NSTX-U/Magnetic Fusion Science Meeting, 10/8/2018

Extending the gyrokinetic divertor heat-flux width study to NSTX-U

C-S Chang, S. Ku, R.M. Churchill

Princeton Plasma Physics Laboratory

on behalf of the XGC Team, and

in collaboration with ITER and JET

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the DOE computing facilities OLCF, ALCF, & NERSC

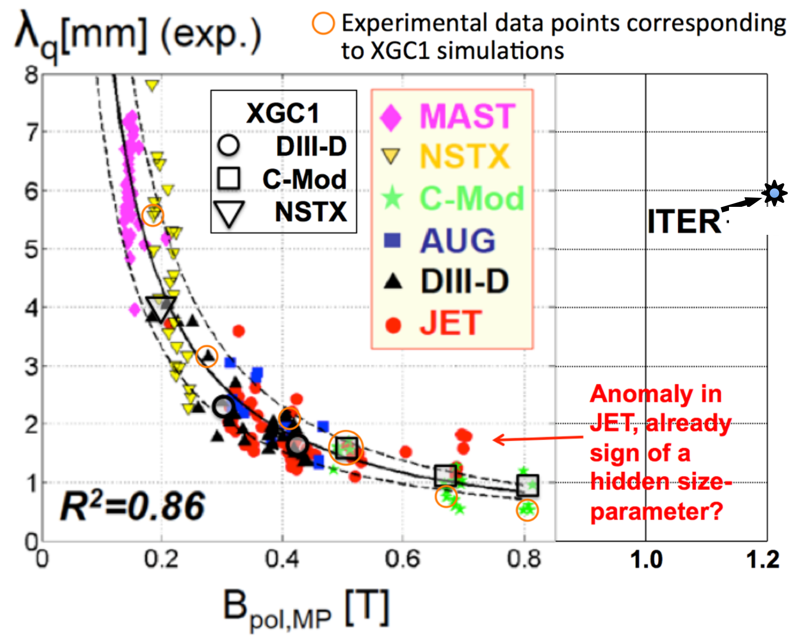
FY2016 Theory Milestone: XGC1 validation on NSTX, DIII-D & C-Mod, and prediction for 15MA ITER

- XGC1 prediction agreed well with the existing experimental results from the three large US tokamaks.
- 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(2D)
- 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: ubiquitous blobby edge turbulence

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

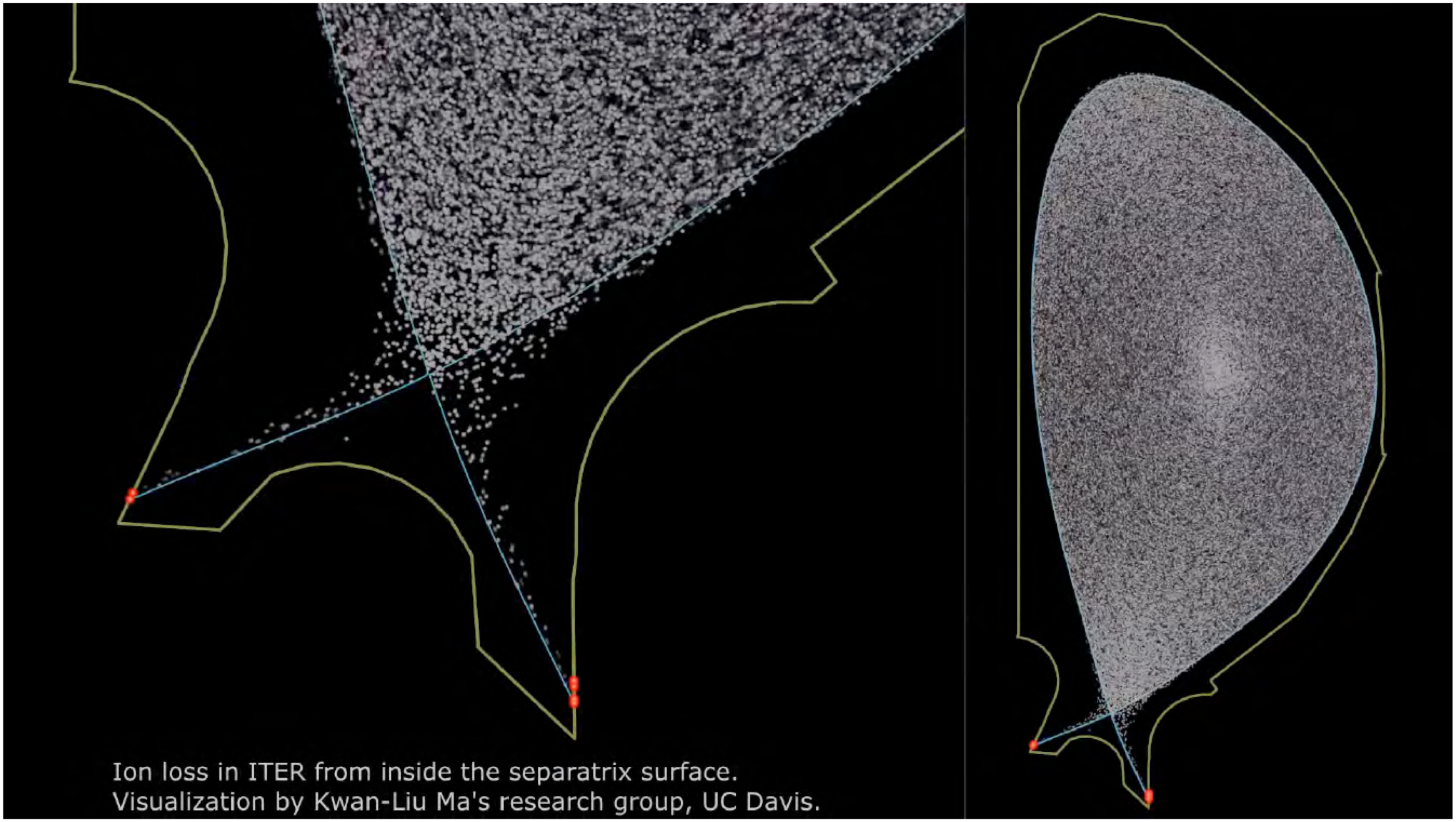
→ Triggered a deeper study

- Size effect: parallel and neutral physics
- ρ_{ip}/a effect: perpendicular physics



XGC1 can study divertor heat-flux at unprecedented detail.

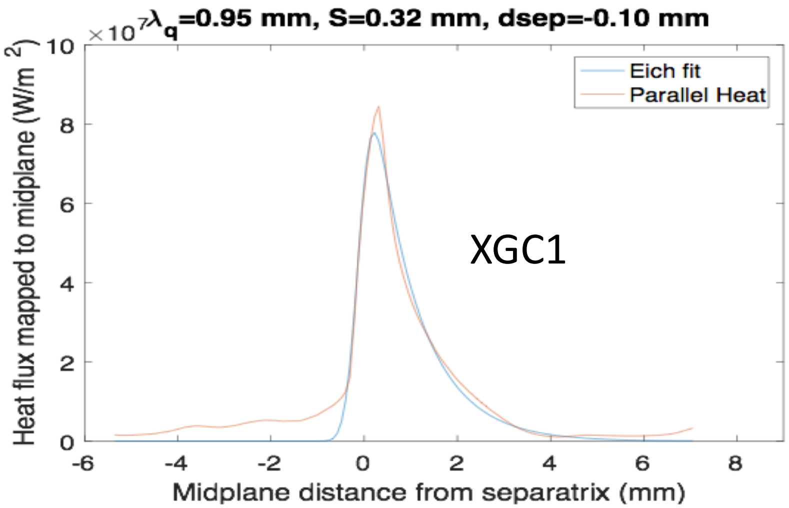
- Ion X-loss from warm pedestal: $\lambda_{NEO} \approx 2(a/R)\ \rho^{w}{}_{iPOL}$
  ~$2(a/R)\rho_{iPOL}$(at separatrix): Basis for λ_q phyiscs in the present tokamaks
- Turbulence widens the orbit-loss hole and also spreads the orbit width

