27th IAEA-FEC, Gandhingar, India, Oct. 22-27, 2018

Wide divertor heat-flux width in ITER from turbulence bifurcation across separatrix

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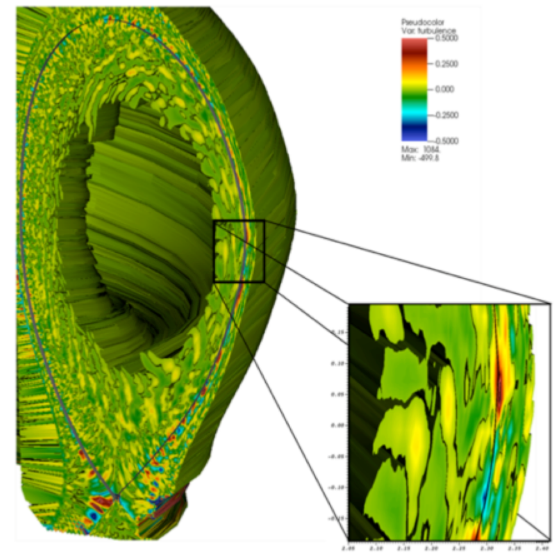
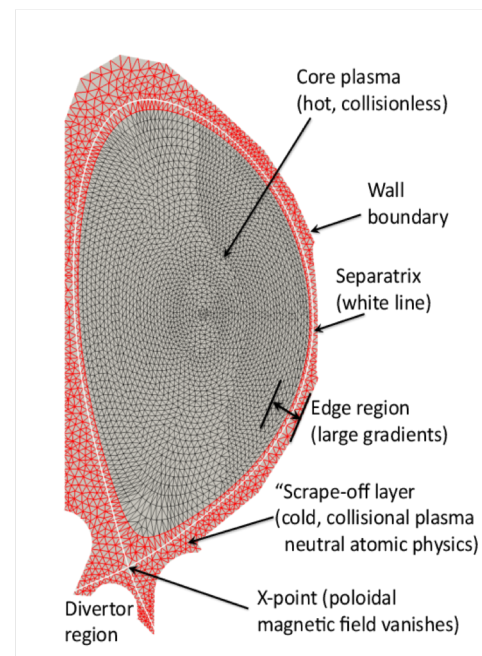
The XGC1 Gyrokinetic Code

- **Total-f PIC, combined with continuum technology**
  - Continuum grid used for nonlinear collision, f_0 evaluation, gyroaveraging, ...
- **In contact with material wall, having heat and momentum source in the core**
  - Far-from-equilibrium (non-Maxwellian)
  - Neutral particle recycling & transport, atomic interact.
- **Magnetic X-point and separatrix (q→∞)**
  - X-point orbit loss from pedestal
- **Total-f: Overlapping multi-scale, multiphysics in space-time: big physics per simulation time step.**
- Unstructured triangular mesh
- Solver: PETSc with Hypre and multigrid (only ~2% of total computing time)
- **Large simulation-size (≳10k particles per grid-vertex) per time-step: ideal for extreme scale computing**
- **Most of the production runs are large-scale: on >50% Titan, >50% Theta, and ~50% Cori.**

XGC1





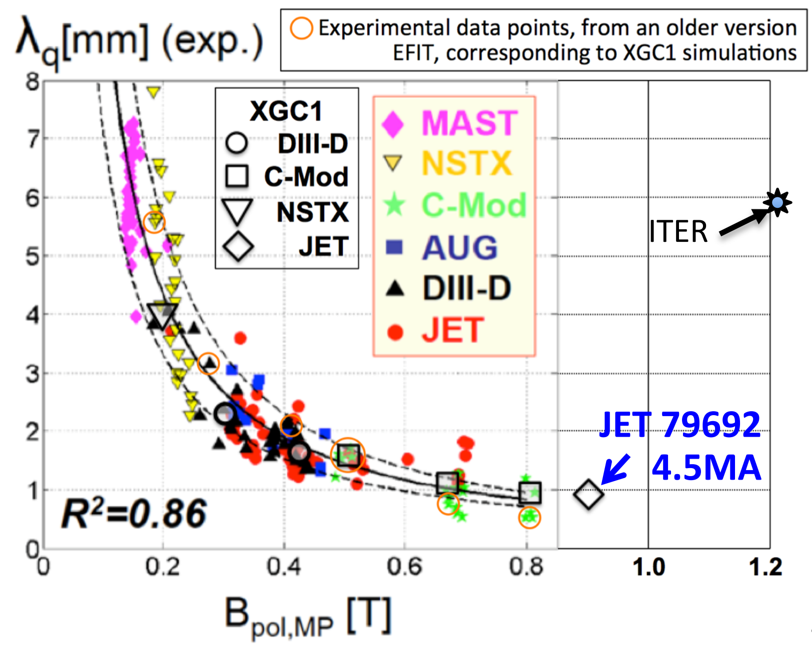
Validation of XGC1, and a surprising result for ITER

- XGC1 predictions agreed well with the existing experimental results from the three large US tokamaks + a JET high-current (4.5MA) case
- Divertor heat-flux width was dominated by the ion neoclassical dynamics
  - X-point orbit-loss type of ion-drift dynamics is the dominant mechanism
  - Turbulent e-transport is a "follower," for ambipolar transport & determining E-field
- λ_q physics agreed with the previous picture presented by
  - XGC0: Report on 2010 US-DOE Joint Research Target study [A. Pankin et al., Phys. Plasmas 22, 092511 (2015)]
  - Heuristic ion-drift model: R. Goldston, NF 52, 013009 (2012)
- XGC1 finds ubiquitous blobby turbulence

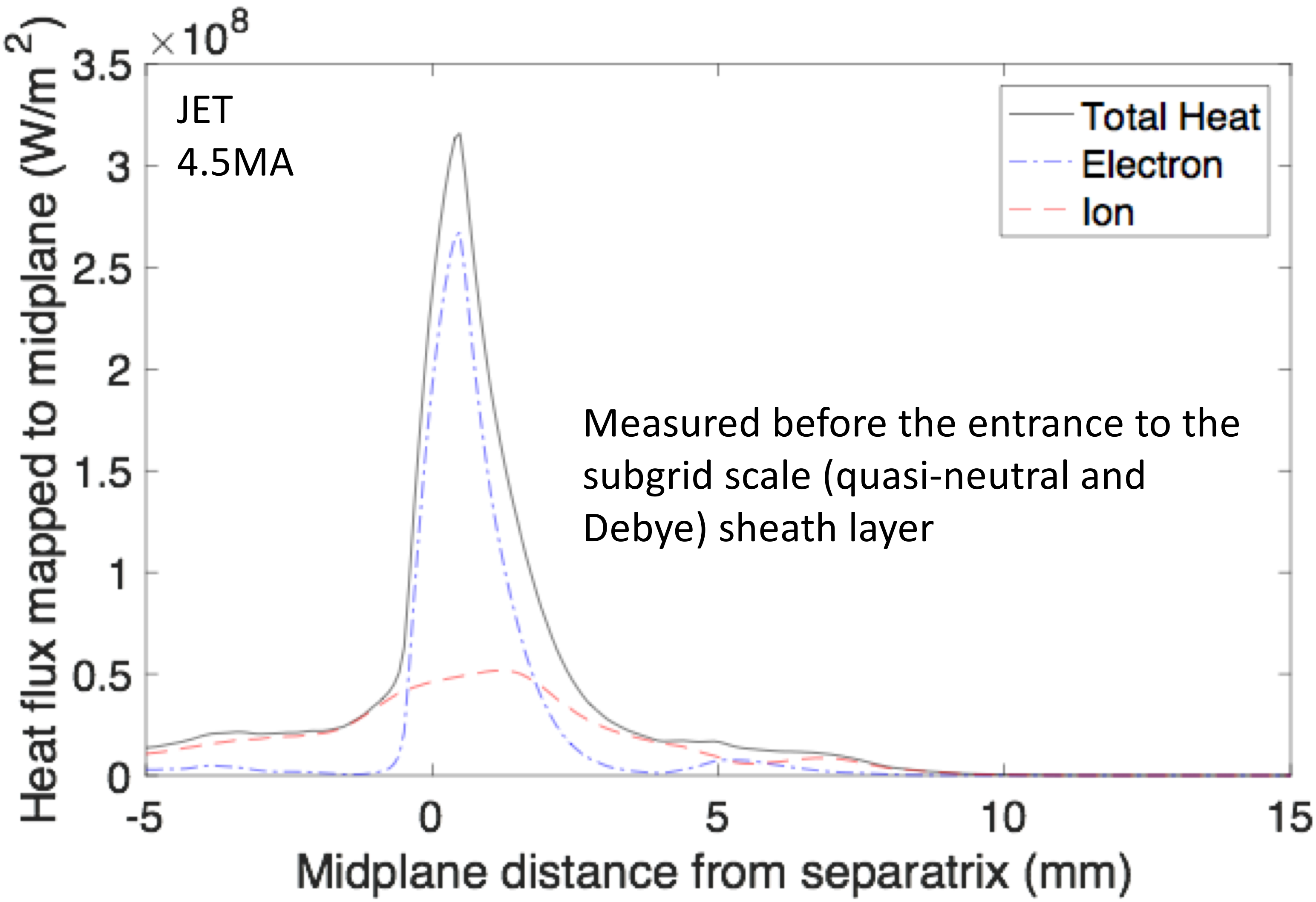
However, the same XGC1 on 15MA ITER produced $\lambda_q^{Eich} \gtrsim 6\lambda_q^{Eich}$. Why???

→ Triggered a deeper study

- Size effect: parallel and neutral physics
- Δ_{banana}/a effect: perpendicular physics

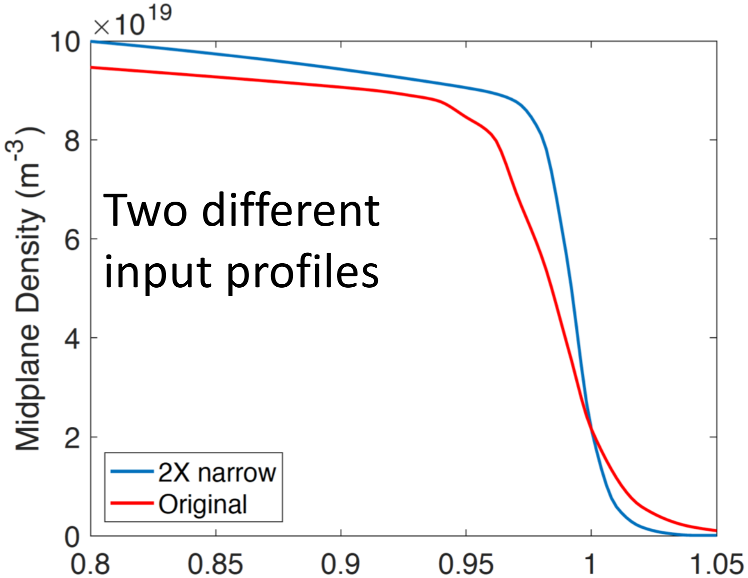


Similarly to other existing tokamak cases, $\lambda_{q,i}^{XGC} > \lambda_{q,e}^{XGC}$ in the JET 4.5MA discharge (and the edge turbulence is blobby)

