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Unveiling the kinetic mechanism for RMP penetration in diverted edge geometry

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SciDAC Proto-FSP Center for Plasma Edge Simulation

Outline

- Introduction
- Many-dimensional RMP puzzle
- The guiding center kinetic code XGC0
- Understanding the RMP penetration into DIII-D plasma
  - **At low $\nu_{e*,DIIID} \sim \nu_{e*,ITER}$, but $n_{e,DIII-D} << n_{e,ITER}$**
  - At $n_{e,DIII-D} \sim n_{e,ITER}$, but high $\nu_{e*,DIIID} >> \nu_{e*,ITER}$
  - Electrical current responses in plasma
- Implication to ITER
  - $\nu_{e*,DIIID} \sim \nu_{e*,ITER}$ and $n_{e,DIII-D} \sim n_{e,ITER}$ in ITER similar shape DIII-D
  - Rotation effect
- Conclusion and discussion

We will discuss the DIII-D plasmas only

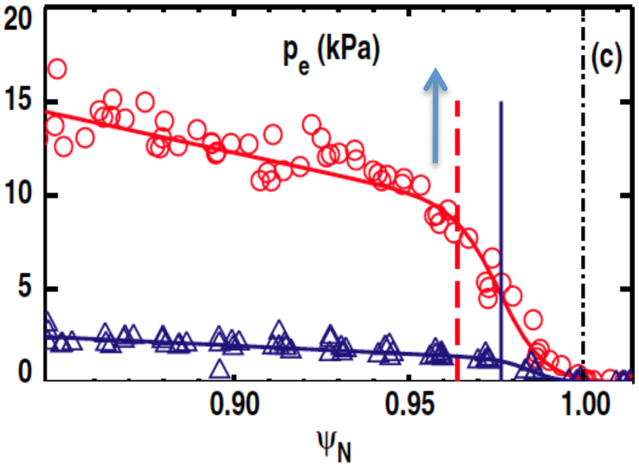
- **DIII-D with n=3 coil array has demonstrated well-diagnosed, repeatable ELM suppression by RMPs**

- **Other experimental results**
  - Mitigation at high ν_{e*} and high n_e in ASDEX-U with n=2 coil array
  - Mitigation in JET with N=1, 2 and
  - Mitigation in MAST with n=3
  - Mitigation in TEXTOR with m/n=6/2
  - ELM triggering in NSTX with n=3
  - ELM suppression by n=1 coil array has recently been claimed in KSTAR, but is not well diagnosed.

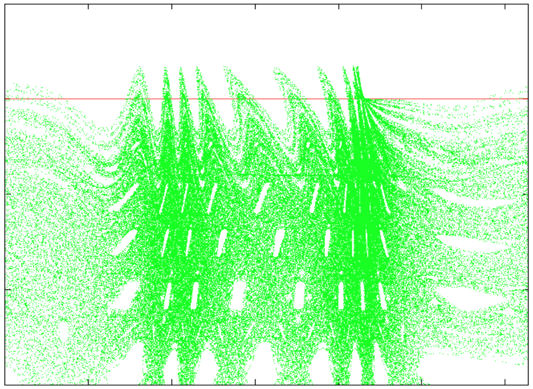
Steep edge pedestal and the RMP coils in DIII-D

Resonant Magnetic Perturbations (RMPs) for suppression of Edge Localized Modes in tokamak plasma

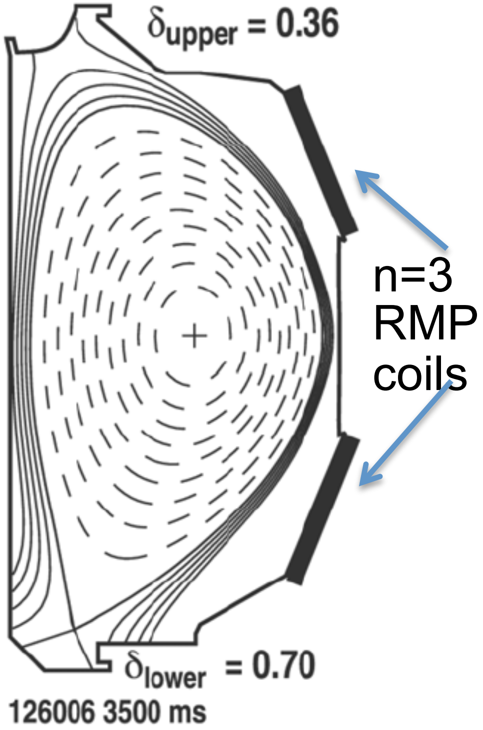
Idea: stochastic magnetic perturbation can ease the steep pressure gradient.



[R.J. Groebner, et al, NF 2009]



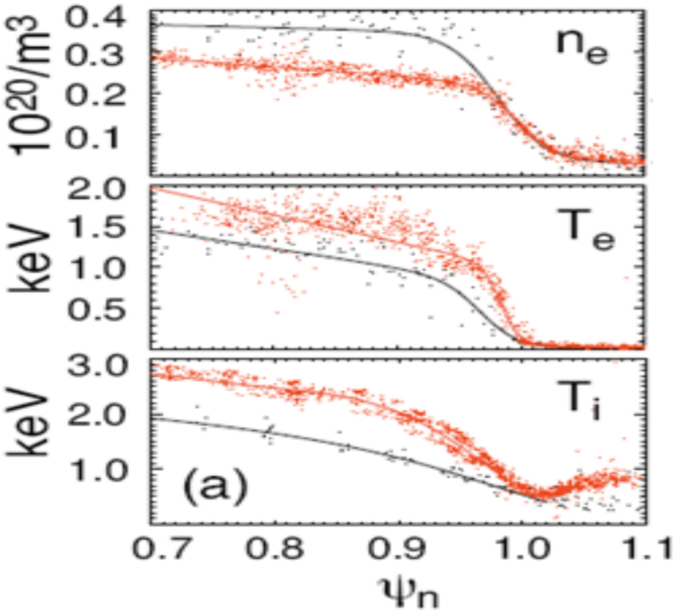
Vacuum RMPs, q_{95}=3.69

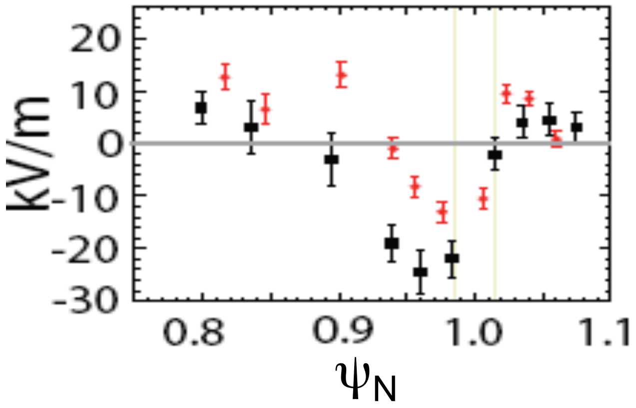


n=3 RMP coils

Many-dimensional puzzle in DIII-D results:
Should be answered simultaneously from first principles

- At **low** ν_{e*} and n_e, DIII-D has ELM-suppressed pedestals. But,
  - Why does $\mathbf{n_e}$ get pumped out? (cf. n_e follows n_i)
  - Why does the $\mathbf{T_e}$ profile not collapse (cf. Rechester-Rosenbluth)?
  - Why does the $\mathbf{T_e}$ barrier remain at the outer part of the original pedestal?
  - How does the $\mathbf{E_r}$**-well** survive the RMPs?
  - Why is there the $\mathbf{q_{95}}$ **windows for** ELM suppression?
  - Why is the "**vacuum Chirikov>1**" only a necessary condition?
- At **high** $\boldsymbol{\nu_{e*}}$ (and high n_e) why is the ELM suppression more difficult?