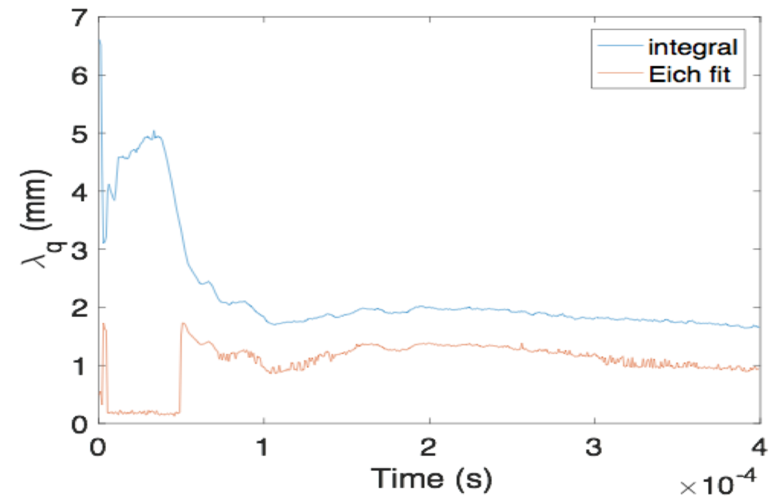


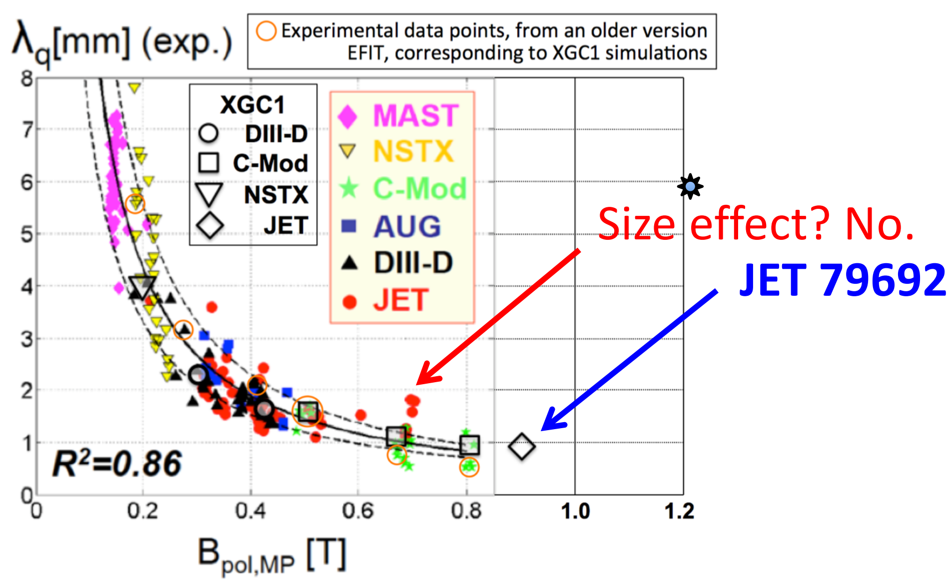
ITER

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

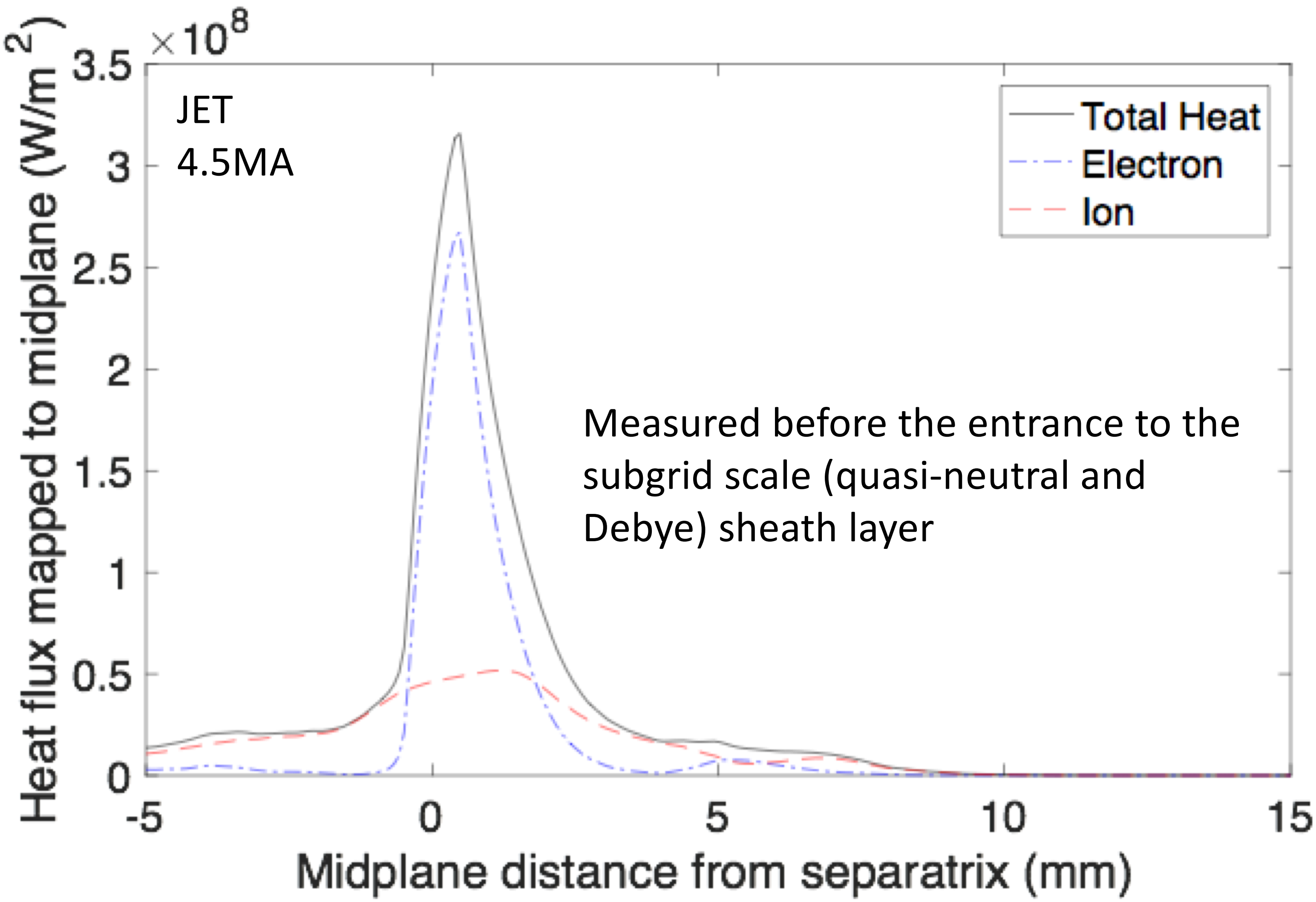
Could not conclude if the effect is from the size or a/ρ_{ip} effect, since both of them are smaller in the 4.5MA Jet than in the full-current ITER







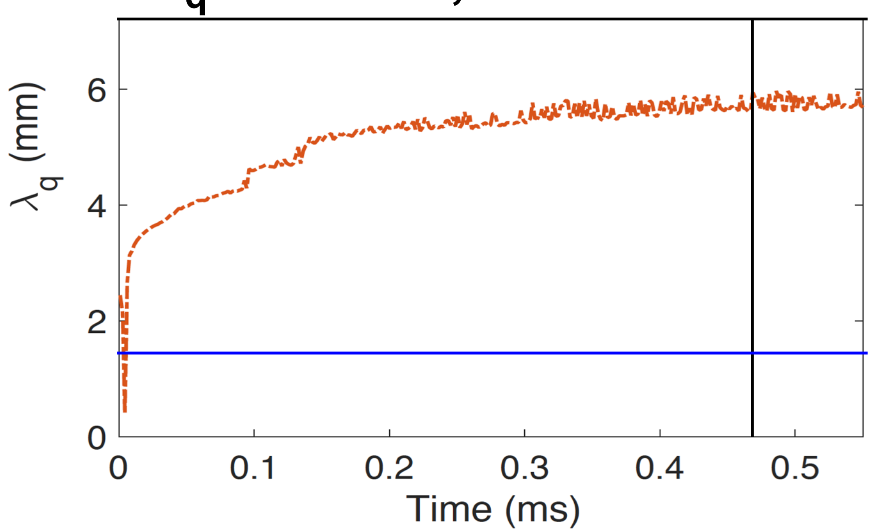
Similarly to other existing tokamak cases, $\lambda_{q,i}^{XGC} > \lambda_{q,e}^{XGC}$ in the JET 4.5MA discharge (and the edge turbulence is blobby)

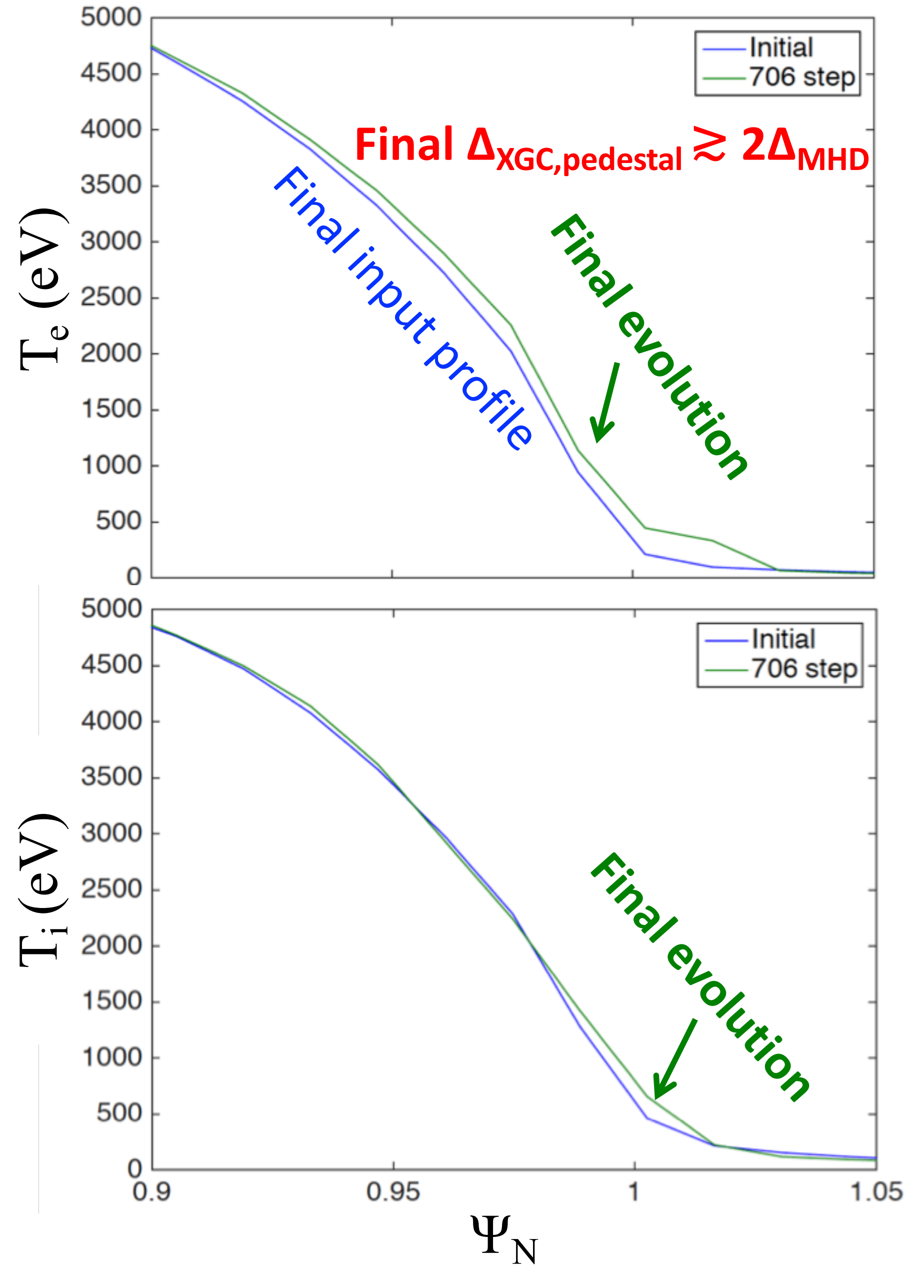


XGC study on a 15MA ITER model plasma

- The MHD-limited pedestal was too narrow: 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; which satisfies, approximately, turbulence saturation across sepratrix, power balance between separatrix and divertor, and λ_q saturation.

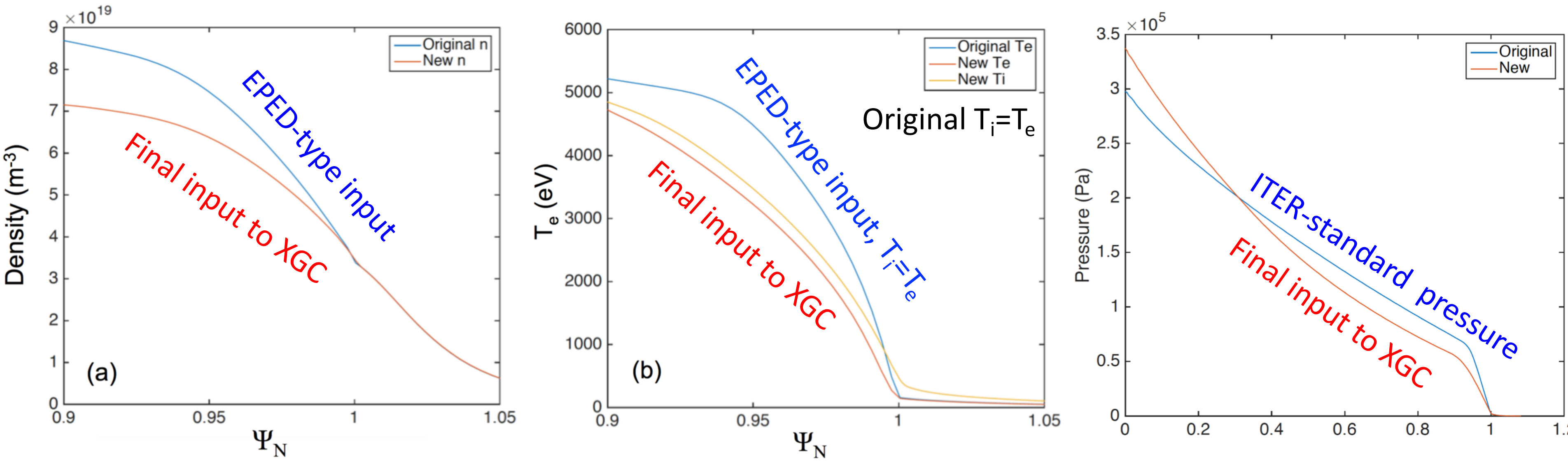
→ λ_q is ≈6mm, not ≲1mm!!!