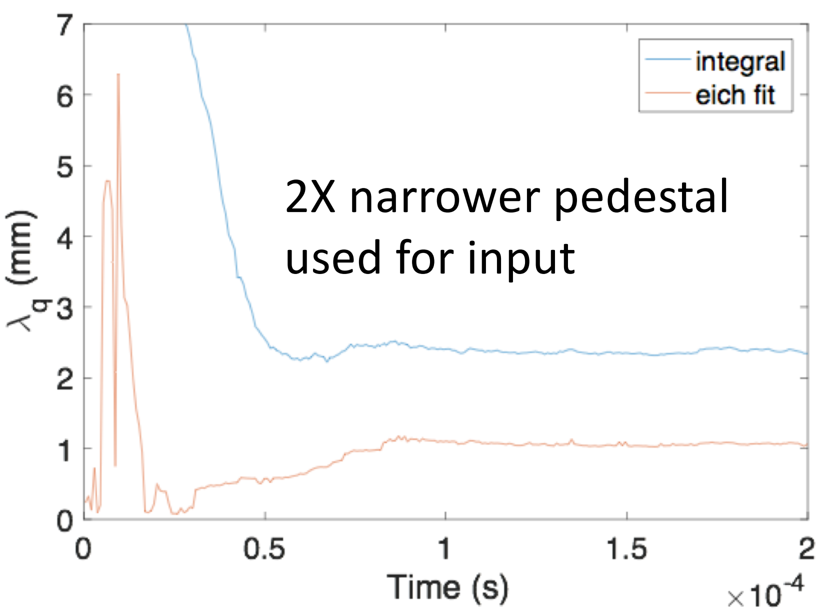


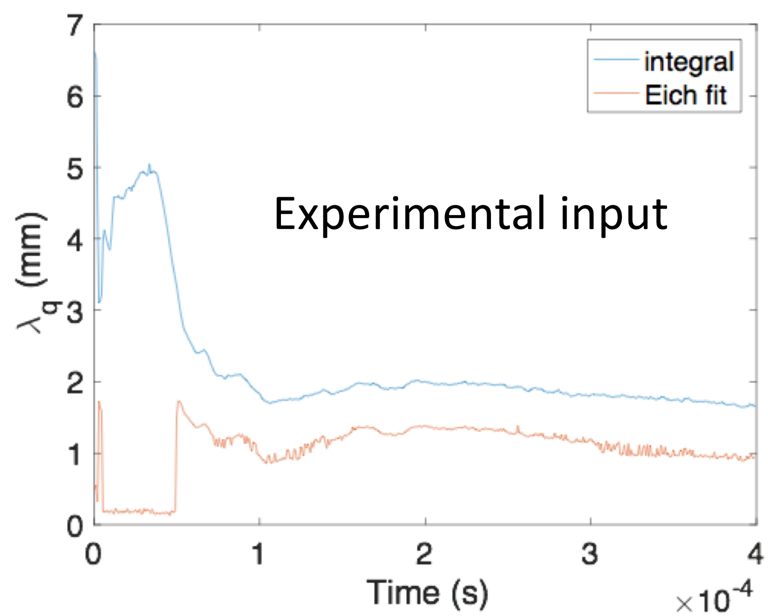
Sensitivity of λ_q to initial plasma profiles on JET

The left-figure at the bottom has ~2X narrower pedestal width, but yields a similar λ_q at the end, due to the turbulence & background self-organization capability of the total-f XGC1.



Conclusion from this and the ITER studies: For Total-f XGC, approximately correct intial plasma profile around the separatrix is good enough.

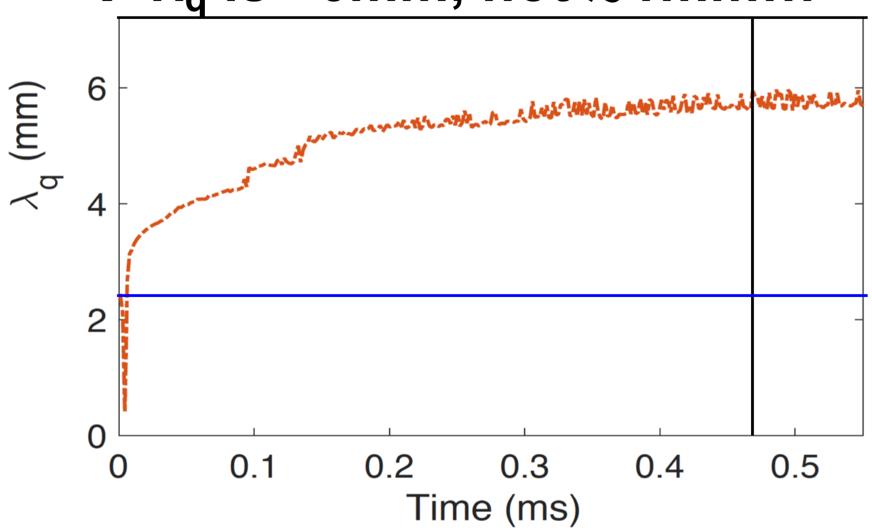


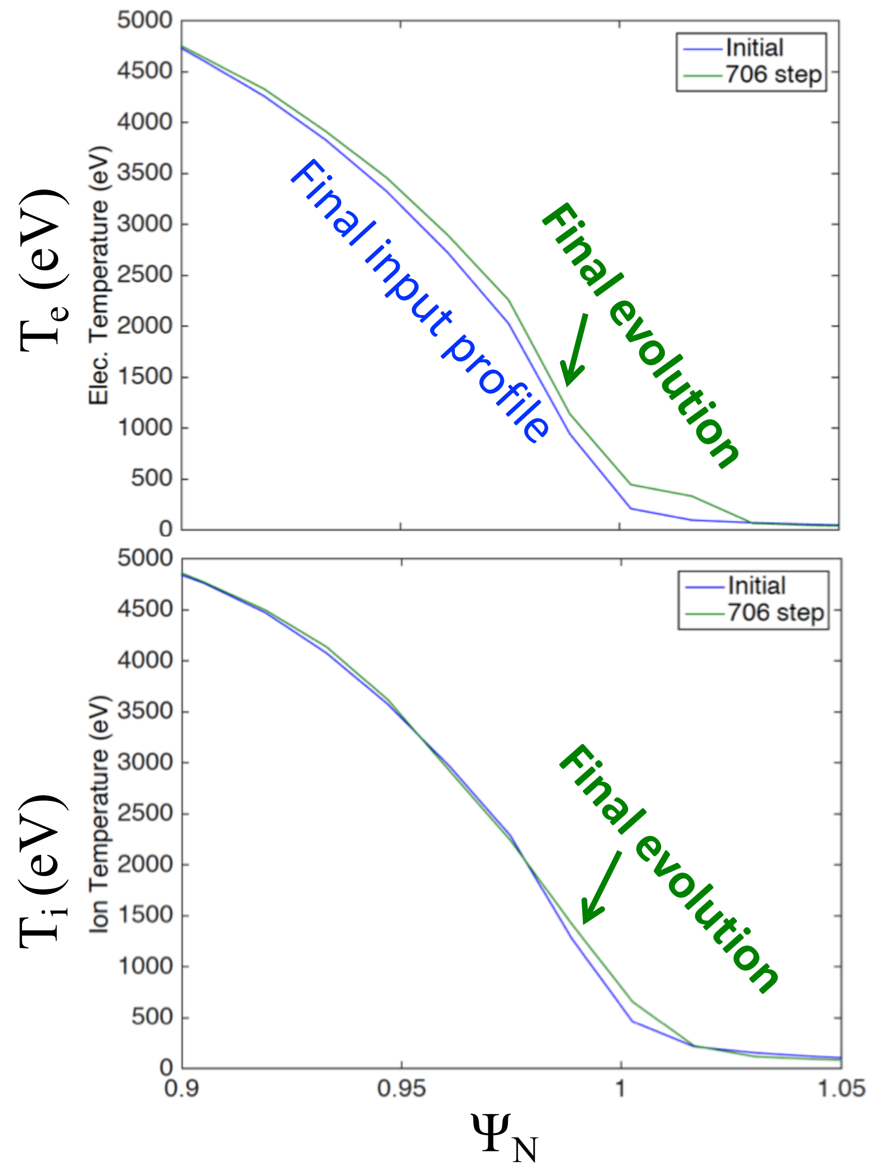


XGC study on a 15MA ITER model plasma

- The MHD-limited pedestal was too steep: too strong turbulence → too high a heat flow across the separatrix and to divertor target ~700MW.
  - But λ_q^{MHD} was still ~6mm
- XGC1 eventually found a self-organized plasma profile across the separatrix; which satisfies, approximately, turbulence saturation across sepratrix, power balance between separatrix and divertor at ~100MW, and λ_q saturation.

→ λ_q is ≈6mm, not ≲1mm!!!

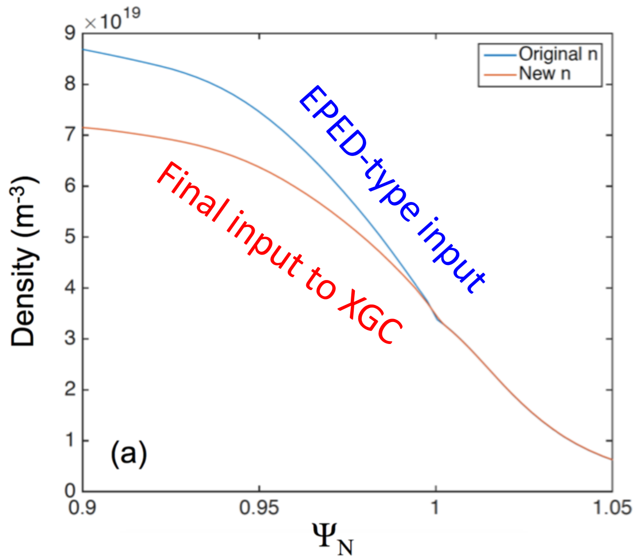


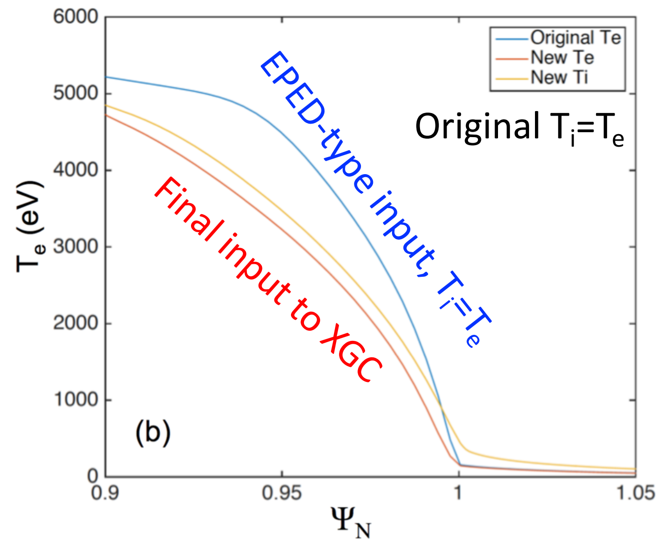


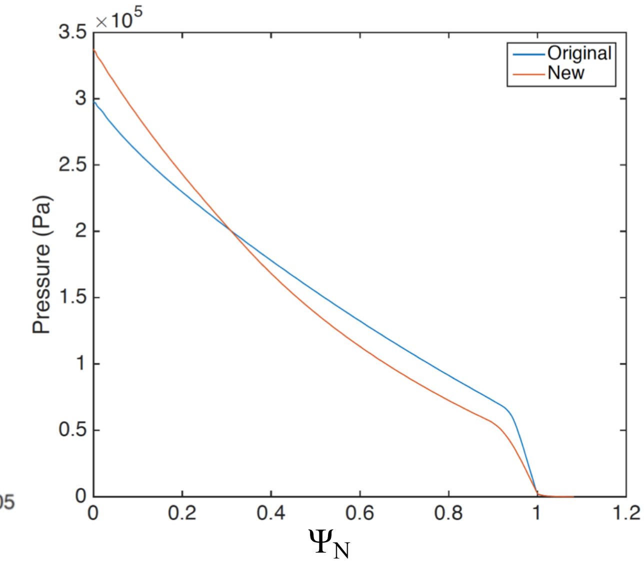
Caution: approximate turbulence and power balance achieved only at ψ_N>0.96.