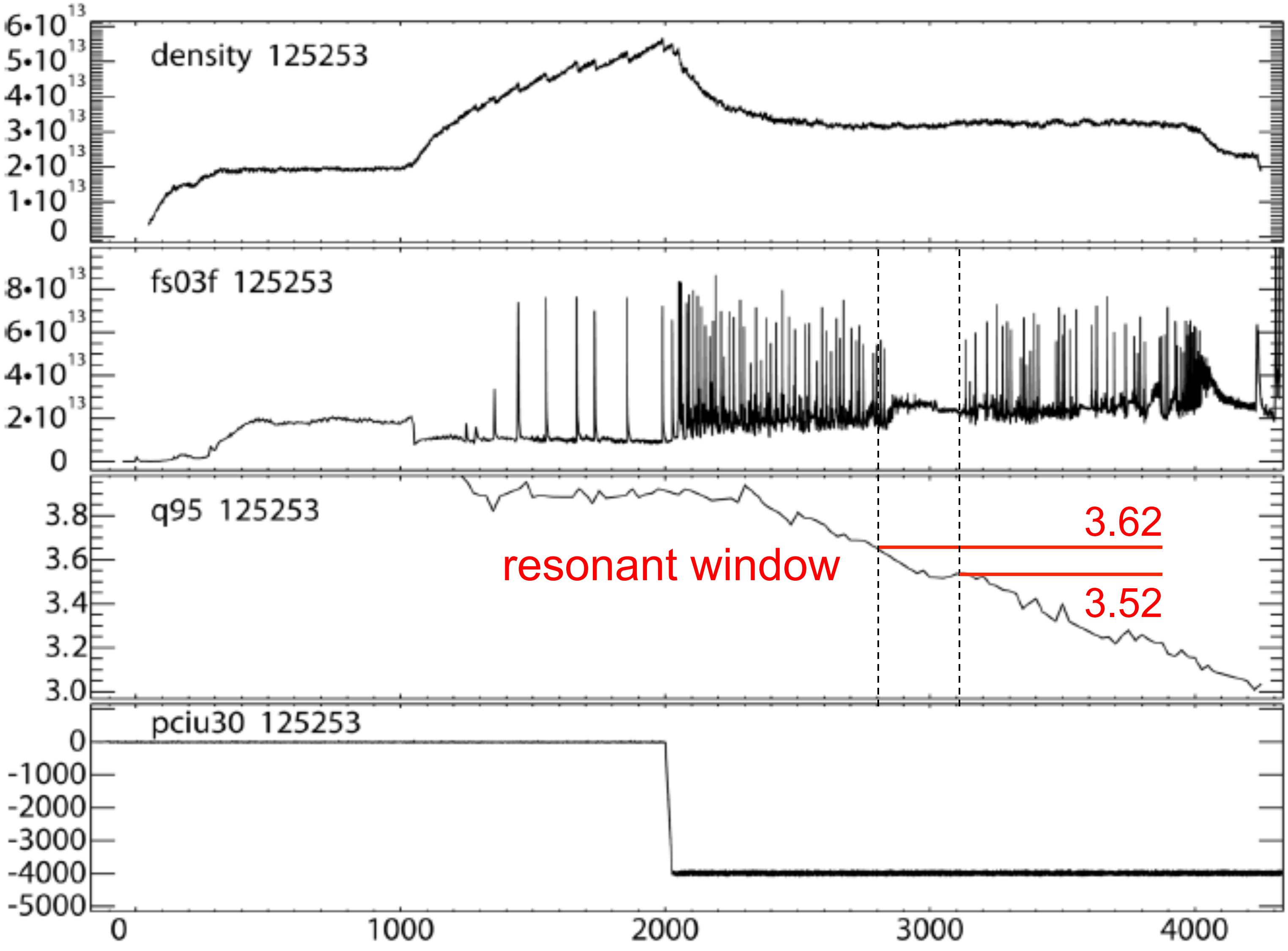




After RMPs

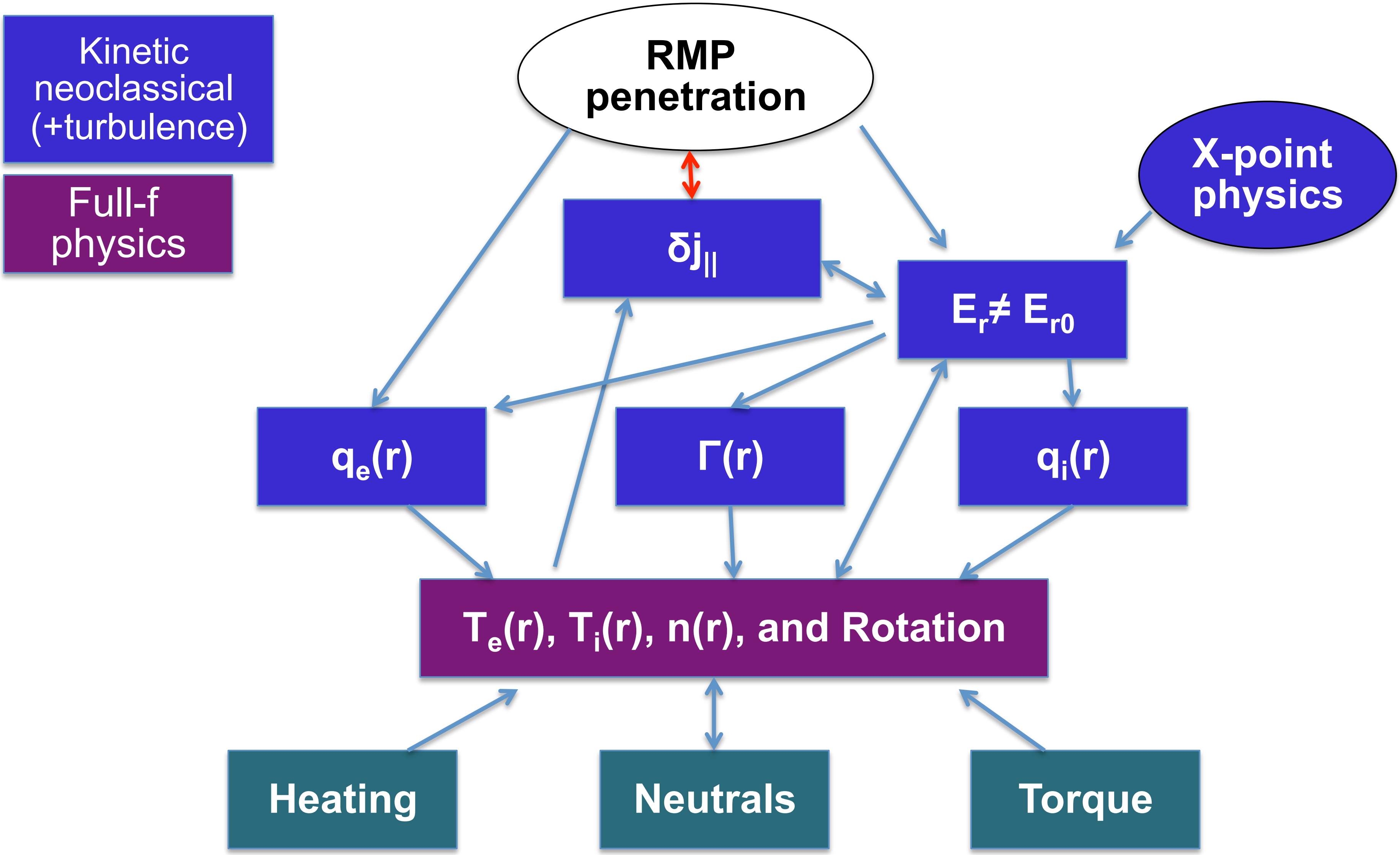
Before RMPs [126006]

ELM suppression window in q_{95}



- **T.E. Evans, et al, NF 2008**

RMP penetration is a multiscale self-organization process. Kinetic trapped-passing physics is a critical part.



Kinetic neoclassical (+turbulence)

Full-f physics

RMP penetration

X-point physics

$\delta j_{||}$

$E_r \neq E_{r0}$

$q_e(r)$

$\Gamma(r)$

$q_i(r)$

$T_e(r)$, $T_i(r)$, $n(r)$, and Rotation

Heating

Neutrals

Torque

XGC0: Kinetic transport modeling code

A simplified, nonturbulent, <Φ>-solver version of XGC1 full-f gyrokinetic turbulence code

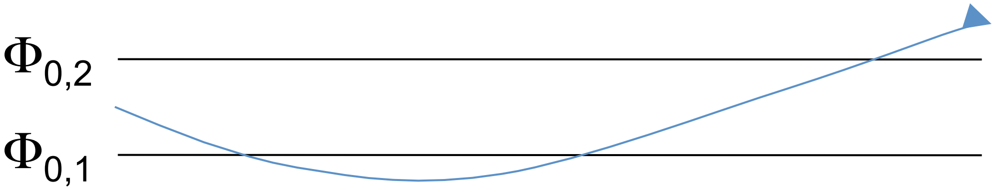
- Full-f PIC, allowing for small 3D δB
- Realistic diverted geometry from EFIT eqdsk
- 5D ion and electron Lagrangian drift-kinetic dynamics (particle/momentum/energy conserving)
- Monte-Carlo neutral atoms (ionization, charge exchange, wall recycling)
- Electromagnetic field solvers: $\Phi(\psi_0)$ and $\delta\psi(\delta J_T)$
- Extended logical sheath at wall
- Heat and torque inputs from core
- Particle-momentum-energy conserving Coulomb collisions
- Modeling of anomalous transport: radial random walk and convection, with independent control of the ambipolar particle and the heat transport
- Grad-Shafranov magnetic equilibrium evolution as pedestal evolves

Limitations/assumptions in the present study

- **Transient wave/instability dynamics in RMP penetration is not included.**
- **n=3 toroidal component only in toroidal Ampere's law solver**
- **Analyze the edge region only, $0.8 < \psi_N$**
- **Assume that turbulence effect is negligible**
  - Prescribe anomalous transport fluxes to fit the pre-RMP profiles
- **Weak stochastic magnetic field ($\delta B/B_0 < 10^{-3}$)**

→ Assume $\Phi(\psi_0)$, $n(\psi_0)$, $T(\psi_0)$ (Rosenbluth-Rechester approach)

→ Assume cantori, coinciding with the unperturbed flux surfaces ψ_0



$B = B_0 + \delta B$

$E_{||} = -\nabla\Phi_0 \bullet \delta B_r / B_0$

- **Thus, neglect δExB convective cell effect from imbedded islands in stochastic sea**
- **RMP study in XGC1 will improve most of these assumptions**

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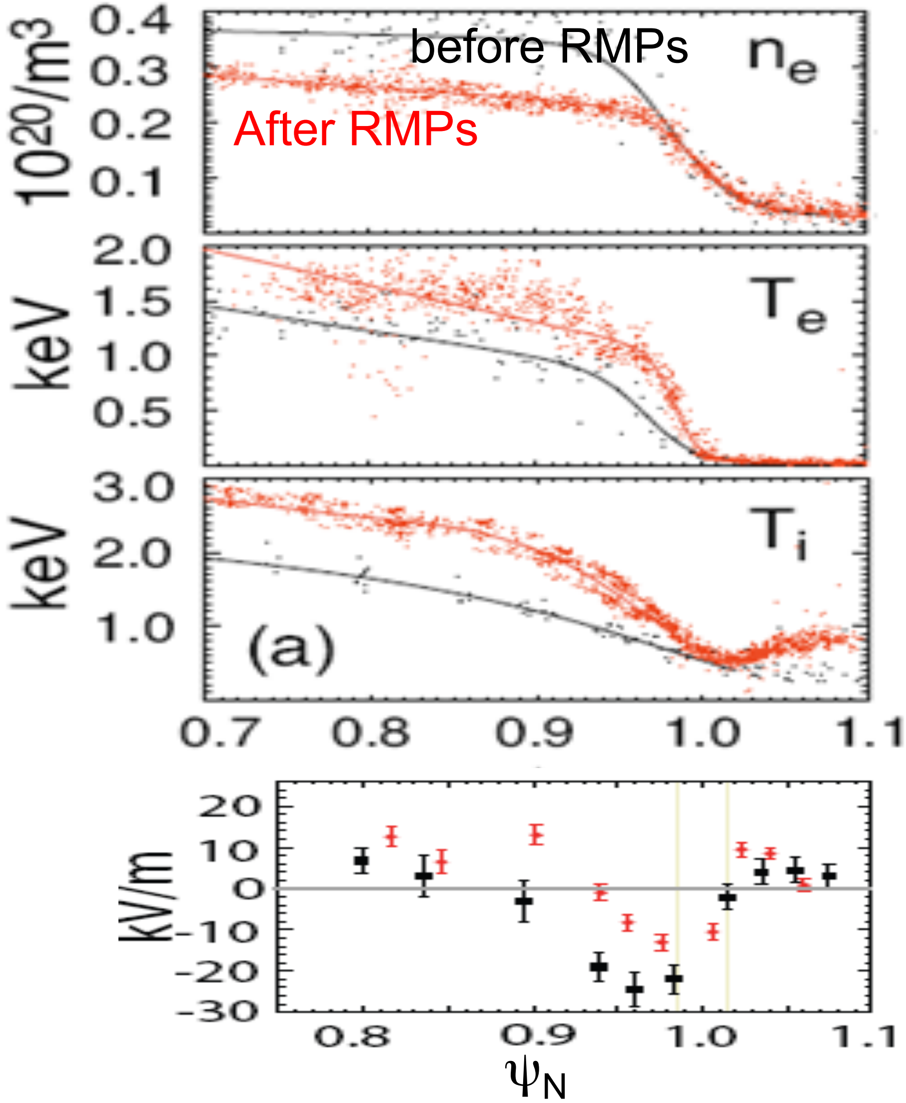
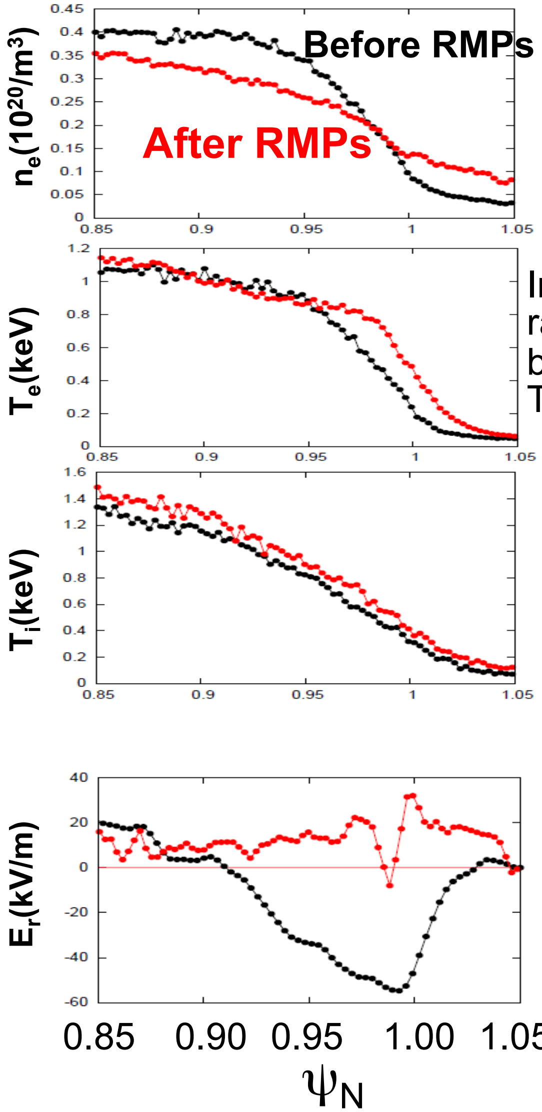
RMP simulation for weakly collisional, low density DIII-D pedestal

- **Modelling DIII-D 126006 RMP shot, n=3**
  - ITER-shaped, ITER-like low collisionality (~0.1) H-mode
- **6 MW of heat and 4 N-m of torque at inner boundary (ψ_N=0.8)**
- **Ad-hoc anomalous transport is included to fit the pre-RMP plasma profile, and is assumed unchanged by RMPs ($D \approx \chi_e \approx \chi_i \approx \chi_\phi \approx 0.1\ m^2/s$)**
  - The RMP driven transport is found to be much greater than the ad-hoc anomalous transport
- **Neutral recycling coeff =0.9**
- **No impurity particles**
- **Vacuum RMP boundary condition at ψ_N=1.06**

