synthetic diagnostics in the code (HPC compute memory) for in situ analysis.
    - ✧ Poloidal blob speed from XGC1 is similar to experimental observation in H-mode (Boedo et al., Phys. Plasmas 2003)

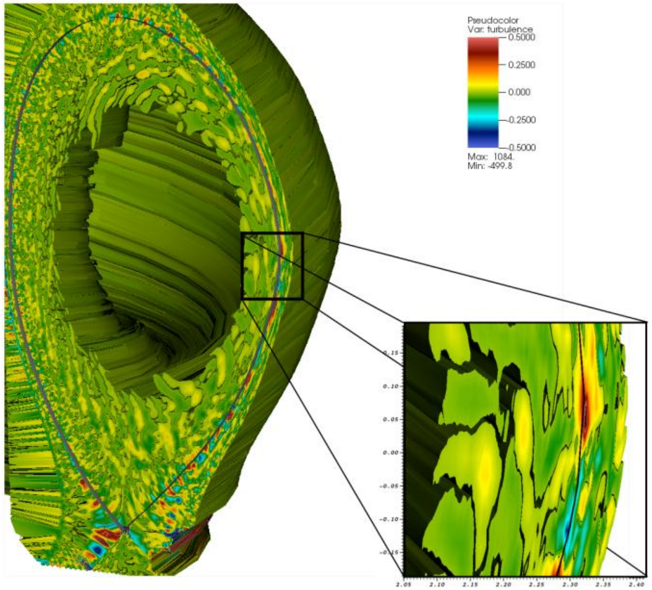
Poloidal potential variation in the scrape-off layer is also calculated in XGC1 (with nonlinear collisions and neutrals)



Divertor heat-load width in attached plasma

- Heat-load footprint has been measured from the three XGC1 simulation points
  - DIII-D H-mode shot #096333
- Electrostatic blobby turbulence, neoclassical physics and nonlinear collisions are included self-consistently.