Input comparison between the "MHD/fluid-limited ITER-standard" pedestal and an electrostatic-XGC1 relaxed pedestal at 15MA

- The XGC1-obtained (approximate) pedestal width at ITER 15MA is $\gtrsim$ 2x MHD/Fluid pedestal width
  - EM effect needs to be studied later
- λ_q ~ 6mm in both MHD and kinetic pedestals





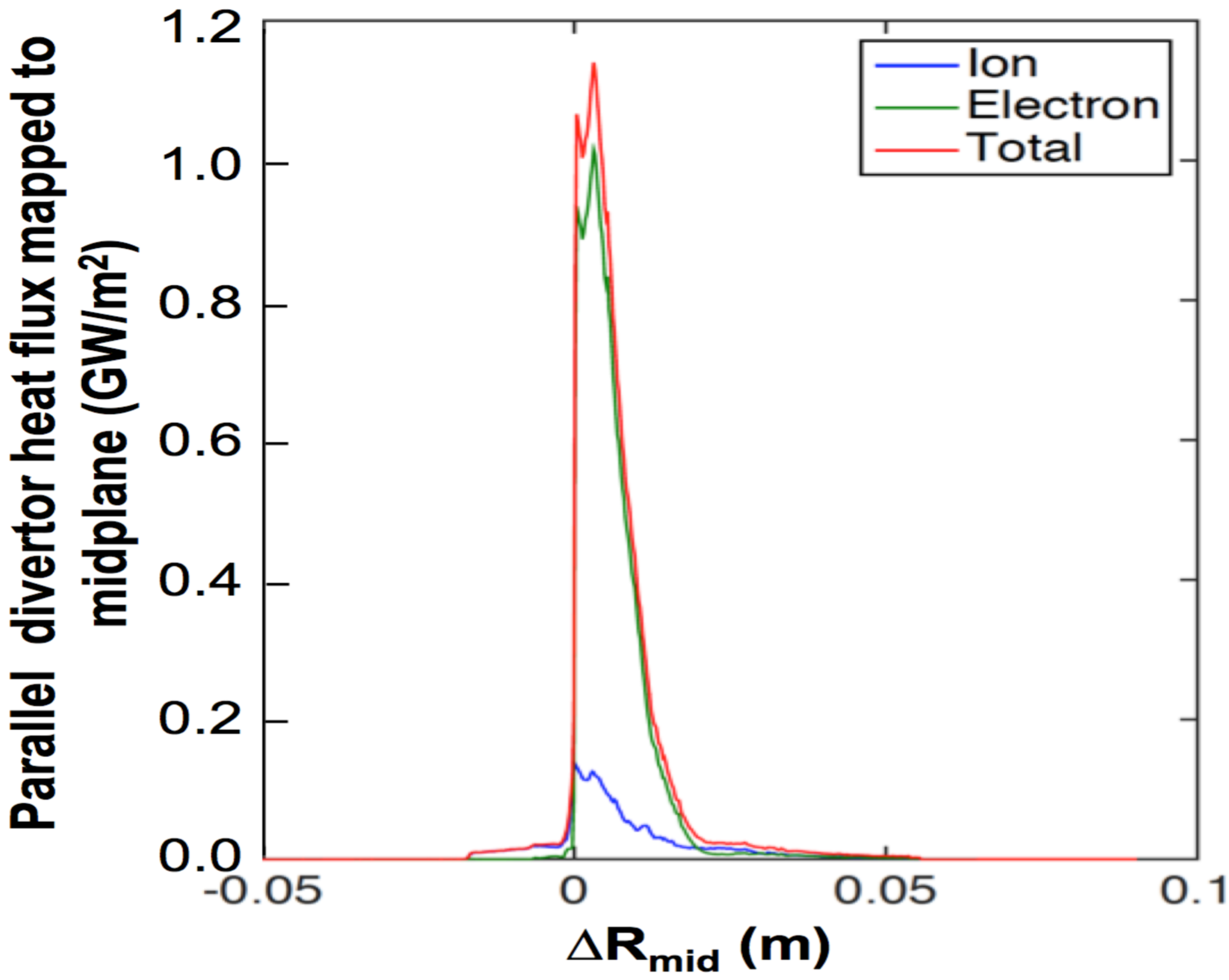


Caution: XGC1 density and temperatures are meaningful only at ψ_N>0.96.

XGC finds $\lambda_{q,e} \gtrsim \lambda_{q,i}$: 15MA ITER is different from the present tokamaks.

- **Heat flux is completely dominated by the electrons in both magnitude and width.**

What is going on?



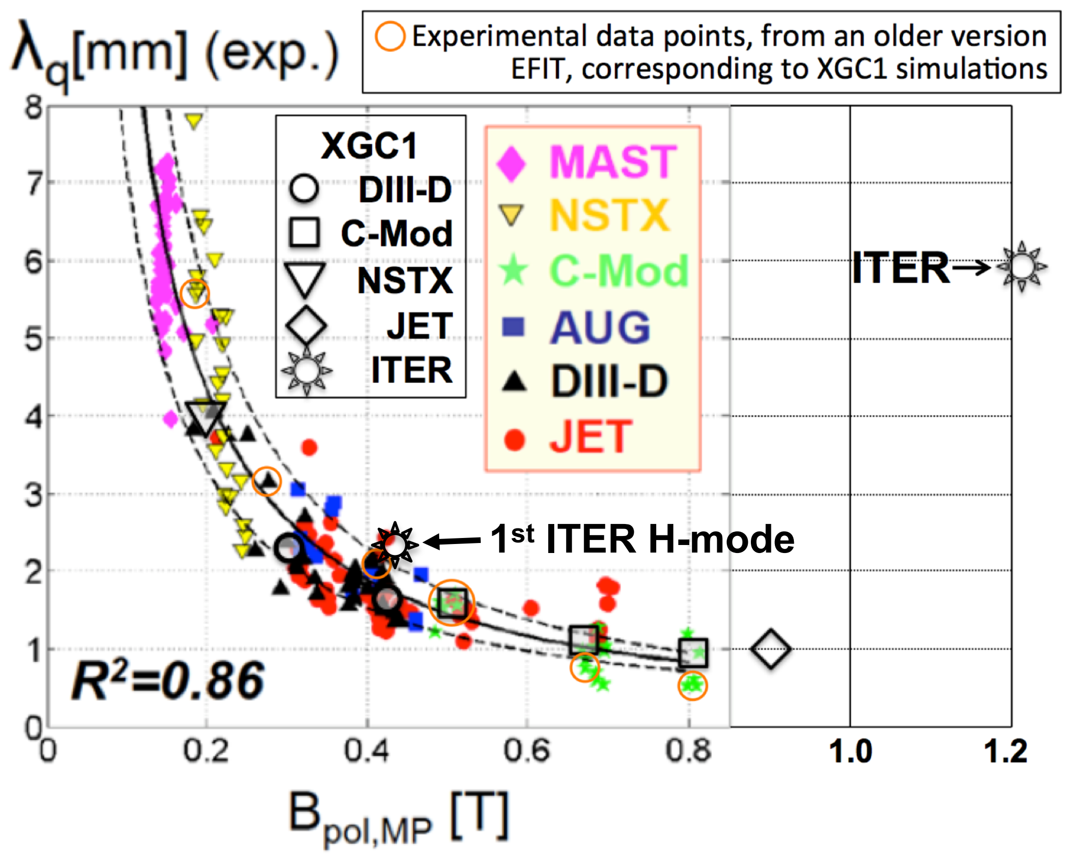
XGC study on a 5MA ITER model plasma

- To check if the enhanced λ_q in the full-current ITER is from the "**size effect**" or from the "Δ_{banana}**/a effect**," a **5MA initial H-mode operation in ITER** has been simulated

  → λ_q **agrees with the present tokamaks → clearly not the size effect**

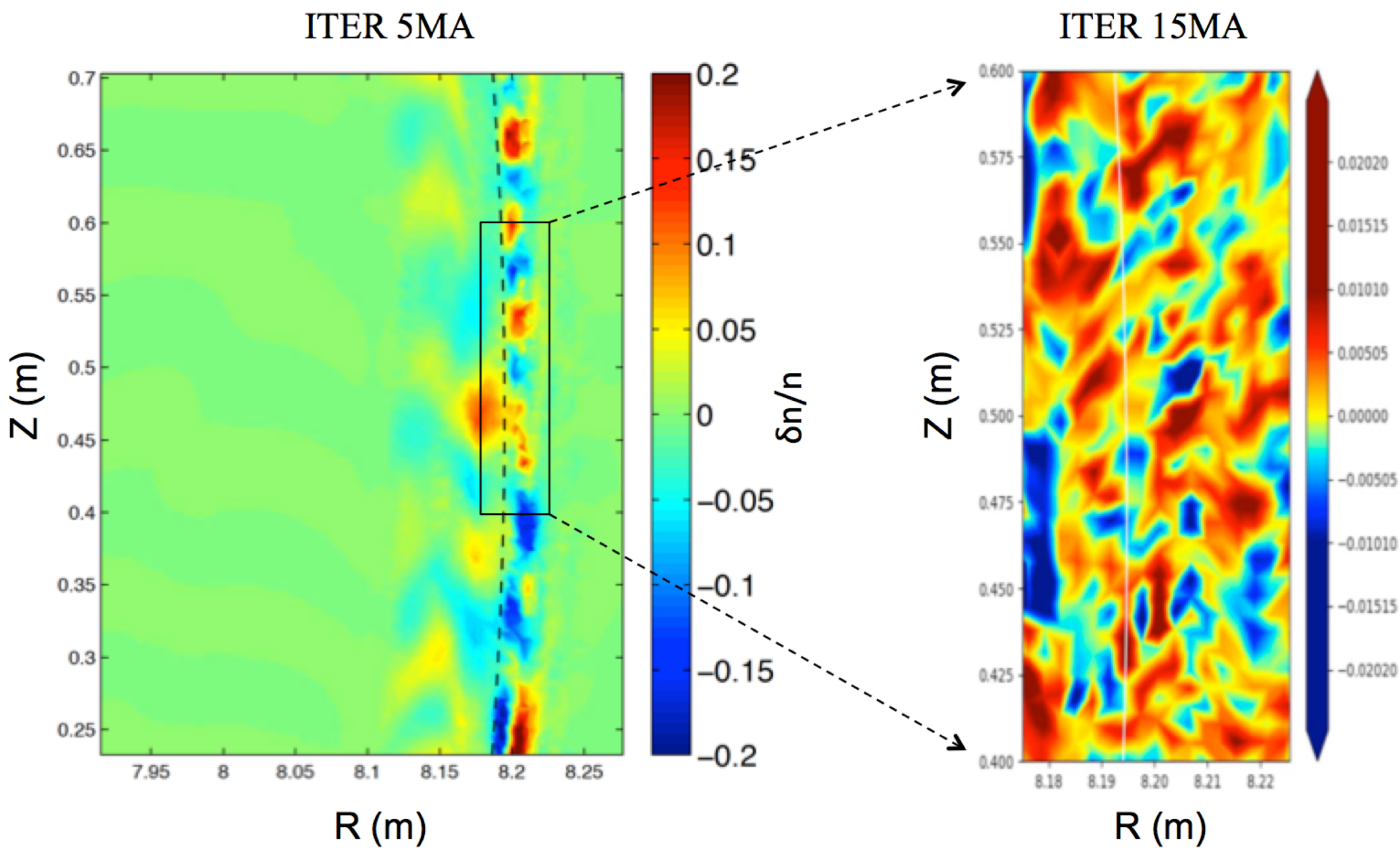
  → **Difference in turbulence is from the Δ_{banana}/a effect**.

