Strike point splitting: a tool for error field analysis

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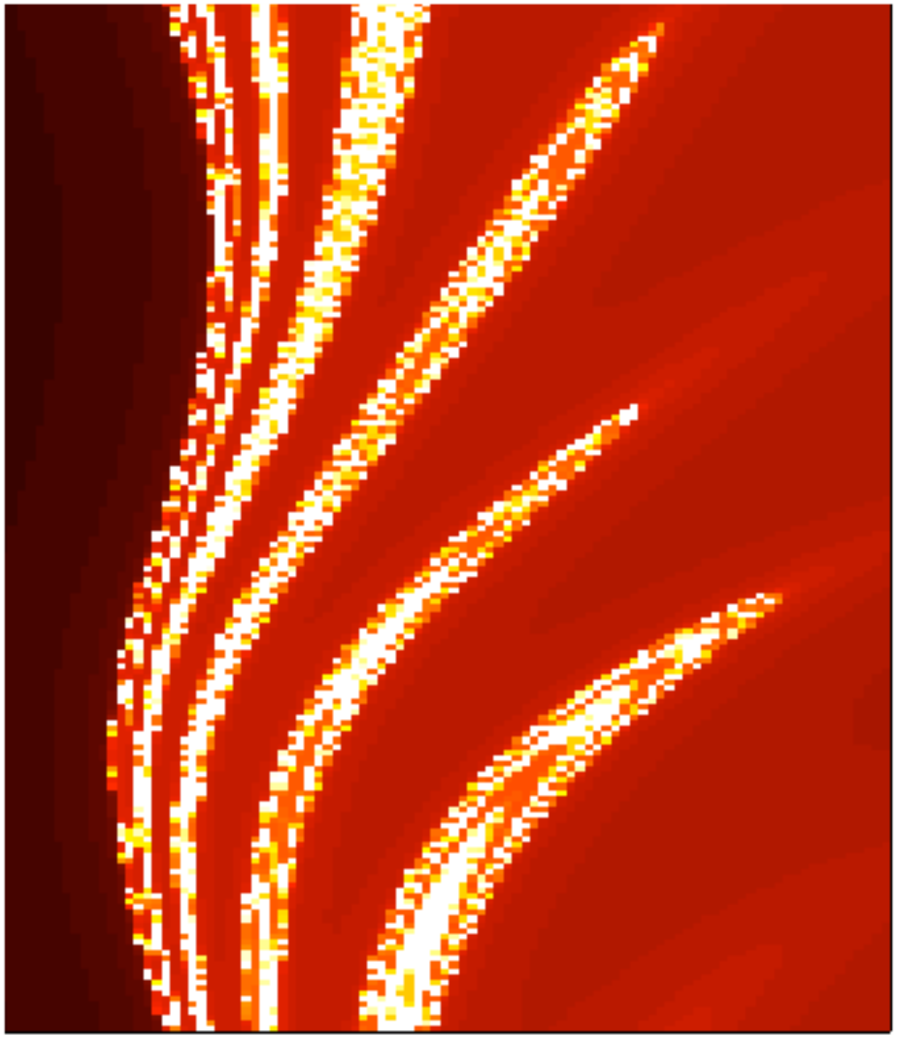

3rd APS-DPP Error Field Workshop
Orlando, FL, November 16th, 2007

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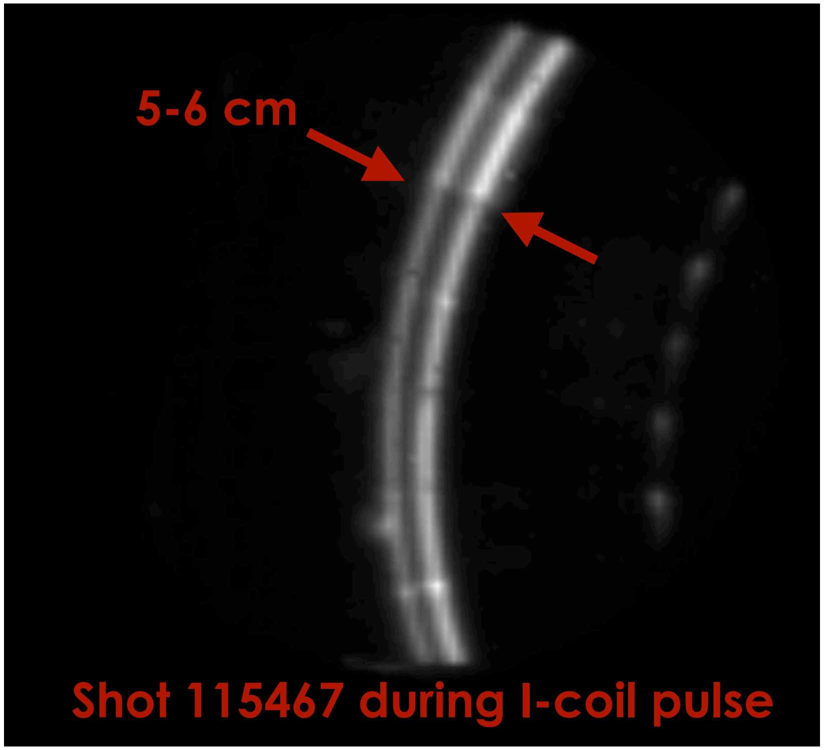
UCSD

Dramatic heat flux splitting was originally observed in high collisionality perturbation experiments



- **Relatively weak fields observed to have a large effect**
  - Is plasma response implicated?
- **Motivates study of field line structure at divertor target**
- **Can we use this technique to spread heat flux in reactor designs?**

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Outline: RMP = Resonant Magnetic Perturbations

- **Strike point structure can be used a probe of upstream magnetic field topology**

- **E3D fluid simulations predict that the strike point deposition profile can be widened by RMPs**
  - Heat flux guided by the invariant manifolds of **B**
  - Analysis also predicts large changes in upstream temperature

- **However, n=3 footprint studies on DIII-D pose a paradox**
  - Non-axisymmetry observed in particle flux & floating potential
  - Heat flux often appears axisymmetric?

- **Possible resolution of paradox**
  - Screening of magnetic perturbations by plasma rotation?
  - Screening of electron transport by large ExB drift?
  - Kinetic flux limitation, others …?

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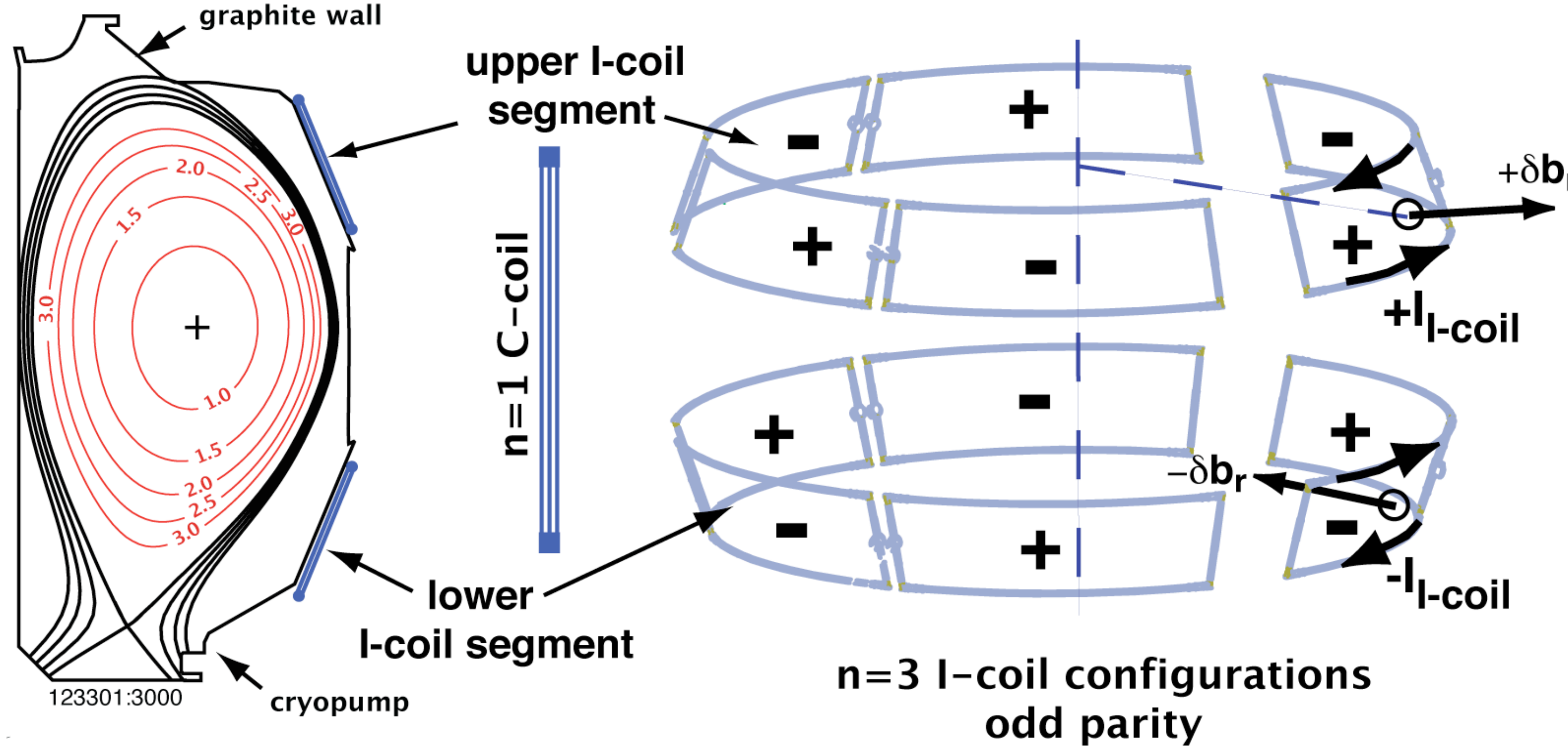
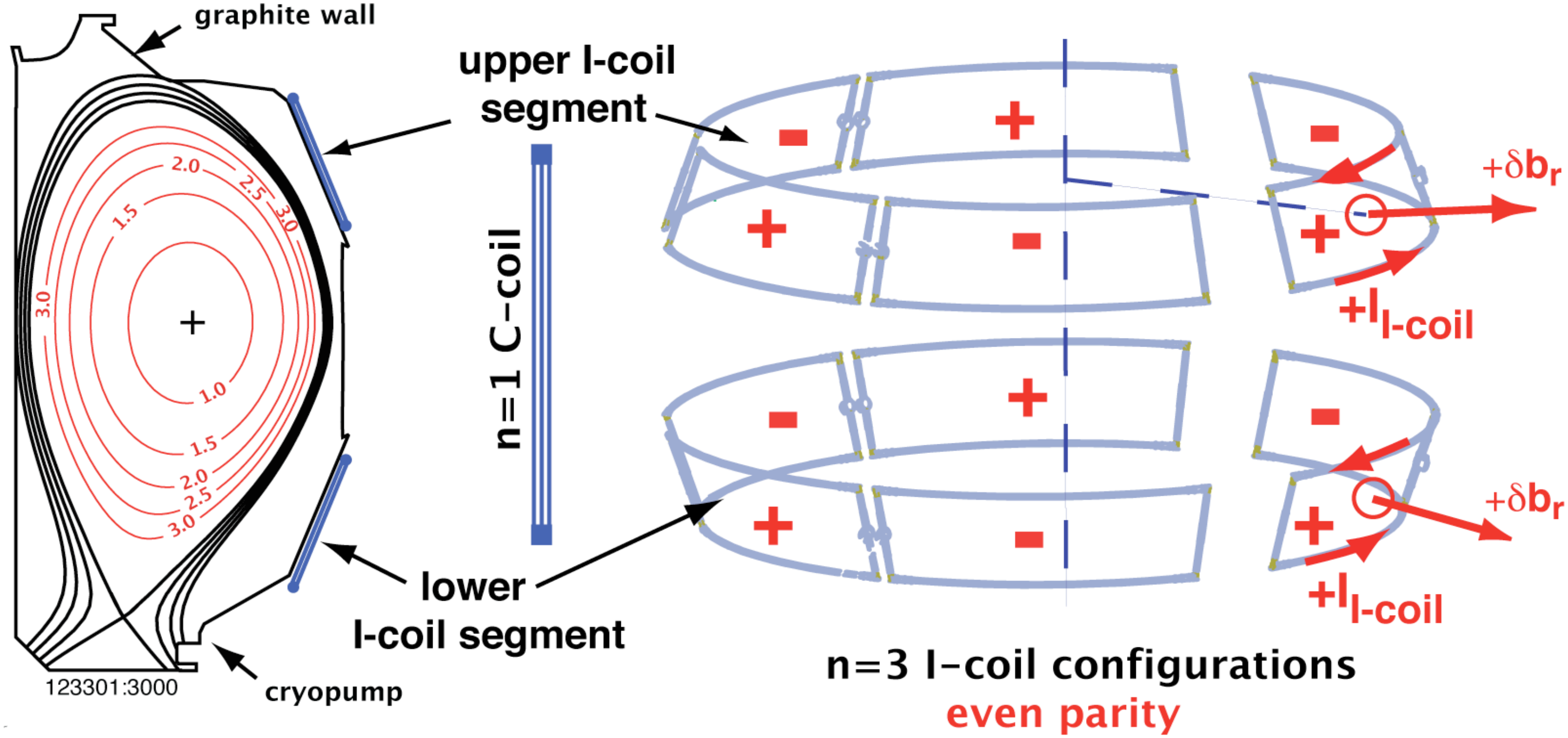
I-coil n = 3 odd parity