Simulation reproduces all the qualitative features of experiment (inside the ELM suppression window, q_{95}=3.58)



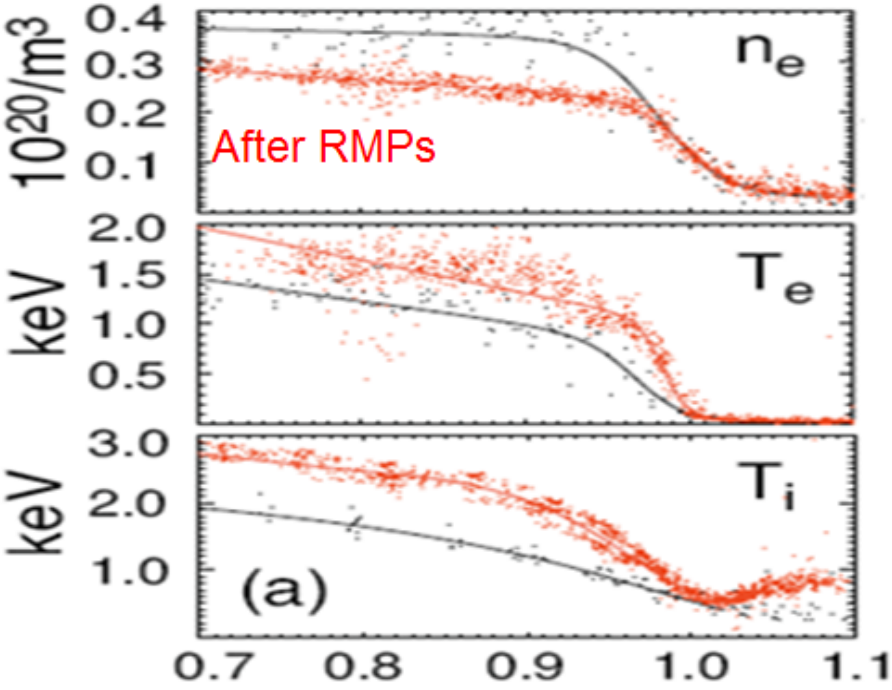
DIII-D Experiment 126006 at ~100 ms after RMPs

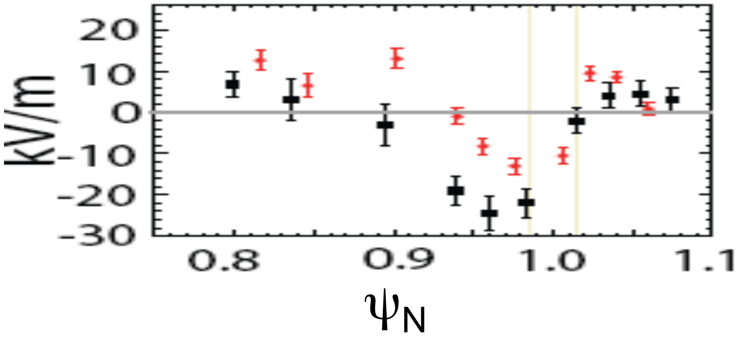


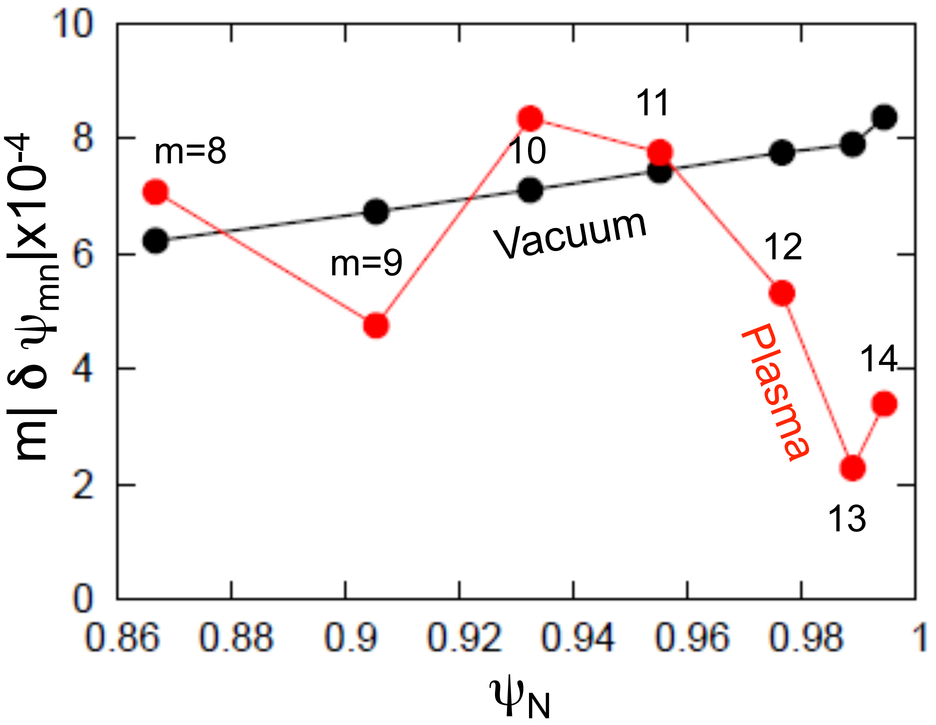
Impurity radiation brings the $T_{e,SOL}$ down

Simulation. at 4ms after the RMP turn-on: still evolving.

Resonant components, thus stochasticity, are suppressed just inside the magnetic separatrix → survival of transport barrier

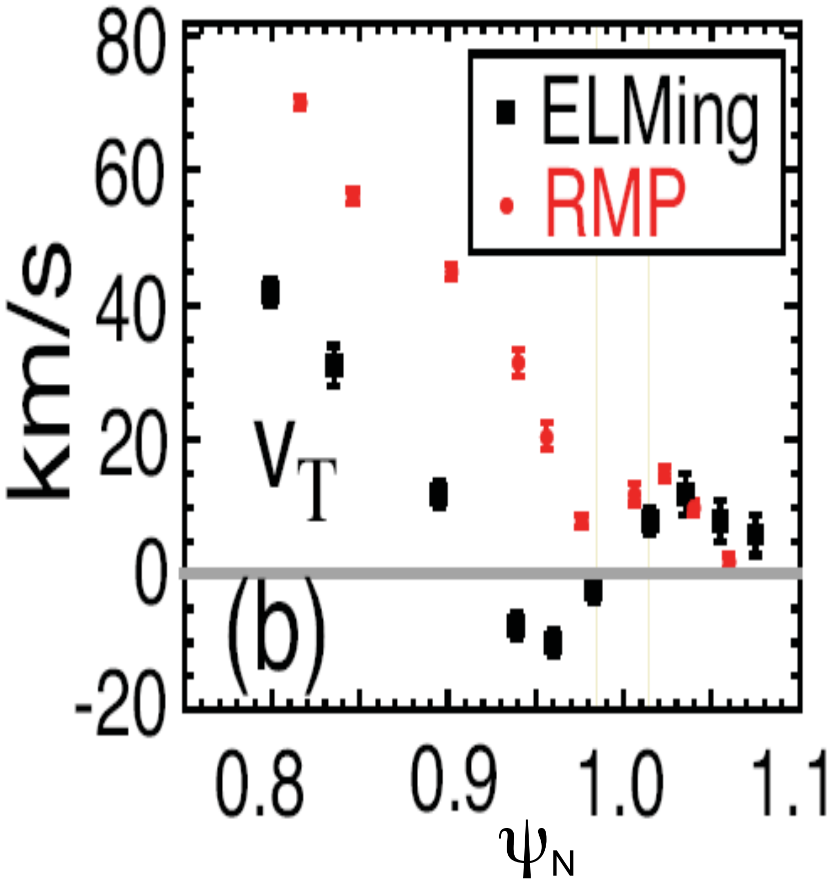






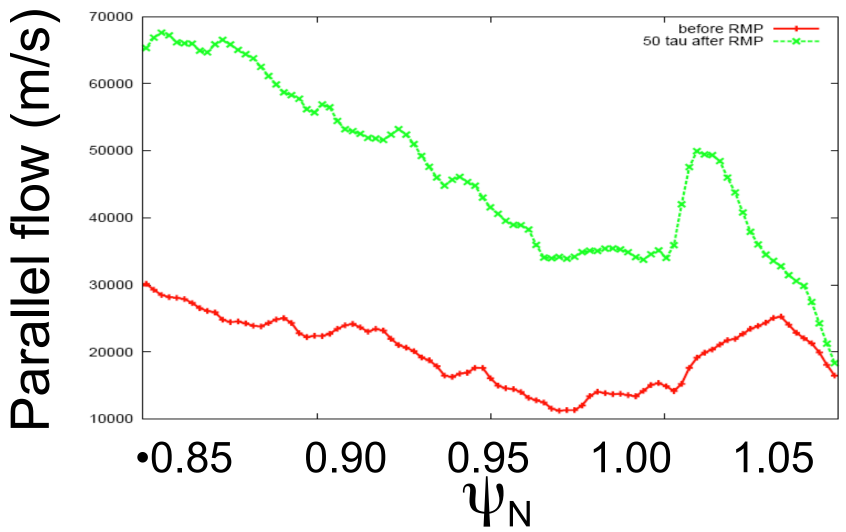
Amplitude of the resonant components v.s. radius, in the ELM suppression window.

Toroidal flow profile also shows quantitative agreement



Experimental observation (126006)

Edge V_T increases in the co-current directiion, with the survival of the "dip."

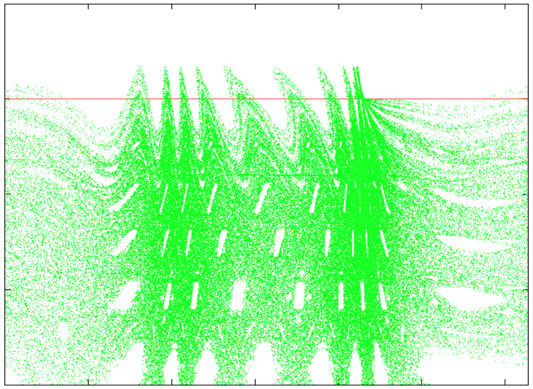


XGC0 Result

Edge V_T increases in the co-current direction, with a similar "dip" as in experiment.

