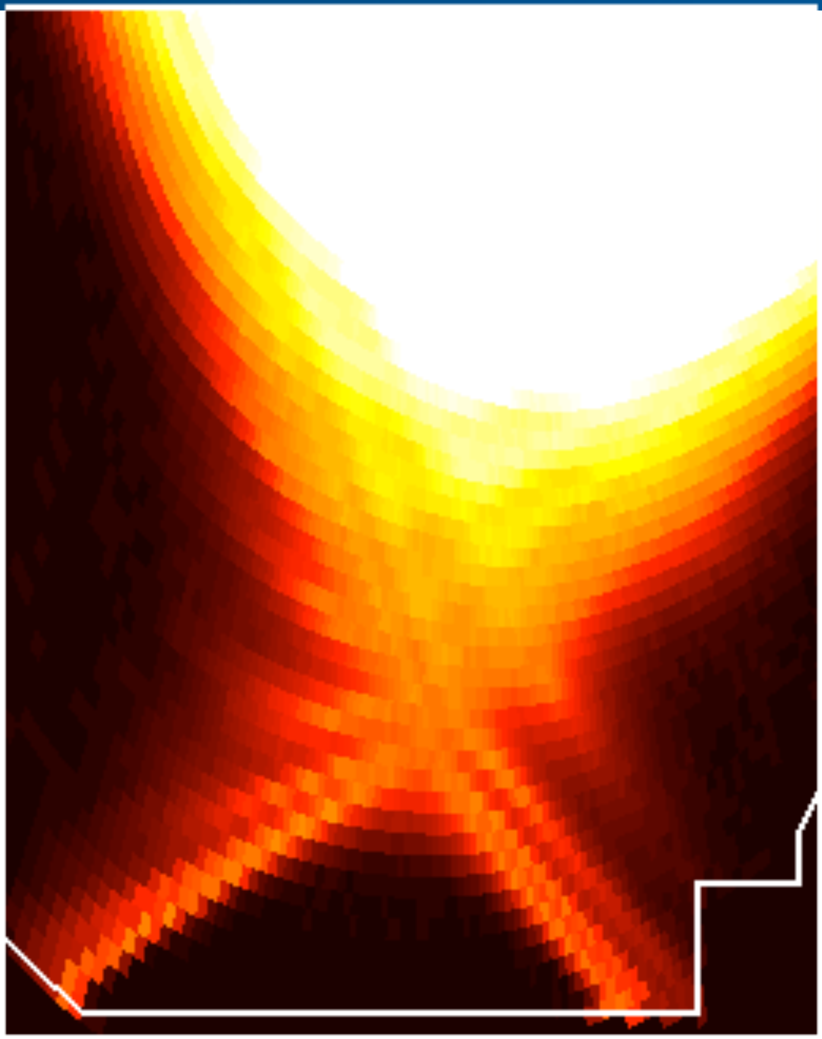
Calculation of the Thermal Footprint of Resonant Magnetic Perturbations in Poloidally-Diverted Tokamaks



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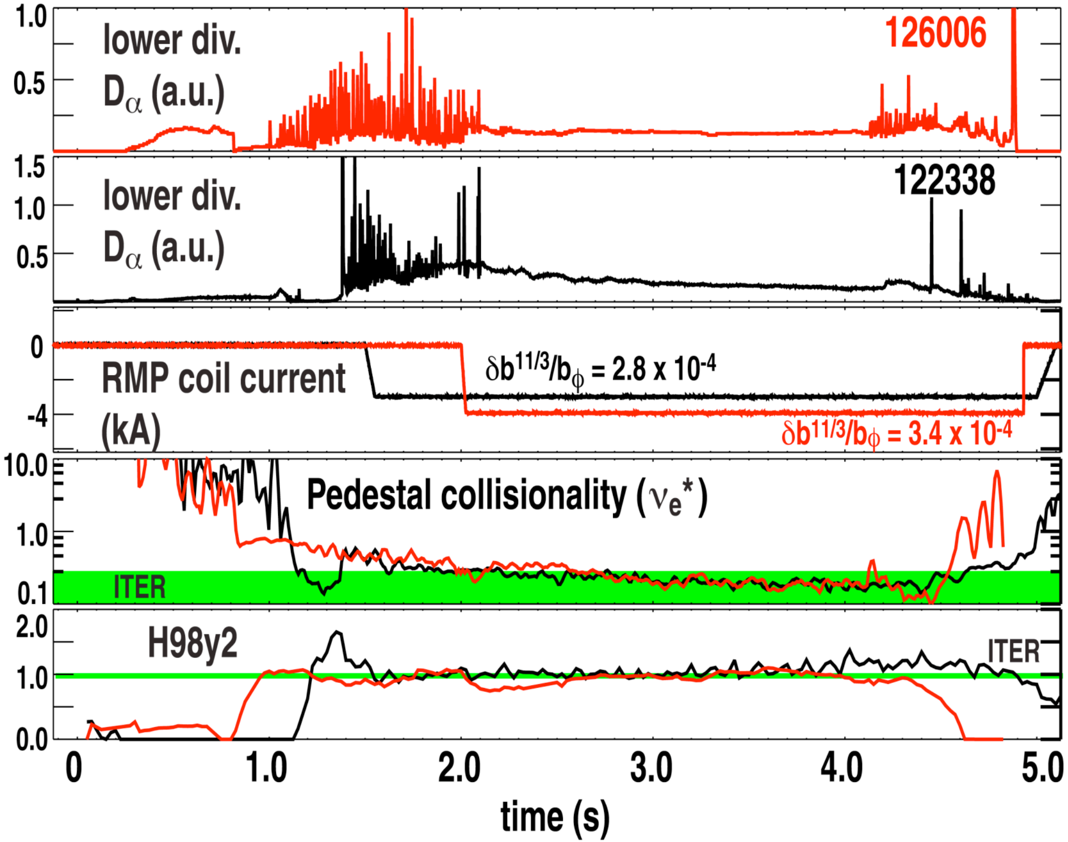
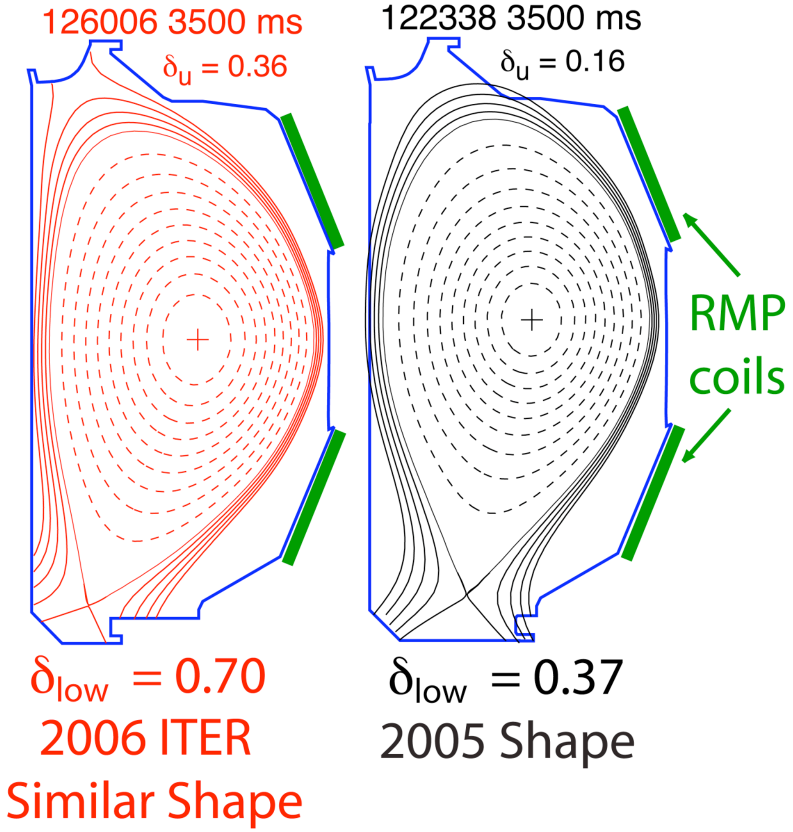
Outline