low stochasticity for q95~3.5



- Parity (even/**odd**) controls magnetic spectrum
- Weak edge resonant perturbation spectrum (**δB_{nm}^{res} ~ 0.8 G**)
- Change in ELM character from Type I to smaller size (Type II or III?)

I-coil n = 3 even parity
high stochasticity for q95~3.5



- Parity (**even**/odd) controls magnetic spectrum
- Strong resonant perturbation spectrum (**δB_{nm}^{res} ~ 6.0 G**)
- Full ELM suppression

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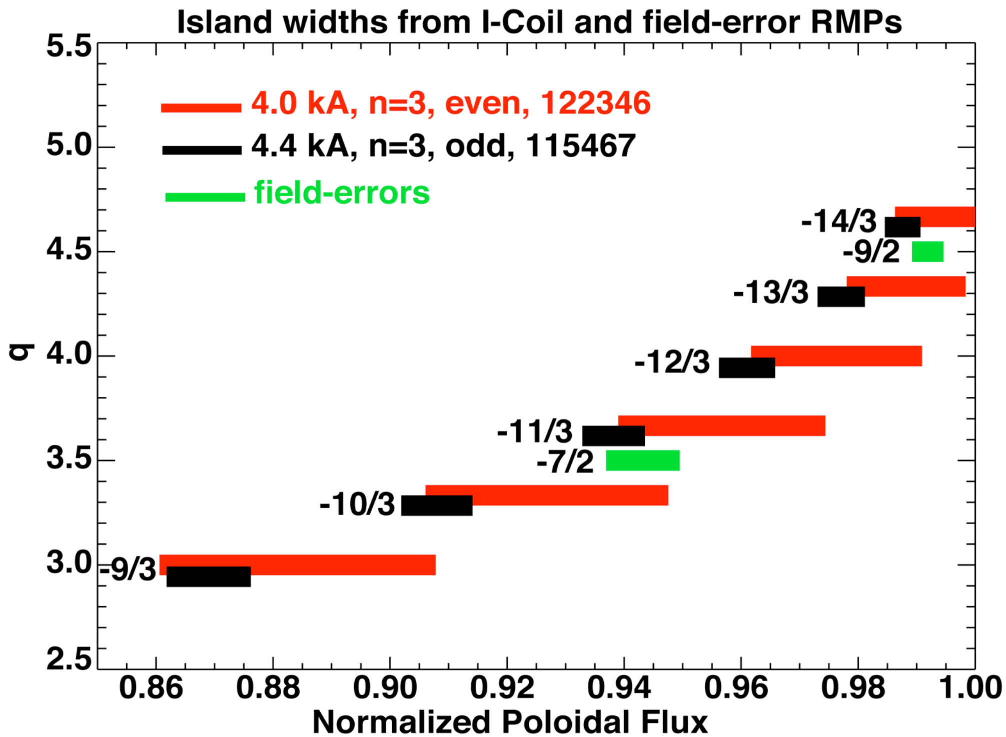
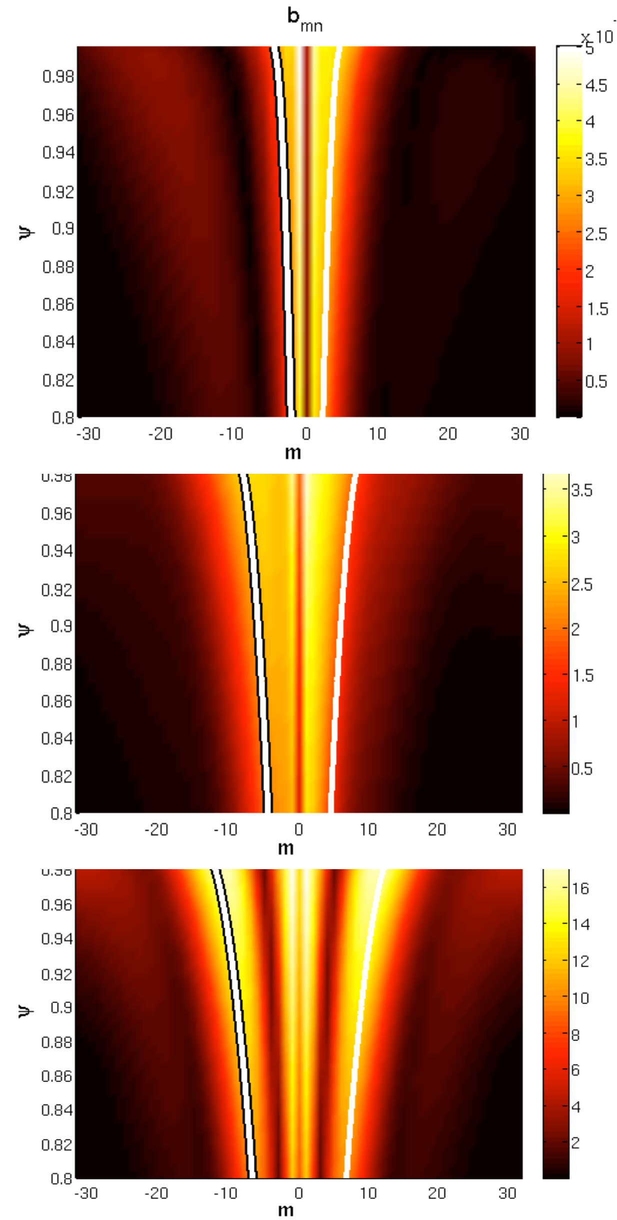
TRIP3D superimposes external coil fields (Biot-Savart) with Grad-Shafranov axisymmetric equilibrium (EFIT)





n=1

n=2

n=3

- Resonant harmonics of δb_{mn} determine the widths of the islands that form in the **vacuum approximation**

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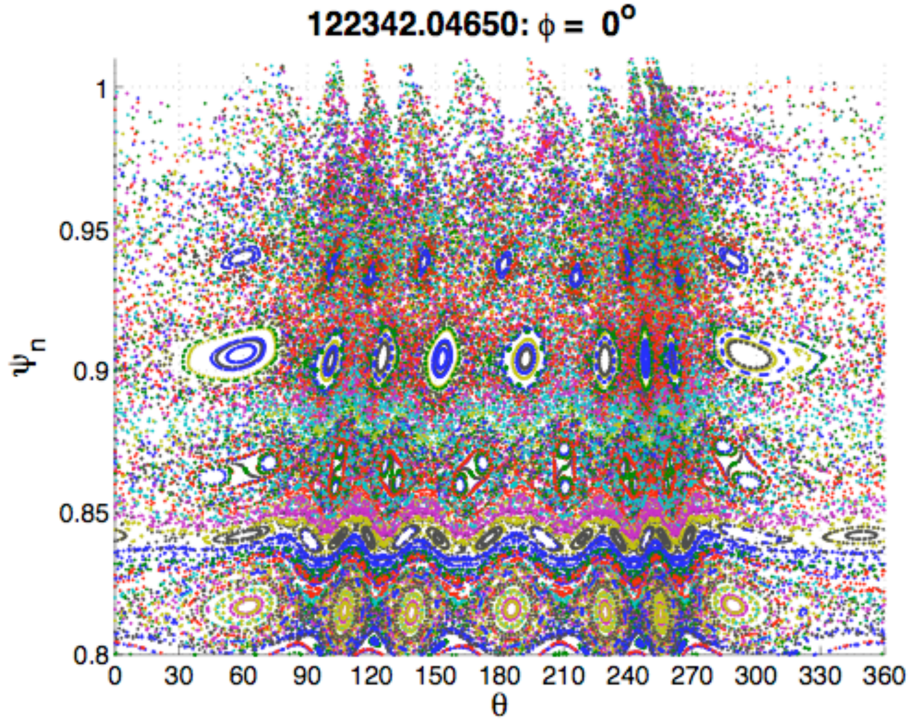
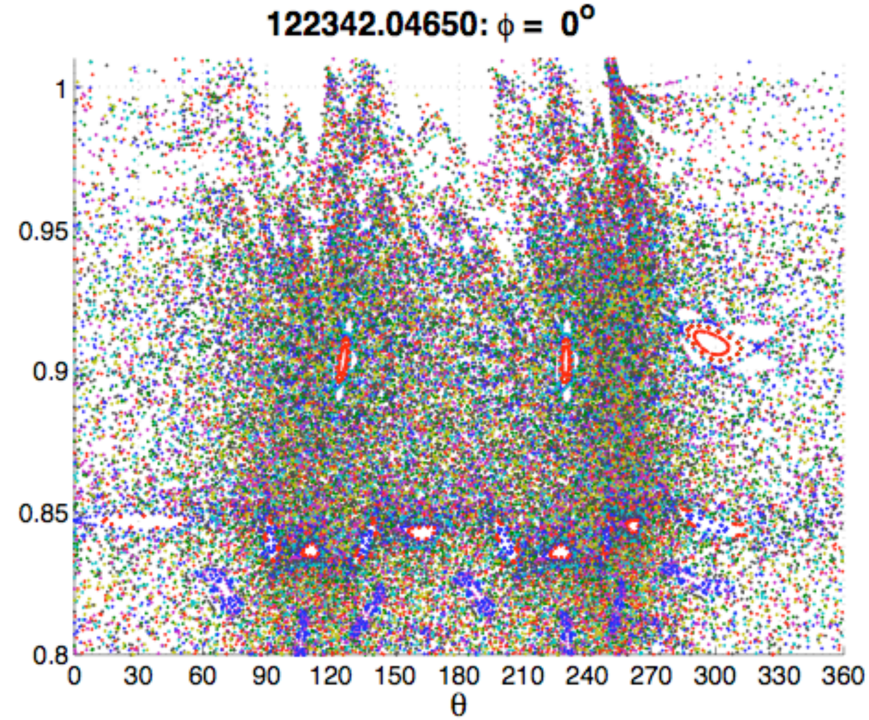
Vaccuum approximation generates strong stochasticity



I-coil only: slow diffusion



I-coil + C-coil + field error: rapid loss

- Vacuum approximation often believed to be sufficient for 0^{th} order magnetic topology in L-mode plasmas: TEXT, TEXTOR, Tore-Supra, stellarators
- Considering amplification and shielding, can this really be true in H-mode?