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

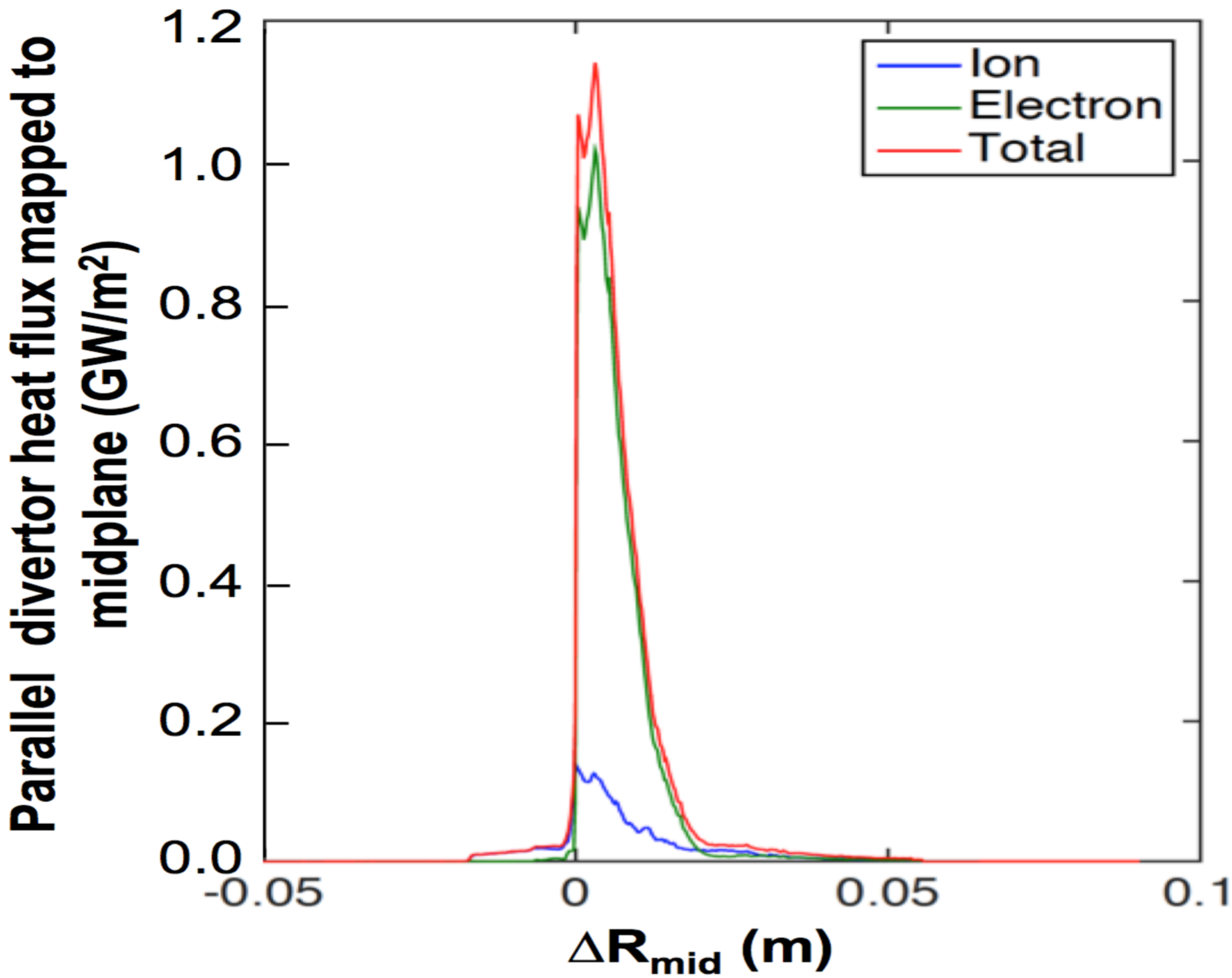
- The XGC1-obtained (approximate) pedestal width at ITER 15MA is $\gtrsim$ 2x MHD/Fluid pedestal width
  - EM effect needs to be studied
- λ_q ~ 6mm in both cases



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

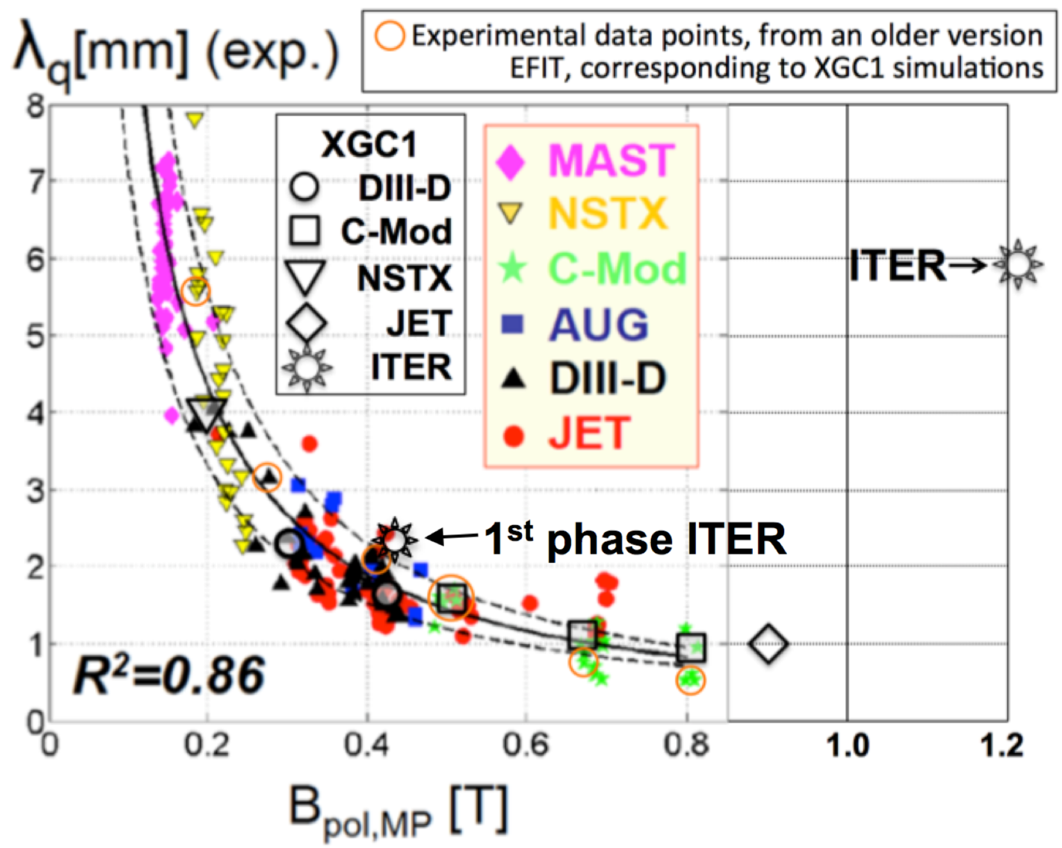
- Heat flux is completely dominated by the electrons in both magnitude and width.

What is going on?



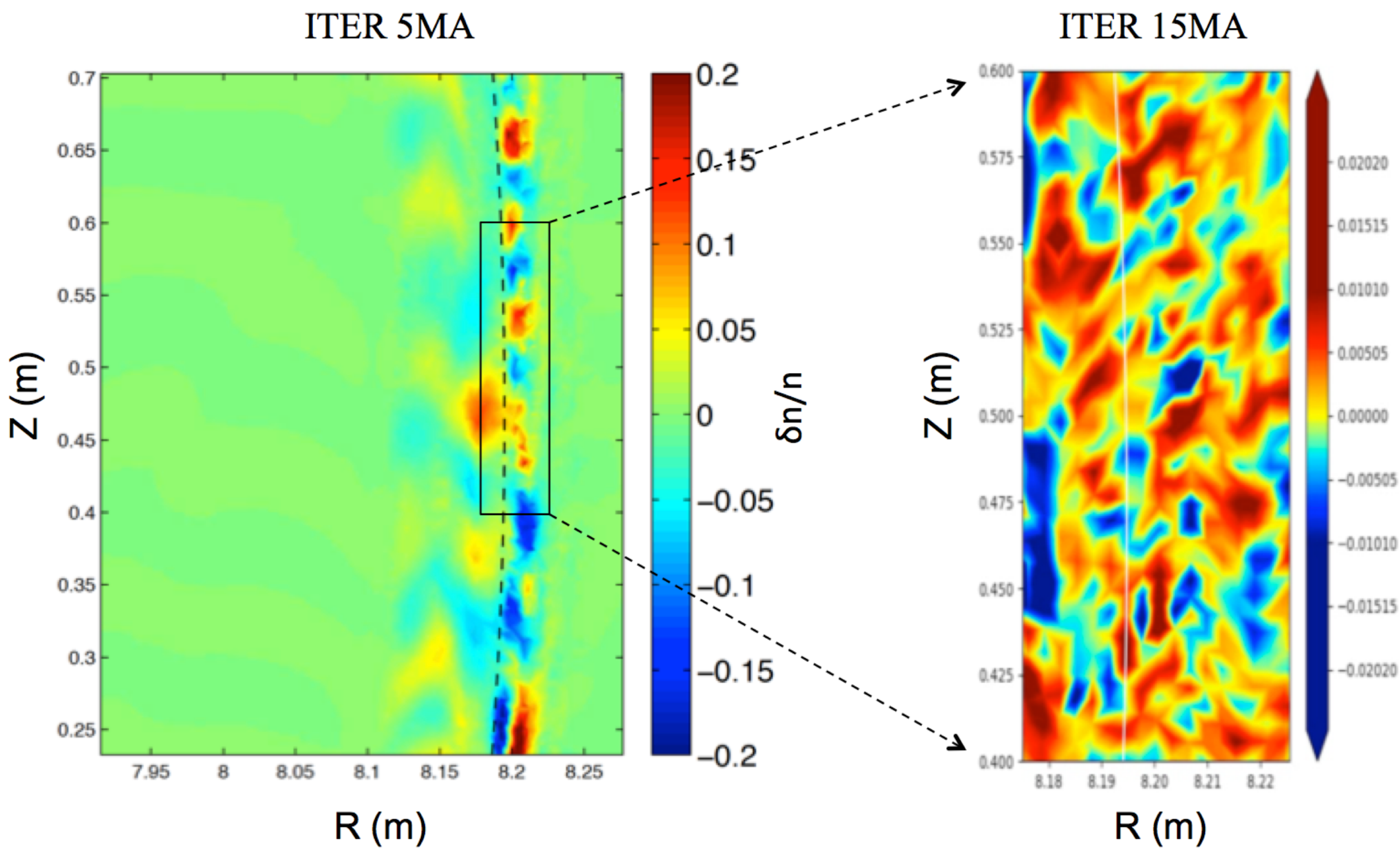
- To check if the enhanced λ_q in the full-current ITER is from the "absolute **size effect**" or from the "**ρ_i/a effect**," a **5MA "first-phase" ITER** has been simulated
  - → **λ_q agrees with the present tokamaks → clearly not the size effect**
  - → **Difference in turbulence is from the ρ_{ip}/a effect**.