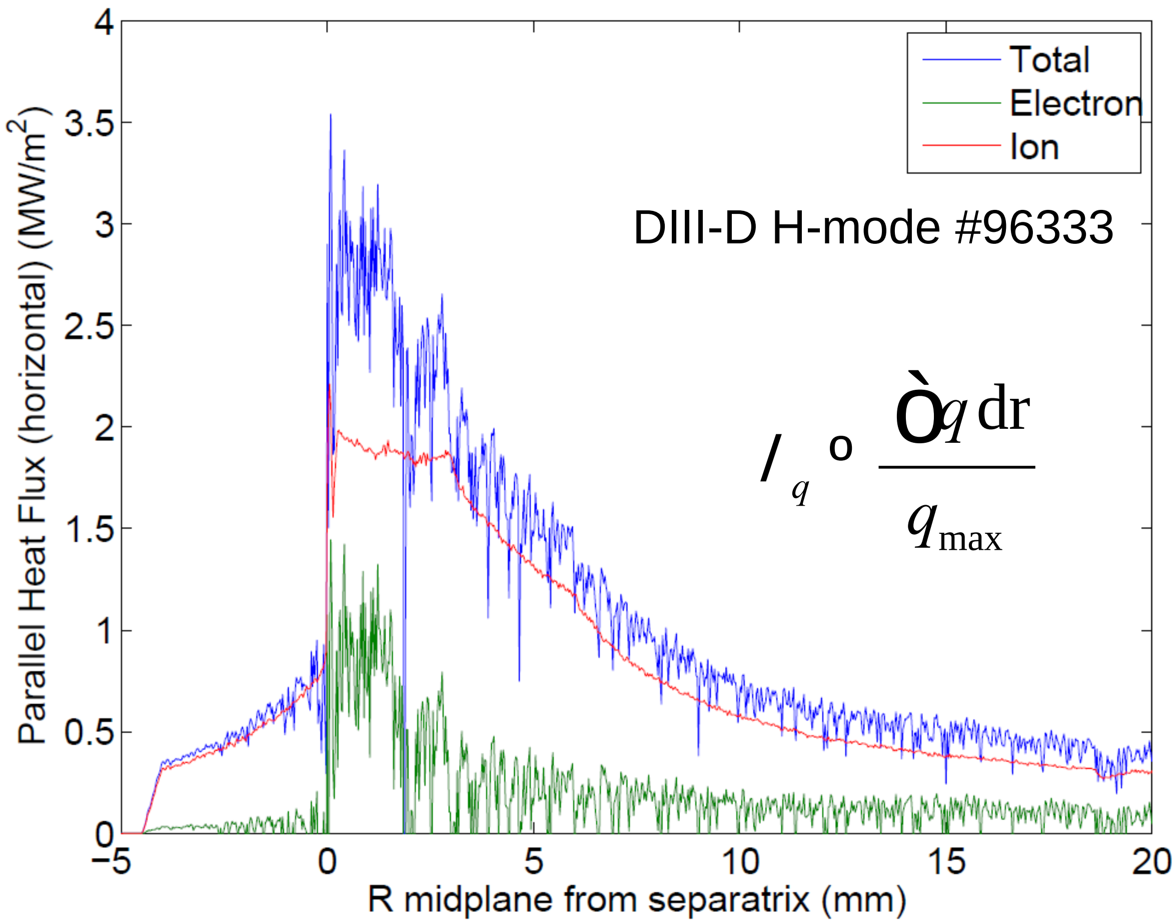




- Calculated heat-load width and I_P scaling are similar to experiment
  - XGC1: λ_q (midplane) $\propto 1/I_P$
- Simulation results should be compared with blue experimental dots ($2.0 < B_T < 2.2$ T)

1 ms simulation time for approximate steady state? Non-thermal kinetic equilibration process is much faster than the fluid equilibration process based on thermal equilibrium diffusion coefficients.

λ_q is dominated by ions in DIII-D

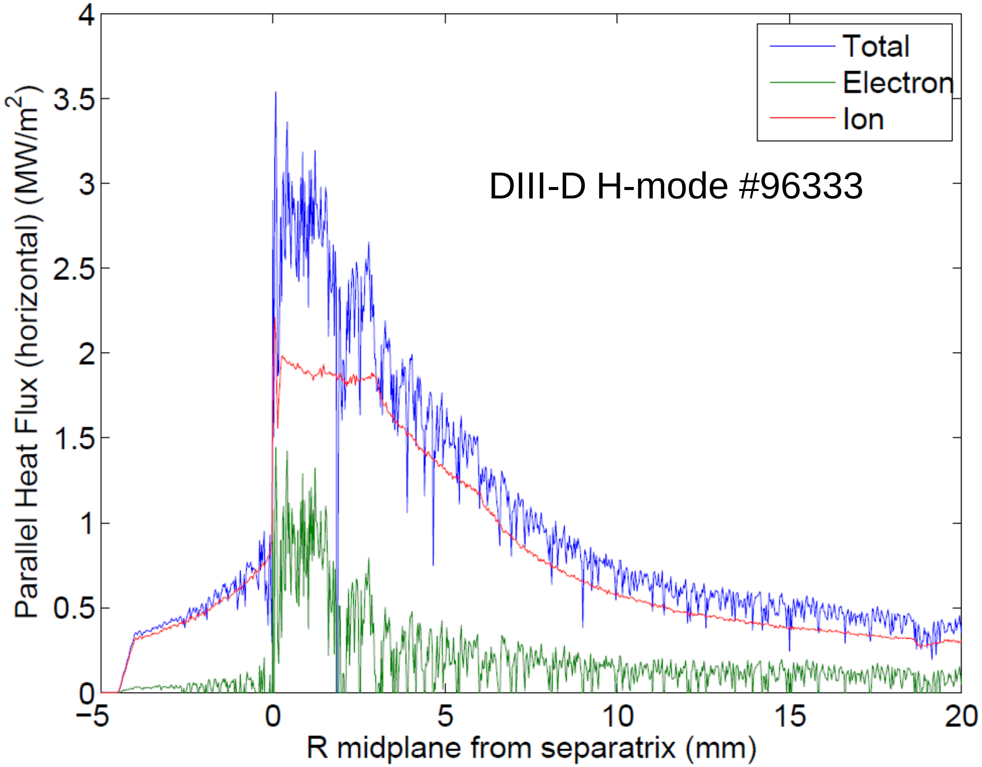


- λ_q =5.1 mm at I_P=0.97MA
  - Neutral particles play an insignificant role in this attached plasma
- λ_q is closer to ion orbit spreading width (~3mm, represented by the red flat top) than the radial blob size (>1cm)

Heat-load spreading by blobs (represented by λ_{qe} ~2mm in the figure) is masked by the ion orbital spreading.