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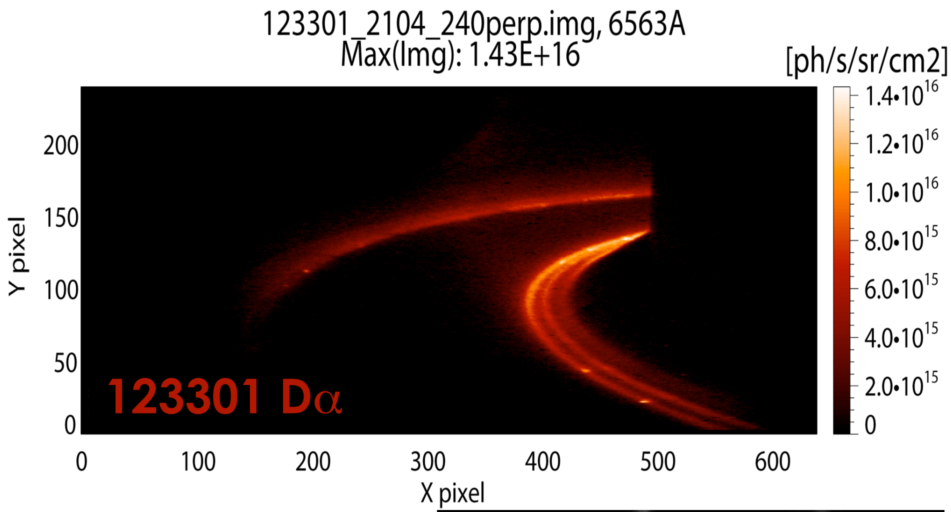
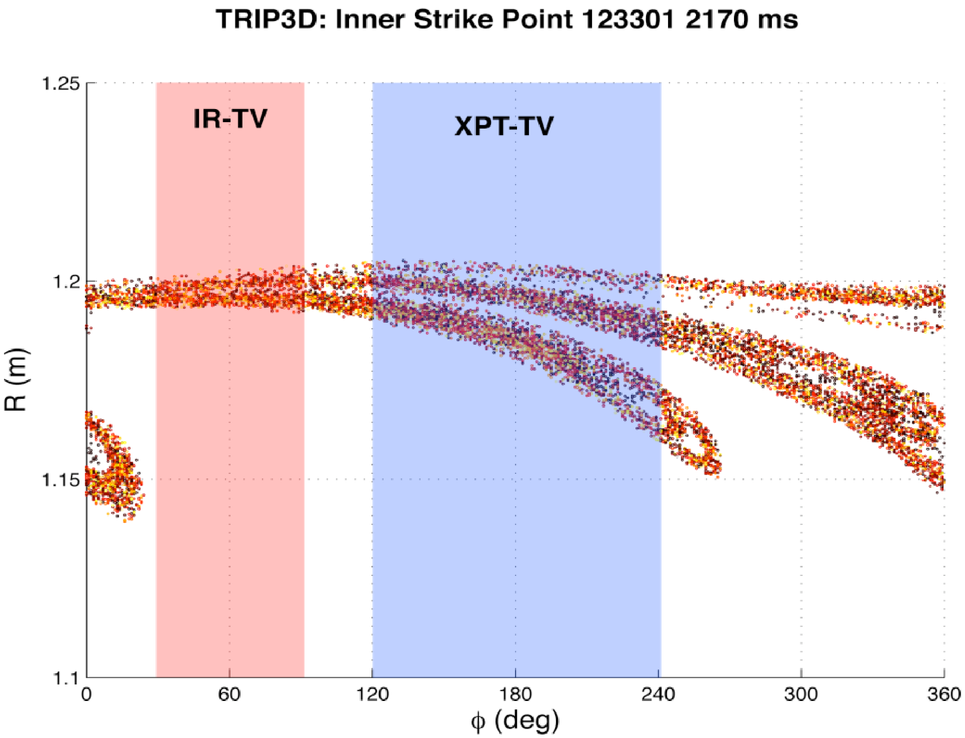
Strike point structure can be used to probe upstream magnetic field topology

- 5cm width qualitatively matches TRIP3D field line tracing

- Width scales as ~ $(\delta b/B)_{res}$





- But, heat flux striations were not observed at 60° IR-TV location

- Inspired transport simulations and an additional IR cameras

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E3D Braginskii fluid transport code developed for stochastic 3D fields

Assumes anomalous ⊥ transport in static background field

- **Energy equation:** (only energy equations used in this study)

$$\frac{3}{2} n(\partial_t T + u_{||} \nabla_{||} T) = \nabla_{||} \kappa_{||} \nabla_{||} T + \nabla_{\perp} \kappa_{\perp} \nabla_{\perp} T + Q_{ei}$$

- **Parallel momentum**

$$mn\left(\partial_t u_{||} + \nabla_{||} \frac{1}{2} u_{||}^2\right) = qnE_{||} - \nabla_{||} p - \nabla \cdot \Pi_{||}$$

- **Quasineutral continuity**

$$\partial_t n + \nabla_{||} n u_{||} = \nabla_{\perp} D_{\perp} \nabla_{\perp} n$$

- **Nonlinear sheath BC's** (R. Chodura)

$$Q = \beta n T C_s \cos\theta_w \sim nT^{3/2} \qquad \Gamma = nC_s \cos\theta_w \sim nT^{1/2}$$

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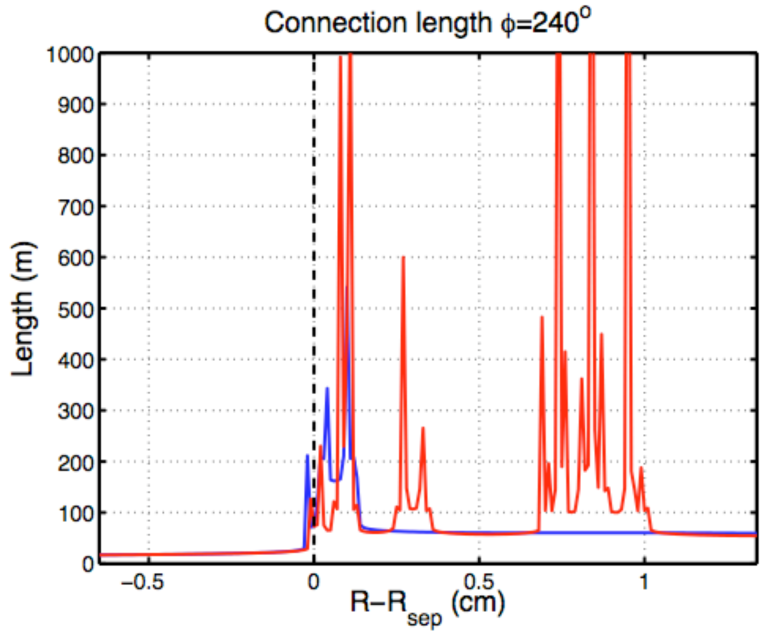
E3D uses *Monte-Carlo* fluid elements & field aligned grid to accurately solve anisotropic fluid equations

- Heat transport highly anisotropic $\kappa_{\parallel}/\kappa_{\perp} = \chi_{\parallel}/\chi_{\perp} \sim 10^{8} - 10^{10}$
- Stochasticity can generate small scales $\ell_{\perp}/\ell_{\parallel} \sim \sqrt{\chi_{\perp}/\chi_{\parallel}} \sim 10^{-4} - 10^{-5}$
- Fractal connection length structure
- **Solution:** Monte-Carlo technique
  - Let *T(x,t)* = p.d.f. for heat packets
  - Evolve using Brownian motion



- Use **local magnetic coordinate systems** to globally cover space
  - Exchange integration for mapping between local subdomains.

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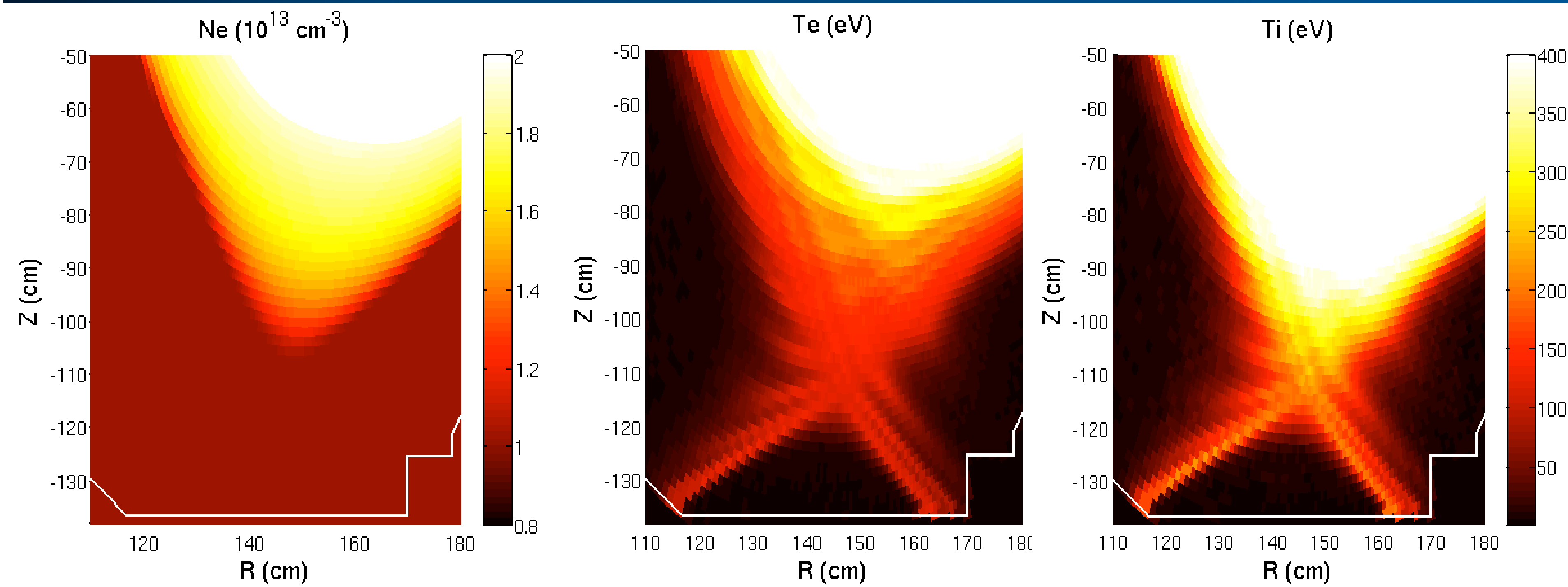
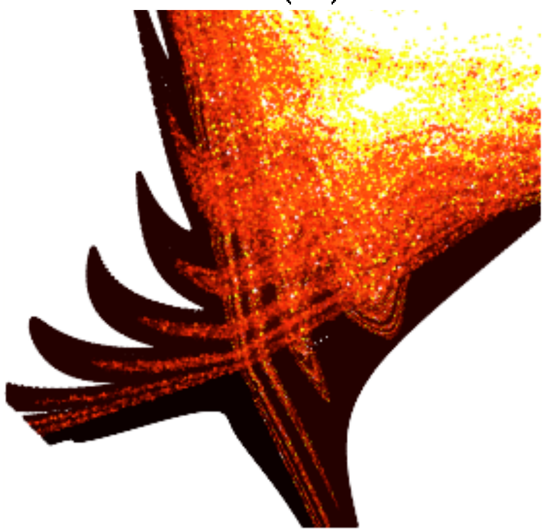
E3D simulations show large effect on Te and Ti due to change in connection length structure