Field line puncture plots, starting from ψ_N=0.96, show stronger connection between pedestal and wall in the ELM suppression window

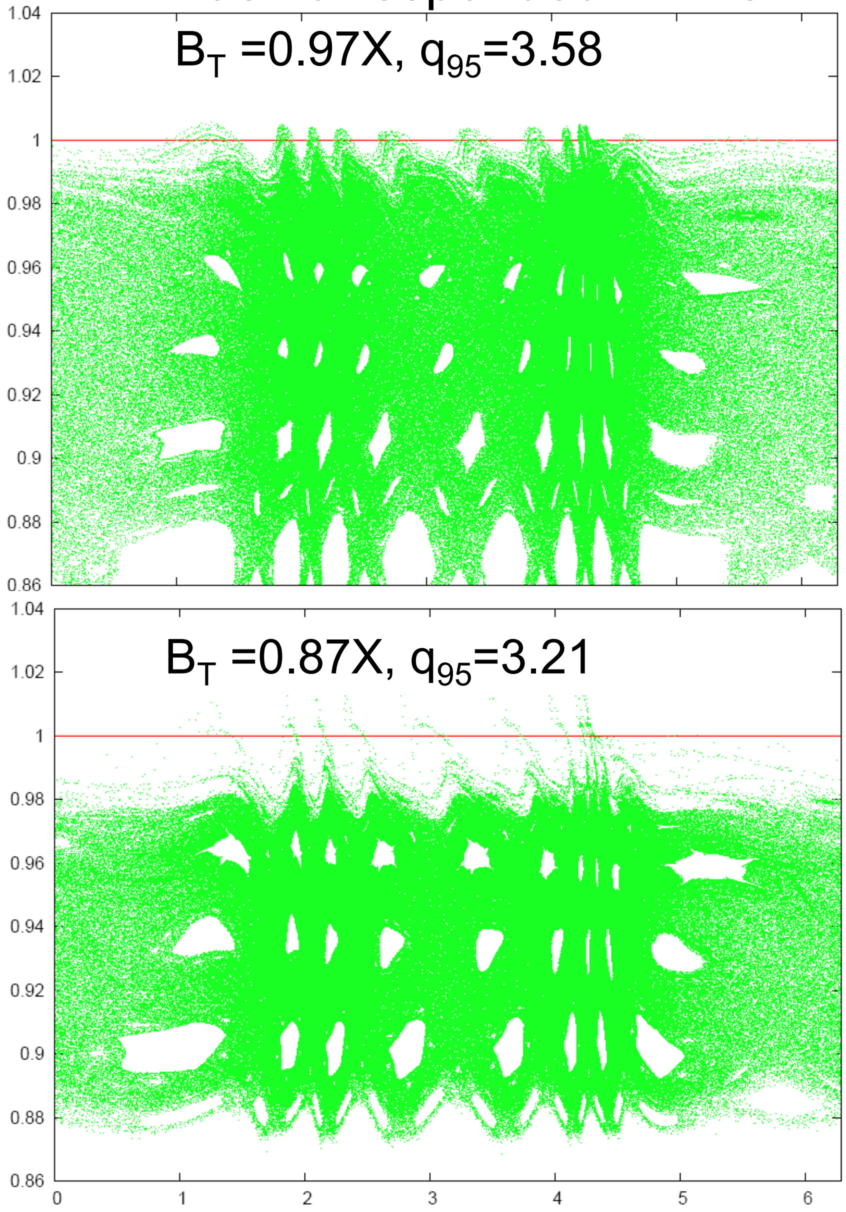
- **In-window:** Field connection between plasma and wall is stronger



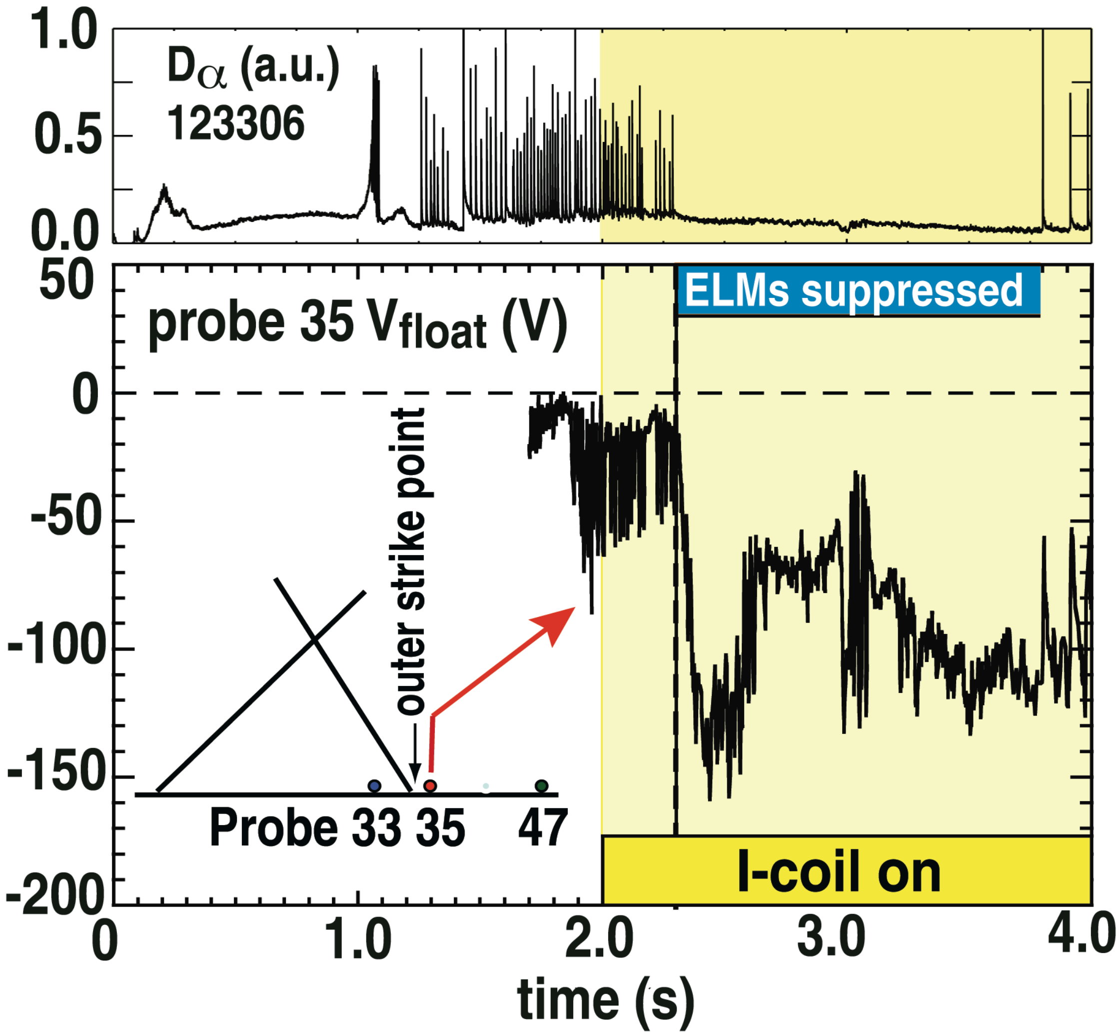
Vacuum RMPs with
B_T =1X $B_{T,EQDSK}$, q_{95}=3.69

- **Out-of-window:** Field connection between plasma and wall is weak

Plasma responded RMPs



Experimental indication of field line connection from pedestal to divertor in ELM suppression window



J. Watkins, et al., J. Nucl. Mater., **363-365** (2007) 708

Inside the q_{95} window, p_e pedestal is somewhat milder and the T_e top moves out radially

Enough to distinguish ELM stable from unstable?