Physical Interpretation of the DIII-D results

- Fast parallel particle motion allow only partial spreading of the heat-load width by blobs before hitting divertor plates
  - λ_{qe} ~2 mm
- Ion orbit excursion Δ_i dominates over the δExB convective spreading by blobs
- In ITER, $\Delta_i \leq$1mm, but the meso-scale blob size $\propto(\rho_i a)^{1/2}$ may remain similar

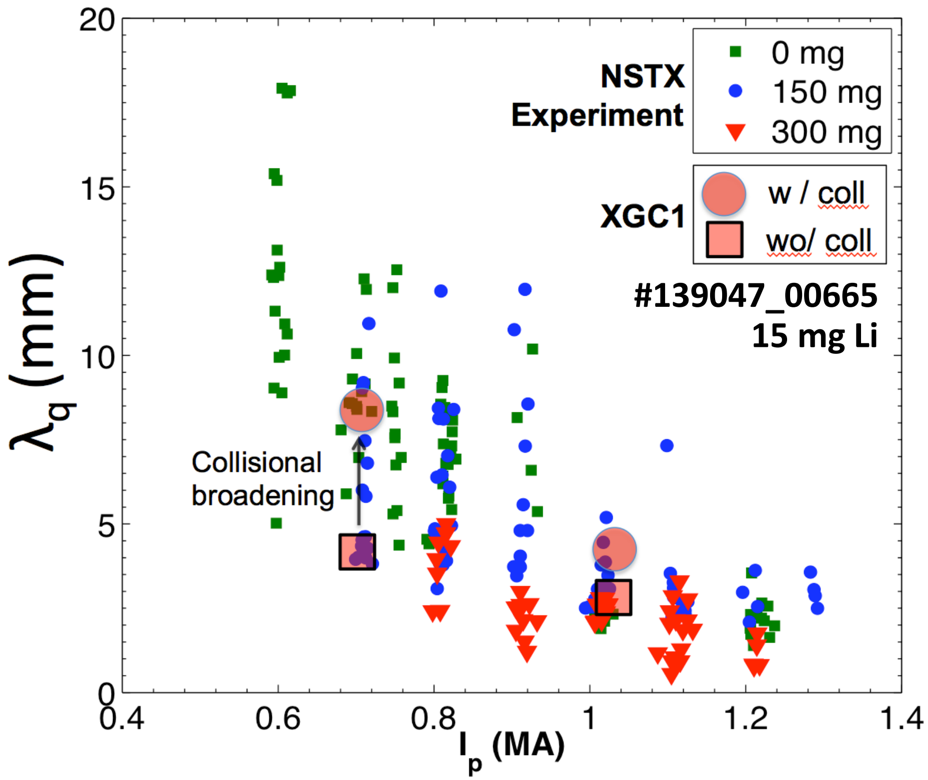


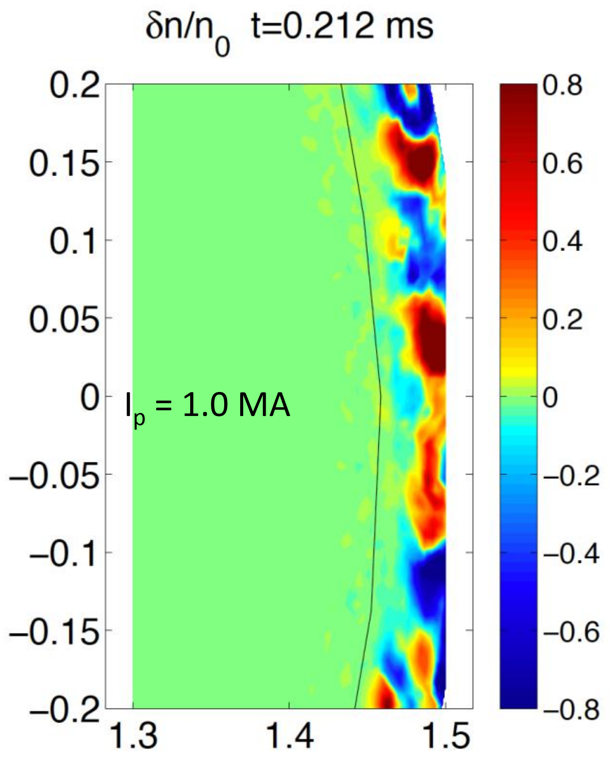
→ Dominance of Δ_i could be lost → breaking of the $1/I_P$ scaling?

An ITER simulation to be done soon to answer this important question

NSTX - Collisional effects on λ_q

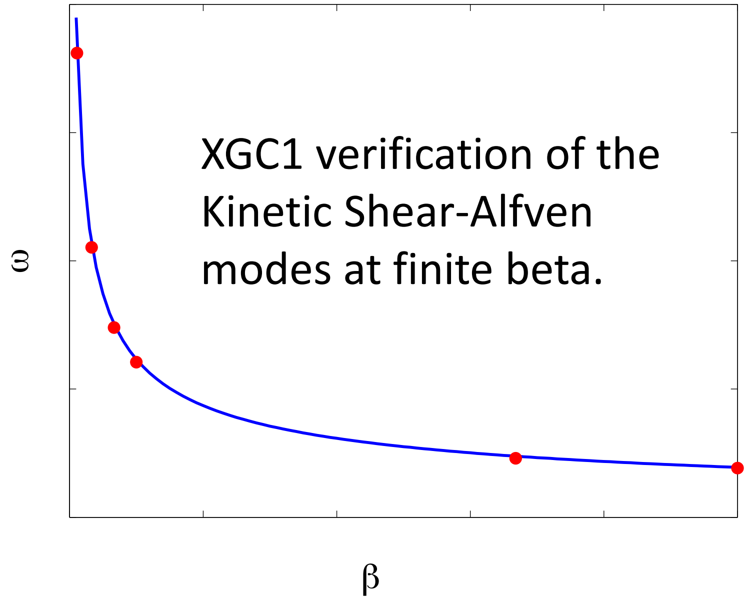
- If the neoclassical orbit width is important for prediction of λ_q, shouldn't the collisions broaden λ_q?
- NSTX without collisions ($\lambda_q \propto 1/I_P^{0.8}$)
- Collisions are found to broaden λ_q significantly ($\lambda_q \propto 1/I_P^{1.45}$)