- **Motivation: ELM control for ITER**
  - Resonant magnetic perturbations (RMPs) have been shown to suppress/reduce ELMs in DIII-D H-mode plasmas (… and JET more recently)
- **Do RMPs control ELMs through stochastic edge transport?**
  - RMPs reduce edge ∇p below Type-I ELM stability boundary
  - **TRIP3D** field line tracer developed for DIII-D external magnetic field model
  - **E3D** Braginskii fluid transport code specialized for stochastic fields
- **Calculation of non-axisymmetric magnetic footprints qualitatively matches experimental observations**
  - **E3D** simulations show that heat flux flows efficiently along the perturbed invariant manifolds of the magnetic field
  - Observations can be used to benchmark magnetic field model
- **However, predicted thermal conduction appears greater than experimental observations**
  - Measured transport appears to be more convective than conductive
  - More physics input required: flux-limited kinetic transport, rotational shielding

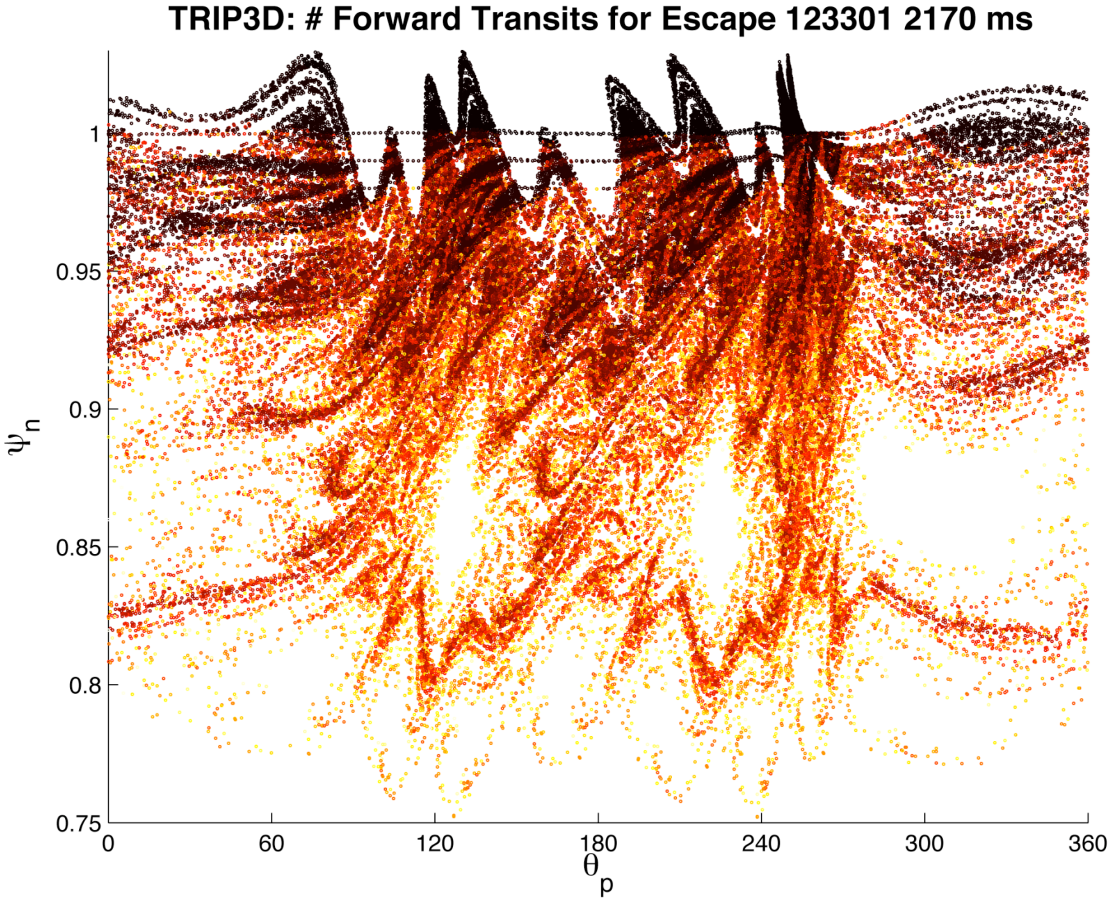
RMPs completely eliminate ELMs in DIII-D with ITER-similar shapes and pedestal collisionalities





- **RMP-induced transport must replace ELM transport!**
- High-confinement tokamaks (H-mode) rely on impulsive ELM transport to remove heat & impurities
- Type-I peeling-ballooning modes very sensitive to pressure ($J_{BS} \sim \nabla p$)

Can stochastic field line transport explain the reduction in edge pressure gradient?