- n_e assumed to be a flux function
- Constant D = 1 m^2/s, $\chi_e = \chi_i$ =1.5 m^2/s
- Connection length develops fractal structure = “**Smale horseshoe**”
- Determines structure of heat flux



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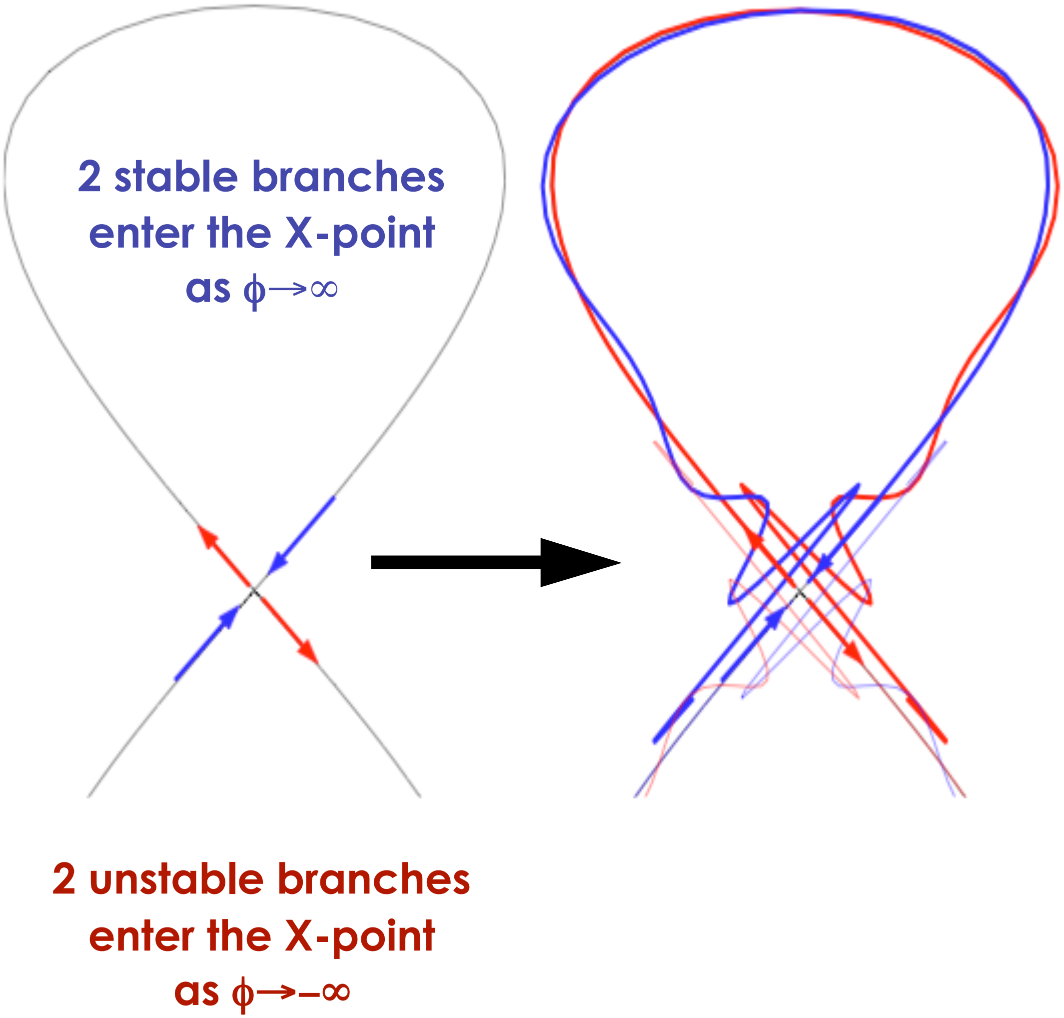
Energy flow to strike points determined by constants of the field line motion

- The X-point is structurally stable -- survives RMP
- The separatrix splits into 4 branches that asymptotically enter the X-point
- The structure is called a **“homoclinic tangle”**
- Existence of both manifolds implies that **axisymmetry is fundamentally broken** along separatrix

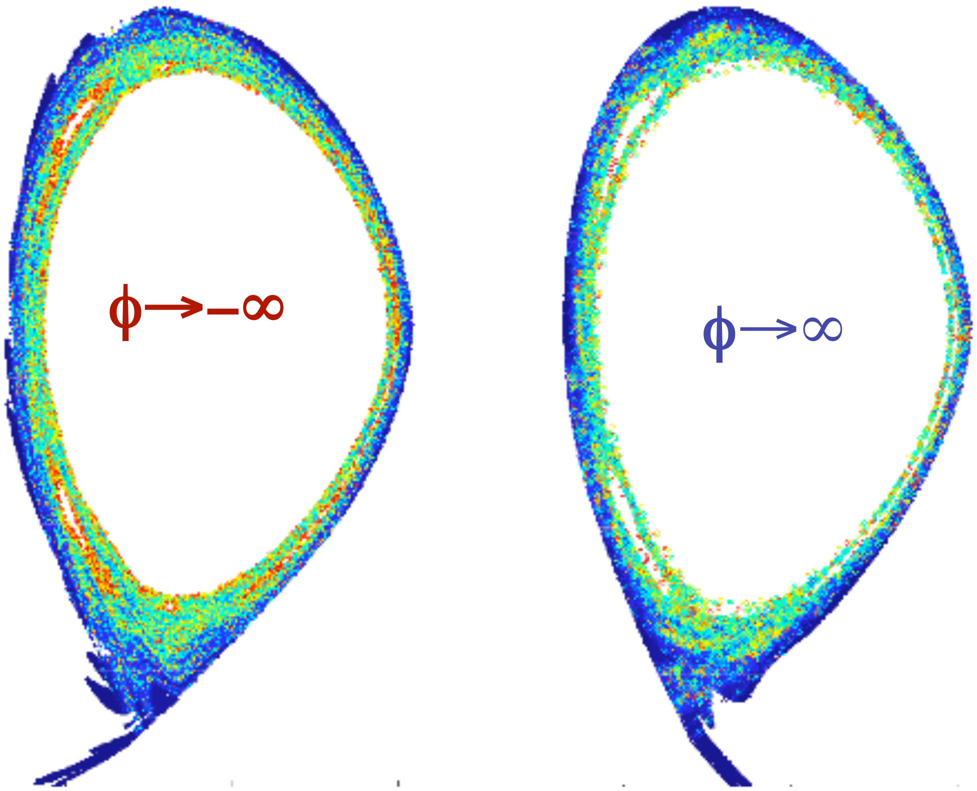


Particles can only escape an invariant manifold through perpendicular transport

- Tangle border can be identified by launching field lines
- **All of these field lines escape!** < 200 turns
- Field lines are trapped by the tangle border because it is an invariant manifold

$$\mathbf{B} \cdot \nabla \psi_{\pm} = 0$$

- Field lines can only escape along the tangle



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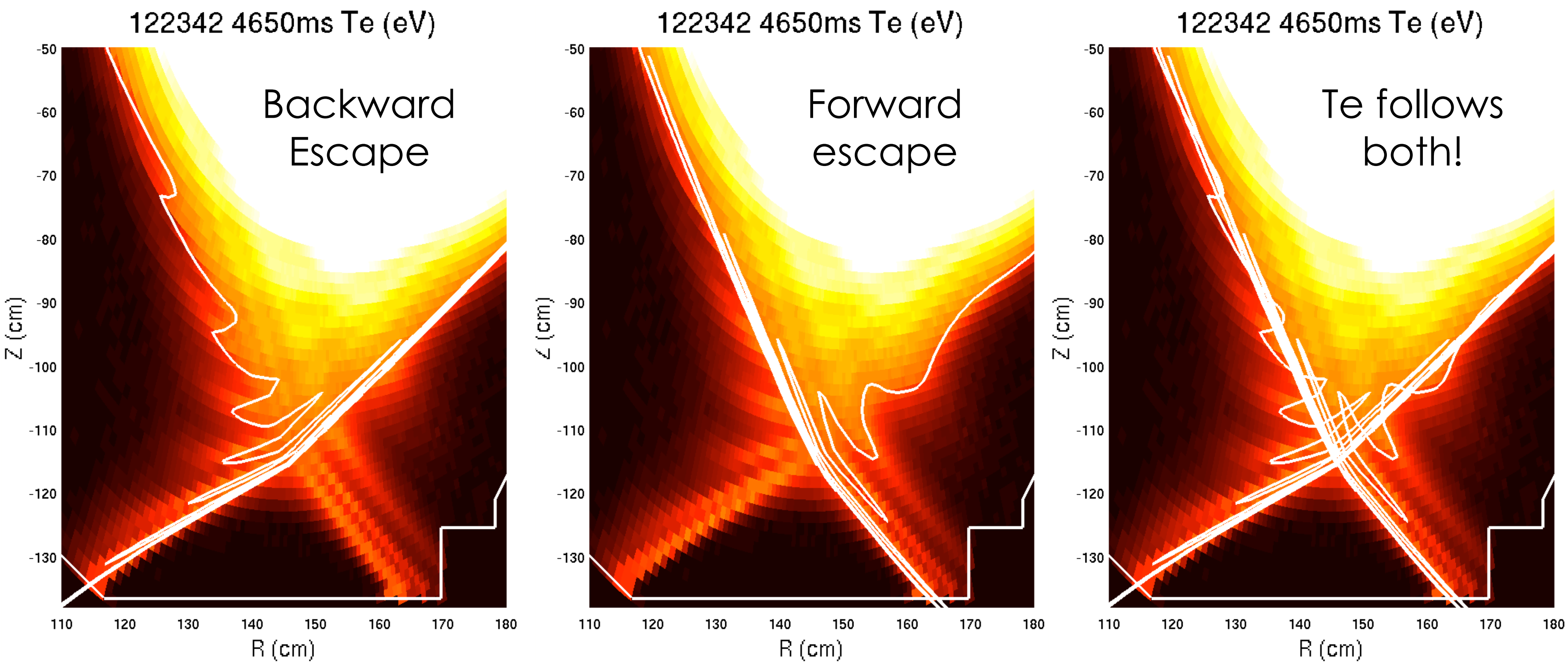
E3D simulations show that the 2 *upper* invariant manifolds efficiently guide heat flux to the target



- Tangle border defines SOL region: $L_K < L_c$ and strike point structure
- Note that private flux region still exists due to short connection length