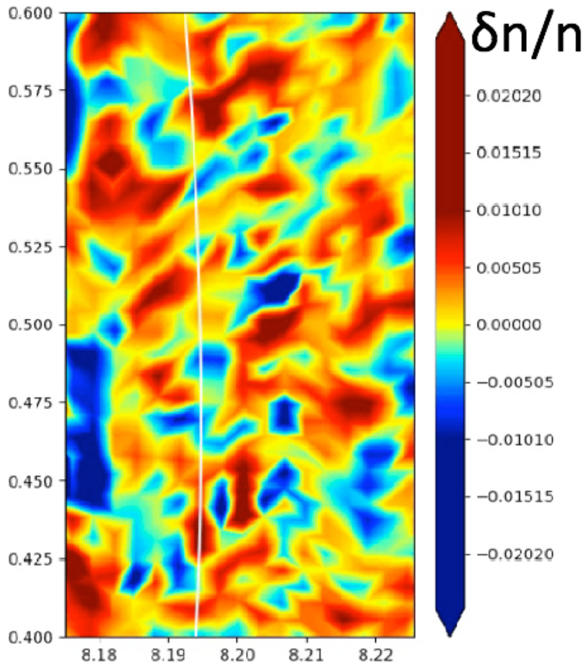
- The "absolute size effect" is related to the parallel physics and the neutral particle transport.
- The "Δ_{banana}**/a** effect" is mostly from the perpendicular physics.
- Exclusion of the pure Δ_{banana} effect will be validated (or invalidated) against the recent highest current C-Mod plasma.

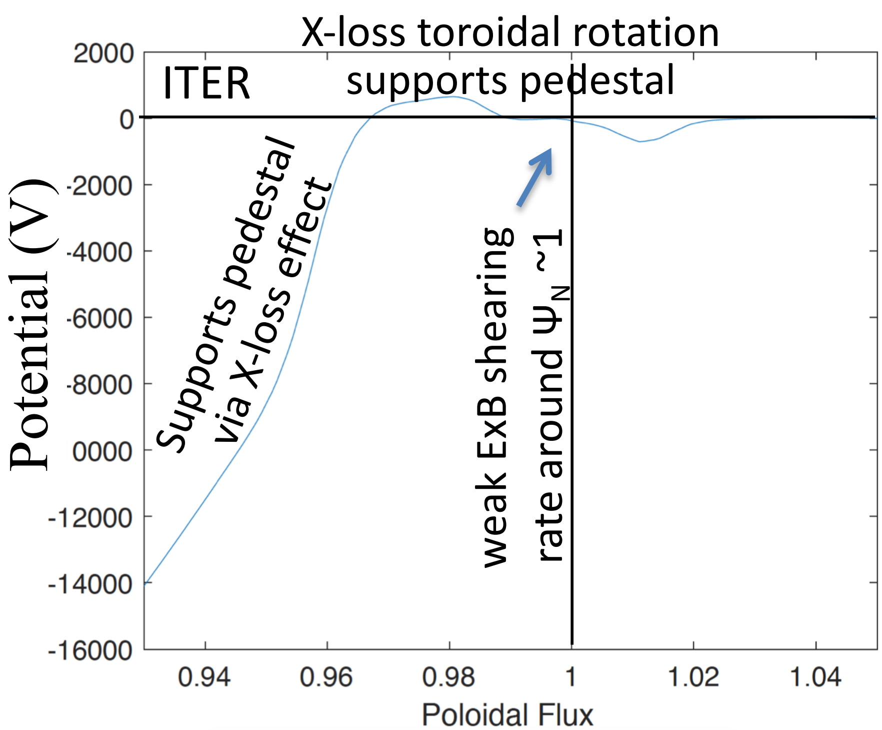


Evidence for an edge physics bifurcation between the higer and lower Δ_{banana}/a values.

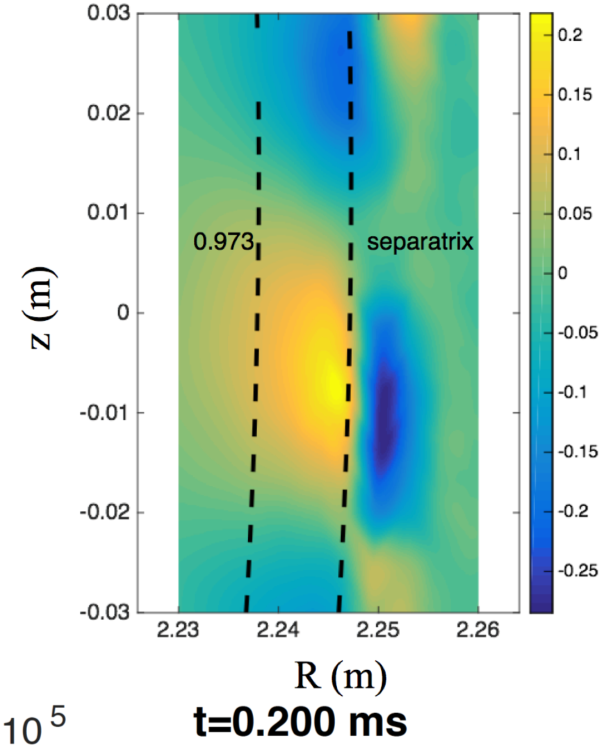
In the low-current ITER, edge tubulence across the separatrix is blob type and the ExB shearing rate is high. In the high-current ITER, the turbulence is streamer type and the ExB shearing rate is low.

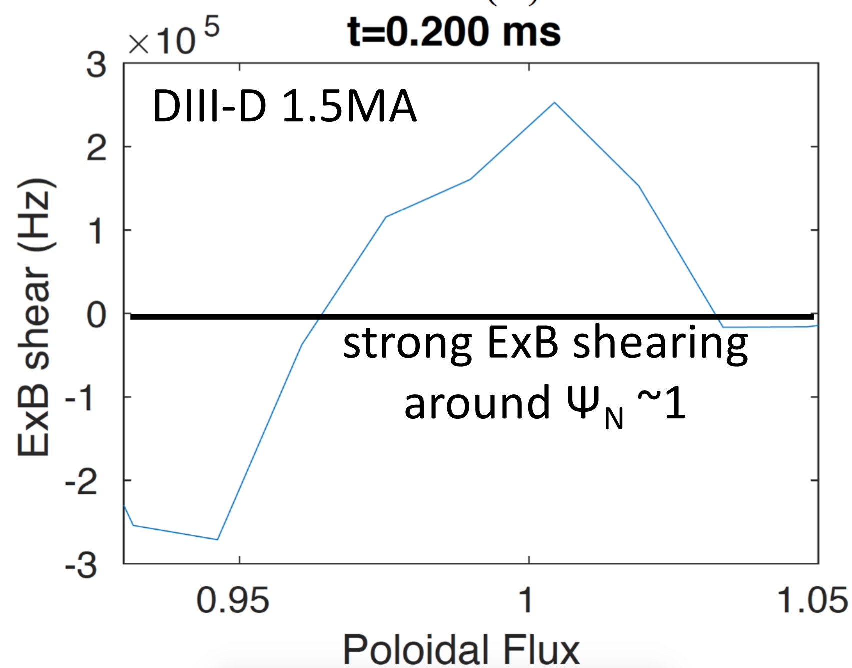




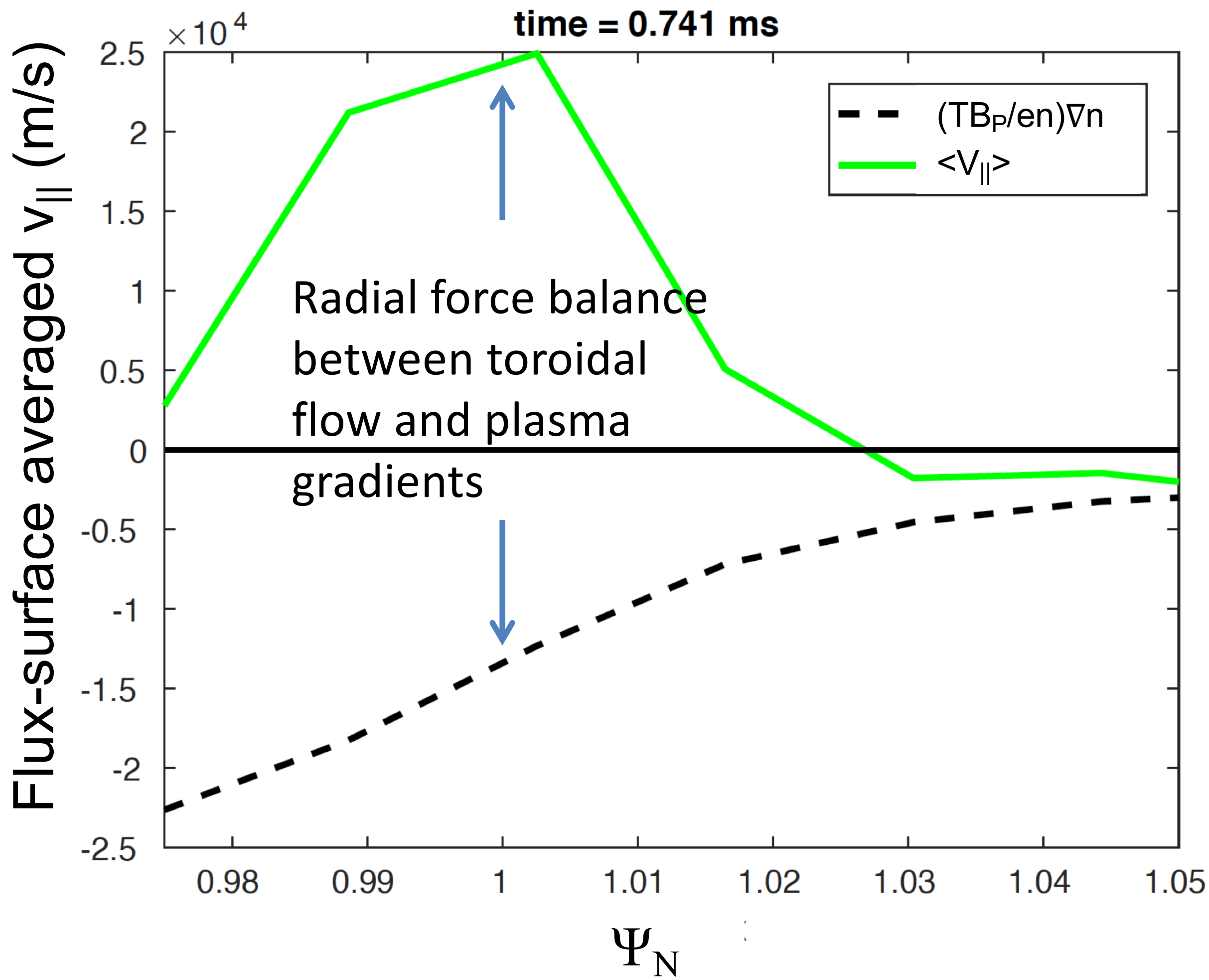


Physics bifurcation between
present tokamaks and ITER

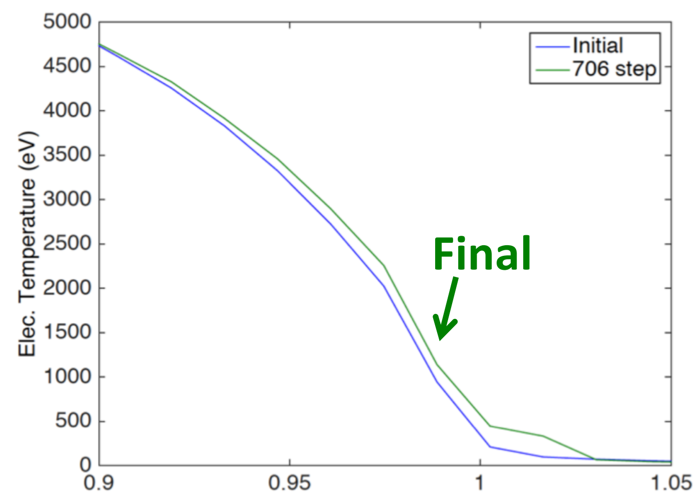




In 15MA ITER edge at Ψ_N~1, the plasma pedestal is supported by toroidal flow ~0.1 V_i, generated by X-loss