- Even-parity RMP induces magnetic diffusion and fractal structure in the edge stochastic layer
- Color = # toroidal transits for escape yellow=200 max black<10

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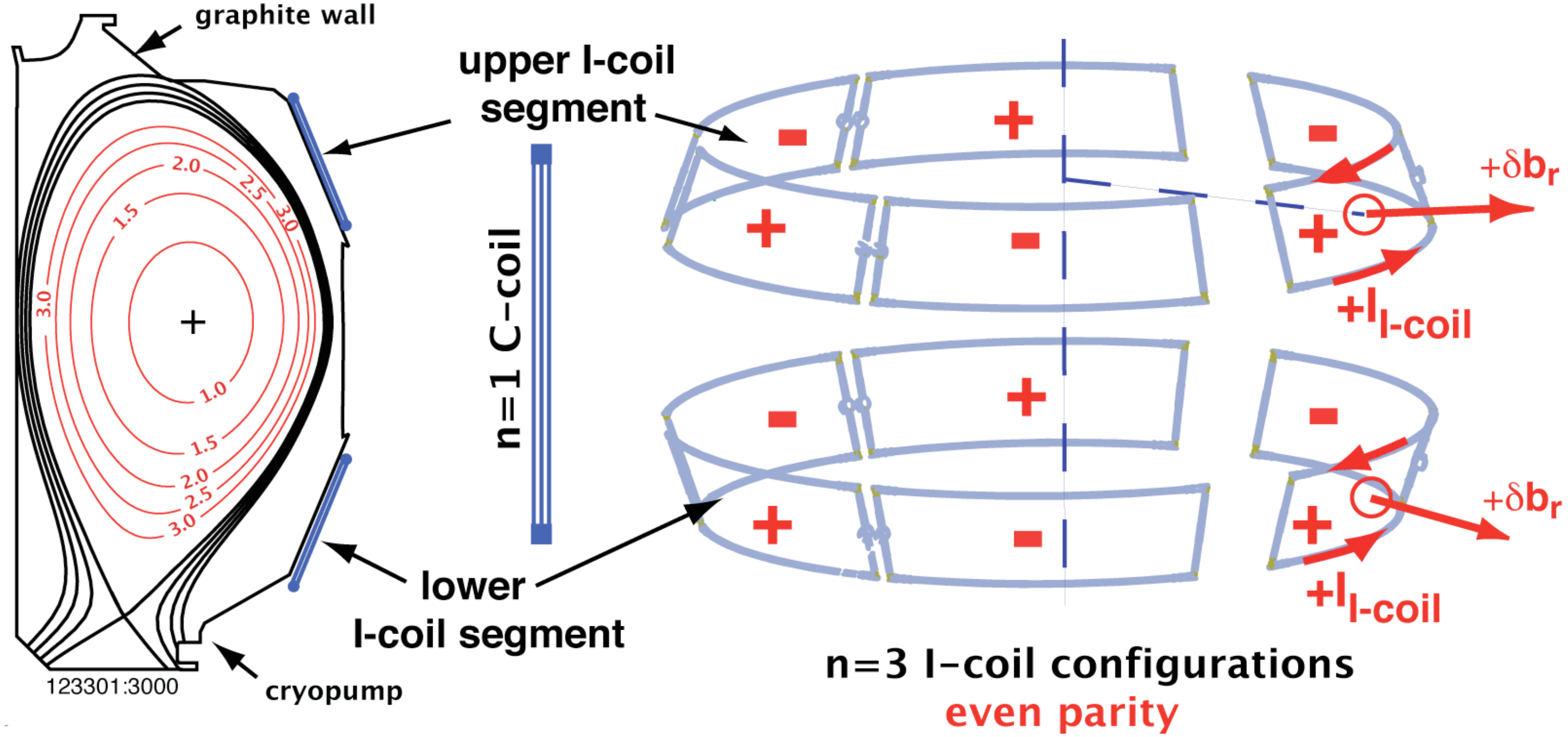
I-coil n = 3 even parity

internal RWM control coil

targets edge q~3-4

high stochasticity



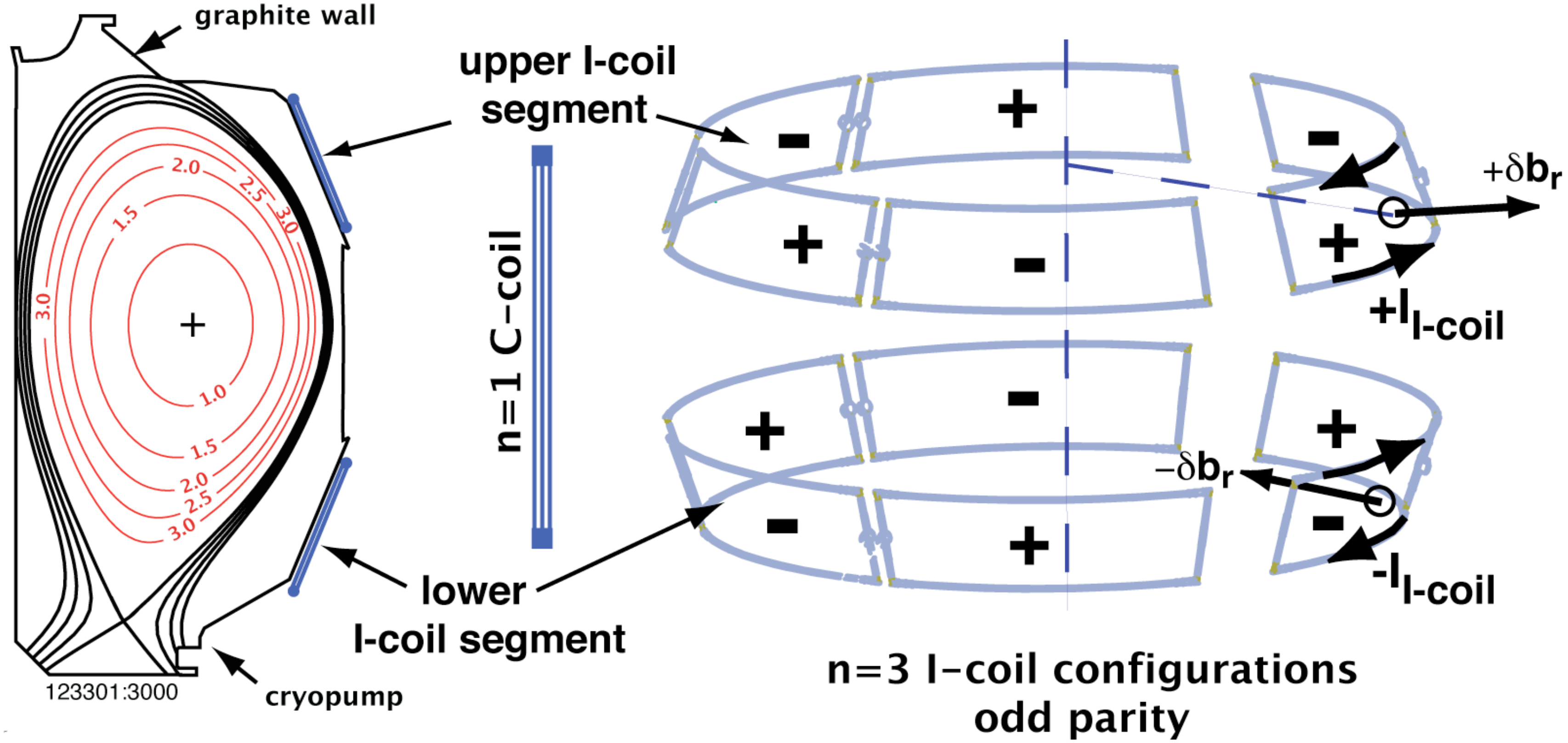
- **Even** parity produces strong resonant spectrum **$\delta B_{n=mq}$ ~ 6.0 G**
- Edge pressure gradient strongly reduced
- Type-I ELMs can be completely eliminated within q_{95} window (3.4-3.7)