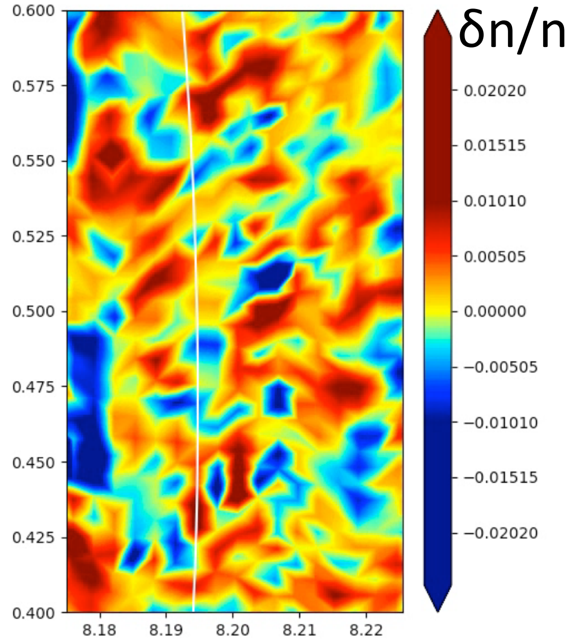
- The "absolute size effect" is related to the parallel physics and the neutral particle transport
- The "**ρ_{ip}/a** effect" is mostly from the perpendicular physics



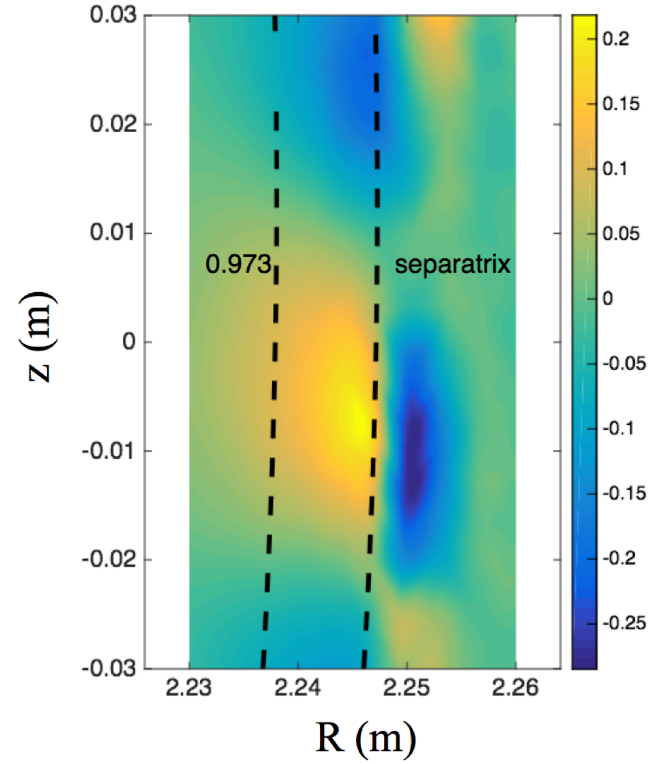
Evidence for an edge physics bifurcation between the higer and lower ρ_i/a values.

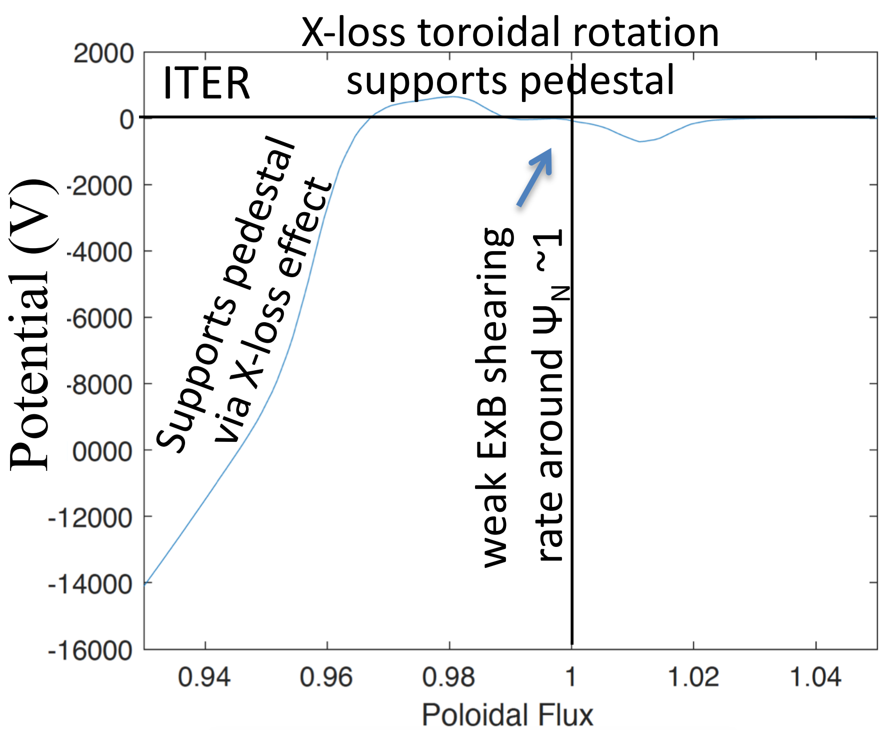
In the low-current ITER, edge tubulence across the separatrix is blob type and the ExB shearing rate is high. In the high-current ITER, the turbulence is streamer type and the ExB shearing rate is low.

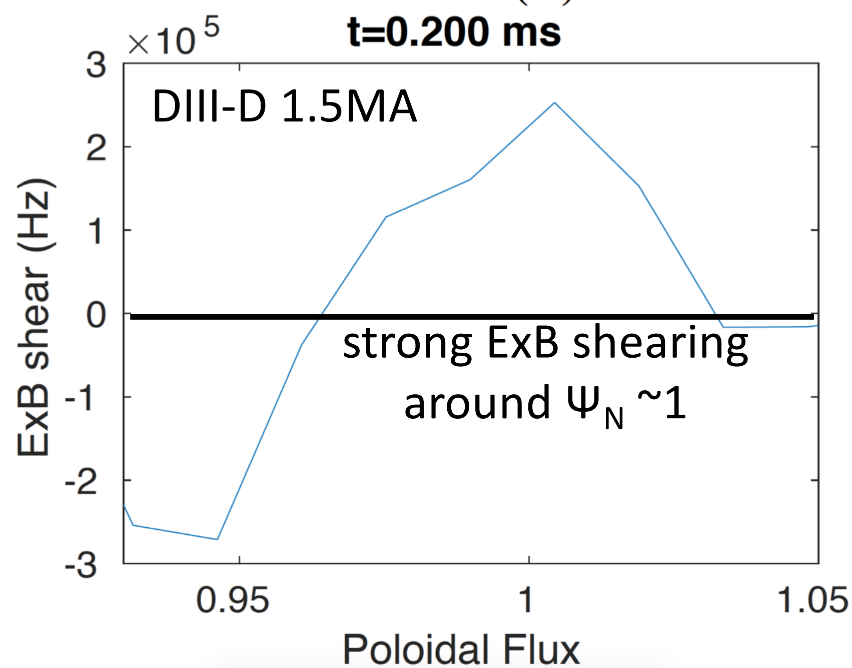




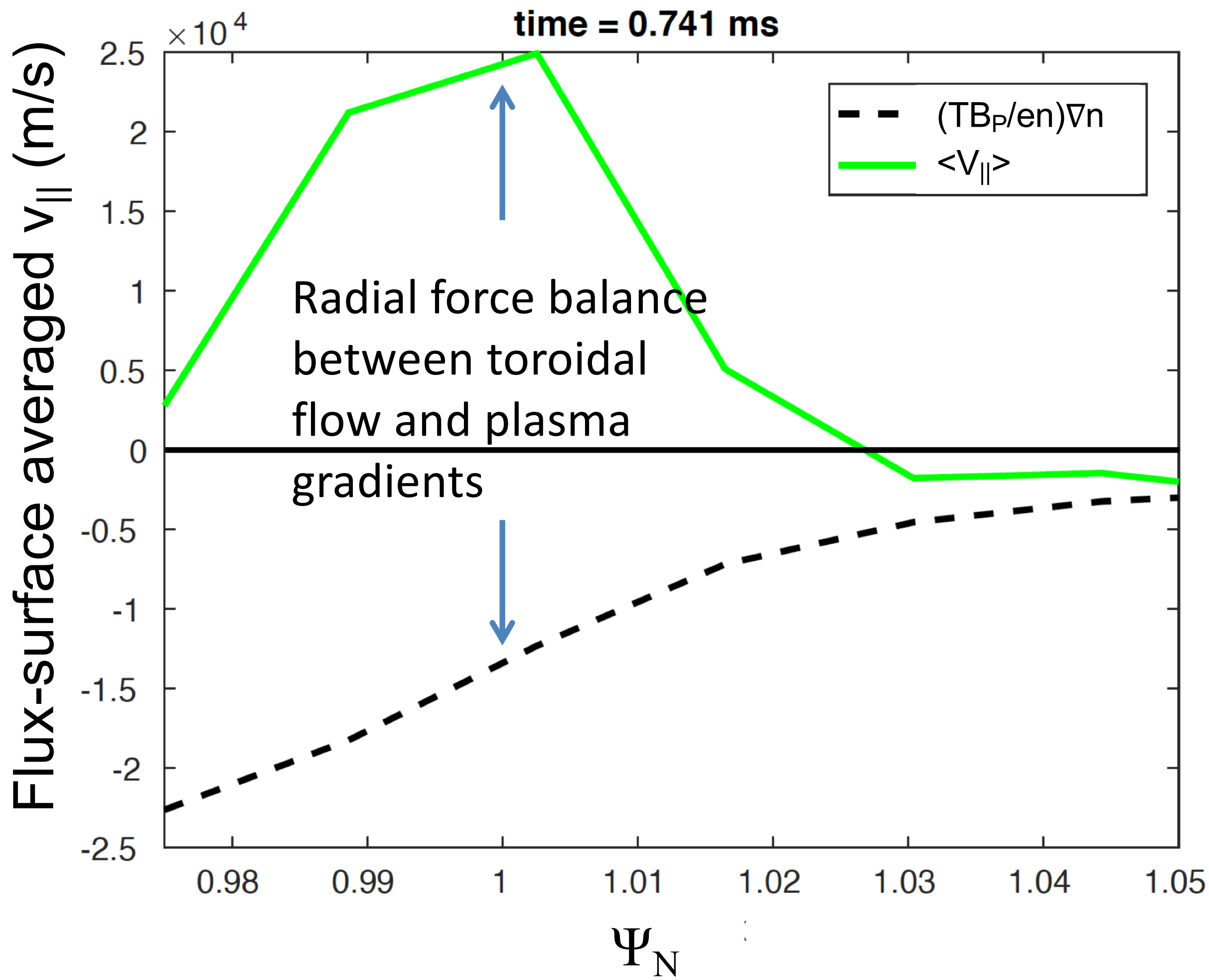
Physics bifurcation between present tokamaks and ITER



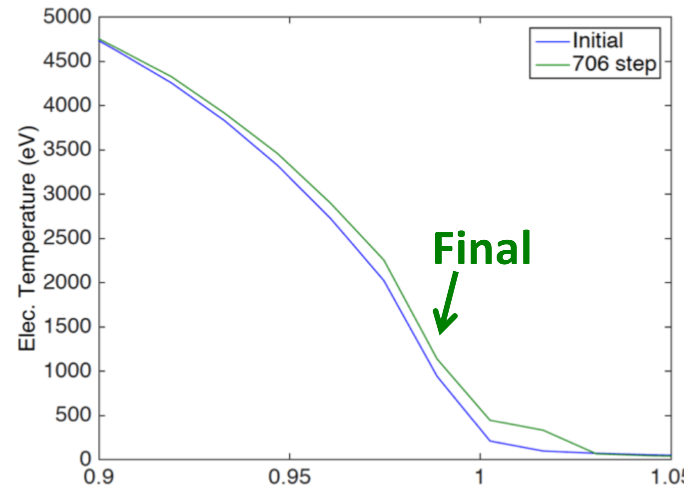




In 15MA ITER edge at Ψ_N~1, the plasma pedestal is supported by toroidal flow ~0.1 V_i, generated by X-loss