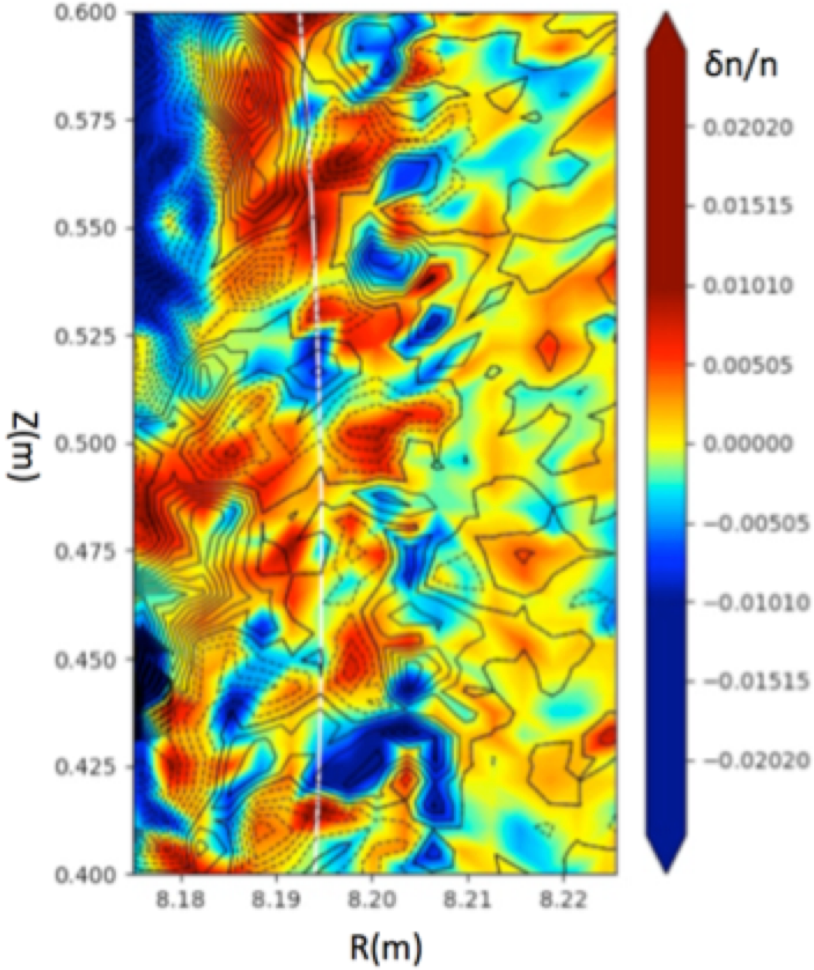


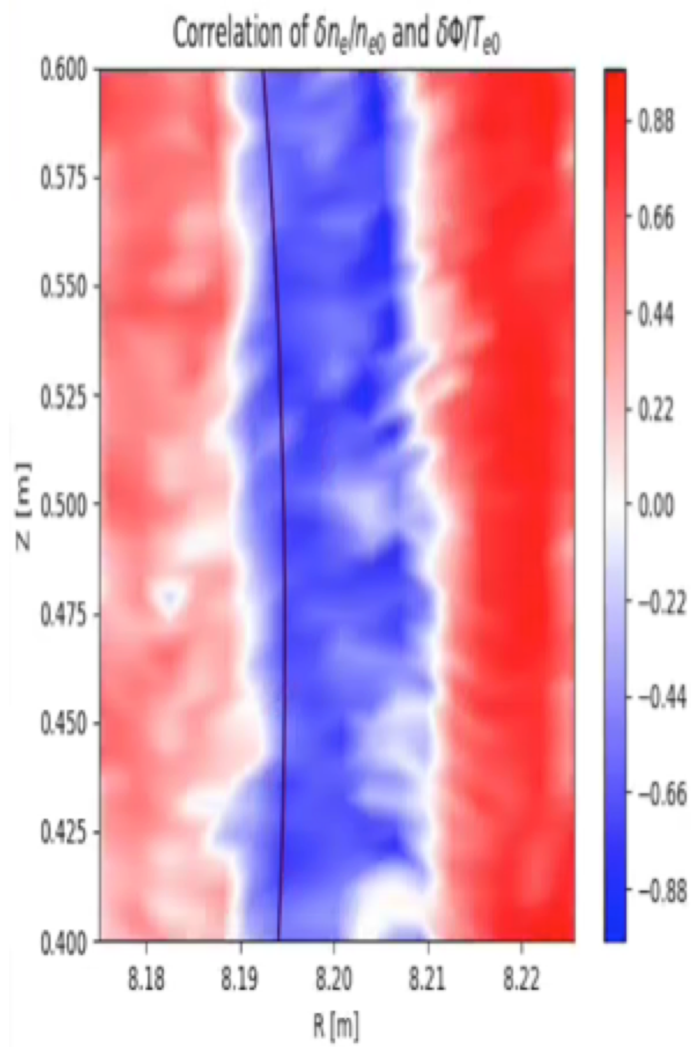
n_e and T pedestals with little E_r, supported by toroidal rotation.



Unlike for the blobby turbulence in present tokamaks, the full-current ITER contains a strong non-adiabatic electron response across the magnetic separatrix,

as evidenced by a large phase difference between δn and δΦ (≳π/2) (left) and a strong de-correlation between their amplitudes (right).



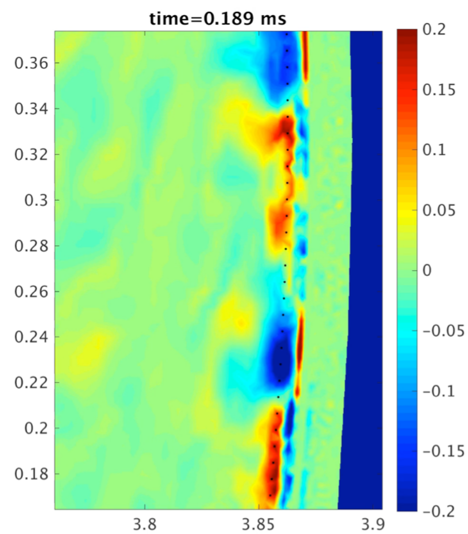


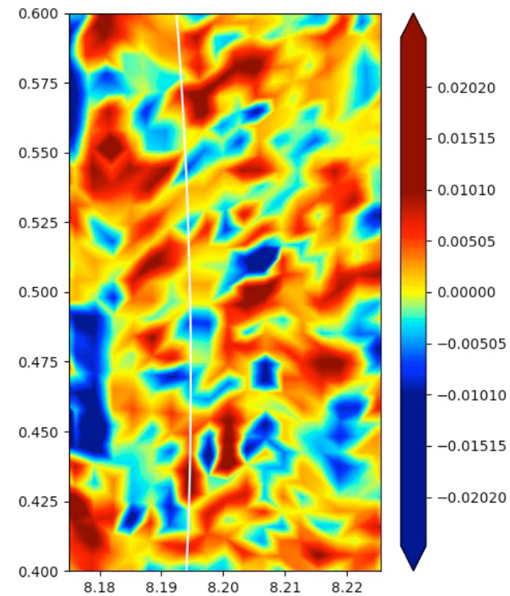
There appears to be a “bifurcation” from Blob- to Streamer-type edge turbulence somewhere between JET and ITER, arising from nonlinear interaction between weaker V_{ExB}' and TEM turbulence.

- Weaker X-loss driven ExB-shearing-rate from the size effect $\gamma_{E\chi B}^{X\text{-loss}} \propto (v_i/a)\ \rho_i/a$
- Failure to stablize TEM turbulence: $\gamma_{ExB}^{X\text{-loss}}/\gamma_{mode} \propto \Delta_{banana}/a$
- TEM turbulence induces large particle flux
- Weakens the ExB shearing rate further.
- Turbulence becomes stronger

→ **Nonlinear bifurcation.**

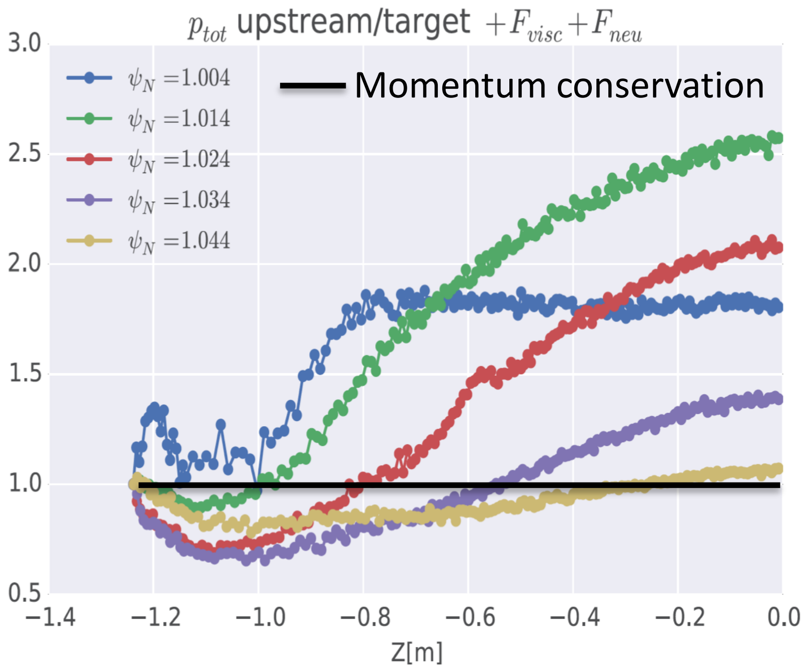
When the ion neoclassical X-loss becomes too weak, the edge plasma self-organizes to expell the heat through microturbulence.