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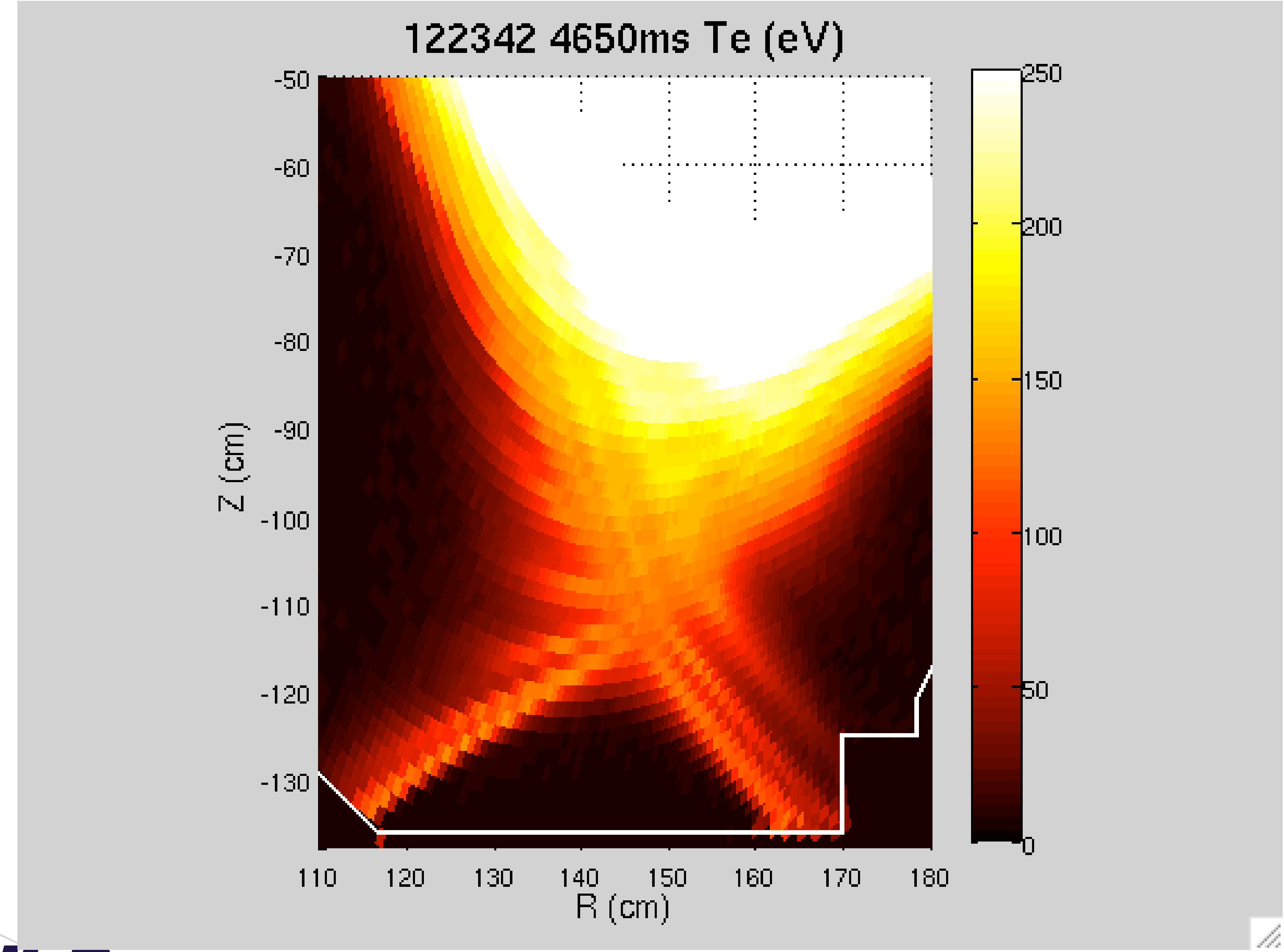
The dynamics of tangle transport can be observed by traveling around the torus



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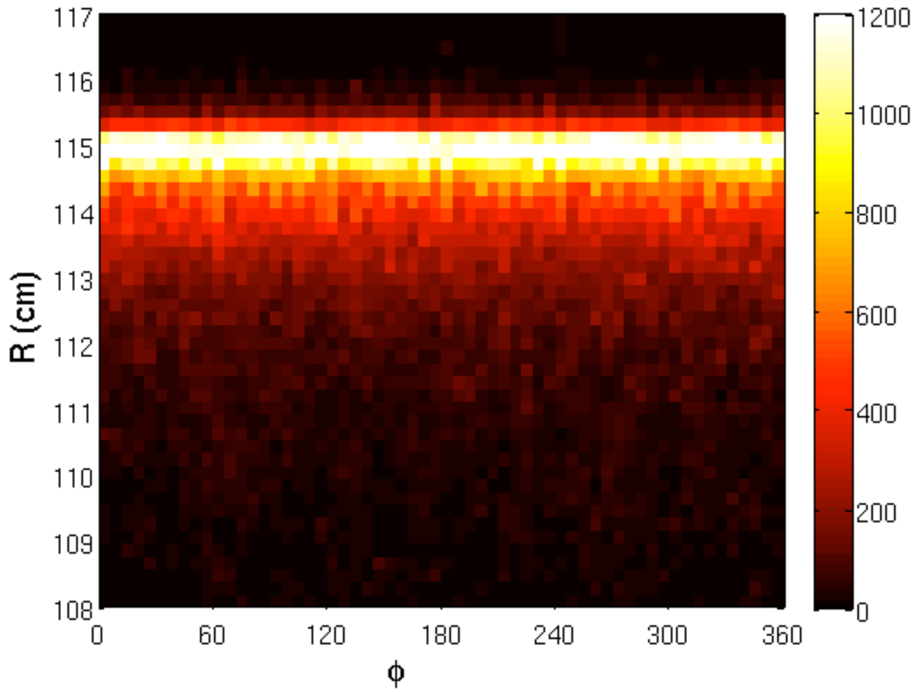
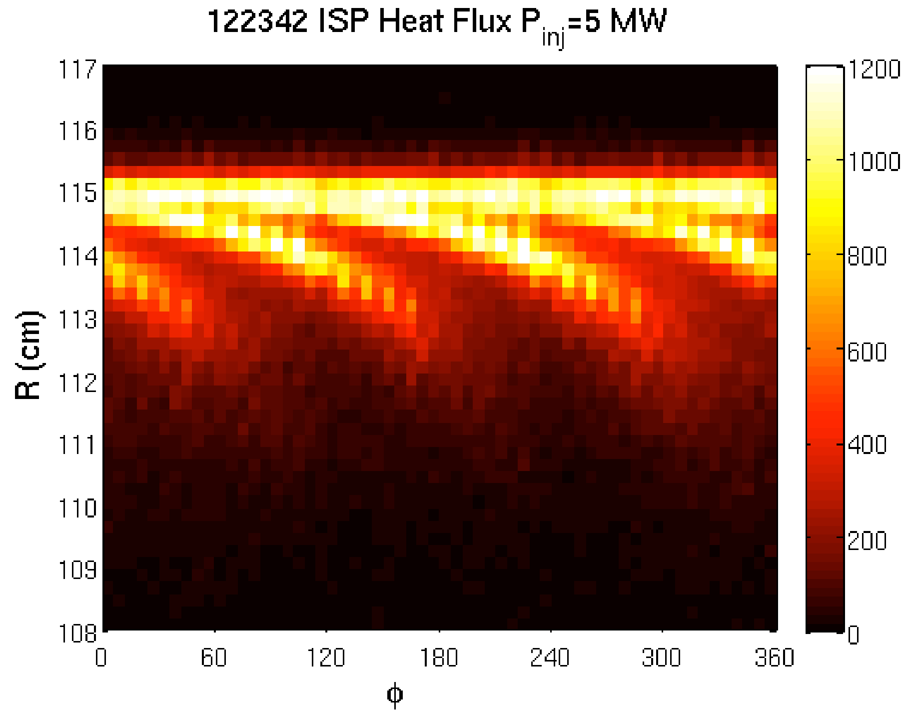
Inner strike-point heat flux profiles predicted to develop non-axisymmetric structure





- **E3D calculations motivated the 2006-2007 experimental campaign**
  - High resolution Langmuir probe array sweeps to measure fluxes
  - New IR camera from TEXTOR at second toroidal location
  - Wanted to verify width and phase of structure & variation with edge q_{95}

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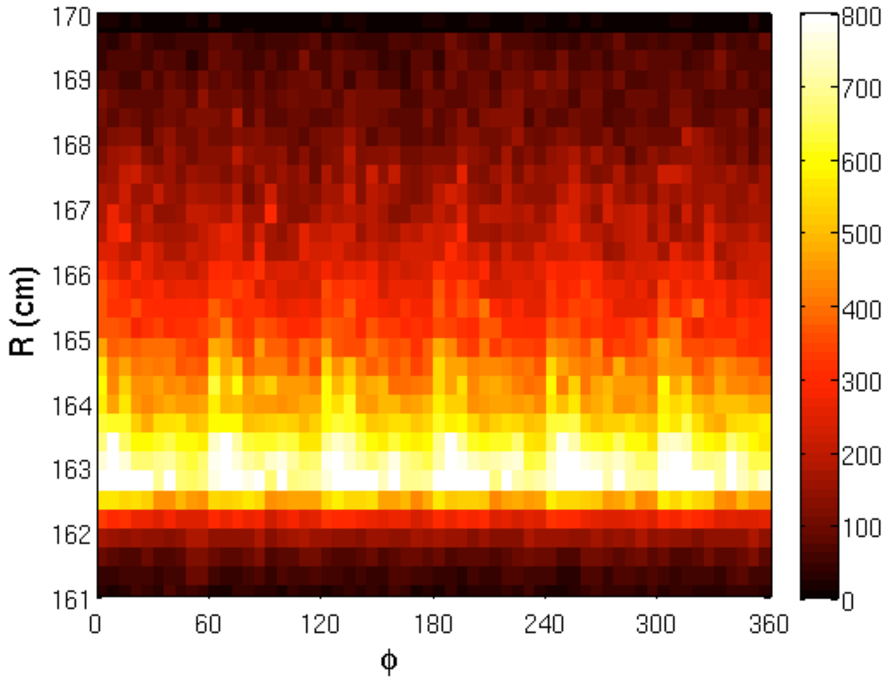
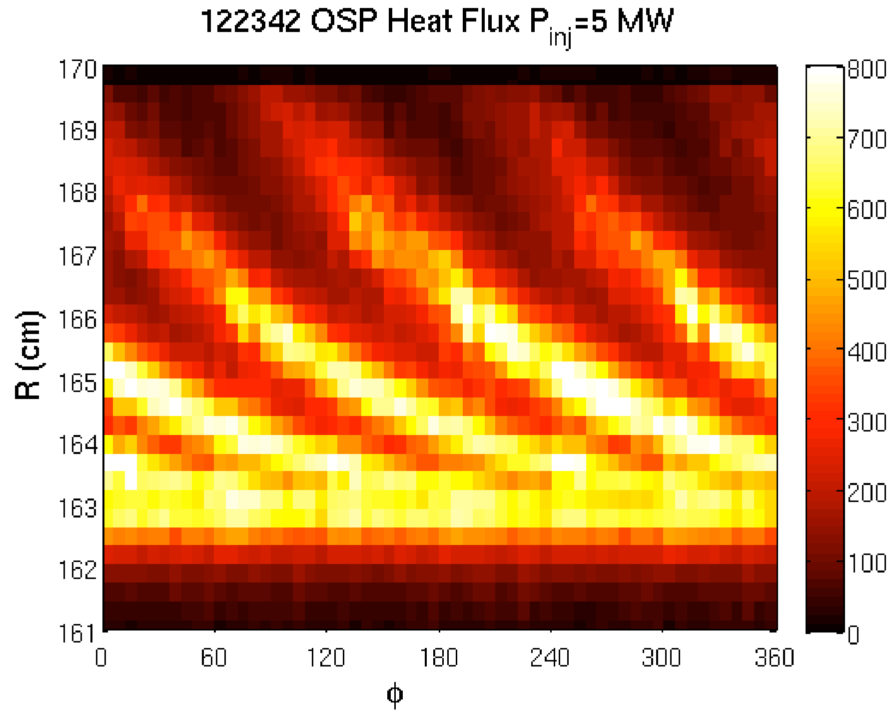
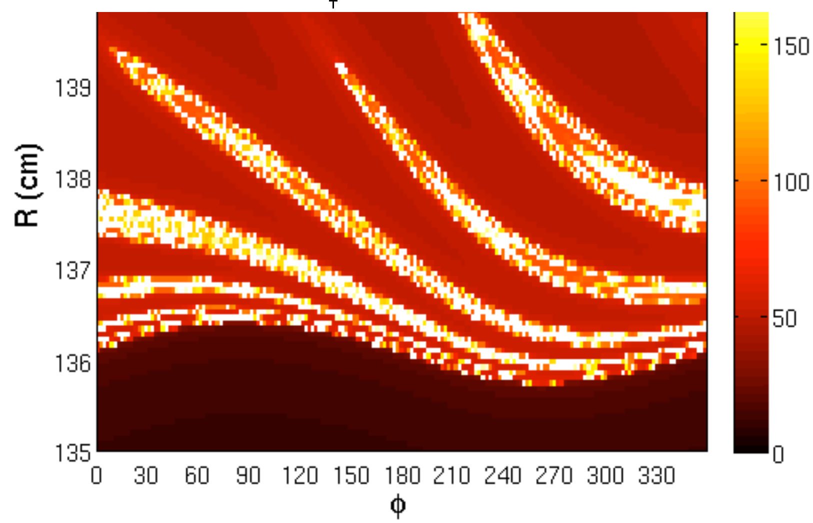
Outer strike-point has even more pronounced non-axisymmetric structure due to flux expansion