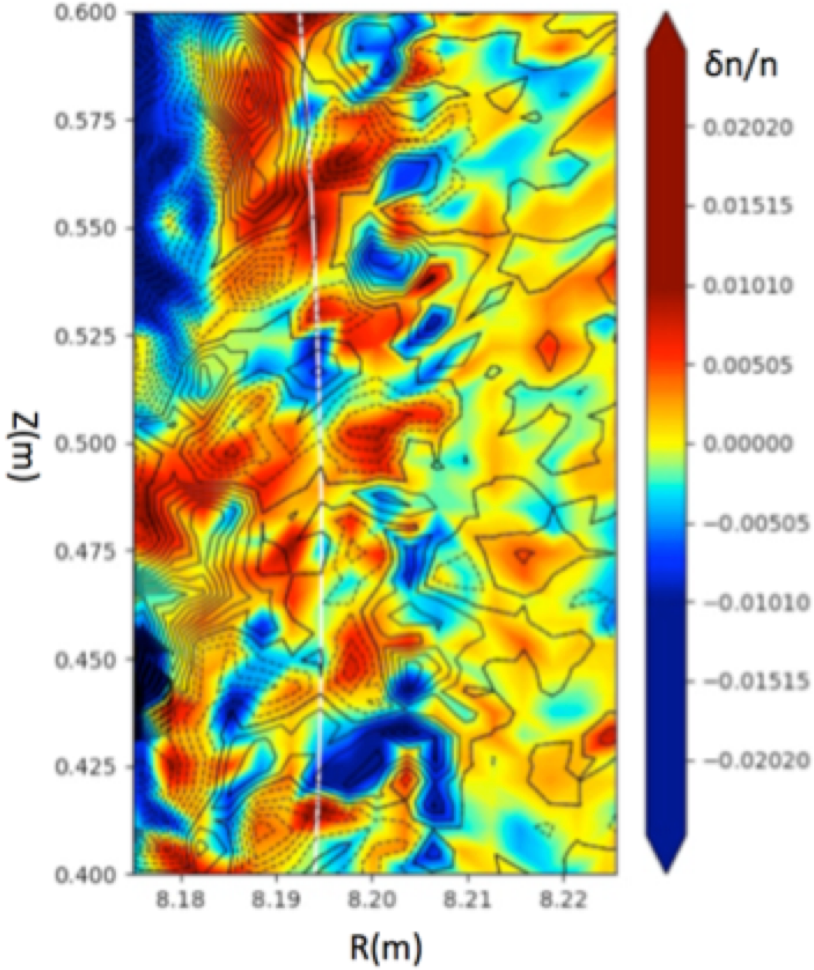


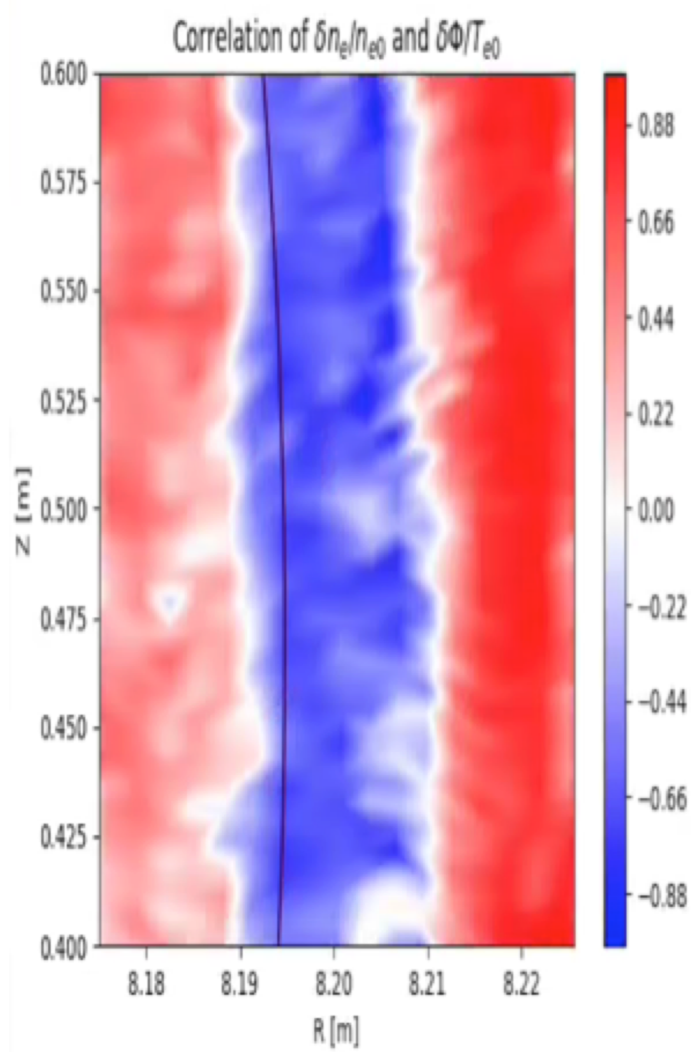
n_e and T pedestals with little E_r, supported by toroidal rotation.



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).



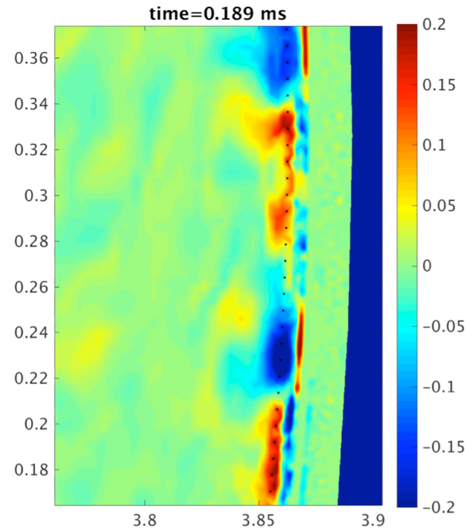


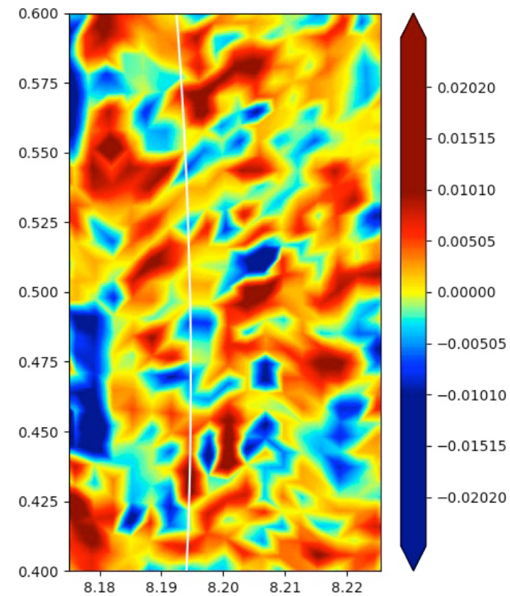
There appears to be a "bifurcation" from Blob- to Streamer-type edge turbulence somewhere between JET and ITER, arising from nonlinear interaction between weaker V_{ExB}' and TEM turbulence.

- 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: $\gamma_{ExB}^{X\text{-loss}}/\gamma_{mode} \propto \rho_i/a$
- TEM turbulence induces large particle flux
- Weakens the ExB shearing rate further.
- Turbulence becomes stronger

→ **Nonlinear bifurcation.**

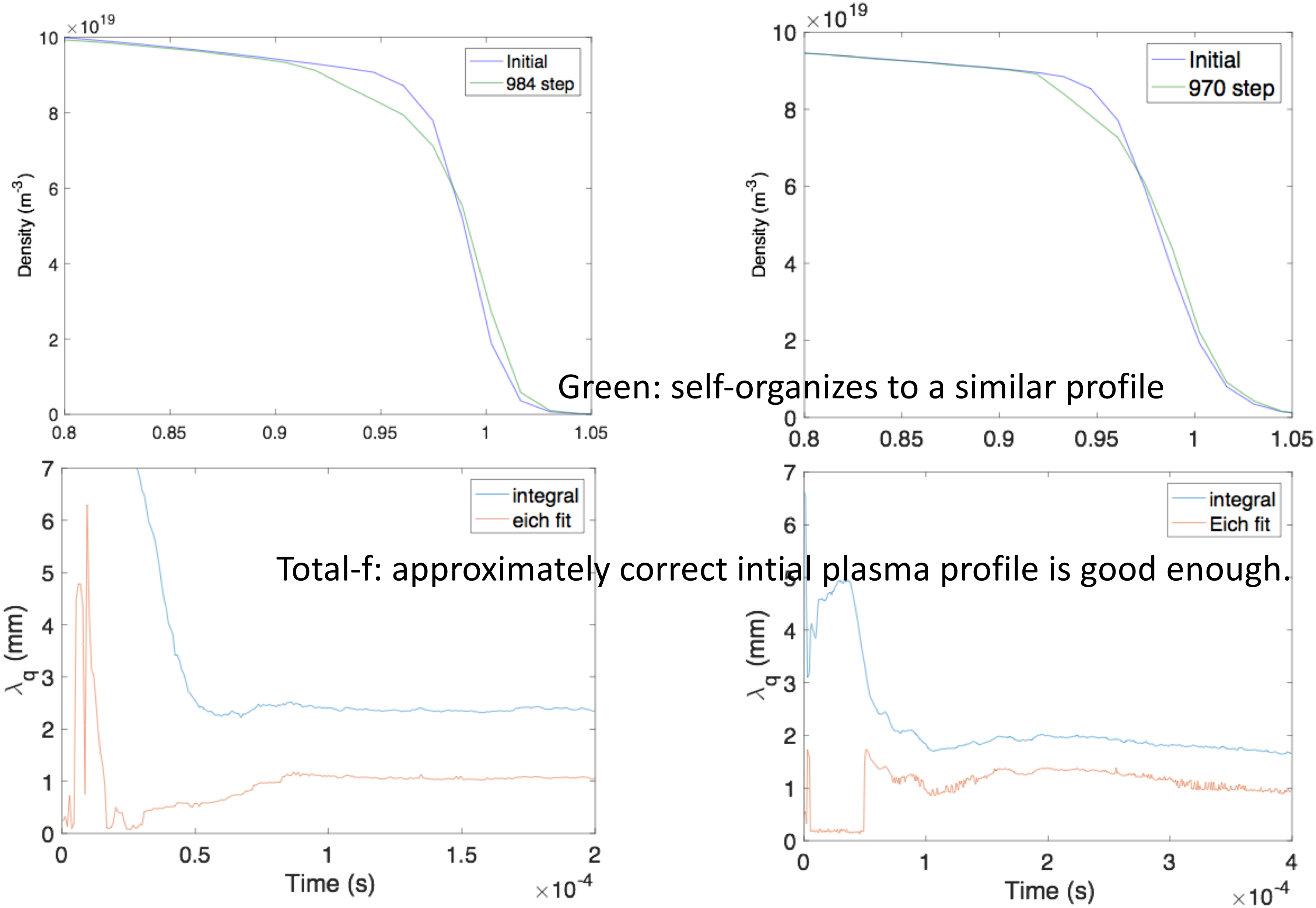
When the ion neoclassical X-loss becomes too weak, the edge plasma self-organizes to expell the heat through microturbulence.





Sensitivity of λ_q to initial plasma profile in JET edge

The left-figure case 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.