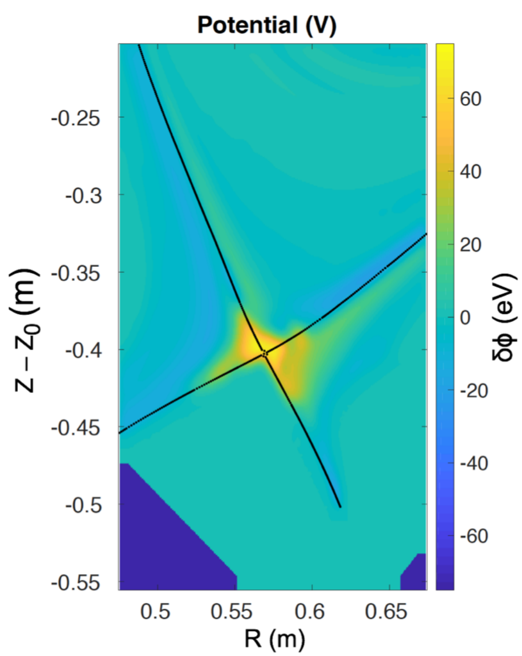


Definition of λ_q should include dissipation by the X-point ExB circulation

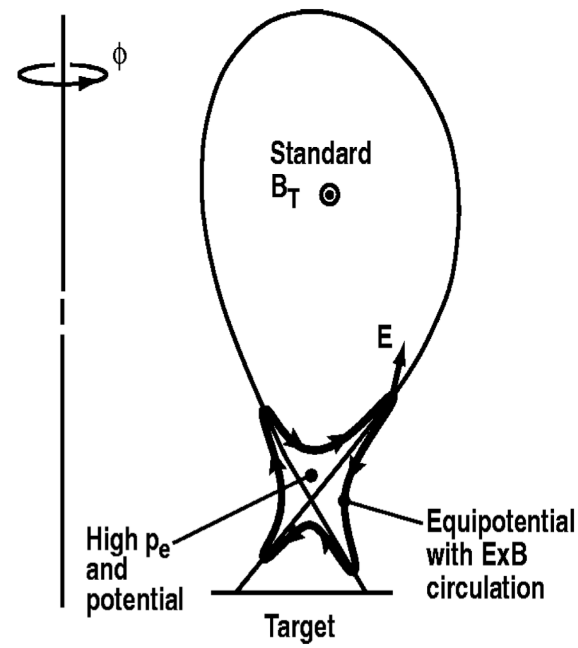
- The upstream-downstream plasma relation is not explained by fluid equations along the field lines, even in sheath-limited regime
  - Experimental: J. Canik et al, PoP 2017
  - Gyrokinetic: **Churchill [TH/P7-26]**; **non-Maxwellian+drift** correction is severe, **CGL is invalid**
- **New: ExB circulation** around the X-point, breaking the flux-tube relationship
  - Chang, Ku, Churchill, submitted to PoP, gyrokinetic XGC, X-loss
  - Schaffer et al., PoP 2001, experimental fast probe



XGCa gyrokinetic, DIII-D: CGL does not conserve parallel momentum



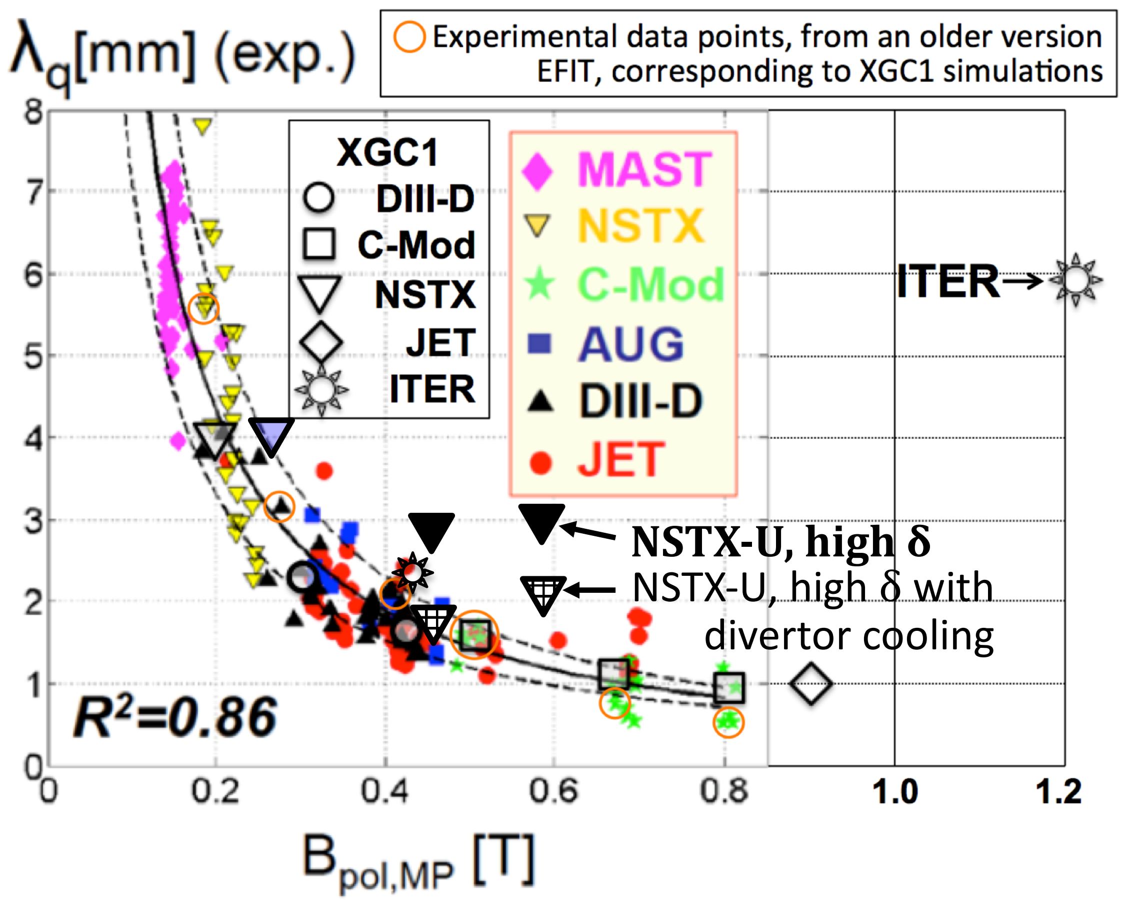
$\Phi_{0,m>0}$ in XGC1, C-Mod H-mode

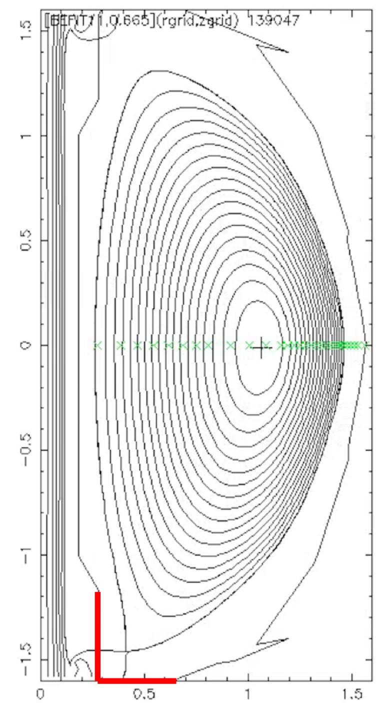


Schaffer's fast probe, DIII-D L-mode

TEM effect on wider λ_q is supported in NSTX-U plasmas

- A high triangularity ($\delta_X \approx 0.8$) NSTX 1MA discharge has been selected as a reference for NSTX-U plasma models: ▽
- 1.5MA and 2MA NSTX-U plasma profiles are projected from ▽
- Unlike other tokamaks, NSTX-U with $\delta_X \approx 0.8$ shows enhanced λ_q, and a reduction by divertor-chamber cooling
  → A good testbed for a λ_q physics study





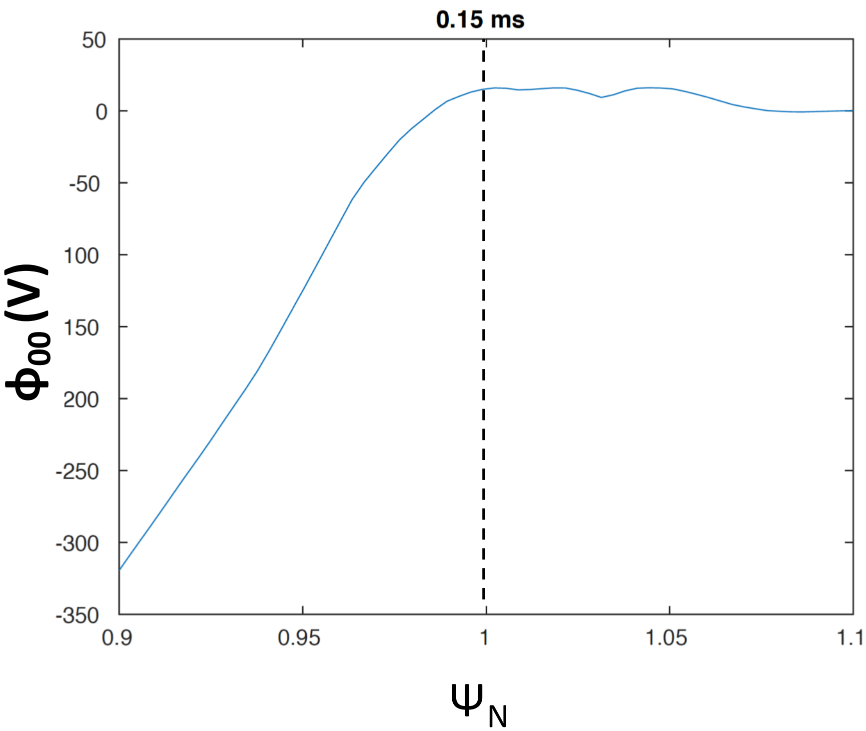
NSTX #139047 as a reference case for an NSTX-U projection

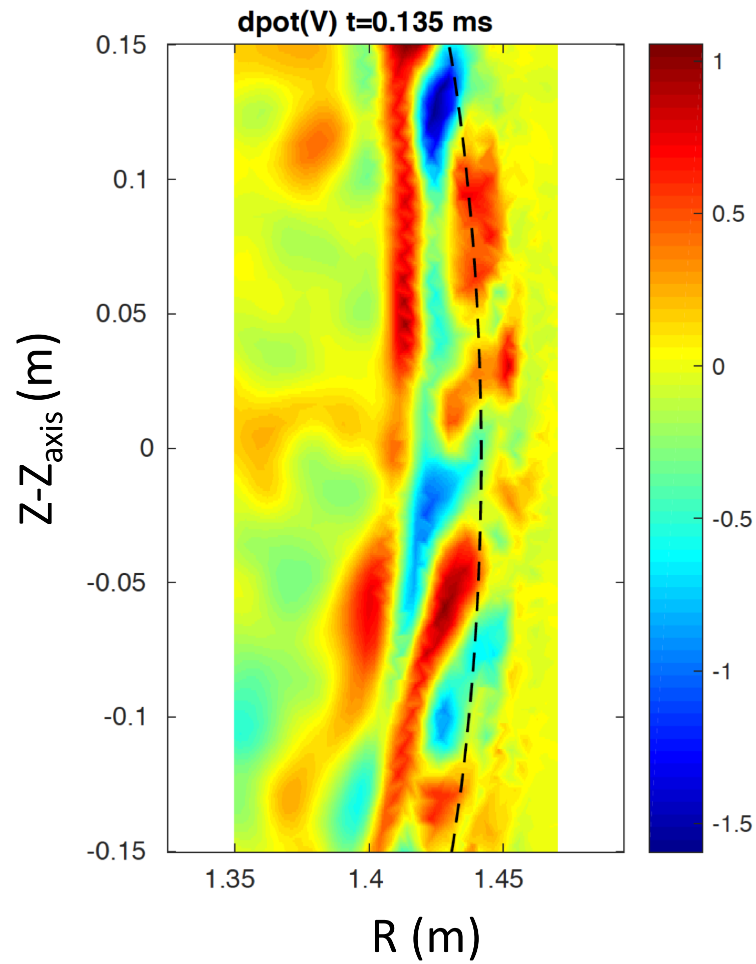
In the high current (2MA) NSTX-U case without the divertor-chamber cooling, where λ_q ~2.5 λ_q^{Eich}, the edge turbulence is not the usual blobs and ϕ_{00} is almost flat across the separatrix

- Stronger TEM drive in a spherical tokamak

→ earlier bifurcation to TEM turbulence

Divertor chamber cooling weakens TEM.