I-coil n = 3 odd parity

internal RWM control coil

targets edge q~3-4

low stochasticity



n=3 I−coil configurations
odd parity

- **Odd** parity produces weak resonant spectrum **$\delta B_{m=qn}$ ~ 0.8 G**
- Edge pressure gradient only weakly affected
- Can find regimes that reduce ELM size (grassy/Type-II?)

TRIP3D perturbation spectrum demonstrates that I-coil parity controls pedestal island overlap

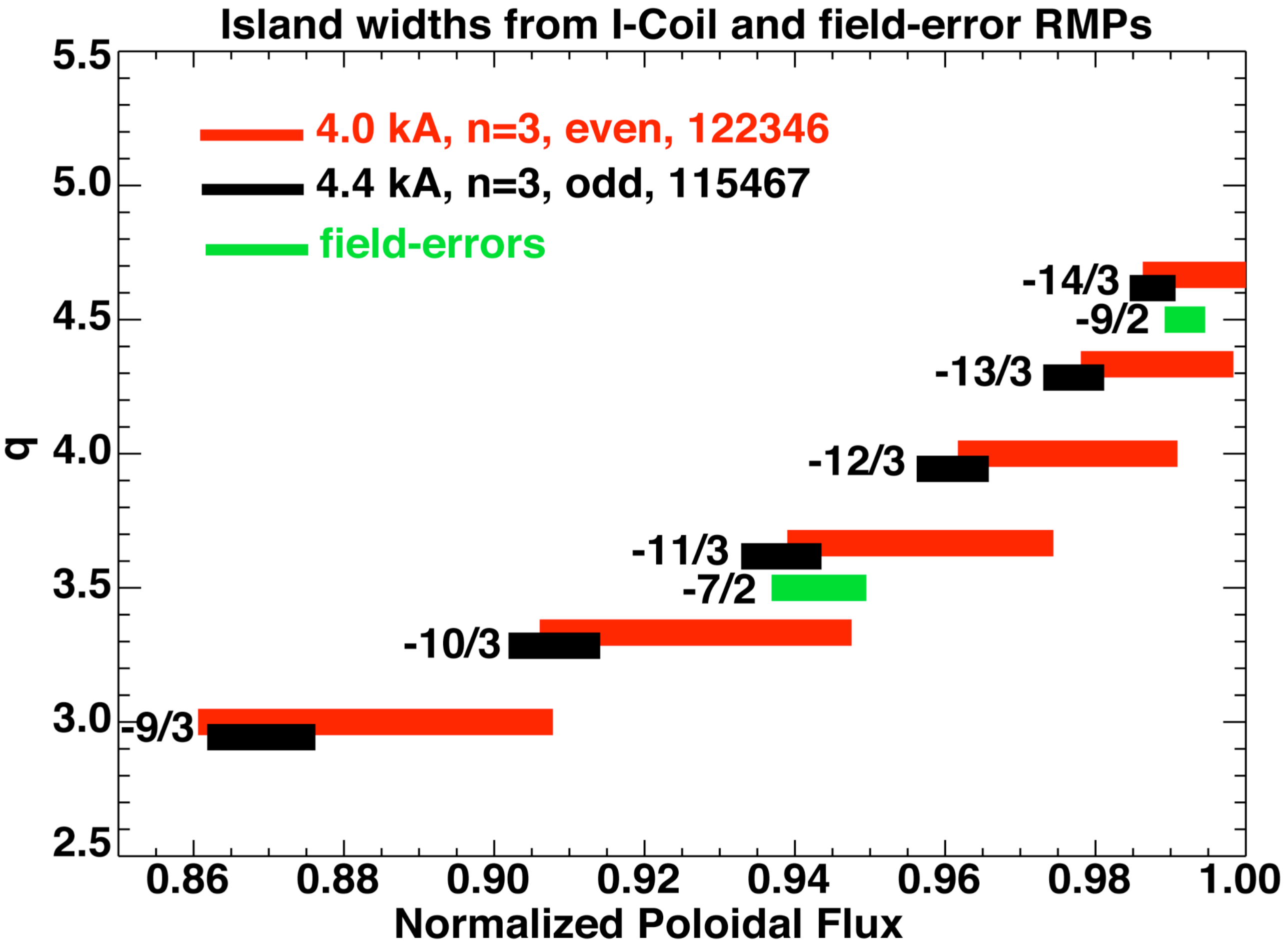
Vacuum calculations suggest:

- Odd (weak RMP) → small islands
- Even (strong RMP) → stochastic

Experiments show:

→ little/no change in pedestal

→ pedestal profile stabilization



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E3D Braginskii fluid transport code specialized for stochastic 3D fields: TEXTOR-DED, W7-X, DIII-D RMP

Assumes anomalous ⊥ transport in static background field

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

$$\boxed{\tfrac{3}{2} n(\partial_t T + u_\parallel \nabla_\parallel T) = \nabla_\parallel \kappa_\parallel \nabla_\parallel T + \nabla_\perp \kappa_\perp \nabla_\perp T + Q_{ei}}$$