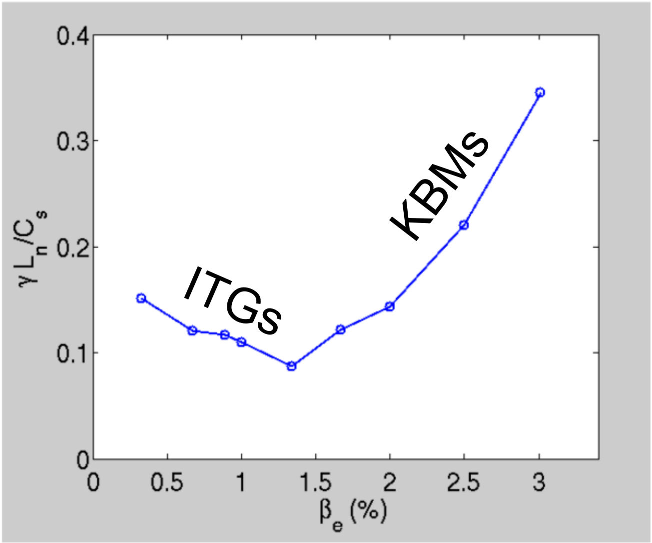


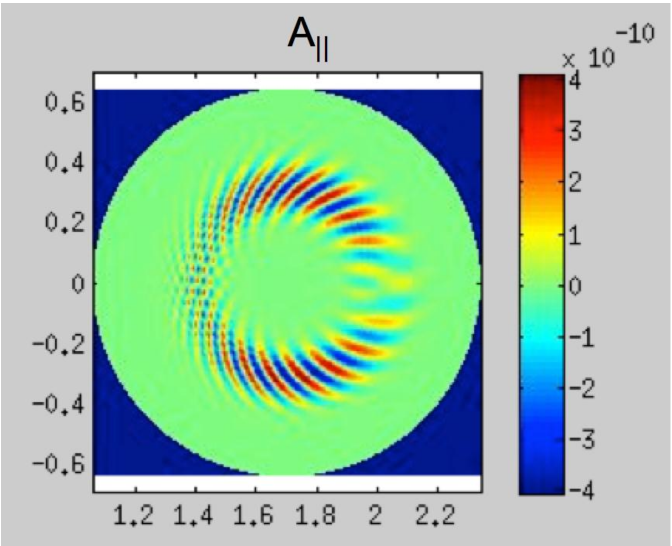


Status of the XGC1 development

- XGC1 is acquiring E&M capability, including reduced MHD modes
  - **Heat-load from gyrokinetic ELMs is to be included**
  - **E&M ballooning mode effect on heat-load is to be included**
- Kinetic shear-Alfven modes and the ITG-KBM transition have been verified