n_e

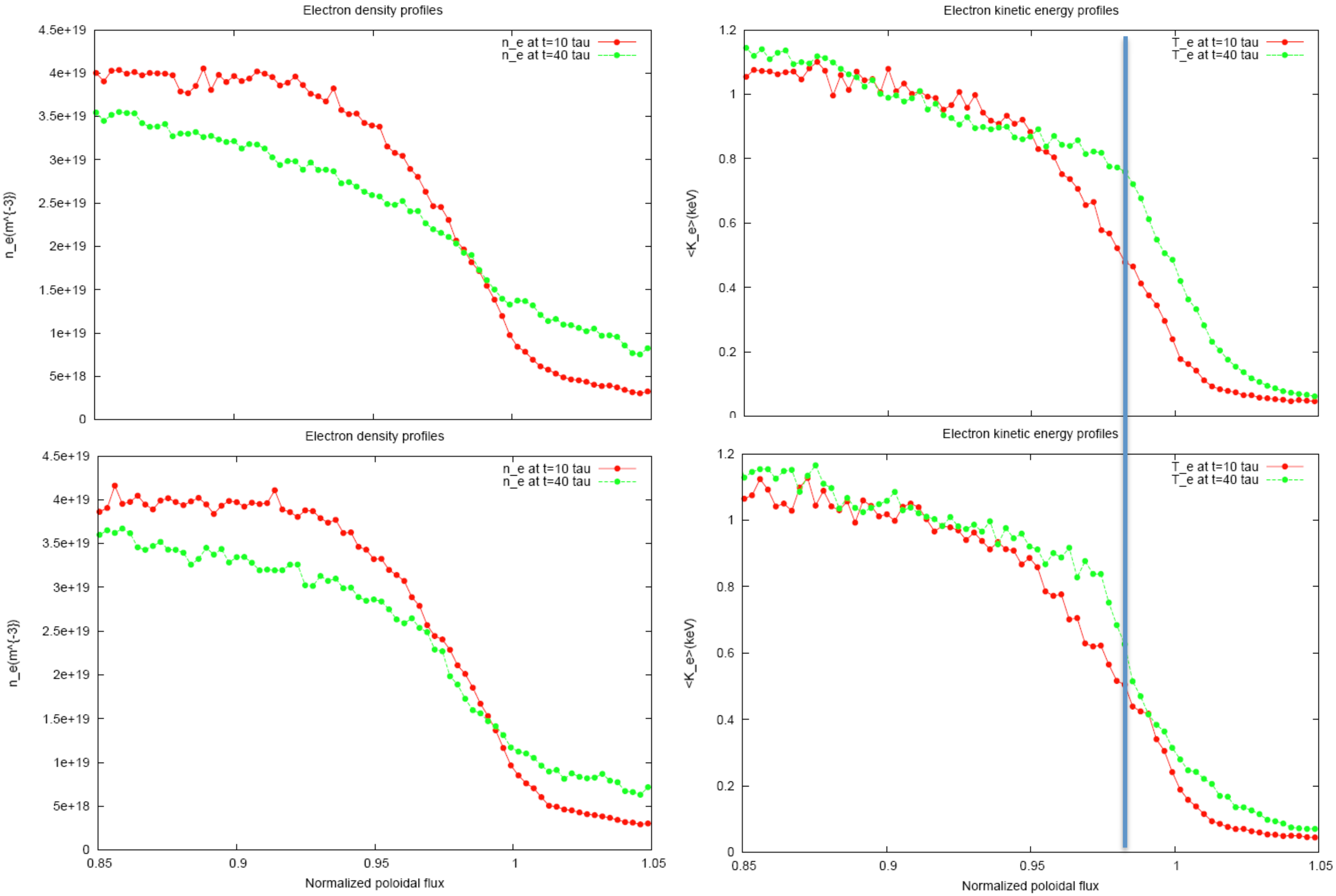
T_e

Inside

q_{95}=3.58

Outside

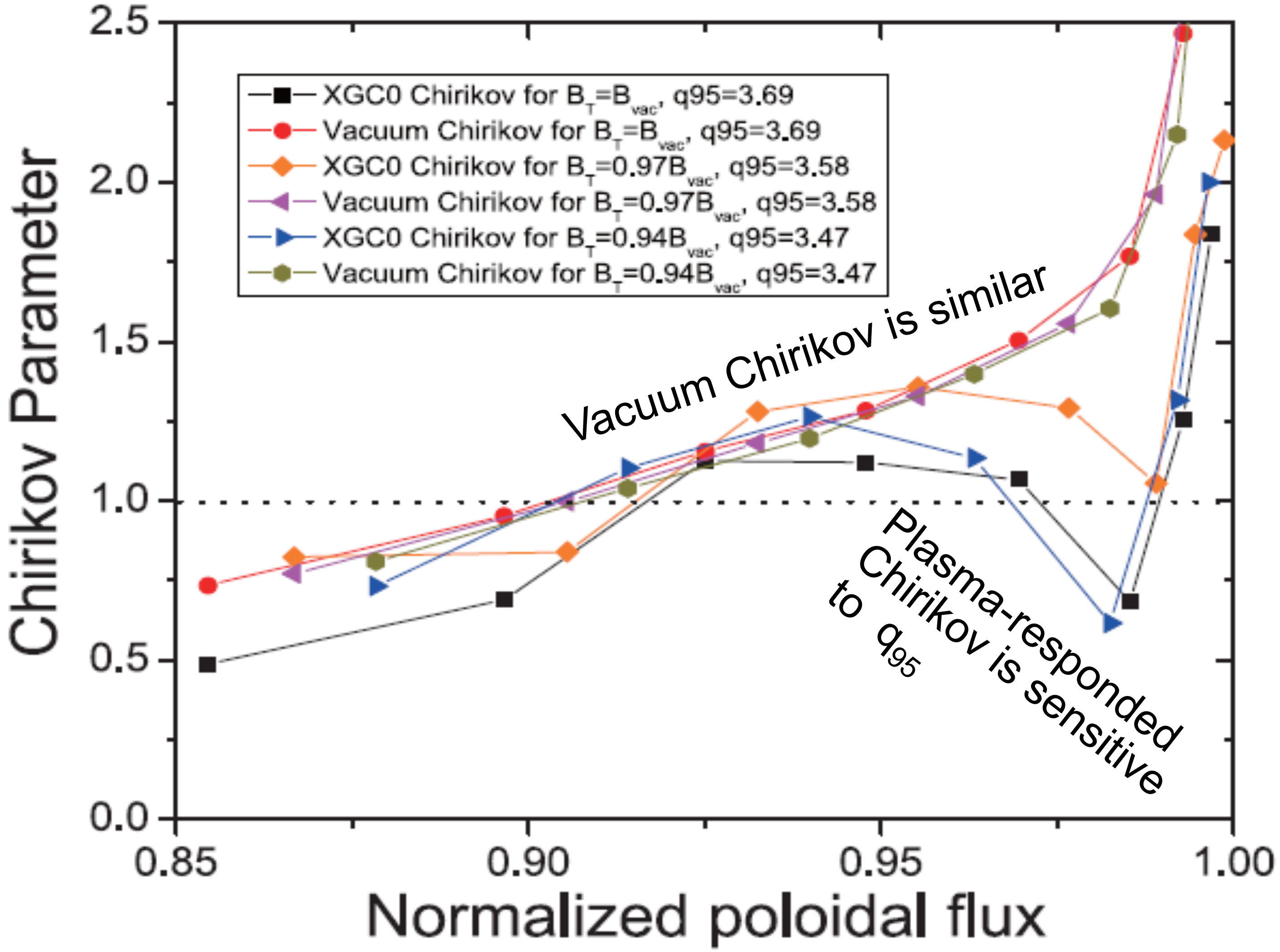
q_{95}=3.21



Vacuum Chirikov is similar, but the plasma responded Chirikov is a sensitive function of q_{95} around 3.6.

Near q_{95} =3.6, Chirikov ≥1 everywhere. Otherwise, Chirikov <1 exists in the pedestal.

→ “Vacuum Chirikov>1 is only a necessary condition.”

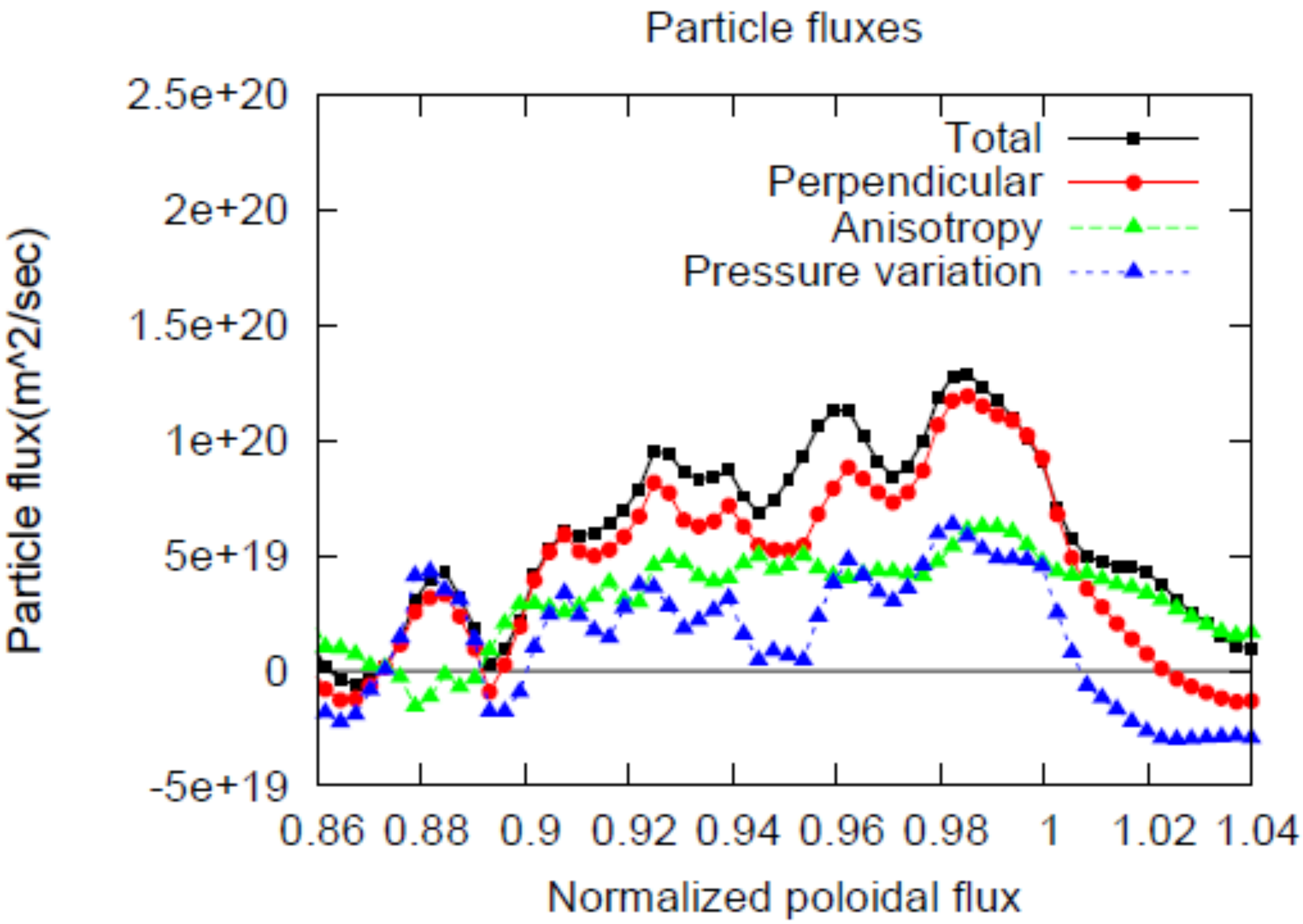


Vacuum Chirikov is similar

Plasma-responded Chirikov is sensitive to q_{95}

Ion particle flux is mostly from perpendicular neoclassical transport in plasma-consistent RMPs, from $E_r \neq E_r$(axisymmetric). Electrons follow ion transport along the perturbed B.

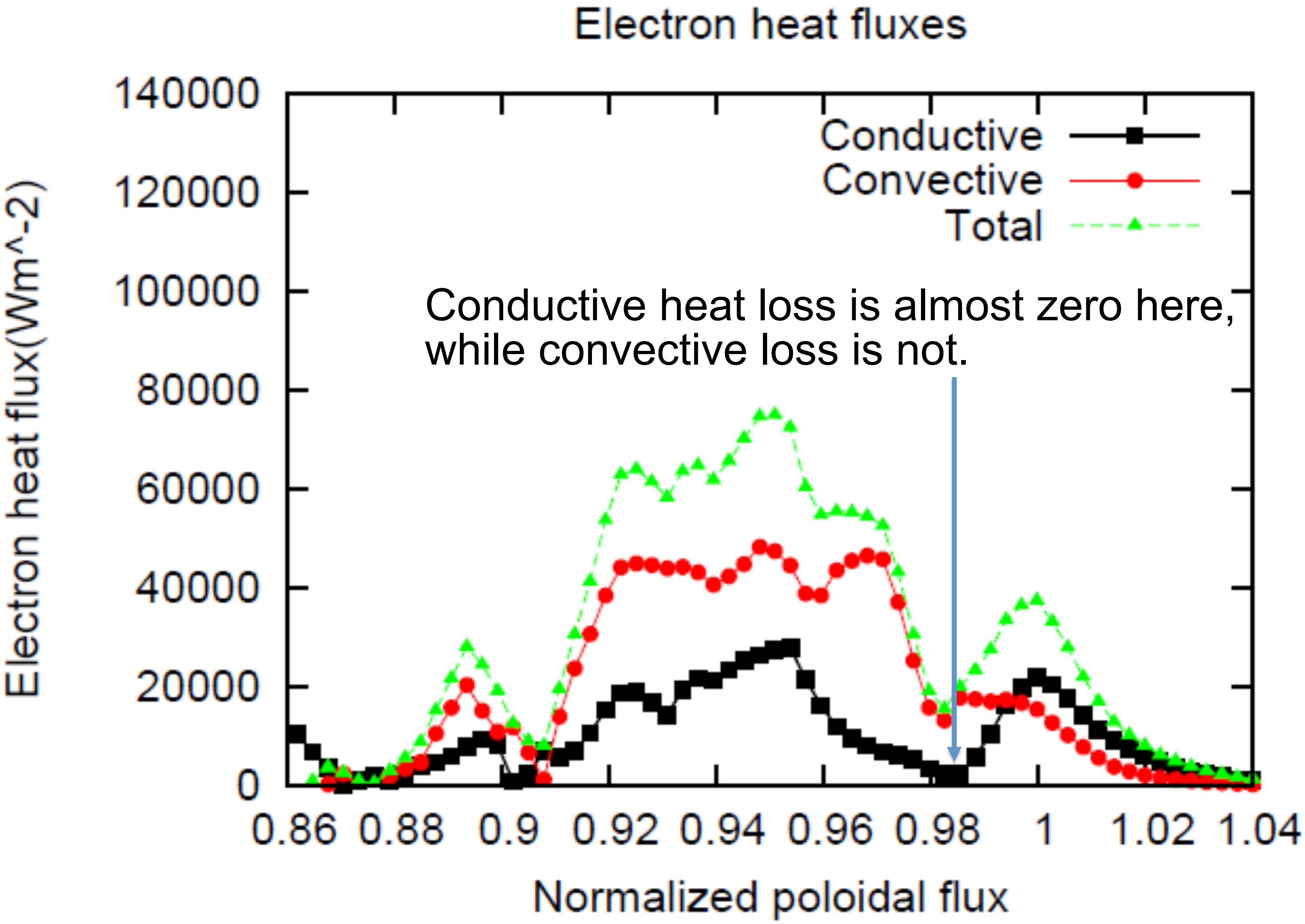
In plasma-consistent RMPs



Parallel electron heat conduction is not dominant over the convective loss: contrary to Rechester-Rosenbluth

(small passing fraction, collisions, perpendular drift, E_r)