- **Parallel momentum**

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

- **Quasineutral continuity**

$$\partial_t n + \nabla_\parallel n u_\parallel = \nabla_\perp D_\perp \nabla_\perp n$$

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

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

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E3D uses *Monte-Carlo* fluid elements in order to achieve high accuracy field line mapping

- Heat transport highly anisotropic

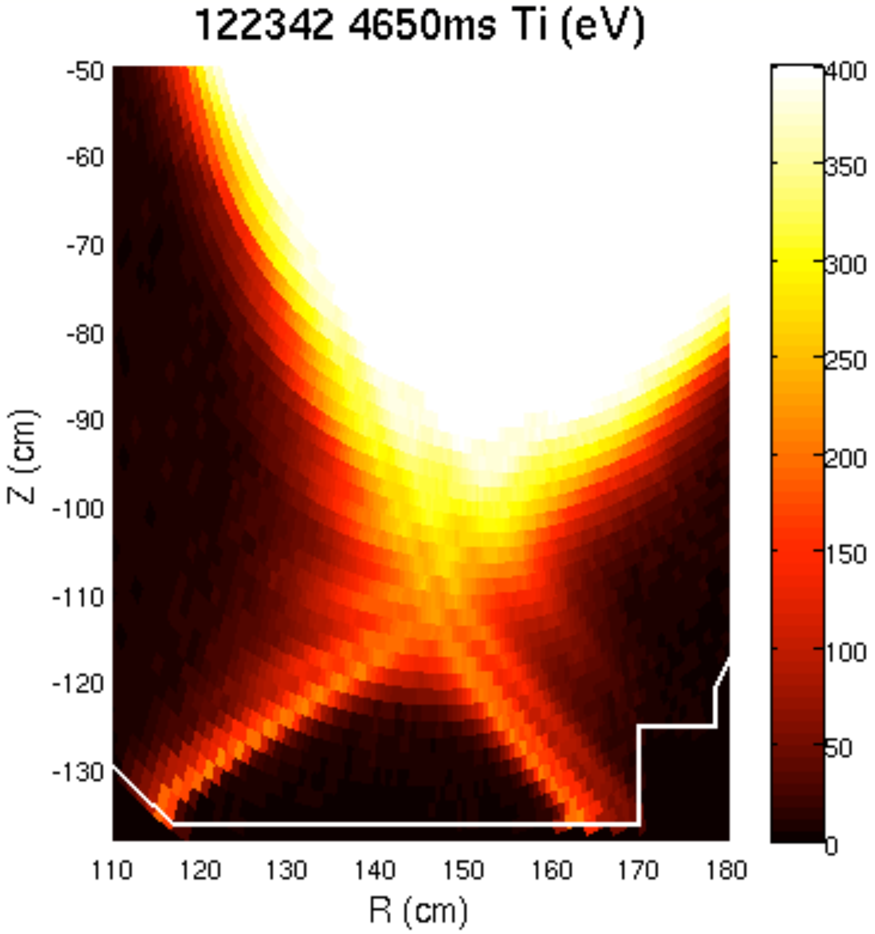
$$\kappa_{\parallel}/\kappa_{\perp} = \chi_{\parallel}/\chi_{\perp} \sim 10^{8} - 10^{10}$$

- Stochasticity can generate small scales

$$\ell_{\perp}/\ell_{\parallel} \sim \sqrt{\chi_{\perp}/\chi_{\parallel}} \sim 10^{-4} - 10^{-5}$$

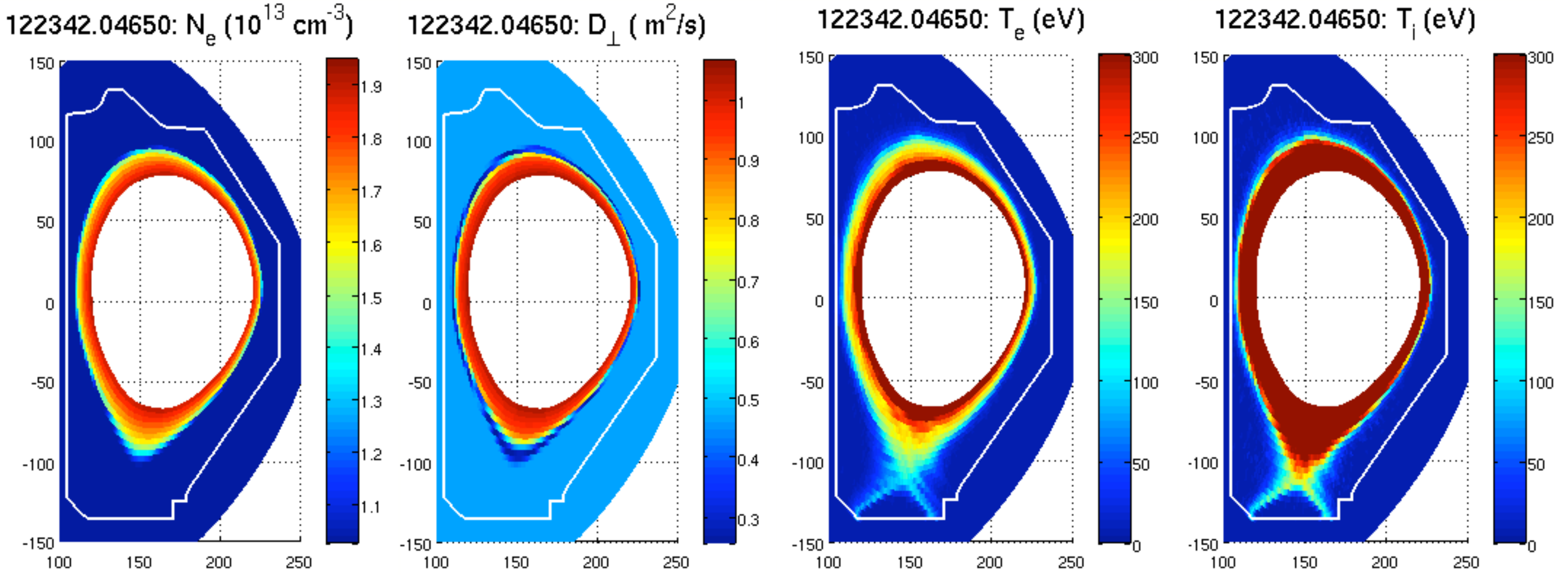
- Simple finite elements cannot capture anisotropy

- Solution: Monte-Carlo technique
  - Let $T(x,t)$ = p.d.f. for heat packets
  - Evolve using Brownian motion



- Uses a series of **local magnetic coordinate systems** to globally cover space. Reduces costly field line integration to a series of mappings between local domains.