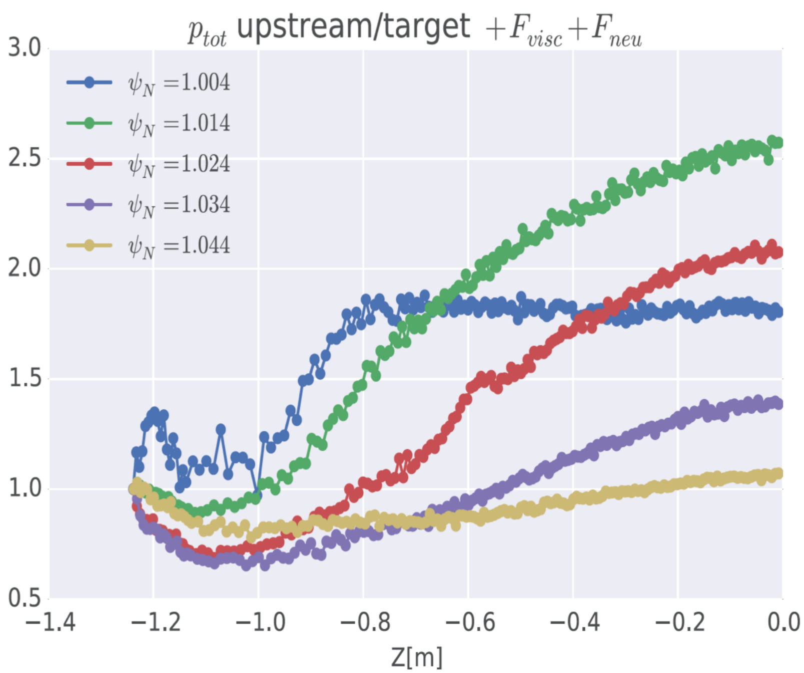


Green: self-organizes to a similar profile

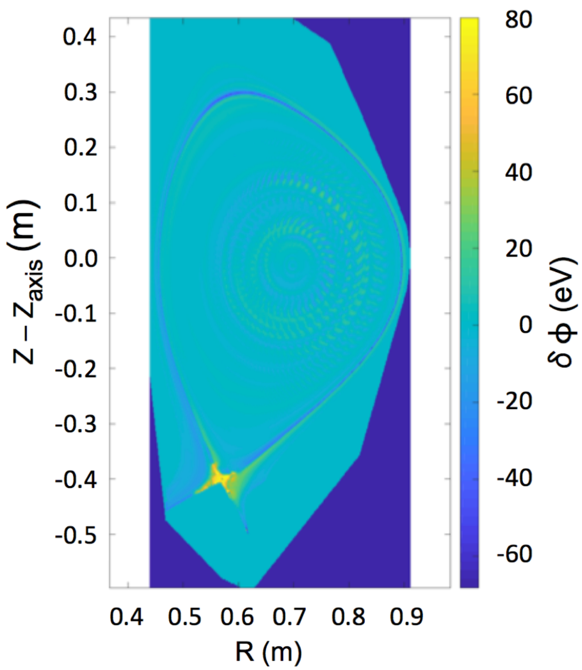
Total-f: approximately correct intial plasma profile is good enough.

The flux-tube picture is problematic: The upstream-downstream "SOL width" relation needs to be re-considered.

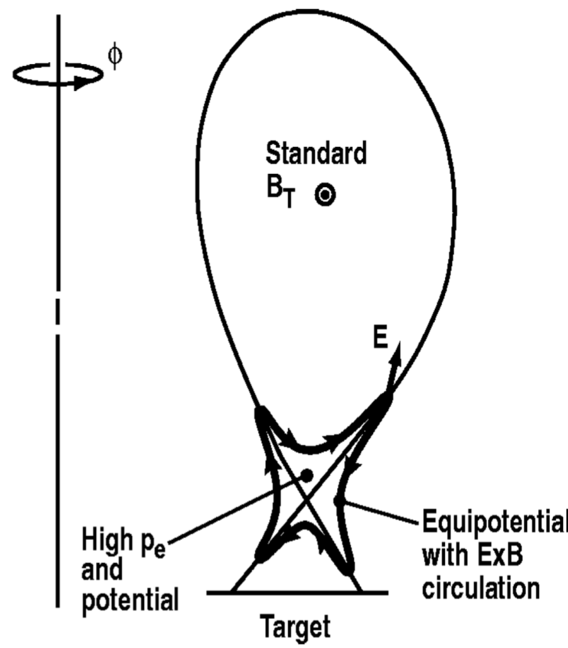
- The upstream-downstream plasma density relation is not explained by fluid momentum balance equation along the field lines, even in sheath-limited regime
  - Experimental: J. Canik et al, PoP 2017
  - Gyrokinetic: Churchill et al, NF 2017
- **New: ExB circulation** around the X-point, breaking the parallel relationship
  - Chang, Ku, Churchill, to be submitted to PoP, gyrokinetic XGC, X-loss
  - Schaffer et al., PoP 2001, experimental fast probe



XGCa gyrokinetic, DIII-D



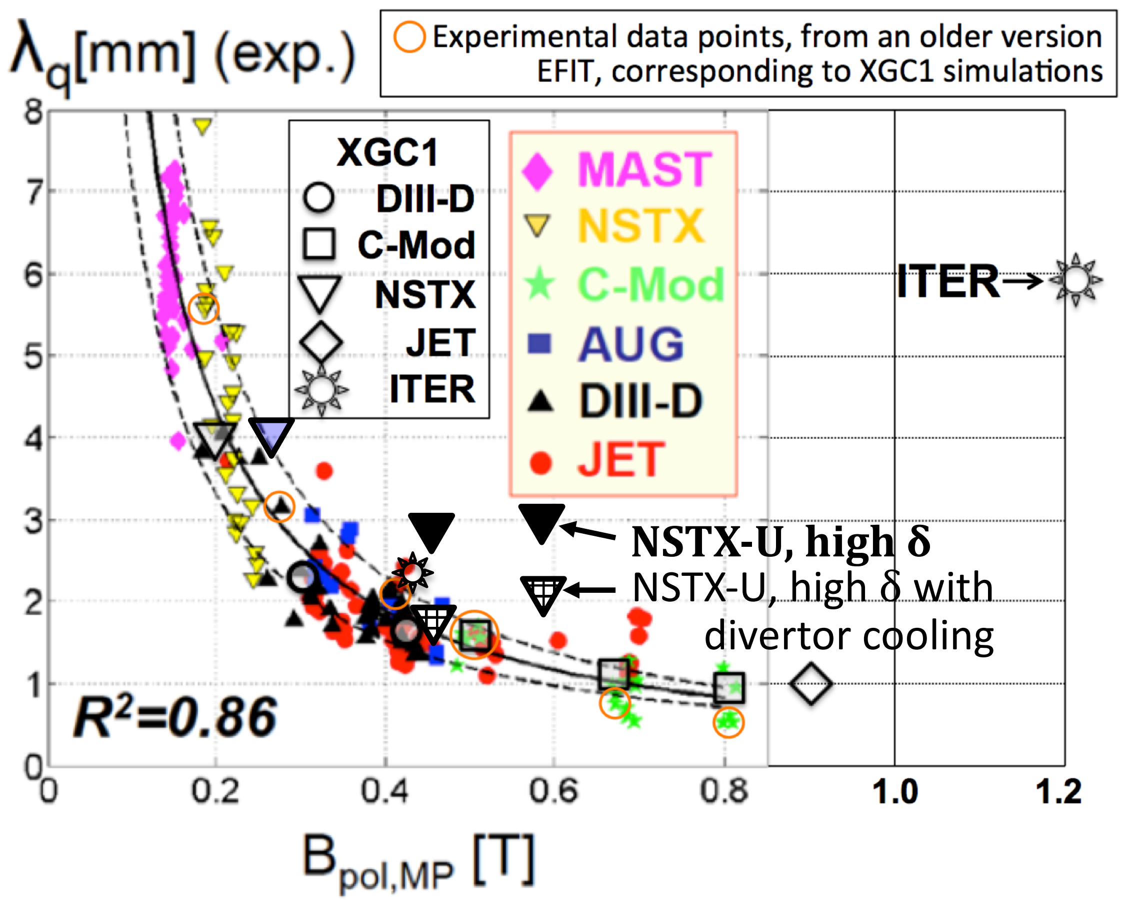
$\Phi_{0,m>0}$ in XGC1, C-Mod H-mode

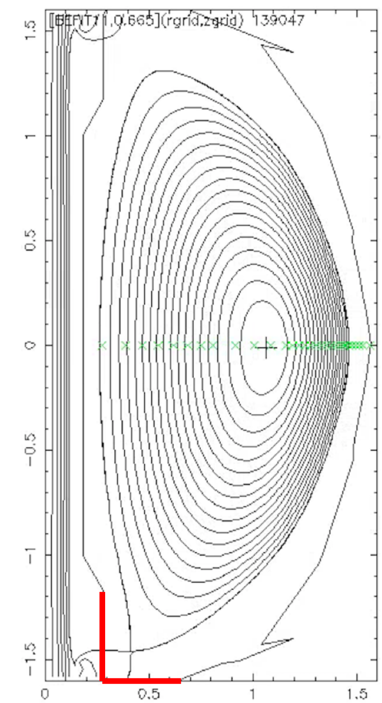


Schaffer's fast probe, DIII-D L-mode

Study of λ_q in NSTX-U model plasmas

- A high triangularity ($\delta_X \approx 0.8$) NSTX discharge has been selected as a reference for NSTX-U plasma models: ▽ [Canal, Ahn, Gray, Menard, Ku, Chang, …]
- 1.5MA and 2MA NSTX-U plasma profiles are projected
- 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: a NSTX-U team formed





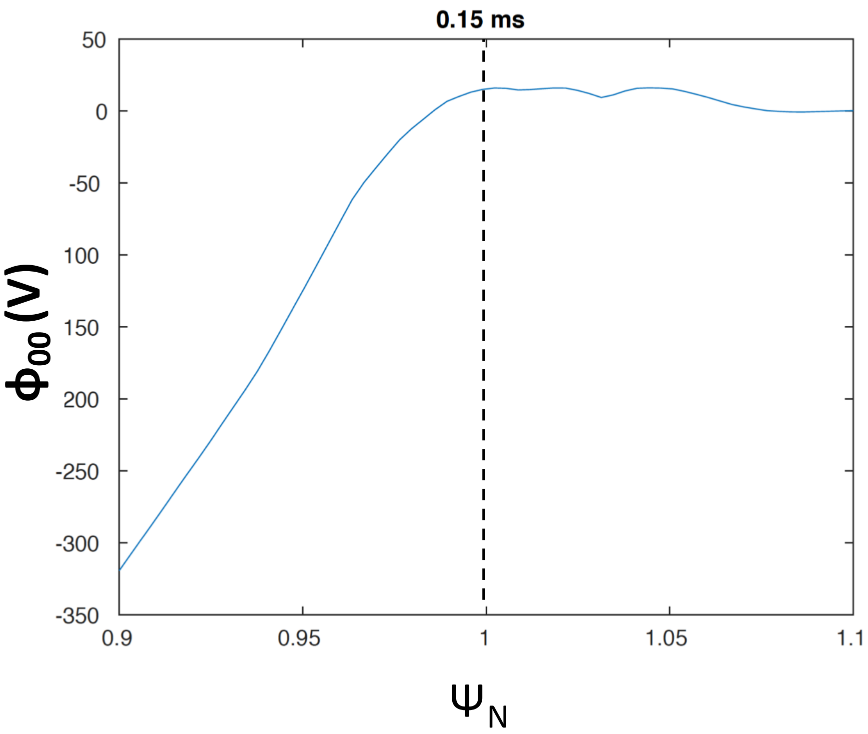
NSTX #139047 as a reference case for an NSTX-U projection