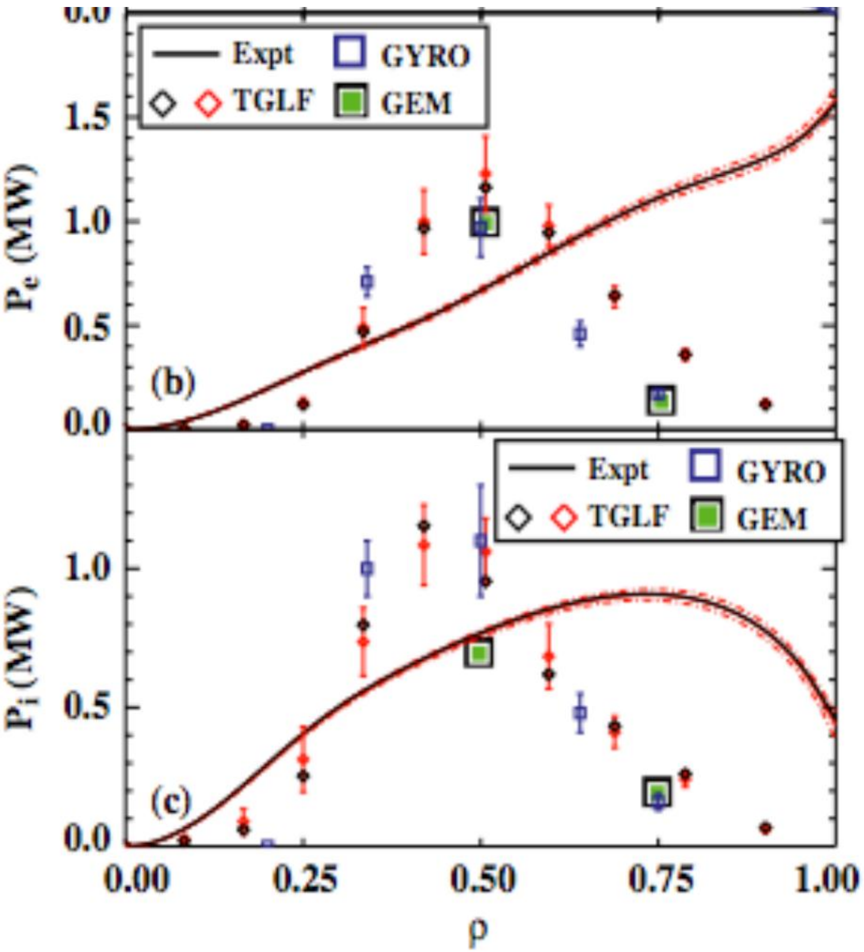




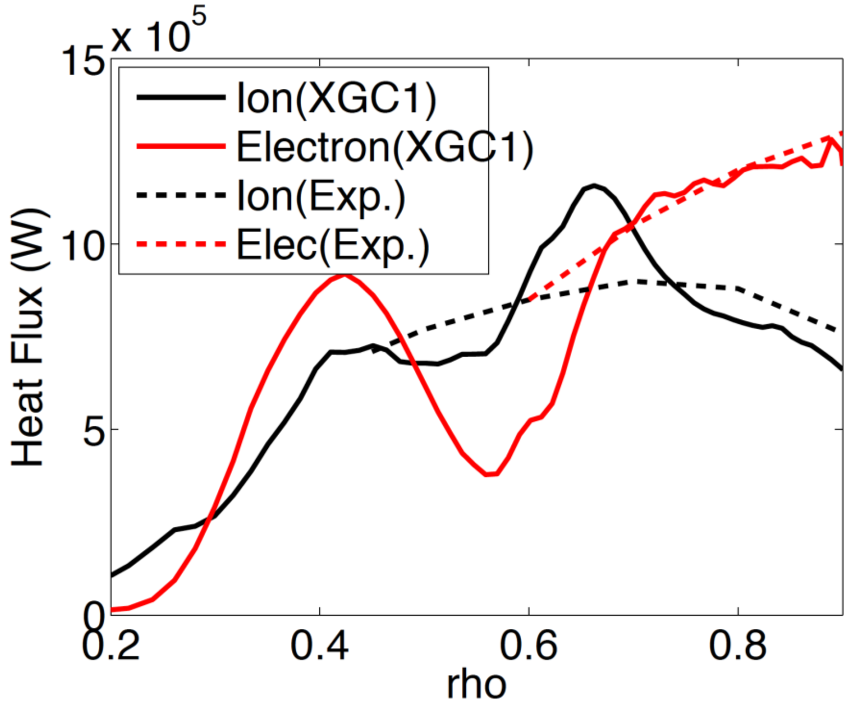
No DIII-D L-mode shortfall in XGC1 with full edge model

2014 INCITE, using 1/3 Mira capacity. 32-way OpenMP threading.

Transport shortfall from the core δf codes, DIII-D 128913