E3D Results: 1D density and diffusivity chosen to match experimental measurements and transport analyses

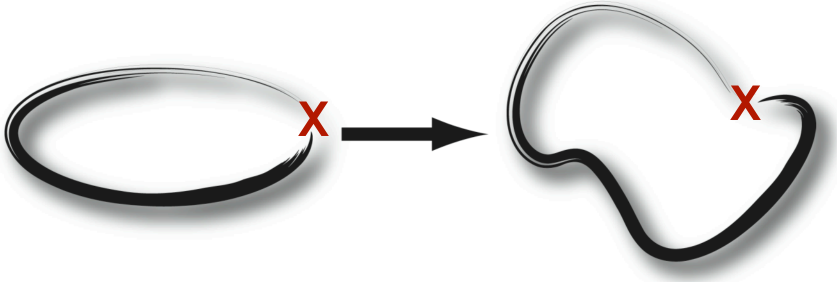


- Which aspects of RMP critically impact the solution?
- What determines the pattern of heat flow?
- Is there still a SOL?
- How is the plasma-wetted target affected?

The RMP splits the separatrix into a “homoclinic tangle”

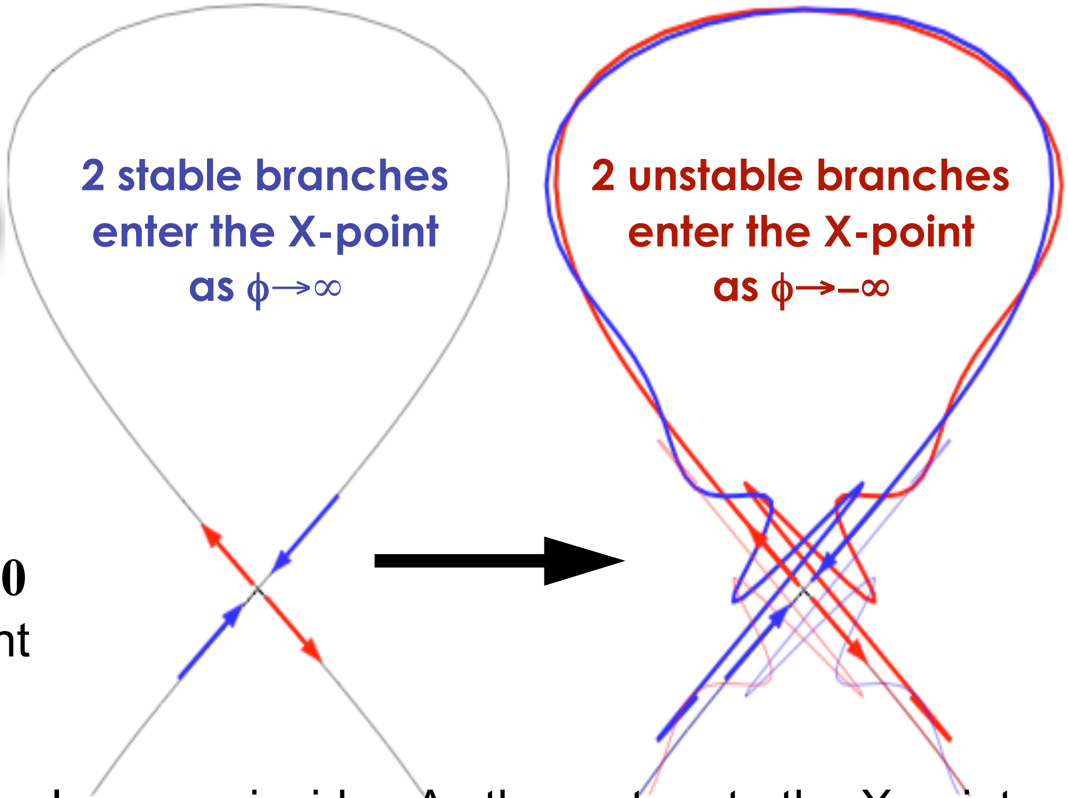
homoclinic = separatrix formed from self-intersecting orbits

What happens to the X-point?



- **The periodic orbit** at the X-point deforms, but generically survives**.**

- The **invariant manifolds** $\mathbf{B}\cdot\nabla\psi(x) = 0$ that asymptotically approach the X-point survive as well, but …