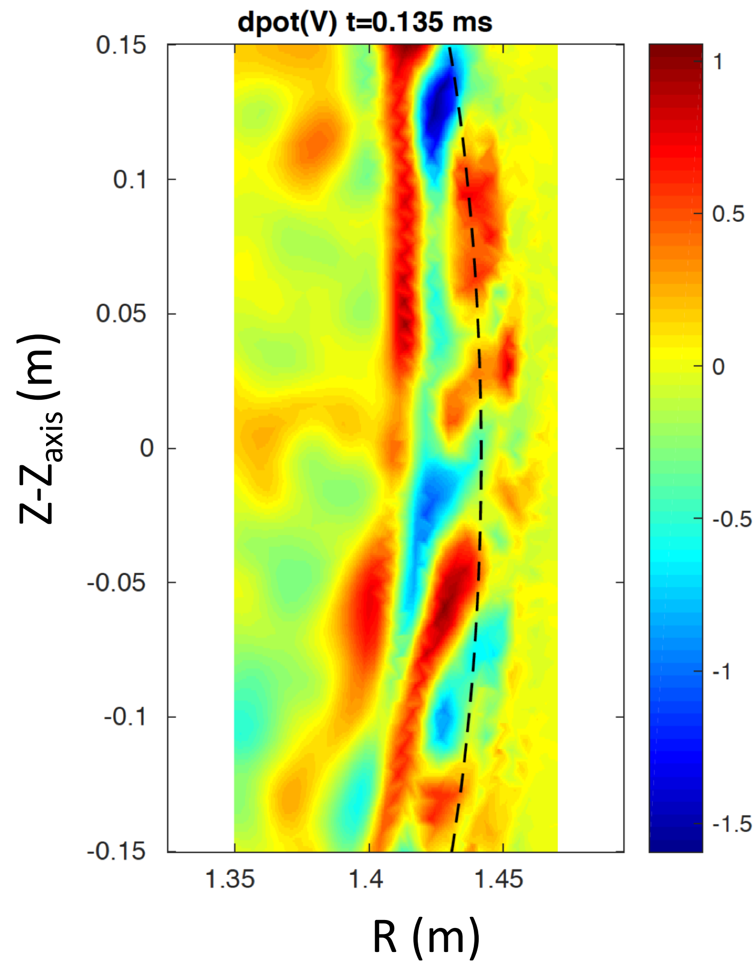
In the high current (2MA) NSTX-U case without the divertor-chamber cooling, where $\lambda_q \sim 2.5\, \lambda_q^{Eich}$, the edge turbulence is not the usual blobs and ϕ_{00} is almost flat across the separatrix

- Stronger TEM drive in a spherical tokamak
- Smaller ρ_{ip} than conventional tokamaks

→ earlier bifurcation to TEM turbulence

Divertor chamber cooling weakens TEM.

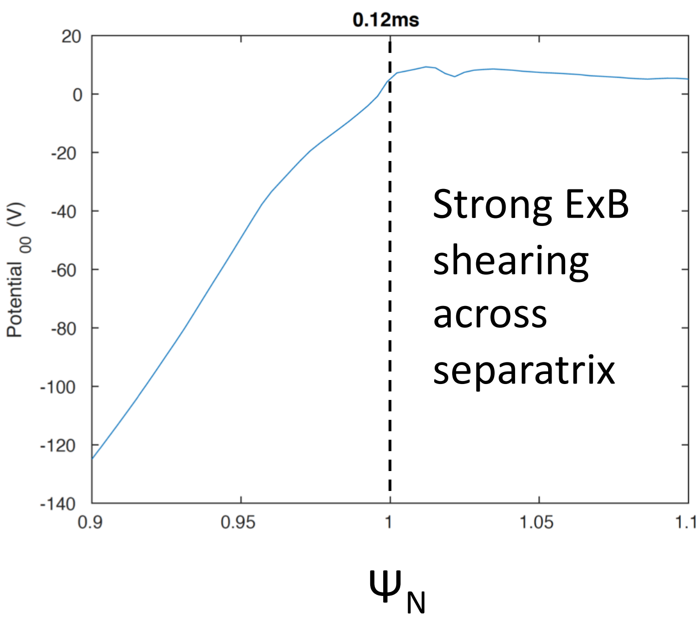




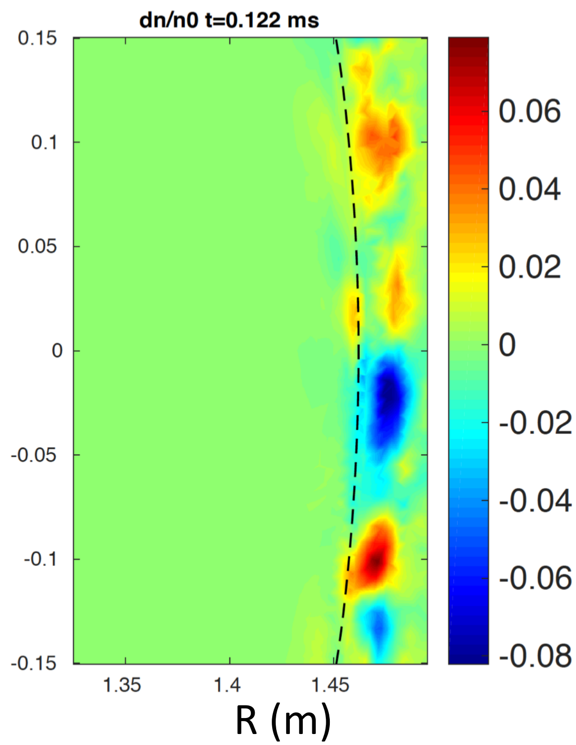
At lower I_P (=1MA) NSTX, the edge turbulence becomes blobby and φ_{00} is more sheared across the separatrix surface ← higher ρ_{ip}/a

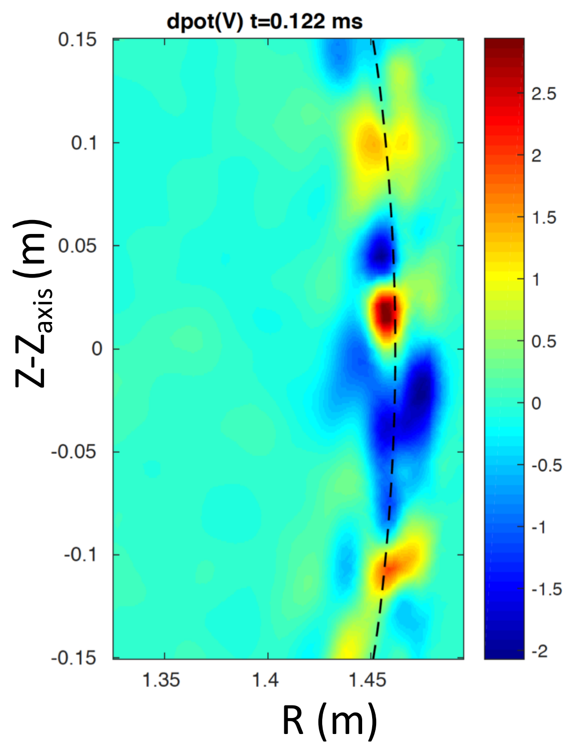
In the NSTX 1MA reference case with the same plasma shape as for NSTX-U, turbulence is blobby.

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



ExB shearing layer has moved radially outward.

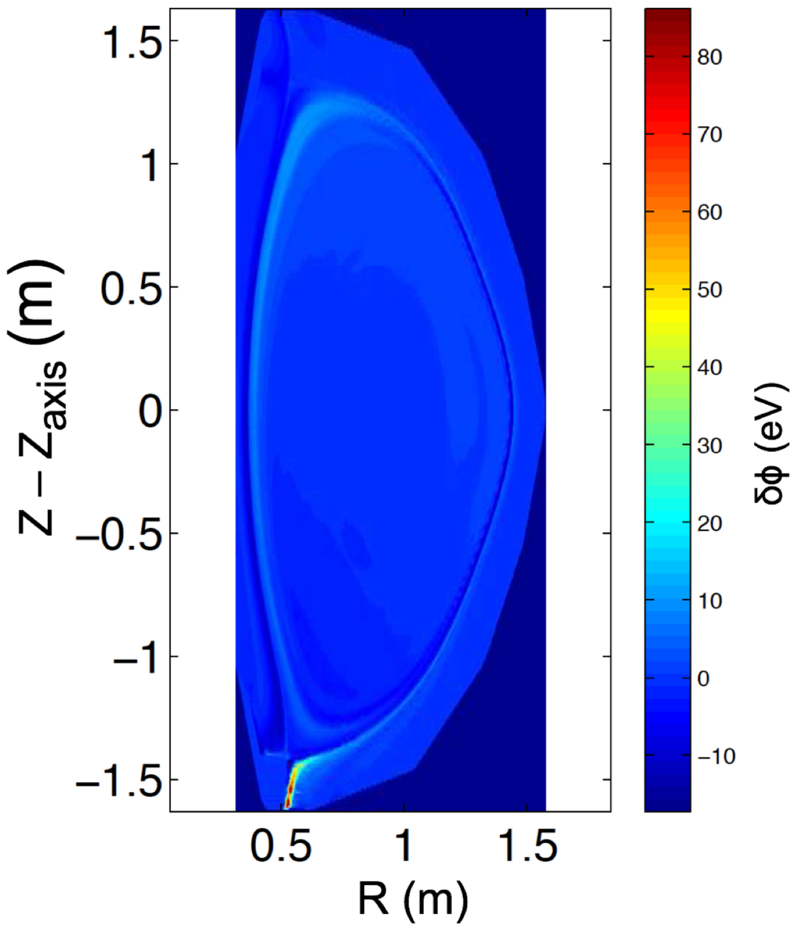




High triangularity NSTX-U has a different ExB circulation near the X-point.

- X-loss of ions, thus the orbit stagnation, occurs mostly on the right-hand side of X-point
- The ExB circulation is not from inside the separatrix surface, but localized to the outboard SOL

How does this affect SOL physics and λ_q?
Under investigation.



$\Phi_{0,m>0}$ in a model 1.5MA NSTX-U plasma

Disccusion

- **The high triangularity, high current NSTX-U plasmas could be a good test bed for understanding the relation between λ_q , turbulence, and the sheared ExB flow.**
  - We may have a reasonable understanding on the effect of the large B_p, thus small ρ_{ip}/a, and large TEM drive (from tight aspect ratio)
  - Does the high triangularity play a role here?
  - In the mean time, we use TCV to study the high triangularity effect?
    - Will the plasma current be high enough in TCV? Equivalently, will ρ_{ip}/a be low enough to see the effect?

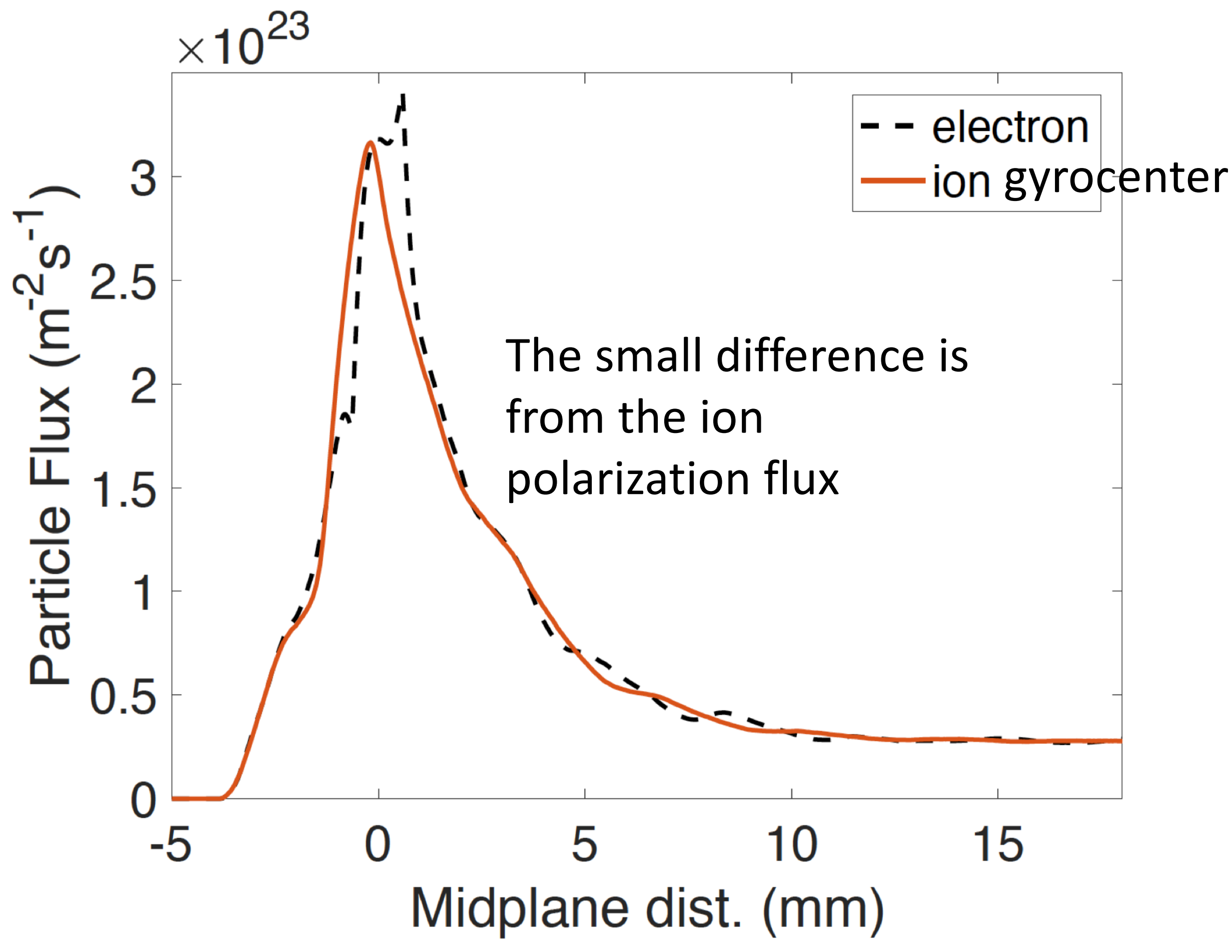
- **Besides looking at the problem from the TEM point, can we look at it from the ExB shearing point?**
  - How can we reduce the ExB shearing rate across the separatrix surface in the present conventional tokamaks? Weak RMP?