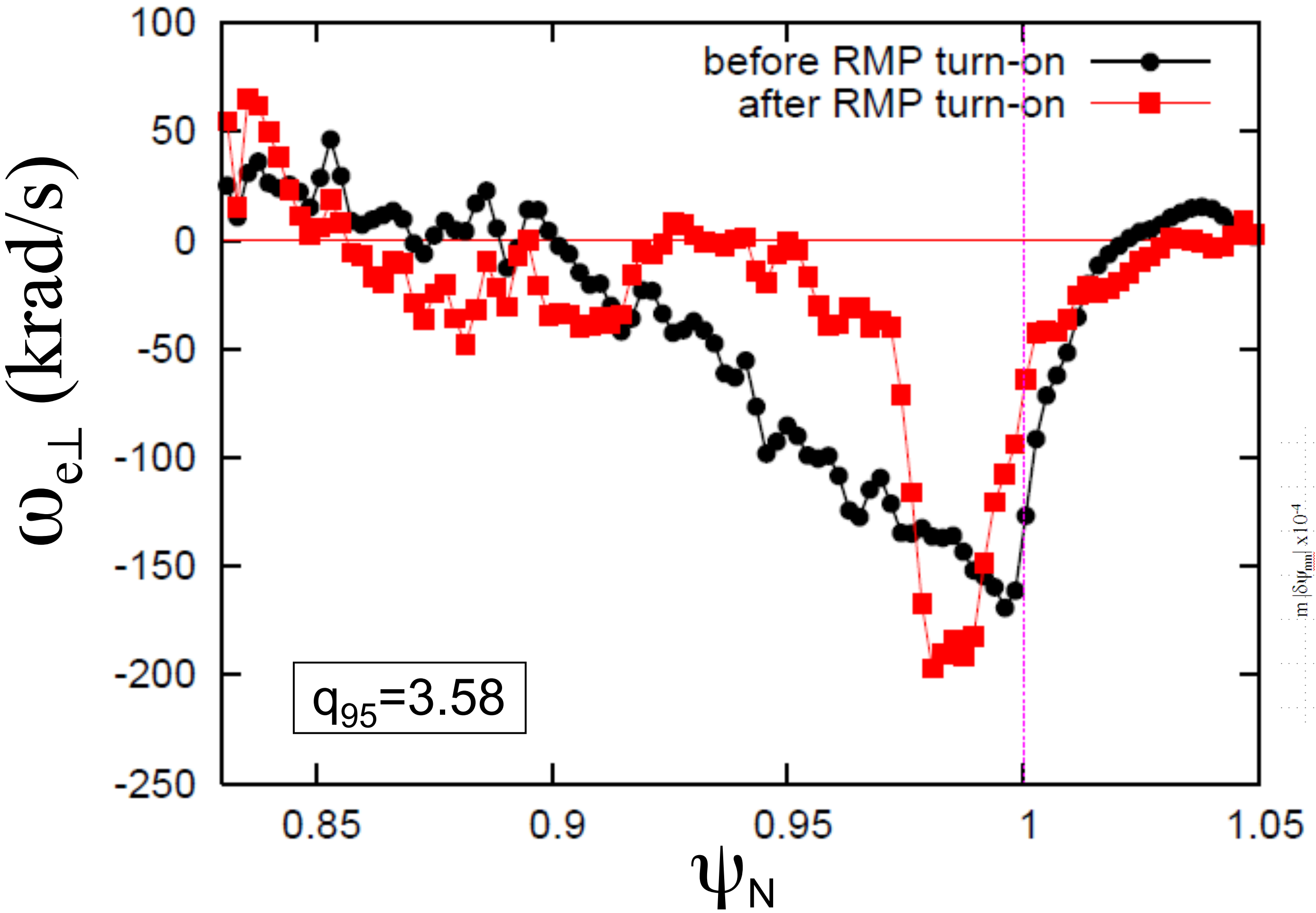
Plasma-consistent RMP case



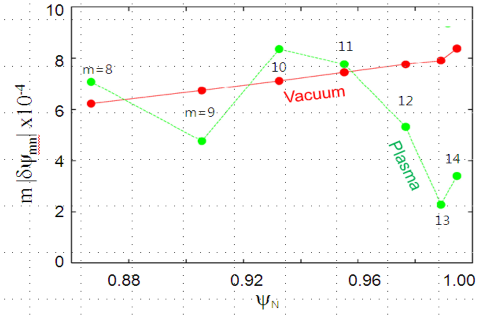
Conductive heat loss is almost zero here, while convective loss is not.

XGC0 finds large $|V_{e\perp} = V_{e*} + V_{ExB}|$ in the barrier-survival region, and zero/small $V_{e\perp}$ in the enhanced transport region

- Pre-RMP based prediction does not hold ground [Cf., Fitzpatrick's flow shielding theory]
- Large $|V_{e\perp}|$ just inside the separatrix is the result of robust X-transport.



Similar result seen in experiment [Moyer]



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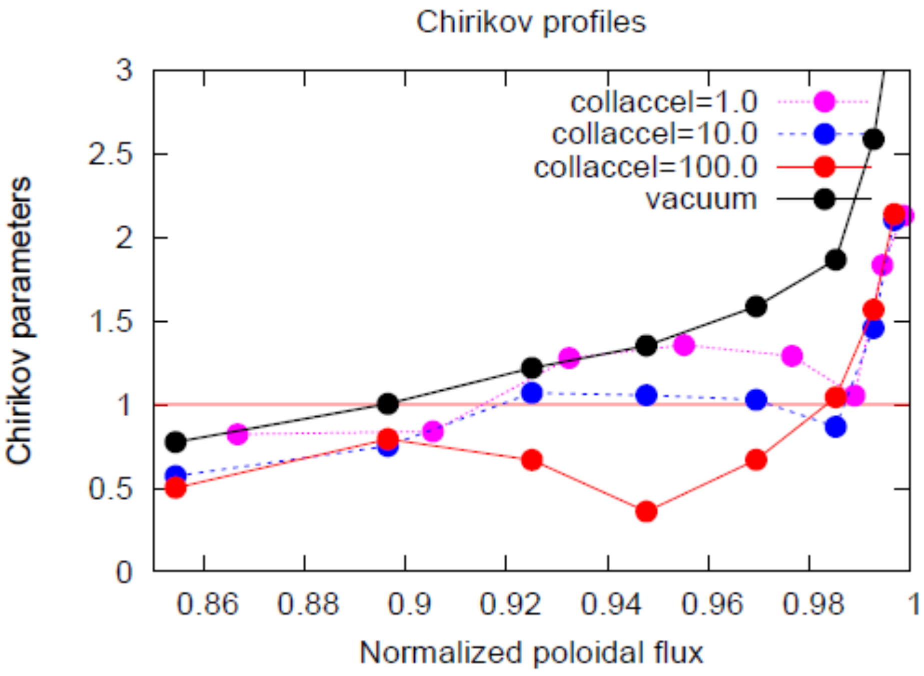
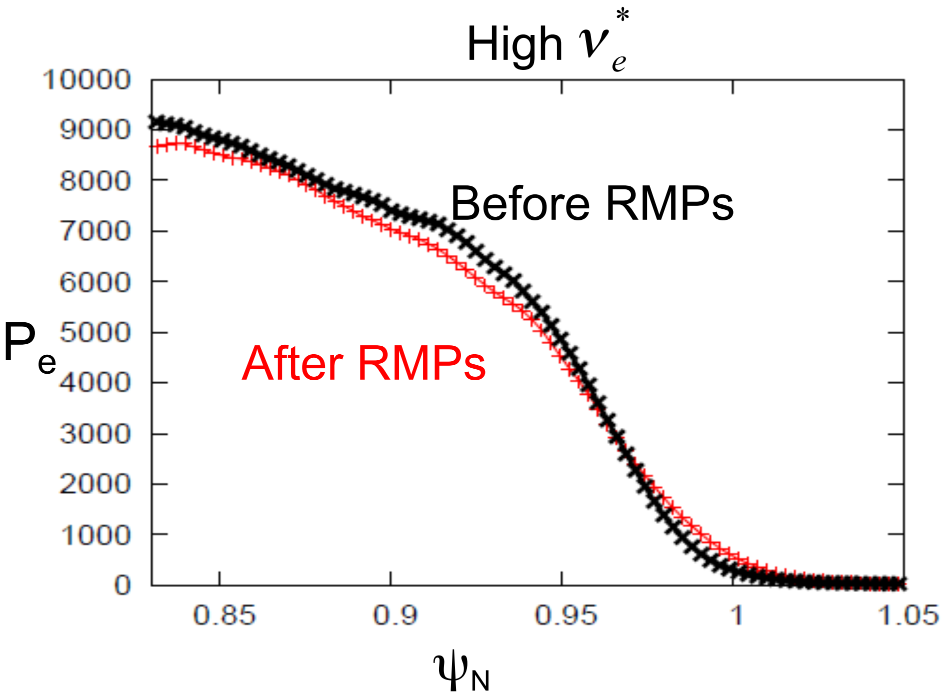
Effect of collisionality

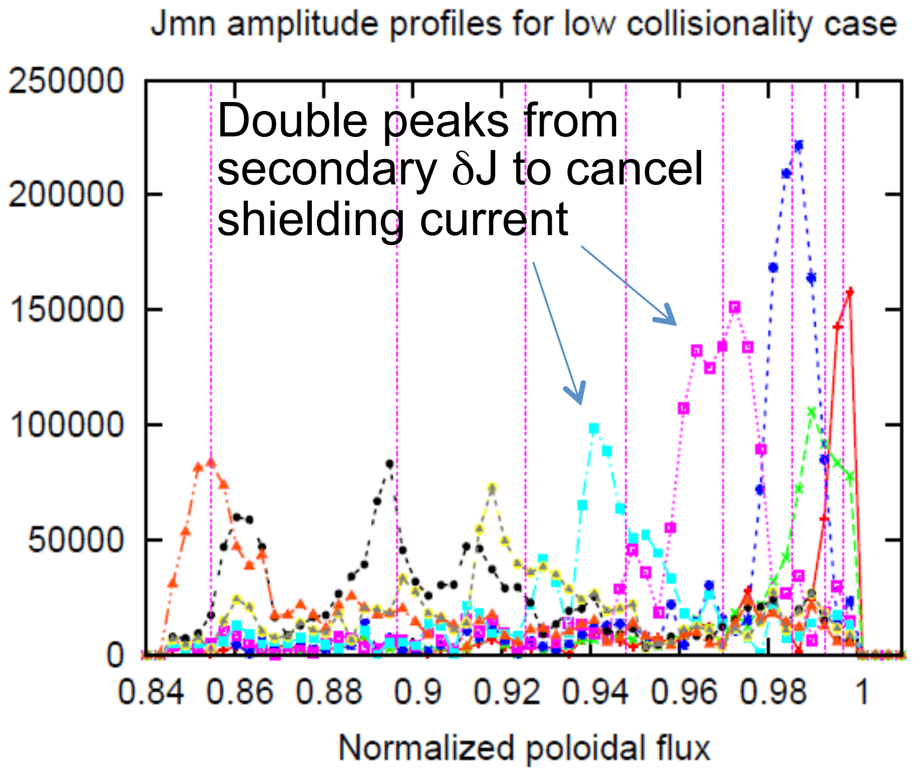
Experiment: As the collisionality increases, RMP-driven transport weakens and the ELM suppression becomes difficult.

Simulation: As the collisionality increases, RMP penetration, thus RMP-driven transport weakens.





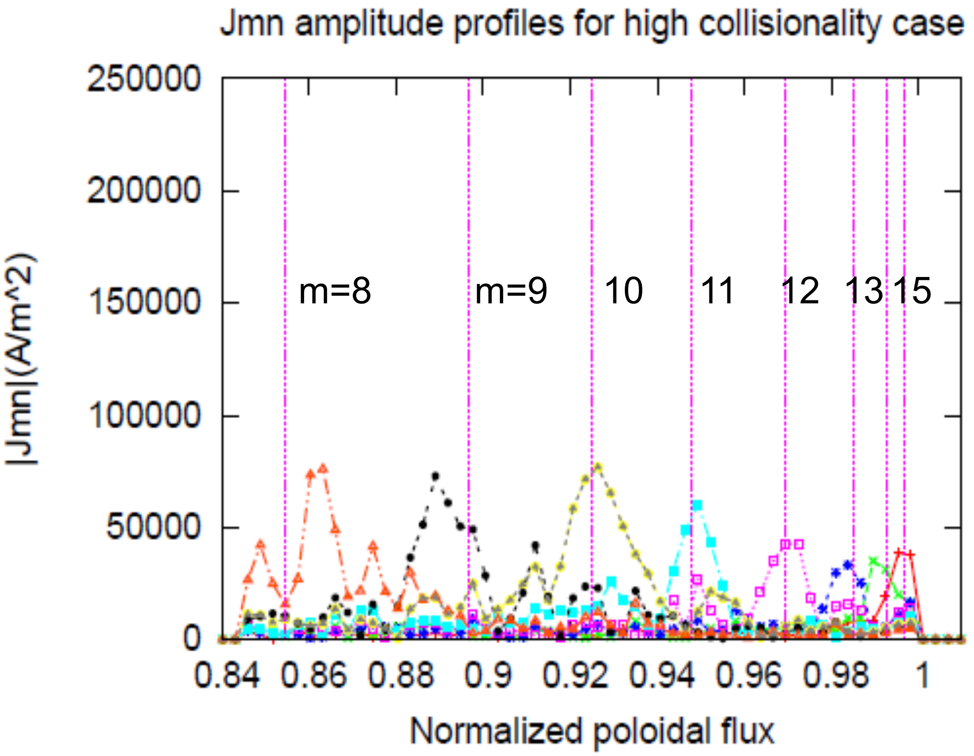
Fourier current amplitudes in the stochastic region shows double peak, with the secondary current pushed inward while the primary current is pulled outward.