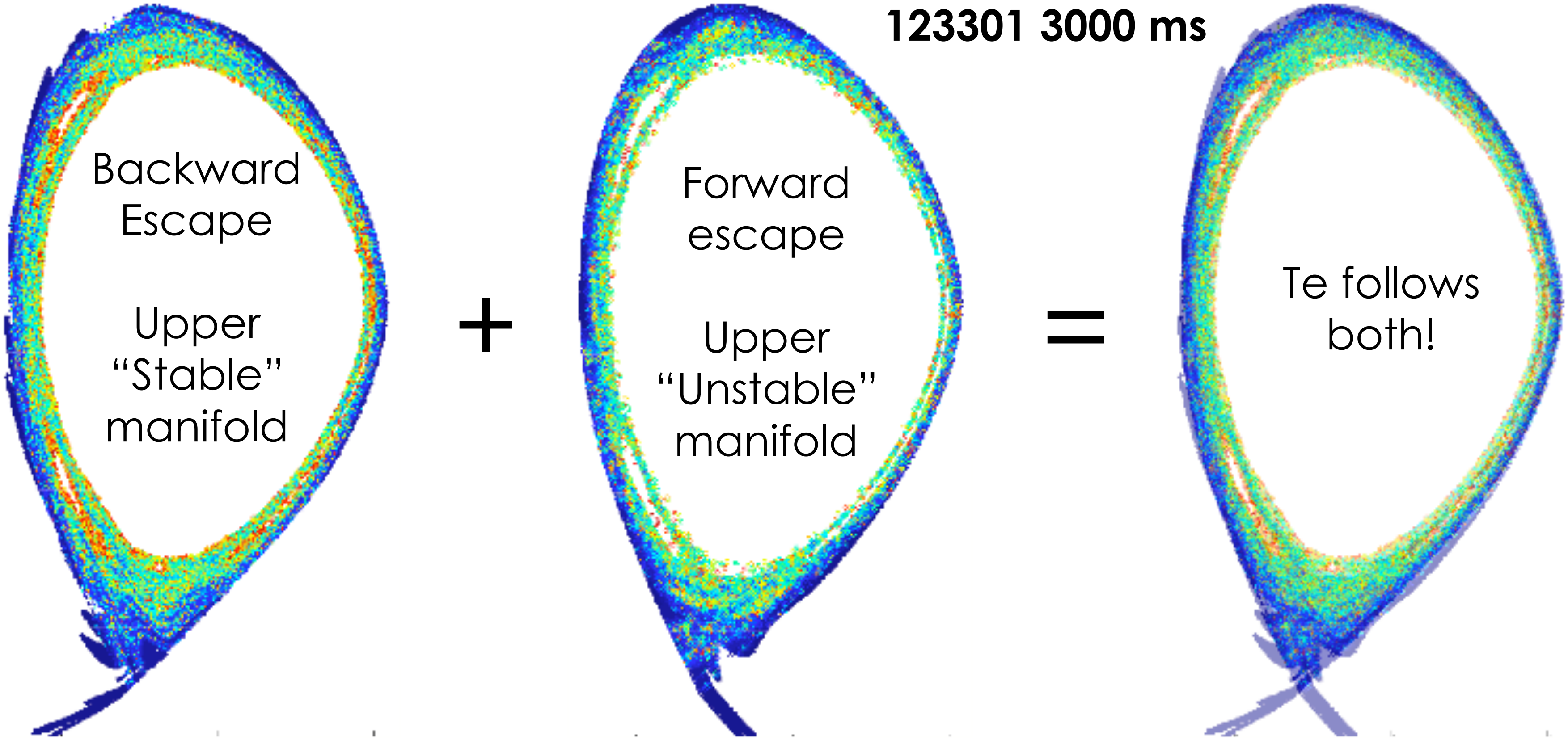


2 stable branches enter the X-point as $\phi \to \infty$

2 unstable branches enter the X-point as $\phi \to -\infty$

- The stable and unstable branches no longer coincide. As they return to the X-point, they begin to oscillate wildly & intersect infinitely often.
- The **homoclinic tangle** is the union of the 4 branches of invariant manifolds.
- **The tangle encodes the structure of chaos:** field lines cannot cross an invariant manifold, they are forced to follow the tangle

The 2 upper *invariant manifolds* determine which field lines exit the plasma and where they strike the divertor targets



123301 3000 ms

Backward
Escape

Upper
“Stable”
manifold

+

Forward
escape

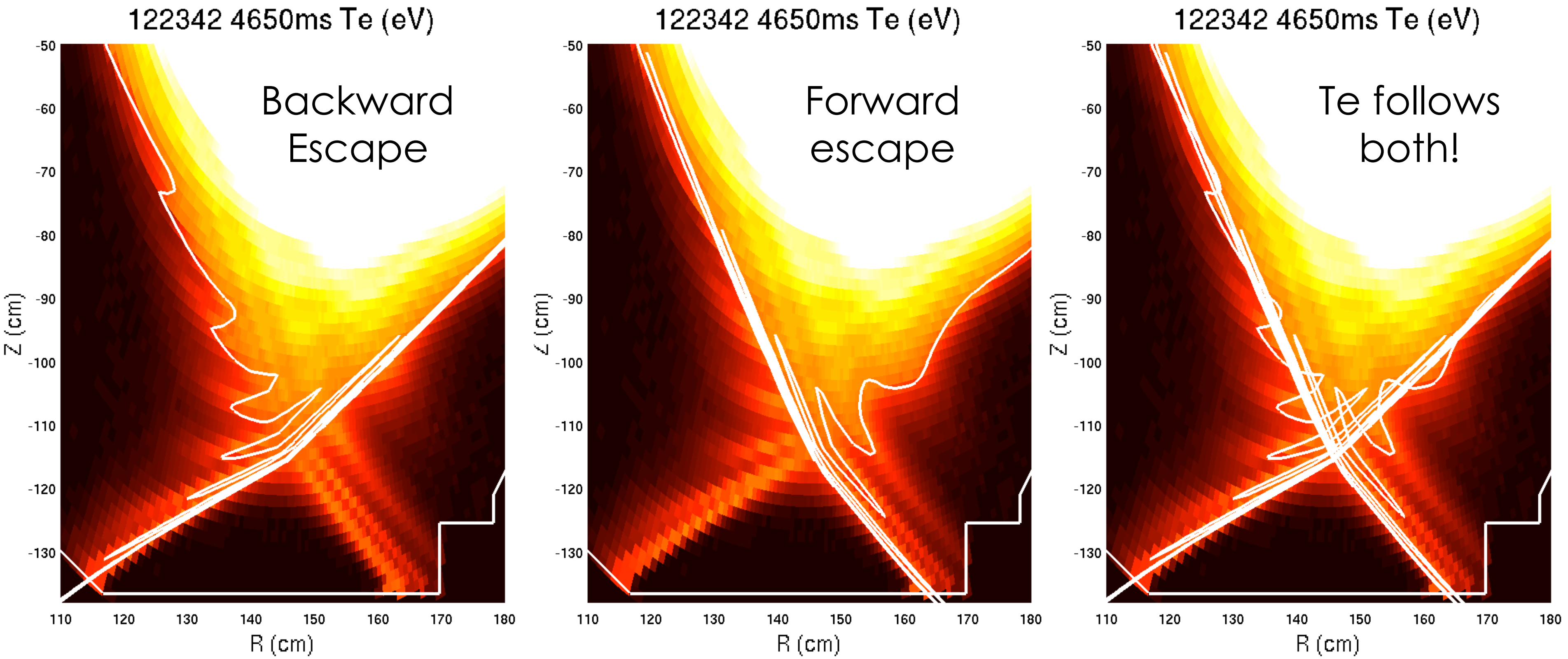
Upper
“Unstable”
manifold

=

Te follows
both!