Rhodes et al., Nuclear Fusion 2011



Ion and electron heat fluxes from XGC1, DIII-D 128913

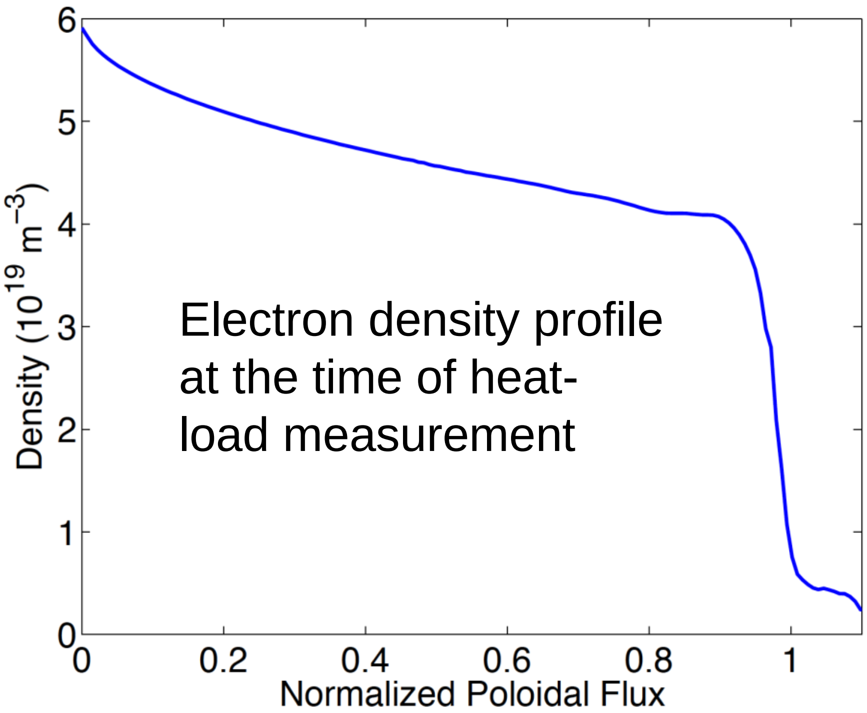
- Evolution of n_e, T, & η profiles from the experimental input is very minimal and within the experimental error bars.