Thank you!

Extra slides

By definition, a gyrokinetic simulation has ambipolar flux. But, the heat-flux width can be different between e & i,

mostly from non-Maxwellian *f*: **warm tail particles**.



GK simulation of Divertor heat-flux width: Prediction and Validation on present devices

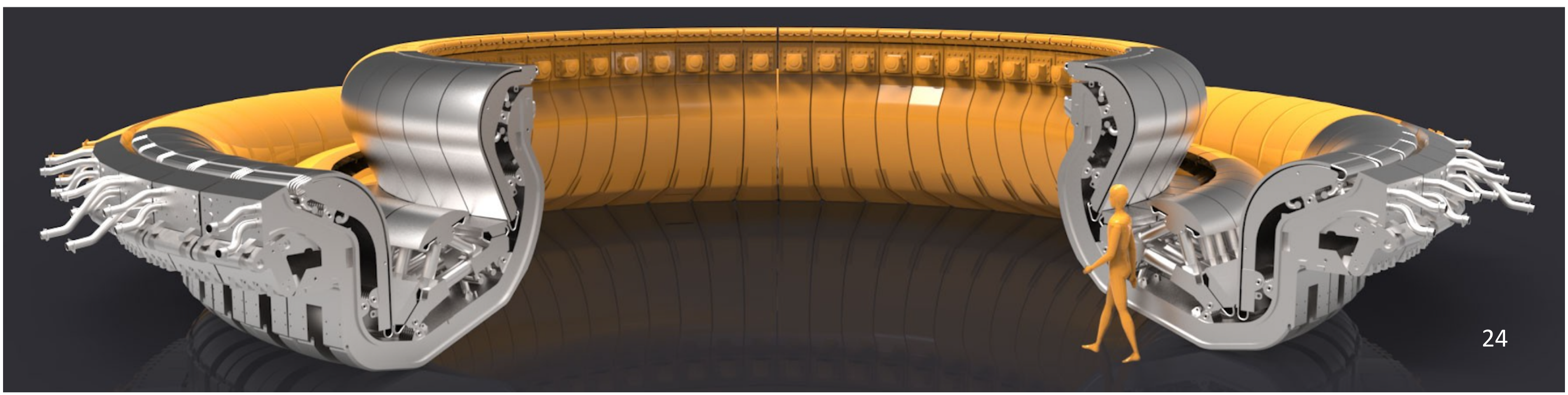
- Discharges are selected for wide distribution of $B_{pol,OM}$.
- Experimental eqdsk data are imported into XGC.

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 1100212023	1236	5.4	0.9	0.81

FY2016 OFES Theory Milestone

JET 79692		3.56	4.5	0.89

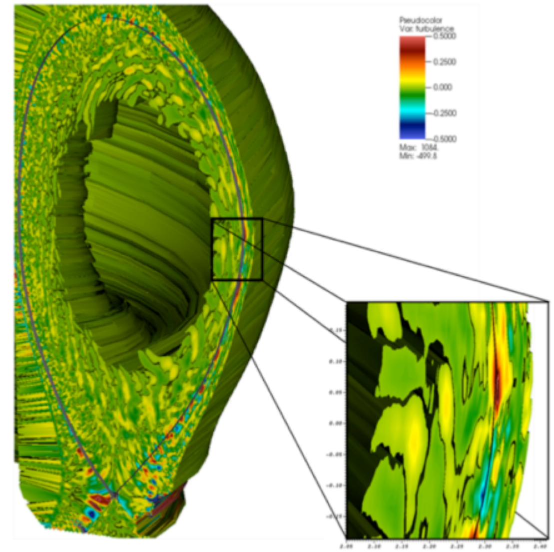
Comm'ty demand

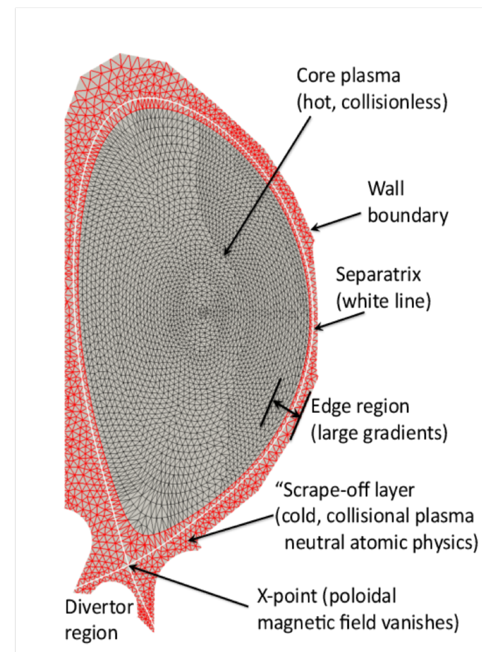


The XGC1 Gyrokinetic Code

- **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





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):

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

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

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

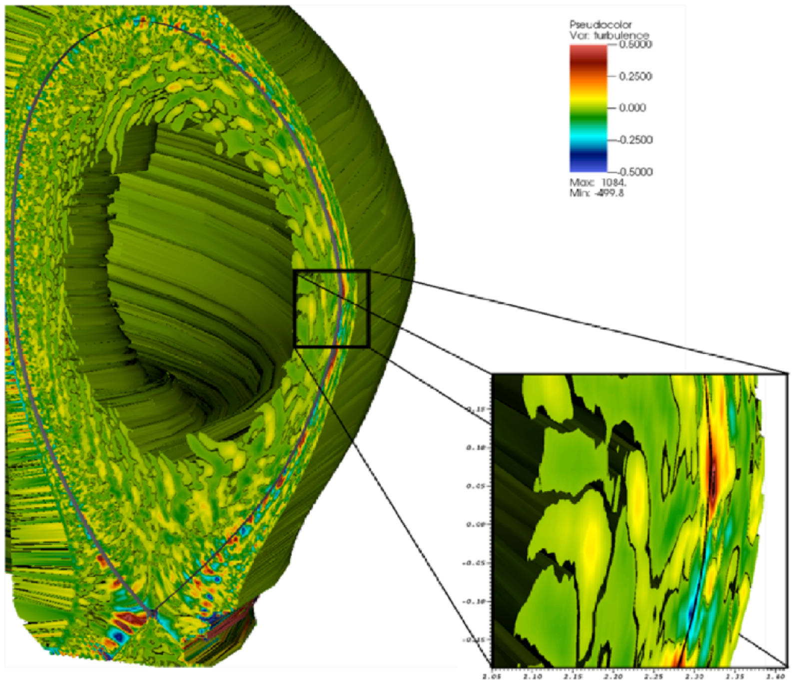
- Ion radial orbit excursion width (~10ρ_i) ~ pedestal & scrape-off layer width; unconfined orbits with neutral recycling → Non-Maxwellian

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.**

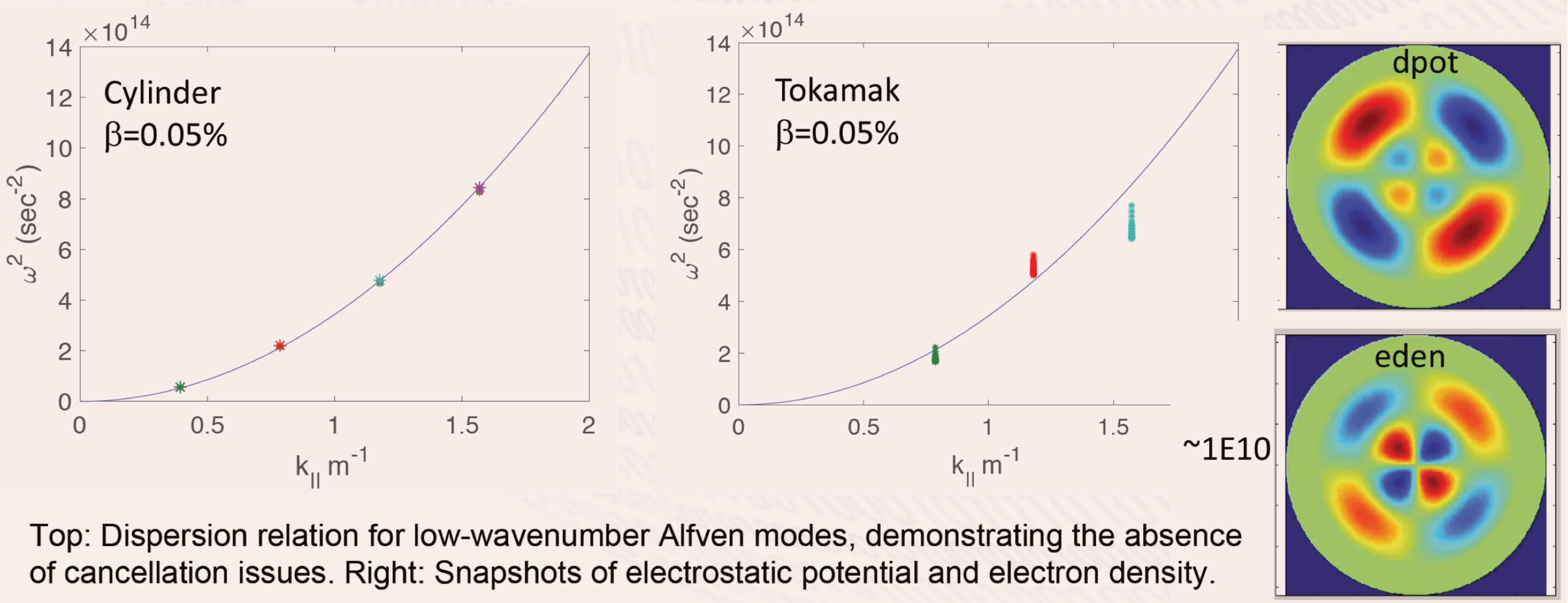
Edge turbulence around the separatrix saturates before the central core turbulence has even started to form.



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.