Jmn amplitude profiles for low collisionality case

Double peaks from secondary δJ to cancel shielding current

Low collisionality

- Strong shielding currents at m≥13 suppresses local RMPs and stochasticity as soon as the RMPs meet the pedestal.
- Secondary currents tend to cancel the primary shielding currents at m≤12, leading to the recovery of RMPs and stochasticity at inner radii.

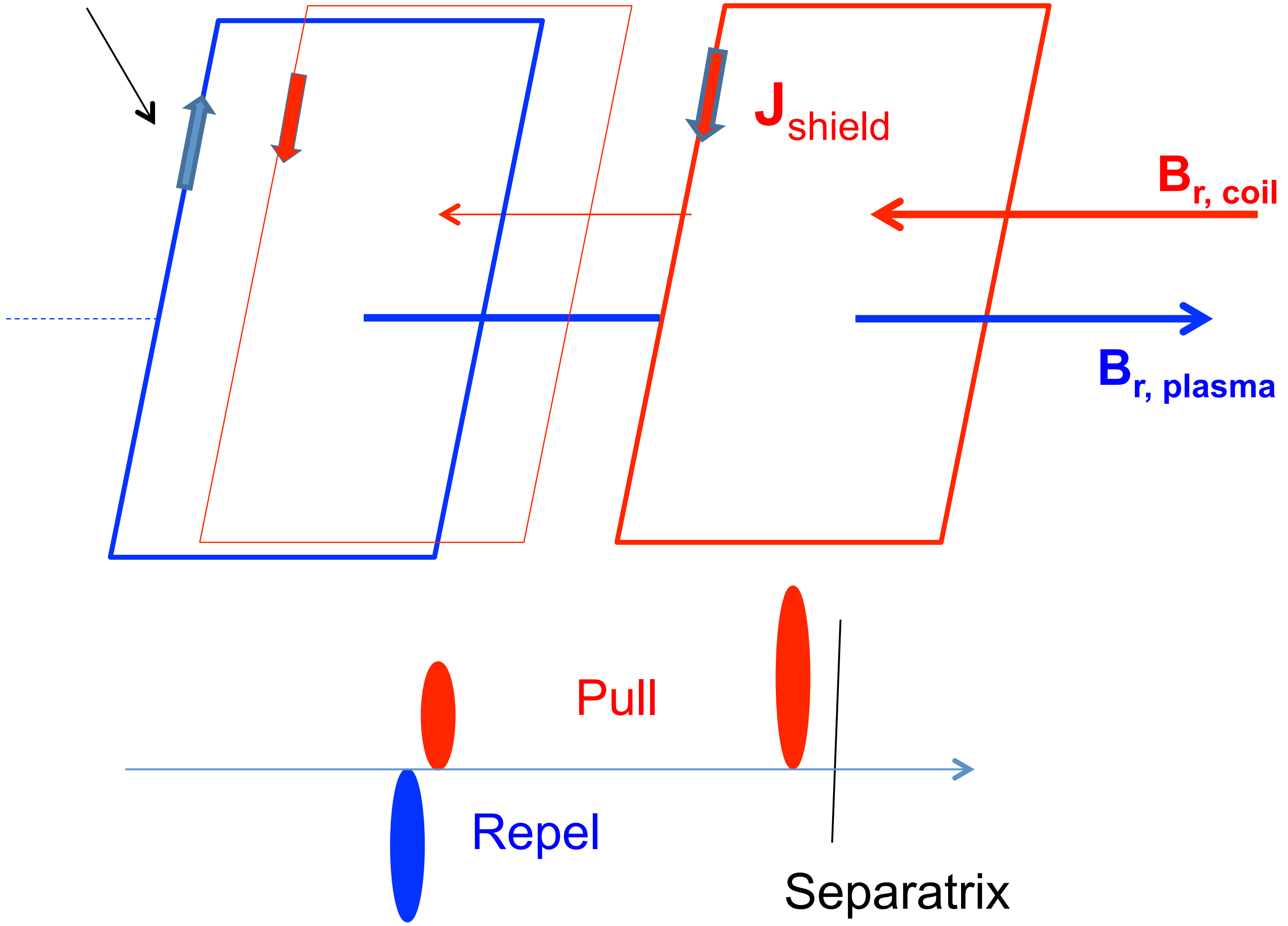

Jmn amplitude profiles for high collisionality case

High collisionality

- Primary shielding currents are weak and does not generate strong secondary currents.
- Primary shielding currents simply accumulate toward inner radii and shields RMPs and stochasticity.
- Some secondary shielding currents develop at deeper insde

Reactive secondary currents to the primary screening currents can cancel the plasma suppression effect, or even amplify RMPs.

Secondary current to block the primary plasma response $\mathbf{B}_{\mathbf{r,plasma}}$



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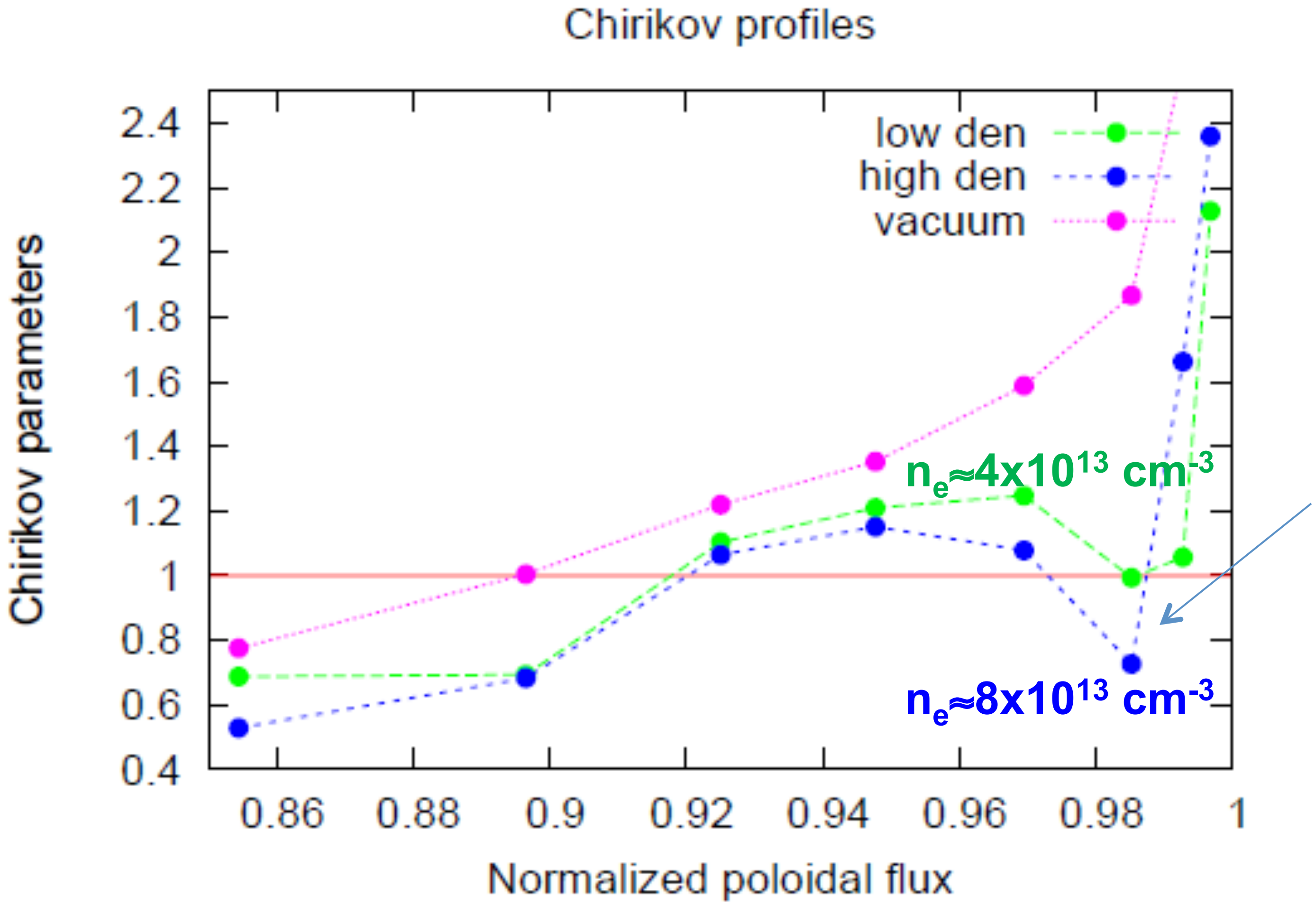
At ITER-relevant collisionality and density in DIII-D: If collisionality is kept low, 2X density increase does not change the stochasticity much

- **It was the high ν_{e*}, suppressing RMPs in the pedestal, not the high n_e**
- **RMP penetration into core becomes more difficult**

→Good news for ITER

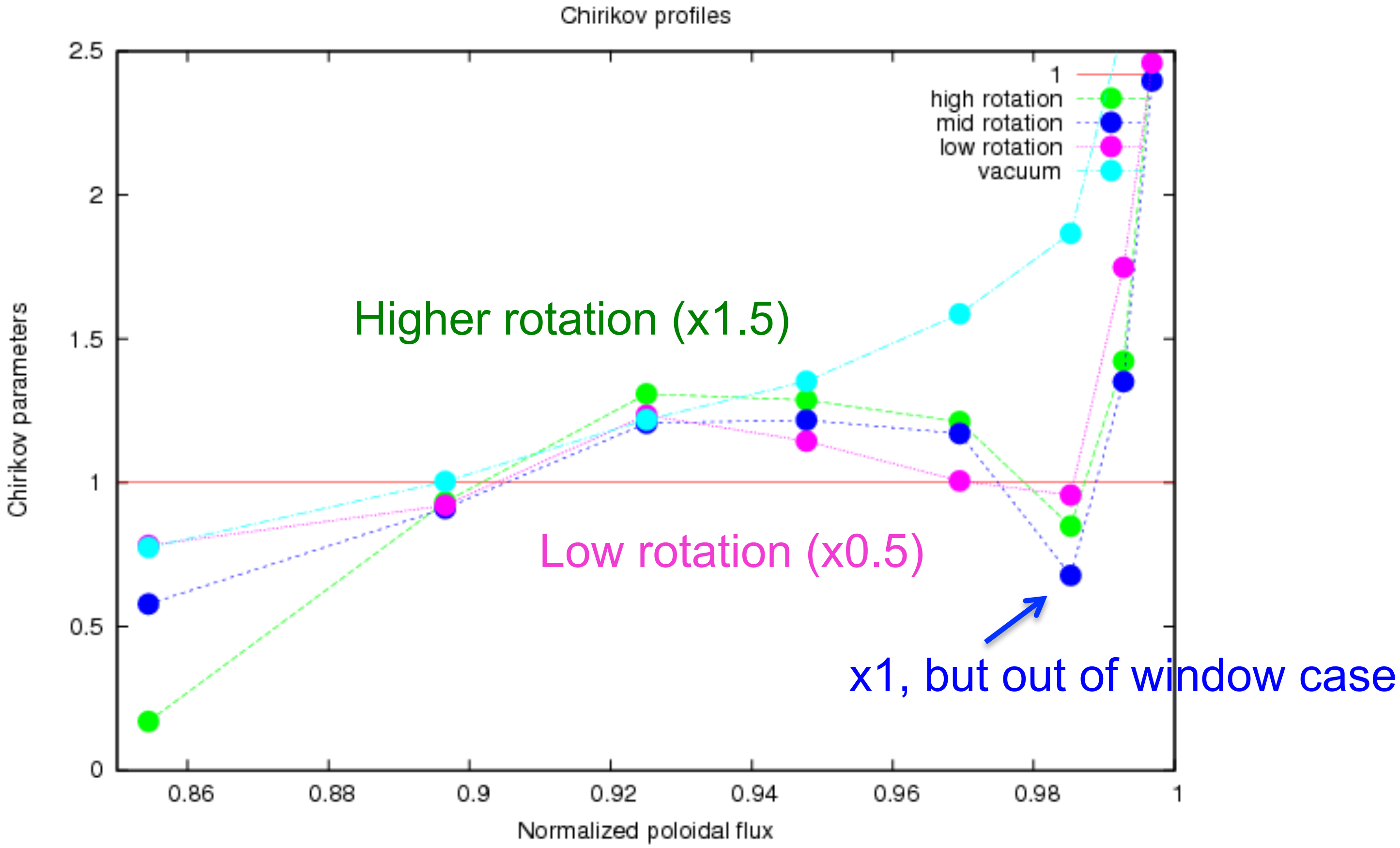


Valley may be raised by adjusting q_{95}.