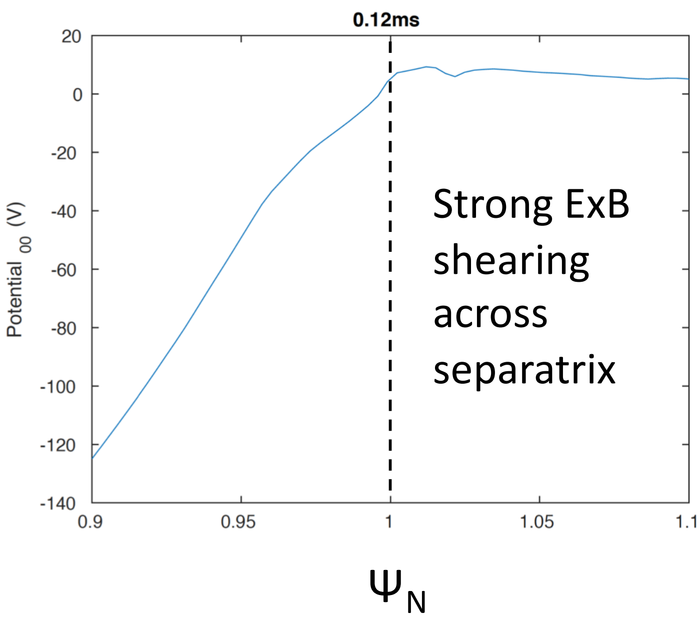




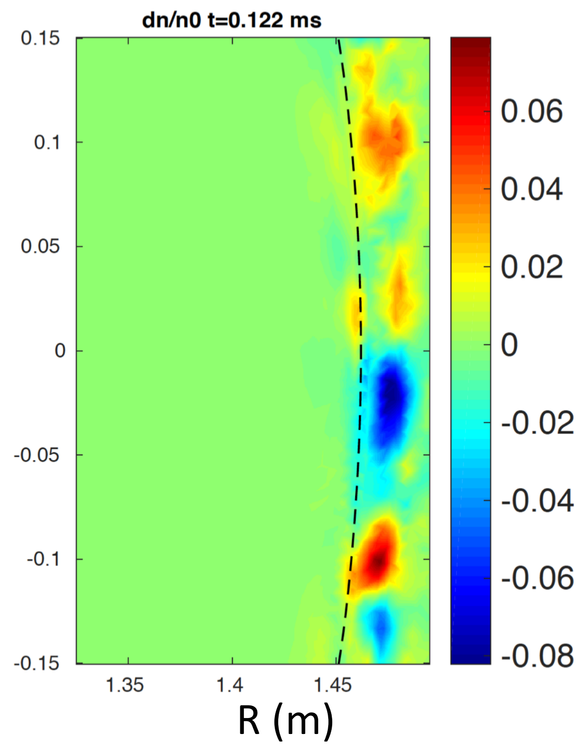
At lower I_P (=1MA) NSTX, the edge turbulence becomes blobby and φ_{00} is more sheared across the separatrix surface ← higher Δ_{banana}/a

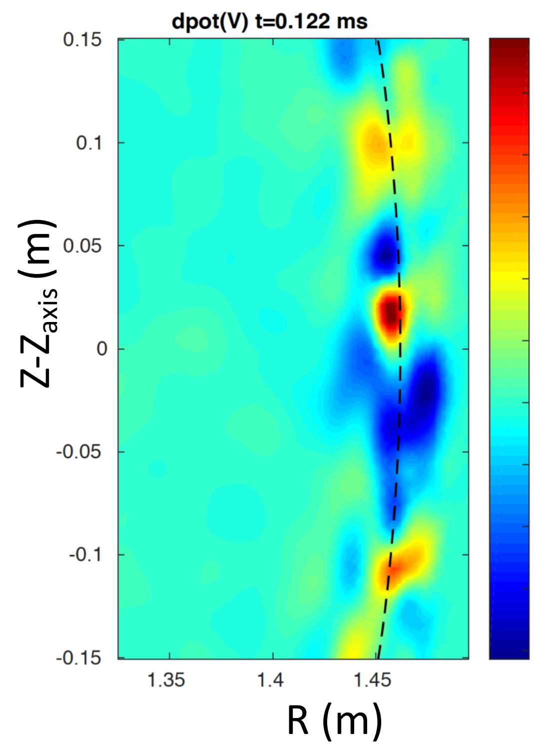
In the NSTX 1MA reference case with the same plasma shape as for NSTX-U, turbulence is blobby.

Turbulence property across separatrix is sensitive to the local ExB shearing rate



ExB shearing layer has moved radially outward.





Conclusion and discussion

- **The XGC-predicted heat-flux widths have been well-validated on the three major US tokamaks: NSTX, DIII-D, C-Mod**
- **Prediction for 15MA ITER: λ_q^{XGC}(15MA ITER) $\gtrsim 6\lambda_q^{Eich(14)}$(15MA ITER)**
- **Since XGC is a total-f code, λ_q^{XGC} is not very sensitive to the initial plasma profile, as long as it is reasonable.**
- **Physics reason for broader λ_q^{XGC} in 15MA ITER than 5MA is revealed**
  - **As I_P increases, $\Delta_{i,banana}/a$ becomes smaller and weakens the X-loss driven E_r shearing rate across separatrix, and the trapped electron turbulence surfaces up to broaden λ_q^{XGC}**
- **NSTX-U seems to confirm this physics reason**
- **The flux tube argument between the upstream-downstream SOL width needs reconsideration**
- **Need other validation ideas: How can we reduce the E_r shearing-rate across the separatrix surface in the present tokamaks?**

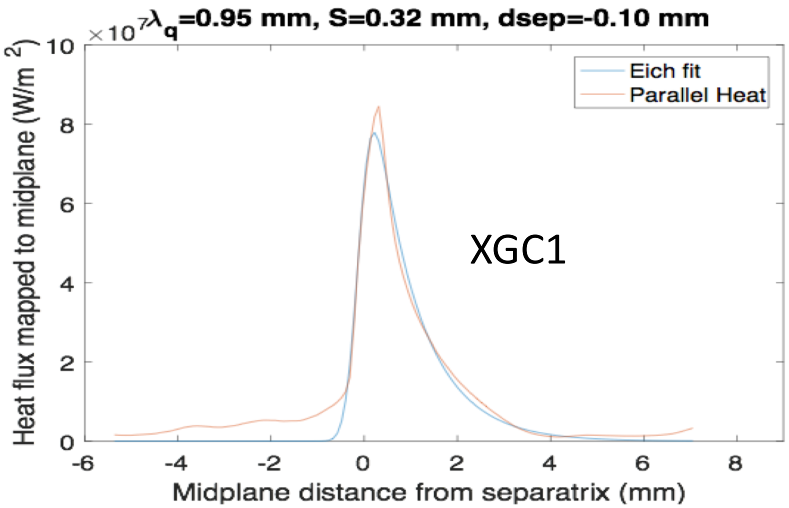
Extra slides

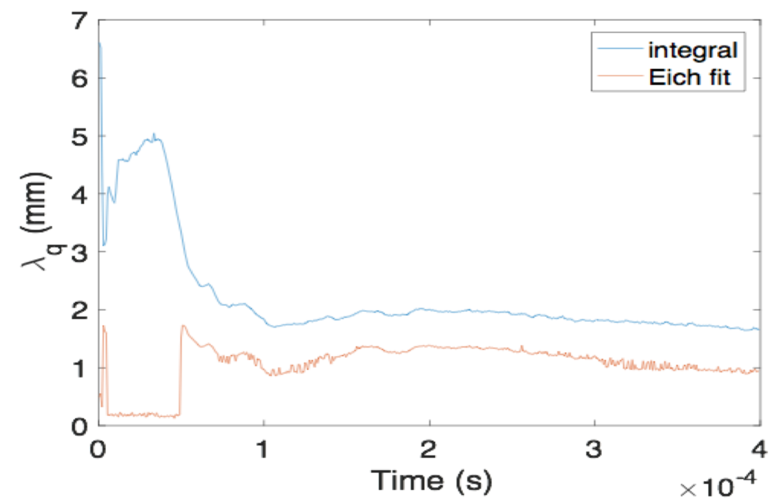
Outline

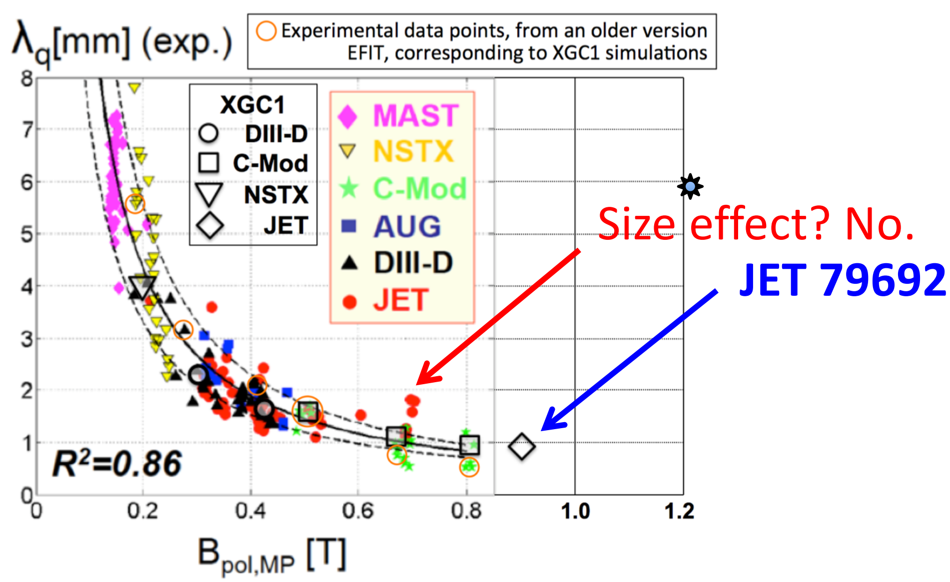
- **The XGC-predicted heat-flux widths have been well-validated on the three major US tokamaks: NSTX, DIII-D, C-Mod**
- **Prediction for 15MA ITER: $\lambda_q^{XGC} \gtrsim 6\lambda_q^{Eich(14)}$**
- **Prediction for high-current JET: λ_q^{XGC} follows $\lambda_q^{Eich(14)}$**
- **Since XGC is a total-f code, λ_q^{XGC} is not very sensitivity to the initial plasma profile, as long as it is reasonable.**
- **Prediction for 5MA ITER: λ_q^{XGC} follows $\lambda_q^{Eich(14)}$**
- **Physics reason for $\lambda_q^{XGC} \gtrsim 6\lambda_q^{Eich(14)}$ in 15MA ITER is revealed**
- **NSTX-U appears to confirm the physics reason**
- **Flux tube argument between upstream-downstream needs reconsideration**
  - Definition of λ_q should include dissipation by the X-point ExB circulation
- **Conclusion and discussion**

Prediction on full-current JET: λ_q^{XGC} from the 4.5MA discharge follows $\lambda_q^{Eich\ (14)}$, as other existing tokamaks do [JET will measure λ_q(exp)]