- Heat flux delivered to regions of long connection length

- **Measurement of heat flux profile should allow verification of magnetic field connection length distribution**



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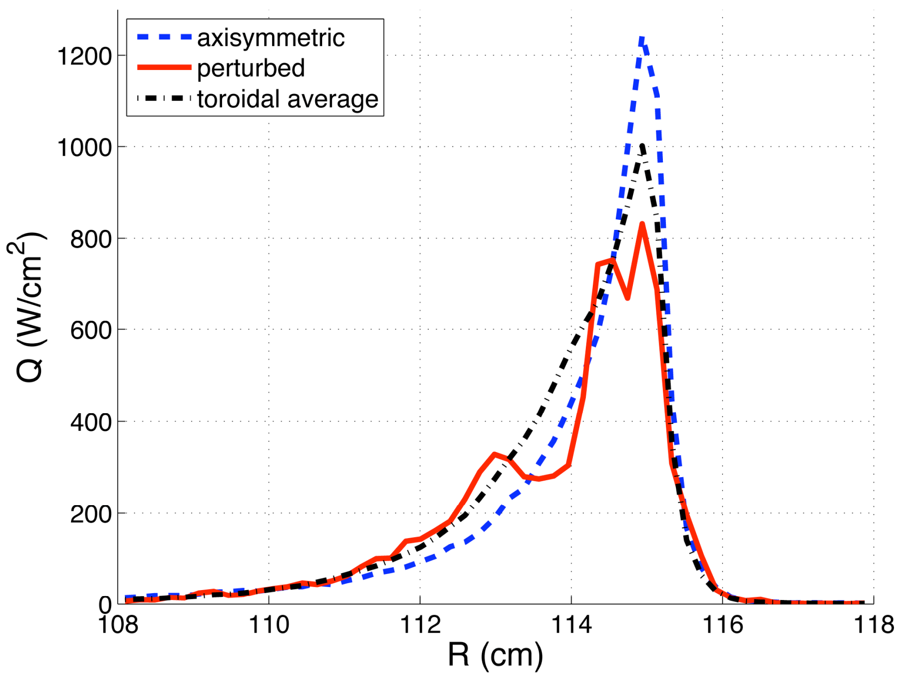
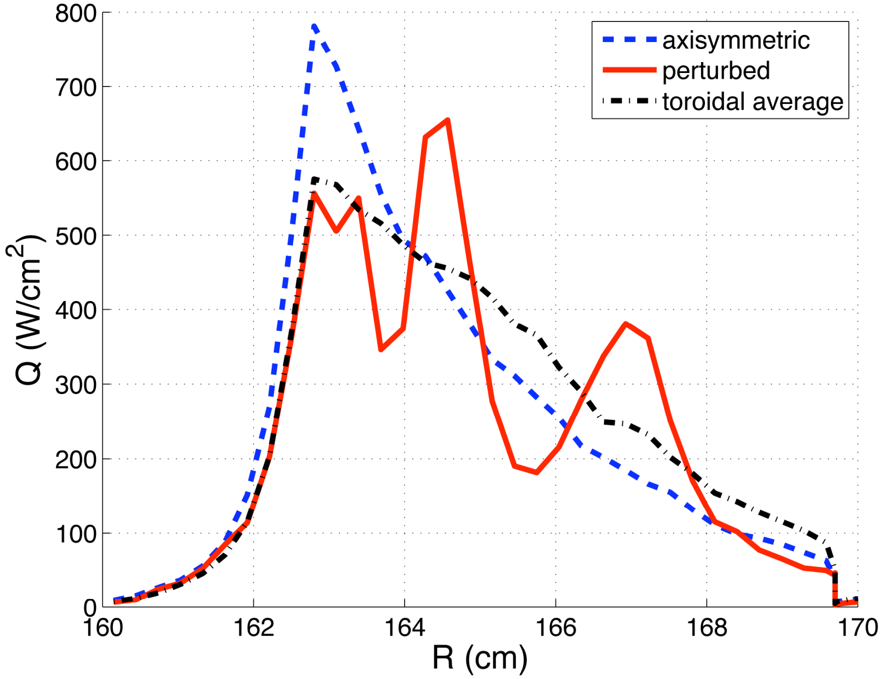
Detailed heat flux calculated at fixed toroidal location





- Field lines efficiently loaded with heat upstream
- Effective area for flux deposition predicted to increase by 50%
  - Direct field line contact area increased, but
  - Perpendicular decay length decreased due to higher temperature
  - Optimization requires accurate calculation of Te and Ti at target
- Rotating tearing activity should produce equivalent toroidally averaged profile

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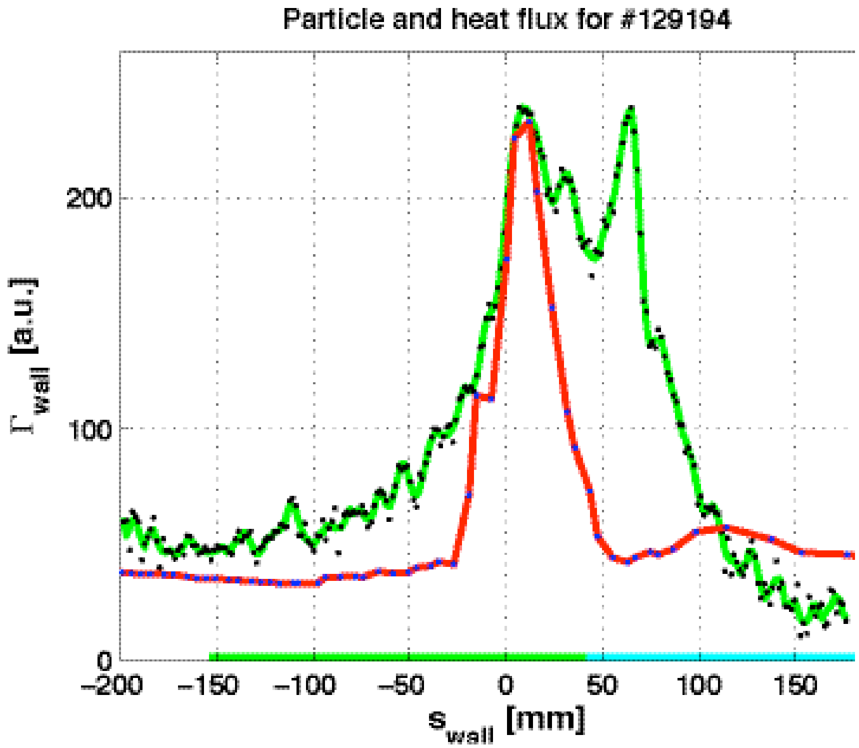
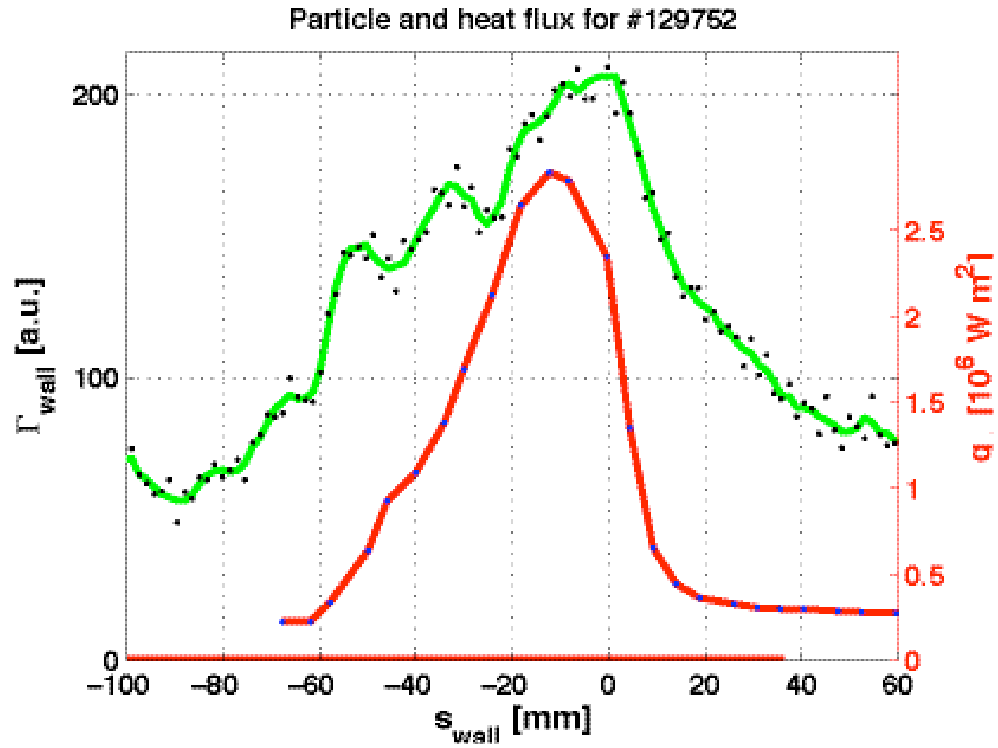
However, measured heat & particle fluxes are quite different!