Rotation effect on stochasticity

Effect of lower rotation on islands/stochasticity penetration to edge pedestal top is minimal → Could be a good news for ITER

- However, low rotation does not suppress islands/stochasticity at the core side
- 50% higher rotation significantly suppresses the RMPs in the core (not at pedestal top, though), without degrading the pedestal performance.
  → Rotation will be good in ITER: same story.



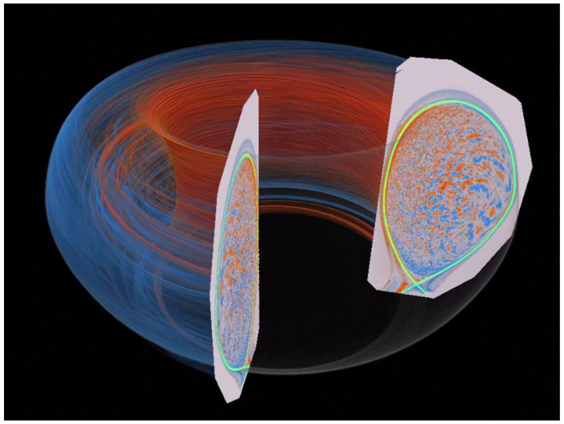
Higher rotation (x1.5)

Low rotation (x0.5)

x1, but out of window case

Conclusion and discussion

- We have a kinetic tool to understand and predict RMP penetration!
- **Plasma-responded Chirikov ≥1 in the whole edge region is a common factor in the ELM suppressed cases (scan in q_{95} and collisionality)**
- **At higher ν_{e*} plasma screens RMPs from most of the edge region**
- **Secondary current response is important**
- **Implication to ITER**
  - Higher density does not destroy the pedestal stochasticity, but helps RMP suppression in core → good news
  - Lower toroidal rotation is goof for pedestal stochasticity. However, core density pumping and NTM may get worse →stronger rotation is better
  - Higher toroidal rotation does not destroy the pedestal stochasticity, but helps RMP suppression in core
- **RMP study will move to full-f gyrokinetic XGC1 for consistency with turbulence and ExB convective-cell effects.**



XGC1 in divertor geometry

Lagrangian Equation of Motion in XGC0

$$d\mathbf{x}/dt = (1/D)[q\hat{v}_{||}\mathbf{B}/m + (q\hat{v}_{||}^2)\nabla \times \mathbf{B} + \mathbf{B} \times \nabla H/B^2]$$

$$d\hat{v}_{||}/dt = -(1/B^2 D)[\nabla \cdot \mathbf{B} + \hat{v}_{||}\nabla H \cdot \nabla \times \mathbf{B}]$$

Where H is the Hamiltonian with flux-function electrostatic potential Φ_0

$$H = (q/2m)\hat{v}_{||}^2\mathbf{B}^2 + \mu B/q + \Phi_0 \ ,$$

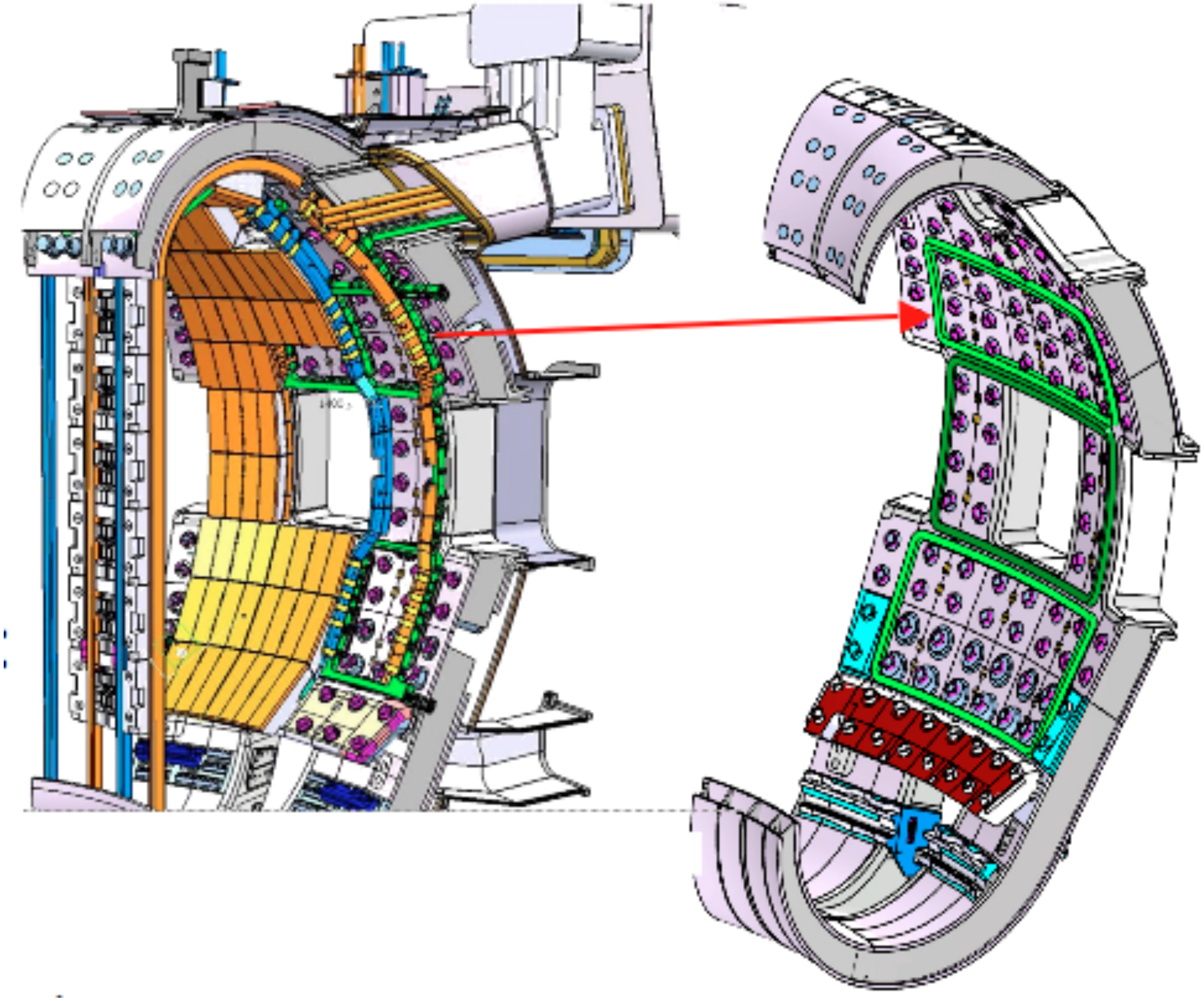
$$\hat{v}_{||} = mv_{||}/qB,$$

$$D = 1 + \hat{v}_{||}\mathbf{B} \cdot \nabla \times \mathbf{B}/B^2,$$

Momentum and energy conserving particle motion.

[LittleJohn, White, and others]

I-coils in DIII-D



[T. Evans, et al, IAEA-FEC 2008]

RMP penetration is a multiscale self-organization process → Full-function kinetic code

- **RMP penetration is sensitive to $\delta j_{||}$: electron dynamics**
- **Electron dynamics in stochastic δB is kinetic (trapped+passing in E_r)**
  - Not only **$\delta j_{||}$,** but also parallel particle and heat transport
- **Ion transport in 3D δB is kinetic**
  - Friction between trapped and passing particles in **$E_r \neq E_{r0}$**(axisymmetric)
- **X-transport (X-point effect) and its effect on E_r is full-f kinetic**
- **Plasma profile and E_r must be evolved together with RMP penetration → full-f kinetic**
- **Neutral particles, heating and torque play significant roles in plasma profile evolution**

→ **Full-f kinetic** simulation in realistic separatrix geometry with neutral recycling, heat source and torque

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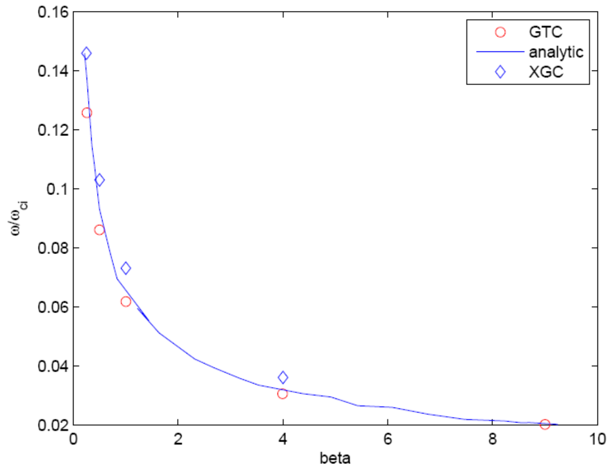
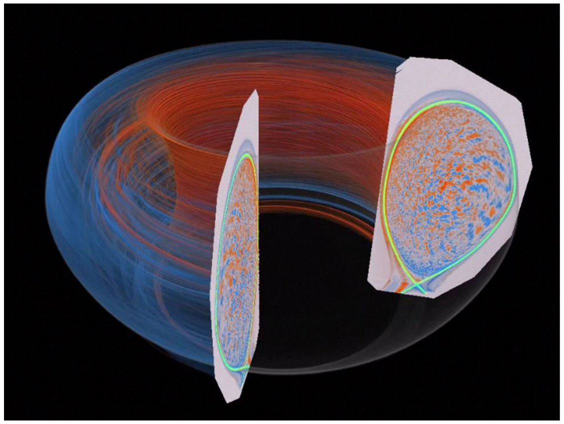
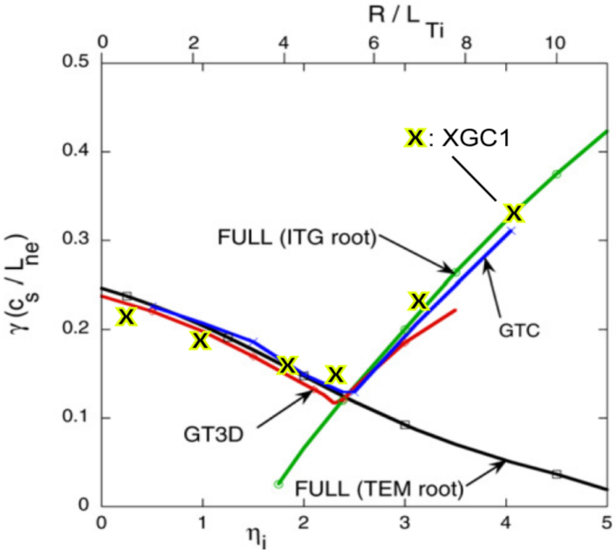
- **Implication to ITER**
  - Higher density does not appear to be deleterious to pedestal stochasticity, but helps RMP suppression in core → good news
  - Lower rotation does not appear to be deleterious to pedestal stochasticity. However, core density pumping and NTM may get worse →stronger rotation is better
- **RMP study will move to full-f gyrokinetic XGC1 for consistency with turbulence and ExB convective-cell effects.**



Verification of E&M Alfven waves in δf XGC1



XGC1 simulation of ITG + neoclassical physics in diverted DIII-D plasma



Verification of kinetic electron dynamics in XGC1 in δf mode. Full-f also verified.