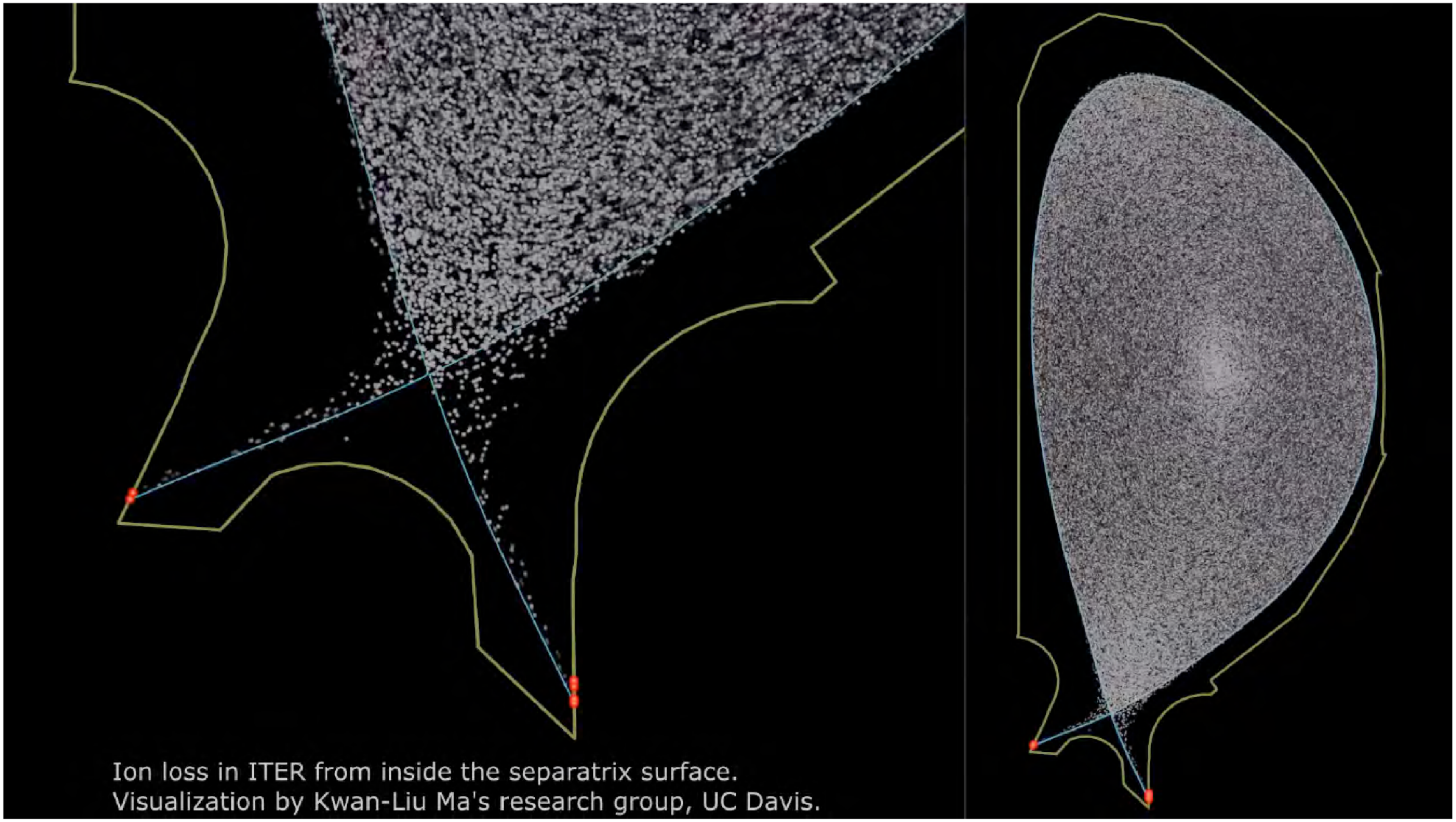
Could not conclude if the effect is from the size or a/ρ_{ip} effect,
since both of them are smaller in the 4.5MA JET than in the full-current ITER







XGC1 can study divertor heat-flux at unprecedented detail.



ITER

Time-scale issue: In the core plasma, *f* evolves slowly

For this argument, let's use the drift kinetic equation for simplicity

$$\partial f/\partial t+(\mathbf{v}_{||}+\mathbf{v}_d)\cdot\nabla f + (e/m)E_{||}\, v_{||}\, \partial f/\partial w = C(f,f) + Sources/Sinks.$$

In near-thermal equilibrium, take the "transport ordering" (= diffusive ordering):

$$\partial f/\partial t=O(\delta^2),\ S=O(\delta^2),\ with\ \delta<<1$$

- Let $f=f_0+\delta f$, with $\delta f\,/\,f_o=O(\delta)$, $\delta <<1$, $v_d/v_{||} = O(\delta)$, $E_{||}/m = O(\delta \text{ or } \delta^2)$

$O(\delta^0)$: $v_{||}\cdot\nabla f_0 = C(f_0,f_0) \rightarrow f_0=f_M$: H-theorem

$O(\delta^1)$: $\partial\delta f/\partial t + v_{||}\cdot\nabla\delta f + v_d\cdot\nabla f_0 + (e/m)\, E_{||}v_{||}\,\partial f_o/\partial w = C(\delta f)$

- ✧ Perturbative kinetic theories then yield transport coefficients $=O(\delta^2)$
- ✧ In this case, fluid transport equations ($f_o\rightarrow n,T$) can be used with analytic or delta-f kinetic closures

→ ***δf*-GK simulation is cheaper per physics time** (small computers)**, but equilibrates on a slow time scale $O(\delta^1\omega_{bi})^{-1}$ ~ *ms***: *Core GK simulation time scale*

A meaningful time evolution of f_0 can only be obtained in a long "transport-time" scale $O(\delta^2\omega_{bi})^{-1}$: Not yet reachable by GK simulation; Multiscale time integration is needed.

In edge, f equilibrates in zeroth-order time-scale

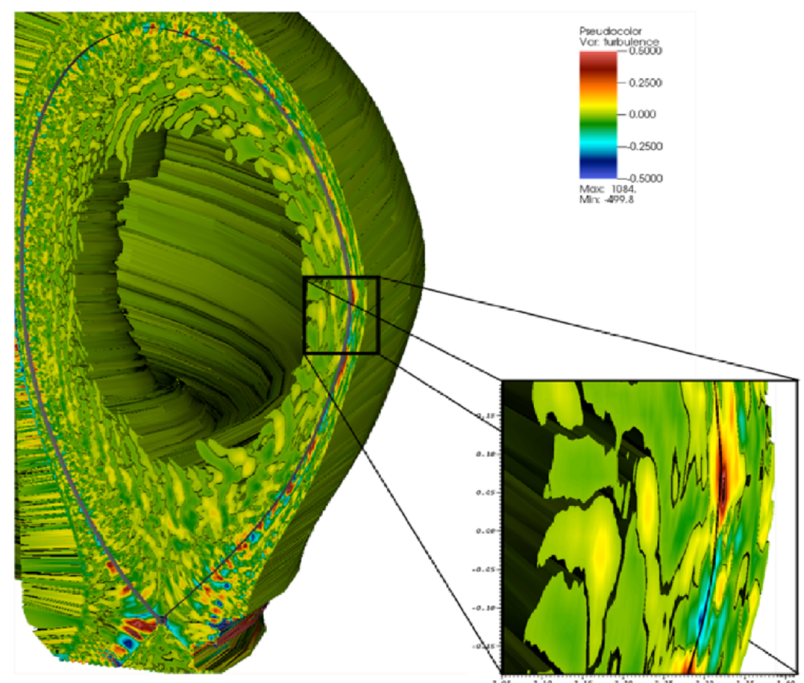
- Ion radial orbit excursion width (~10ρ_i) ~ pedestal & scrape-off layer width; unconfined orbits with neutral recycling → Non-Maxwellian

All terms can be large: ~ either *$O(\omega_{bi})$ or $O(\nu_C)$*

  - $\mathbf{v}_{||} \cdot \nabla f \sim \mathbf{v}_d \cdot \nabla f \sim C(f,f) \sim eE_{||}v_{||}/m\, \partial f/\partial w \sim O(\omega_{bi})$ ~ 0.05 ms in DIII-D
  - *f* equilibrates very fast and stiff: $\partial f/\partial t + (\mathbf{v}_{||}+\mathbf{v}_d) \cdot \nabla f\, (e/m) + E_{||}v_{||}\partial f/\partial w = C(f,f)+S$
  - Higher order corrections are unimportant

- Fast-evolving non-equilib. kinetic system
  - **Fluid equations (with diffusive closure) yields an artificially long time scale.**

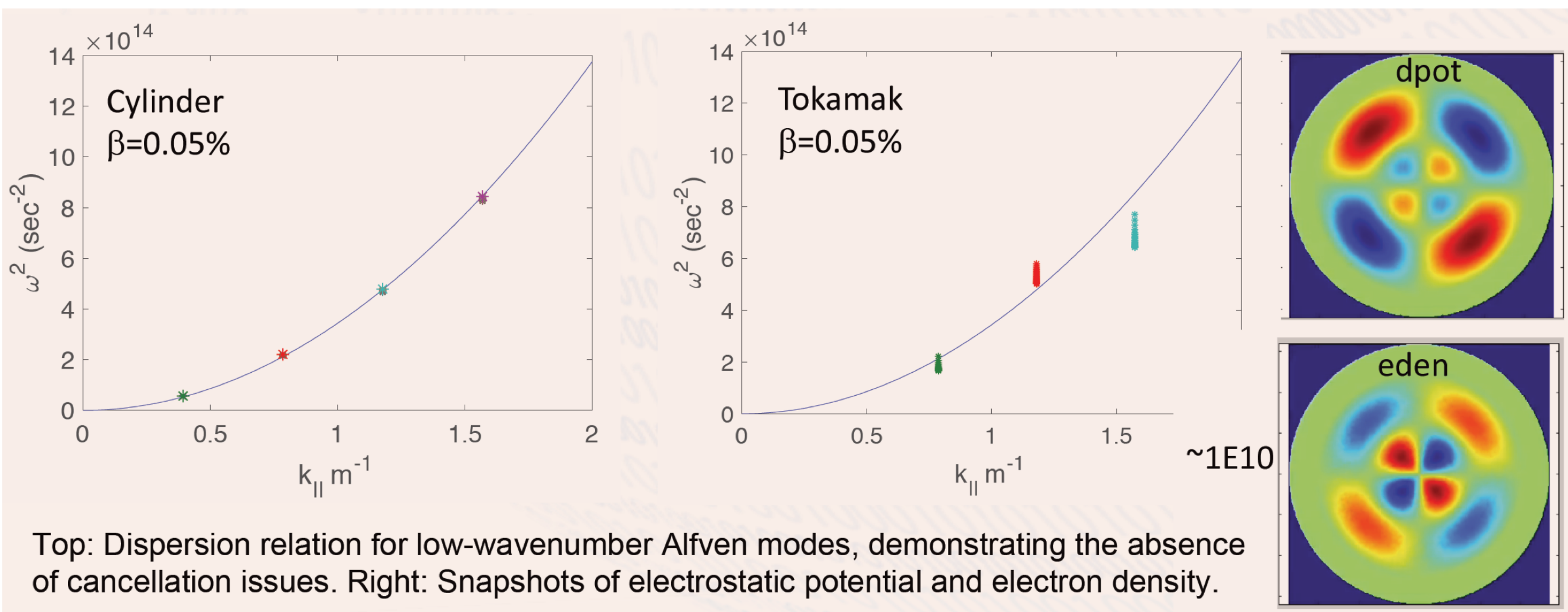
Edge turbulence around the separatrix saturates before the central core turbulence has even started to form.



Ideal for extreme scale computing: big physics in small number of time steps.

Fully Implicit EM XGC1 will answer the EM effect on λ_q

- We first implemented Chen-Parker's split weight scheme
  - The "cancellation problem" was an issue when XGC stresses the long-wave length physics, too.
- We then implemented two other EM algorithms that do not suffer from the cancellation problem
  - Hybrid EM algorithm for fluid-electron type turbulence (fluid electrons + GK ions)
    - In production
  - Fully implicit EM algorithm by L. Chacon
    - At the moment, the electron time-stepping algorithm is ~5X more expensive than the present ES time-stepping
    - Wating for Summit



Top: Dispersion relation for low-wavenumber Alfven modes, demonstrating the absence of cancellation issues. Right: Snapshots of electrostatic potential and electron density.