129194 inner strike point 3.0-3.2 sec **129752 outer strike point 3.2-3.6 sec**

- Heat flux appears to be axisymmetric?
  - **Neither IR camera shows significant strike point splitting**
- TEXTOR IR camera placed at 165°
- DiMES camera (filtered Dα) at 157°

(M Jakubowski & O Schmitz, FZ-Julich)

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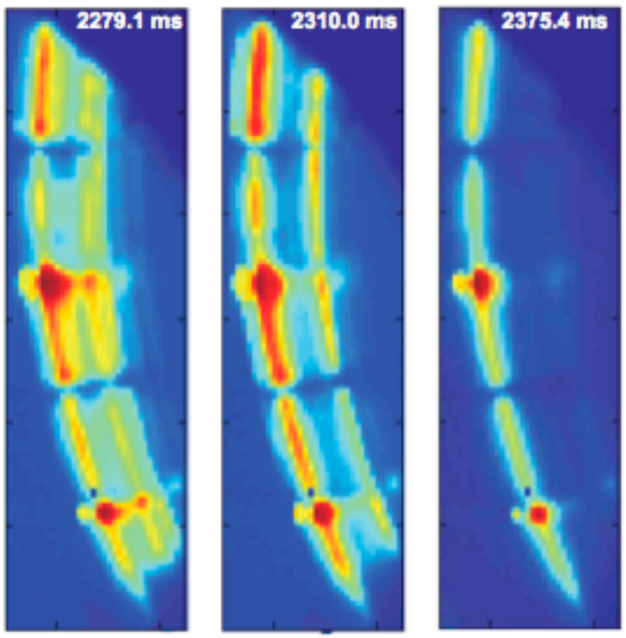
The outer lobes are thermally isolated from the interior except during radial transport events

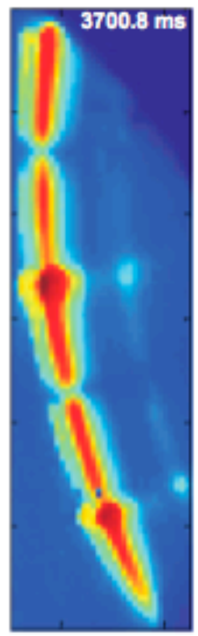
- **ISP splitting in IR measurements #129194**

ELM & RMP(no ELM suppression)



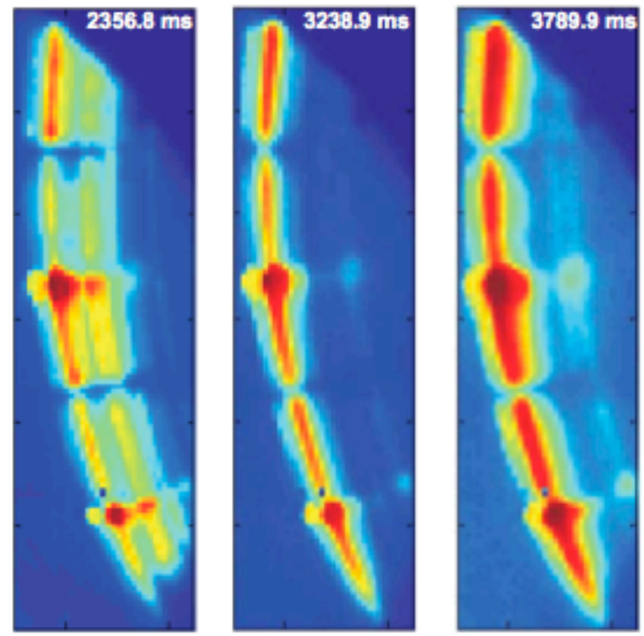
ELM heat expell fills lobes, i.e. fillamentary ELM structure is governed by RMP helicity

ELM supression



very tiny imprint of outer lobe in heat flux

right after pellet with RMP



pellet cause sufficient convective heat expell to map magnetic footprint

⇨ **increased radial heat flux is needed to detect SP splitting**

(M Jakubowski & O Schmitz, FZ-Julich)

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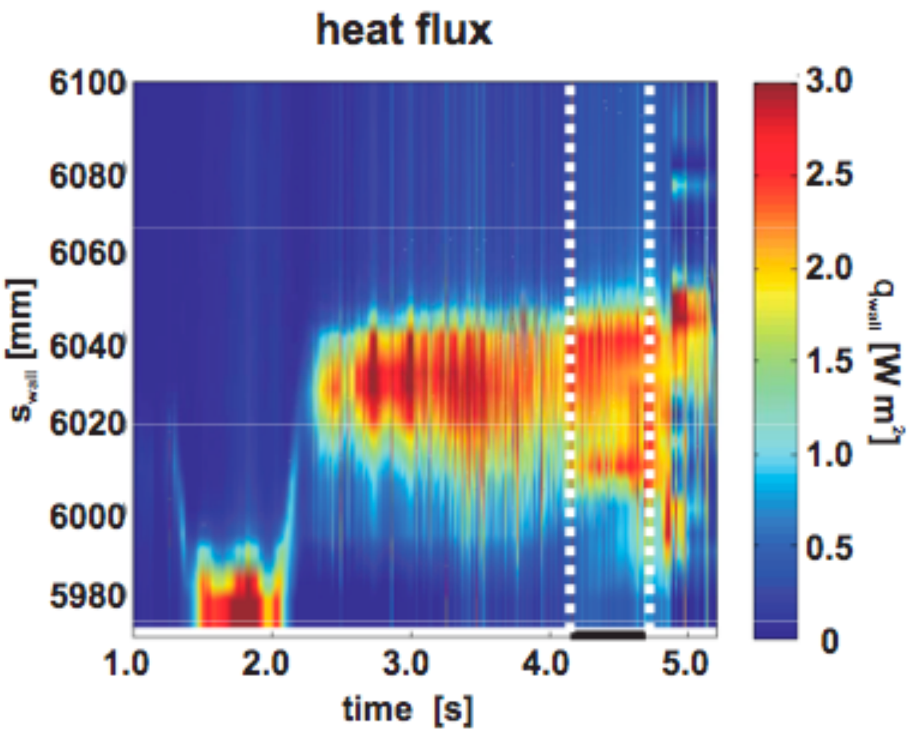
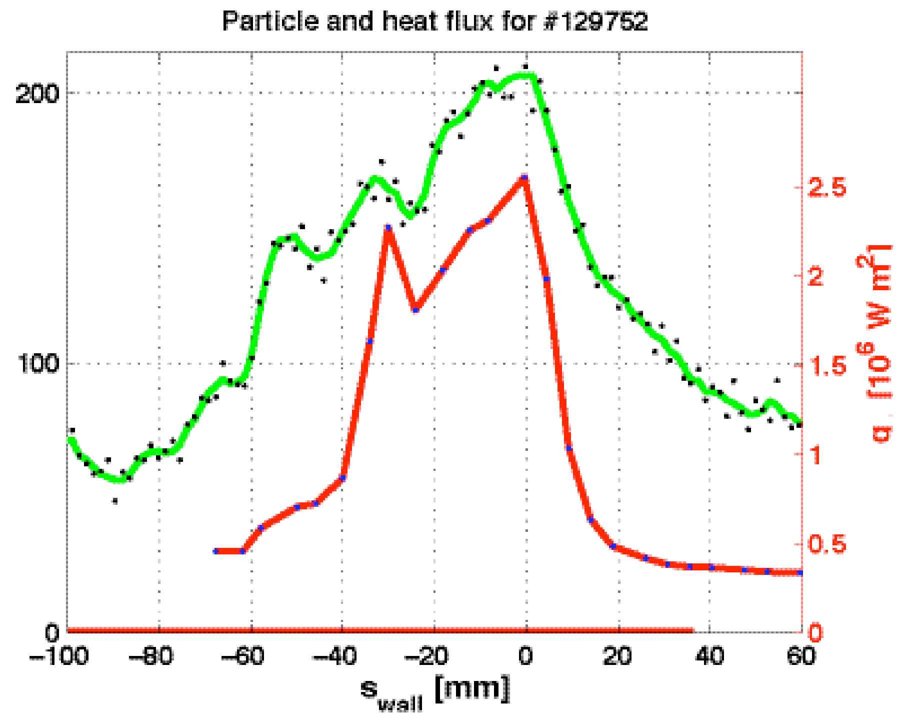
When a large n=1 mode appears heat flux splitting is observed!



129752 outer strike point



Fluxes averaged over 4.1-4.5 sec

- After 4 sec “quasi-stationary locked mode” appears
- Produces large n=1 signal on magnetic sensors
- Eventually terminates discharge (plasma strikes wall at 4.6 sec)
- Different than particle flux, apparently still determined by I-coil RMP

(M Jakubowski & O Schmitz, FZ-Julich)

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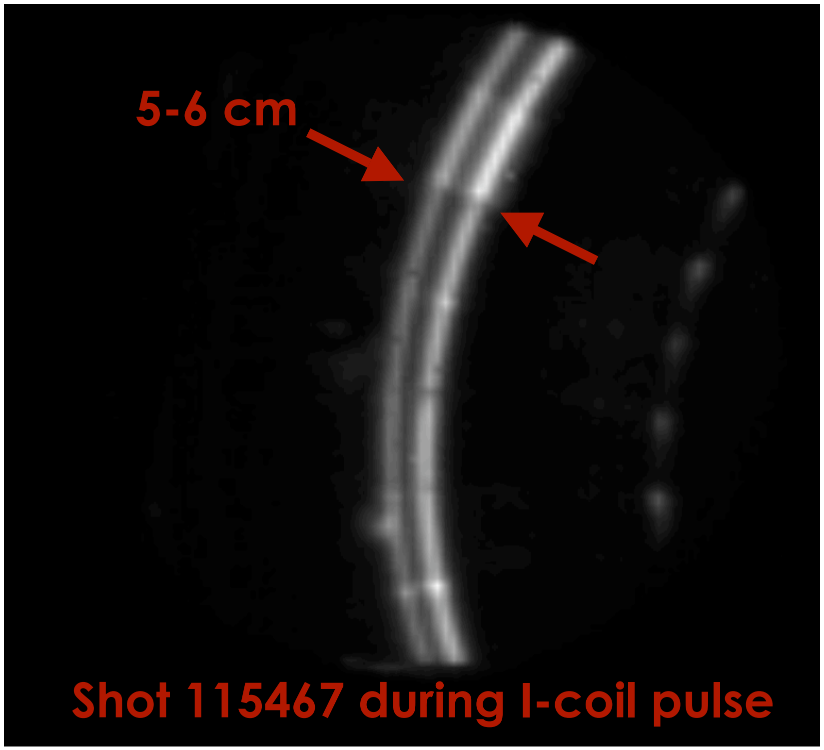
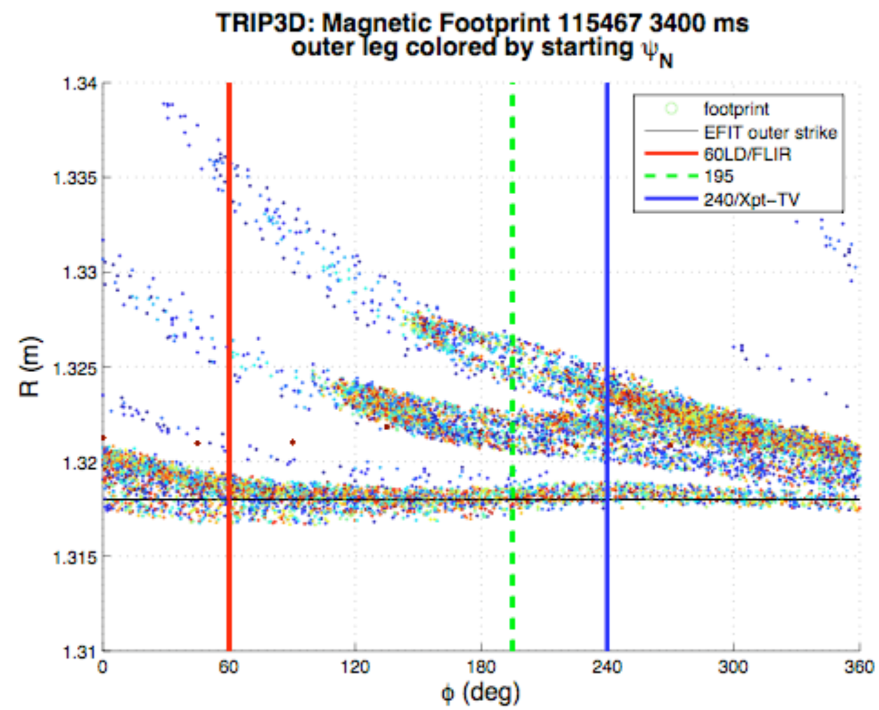
Original case may actually indicate field error amplification after core rotation slowed to ~ zero