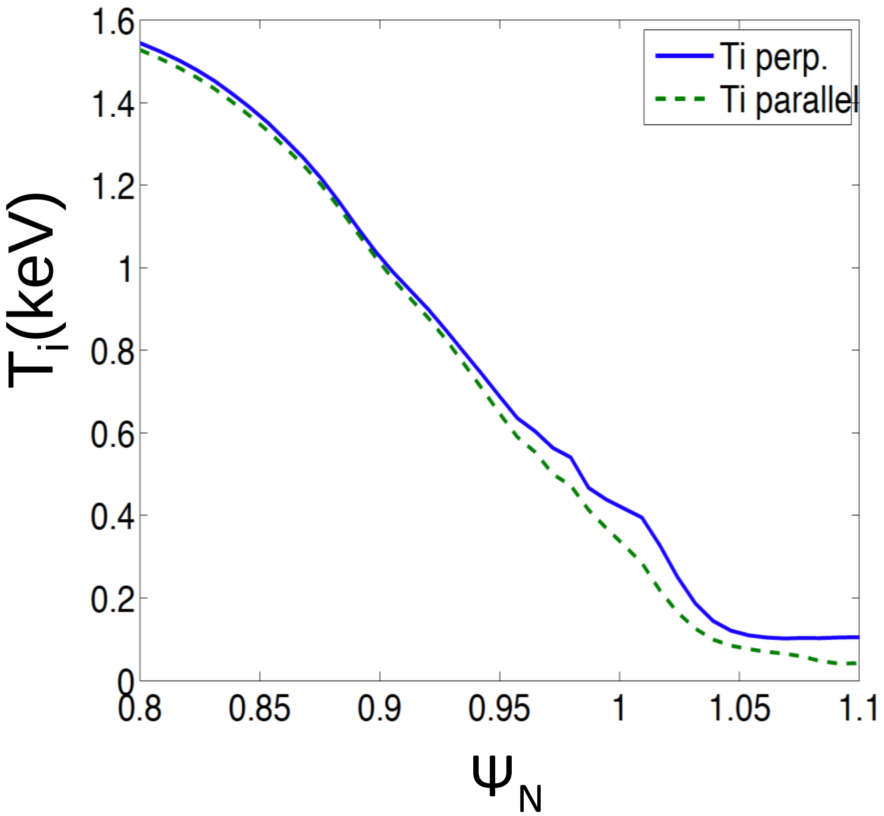
Conclusion and Discussion

- In the present-day tokamak devices, the previous neoclassical XGC0 and gyrokinetic XGC1 study show nearly $\lambda_q \propto 1/I_P$
  - It appears that neoclassical orbit effects are large and dominant relative to the blob spreading of λ_q.
- However, in ITER where the neoclassical ion orbit excursion is ≤1mm, and the $1/I_P$ trend may fail due to the blob size $\propto (\rho_i a)^{1/2}$ effects
  - These important XGC1 simulations are to be done soon in an ITER model plasma
- Electromagnetic capability is coming online in XGC1
  - Nonlinear evolution of ELM (nonlinear saturation of PBM) impact on divertor heat-load
  - Other electromagnetic turbulence effects
- XGC1 with full edge model does not show DIII-D L-mode shortfall

Relationship between midplane ∇p-width and λ_q?

- T_i has the widest extent into scrape-off in this simulation
- Δ_{Ti} is <1.5mm while $\lambda_q \approx$ 5mm.





- The assumption $\lambda_q \approx \Delta_p$ at outboard midplane is invalid.