- **Odd parity RMP ~5X weaker than even parity**
- **5-6 cm measured width, but only 2 cm predicted?**
  - Only has 2 striations, not 3
- **Evidence for much larger field**

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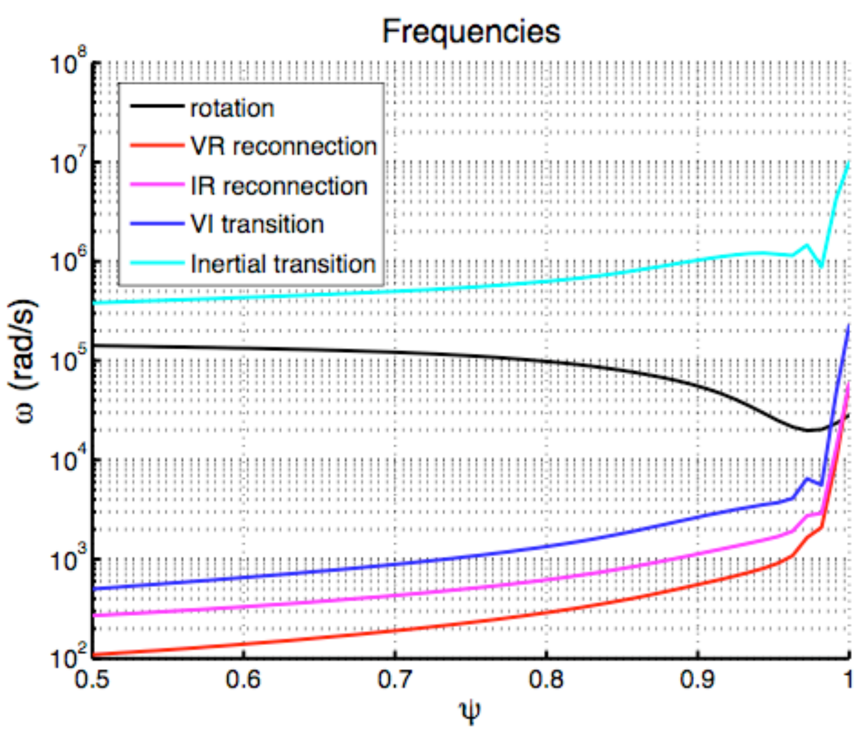
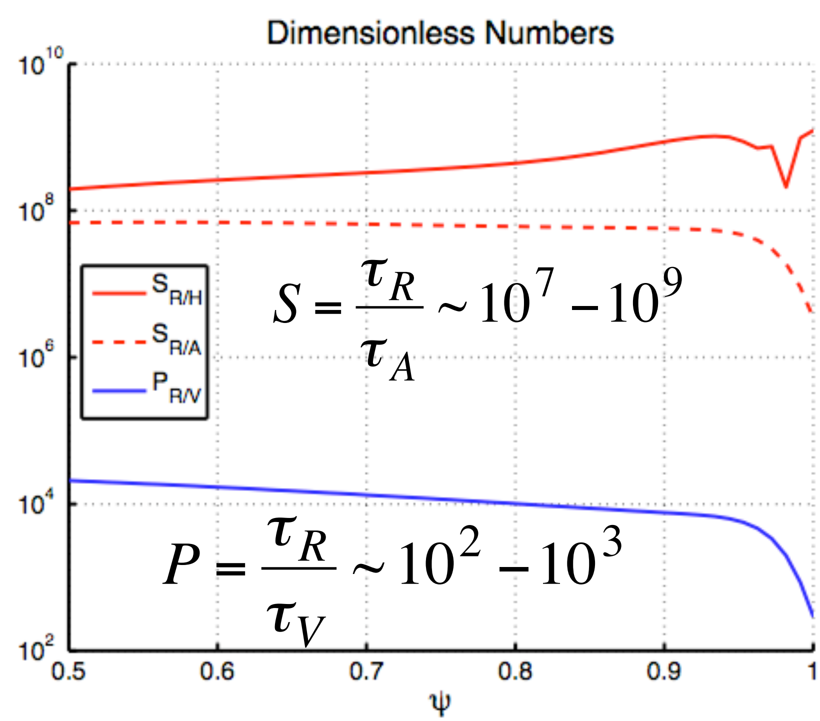
Rotation can screen resonant fields from the plasma

- To open an island, the perturbation must excite a stable tearing mode
  - **Reconnection amplitude determined by tearing dispersion relation**

$$\Delta'_{layer} = \Delta'_{tear} + \Delta_{ext}\frac{b_{vac}}{b_{tear}} \quad \rightarrow \quad \frac{b_{tear}}{b_{vac}} = \frac{\Delta_{free}}{-\Delta'_{tear} + \Delta_{layer}} \sim \frac{1}{1-(-i\omega\tau_{layer})^{\alpha}}$$

- Resonant modes must vanish at rational surface unless $\omega < 1/\tau_{layer}$
  - **But DIII-D edge rotation speeds are 10-100 krad/s > 1/ τ_{layer} ~ 0.1-10 krad/s**





2 state model: ideal interior & vacuum exterior

- Captures entire phenomenology with a single parameter: the location of the ideal ➔ stochastic transition

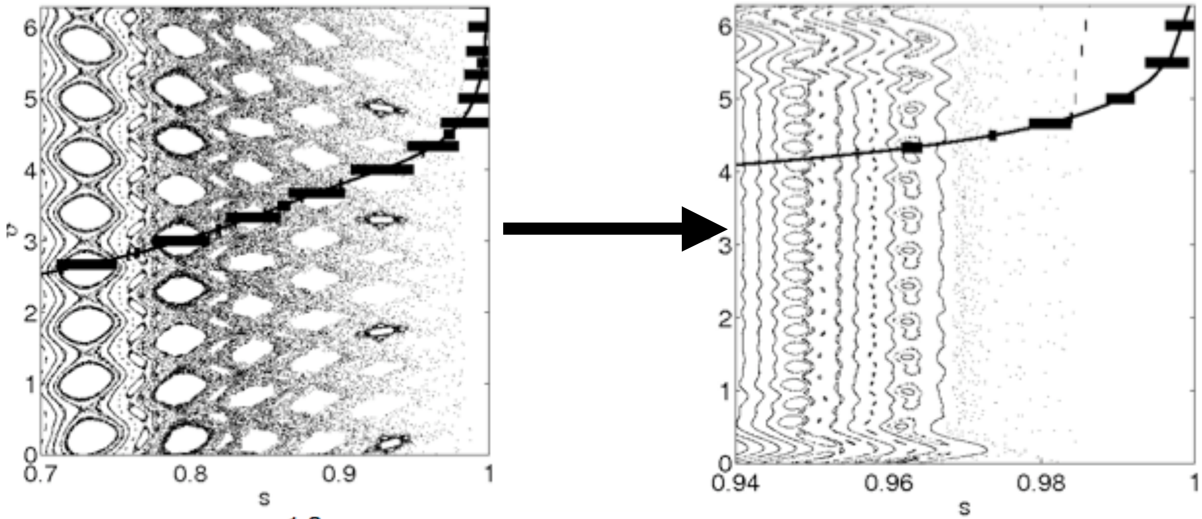
- **Kinetic model** for collision-less tearing only allows 1-2 % stochastic region

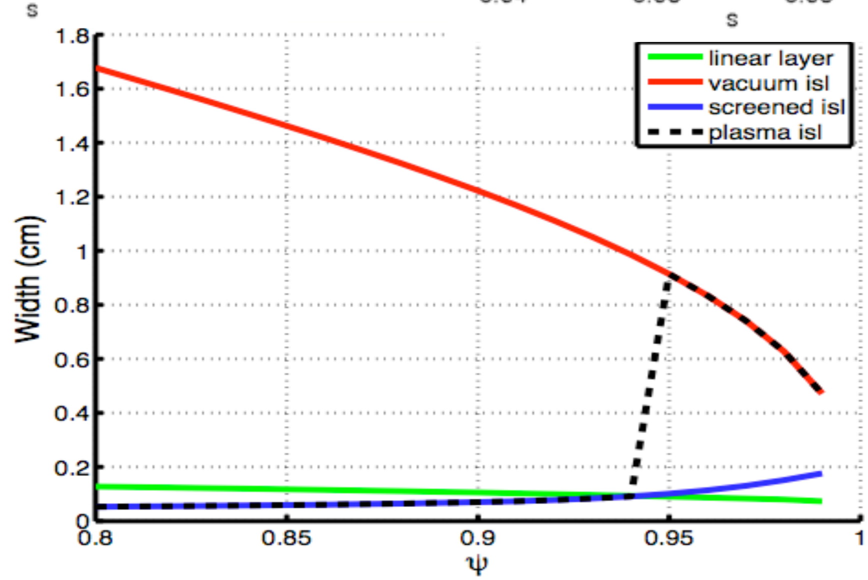
- **Diamagnetic frequency offset required** to interpret results: electrons are slowed but ions are accelerated

- **Single fluid model** may allow 2- 4% stochastic region Visco-Resistive regime

$$\delta_{layer} \sim S^{-1/3} P^{1/6} r \sim 1mm$$

$$\tau_{layer} \sim S^{-1/3} P^{1/6} \tau_R \sim 10 - 100ms$$





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Summary

- **E3D calculations show that the strike point heat flux profile can be used as a sensitive probe of the magnetic field line topology**
  - Constants of the field line motion direct energy outflow and determine connection length structure on the target
  - Target heat flux becomes non-axisymmetric & spreads over wider area
  - Fluid simulations predict large impact on energy conservation

- **N=3 experimental results pose paradoxes!**
  - Particle transport definitely increased, becomes non-axisymmetric
  - Heat transport appears relatively unaffected, remains axisymmetric
  - Structure is thermally isolated from interior until radial transport events such as ELMs or pellets are active

- **Plasma response is definitely implicated in examples of N=1 splitting**
  - Requires amplification of internal error field

- **Paradoxes can be resolved by limitation of thermal transport**
  - Shielding of resonant fields by plasma rotation, etc.