- The invariant manifolds trap interior field lines as they attempt to escape
- **All of these field lines escape** through the non-axisymmetric divertor legs
- Color = # toroidal transits for escape (red=200 max, blue<=20)

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 footprint structure
- Private flux region still exists due to short divertor connection length

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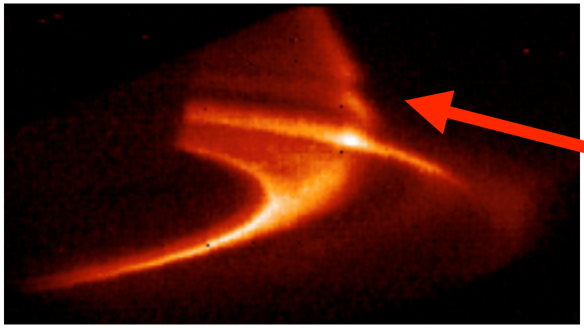
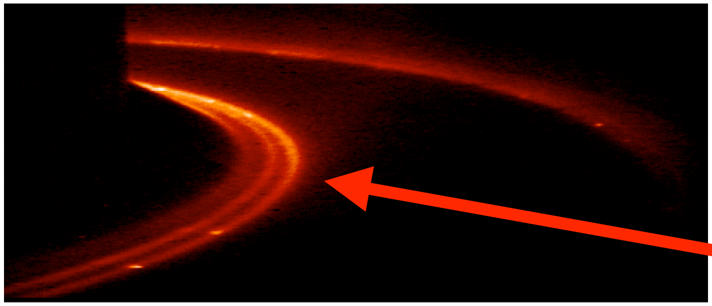
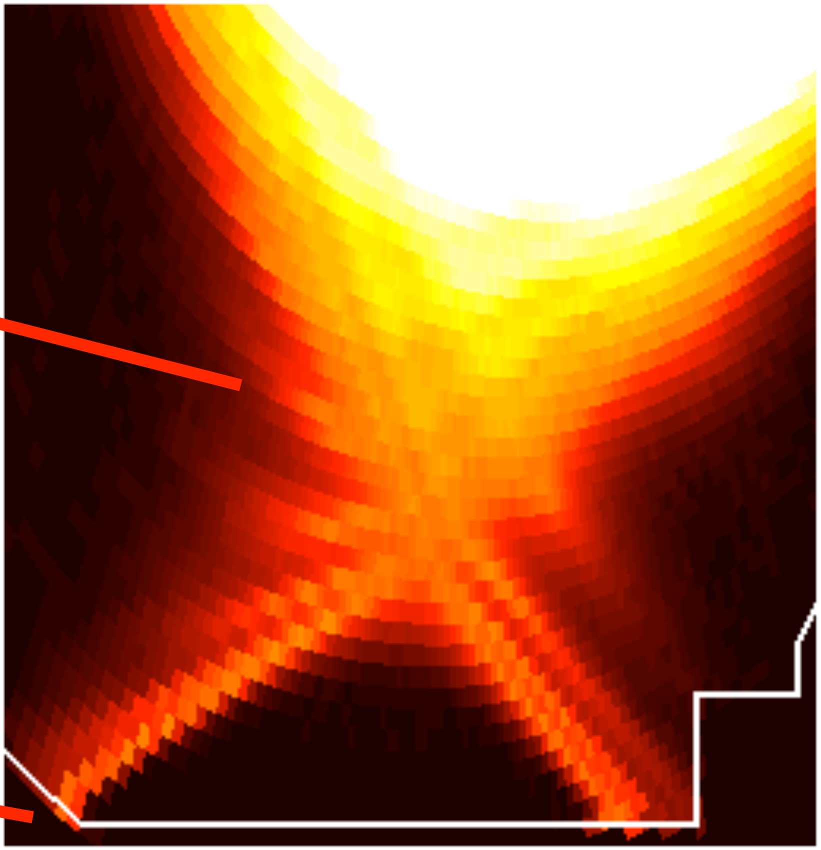
The predicted tangle forms non-axisymmetric magnetic footprints which have been experimentally observed

123300: filtered CIII Xpt-TV



123301: filtered D_α Xpt-TV

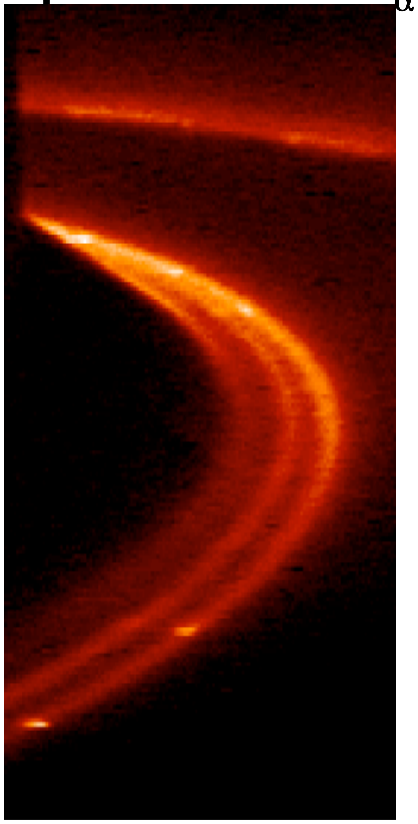




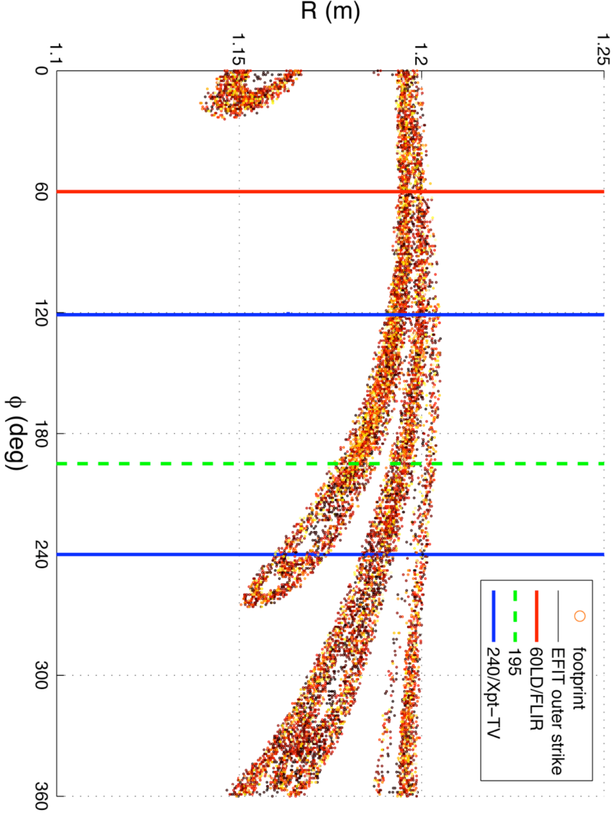
- T_e reflects a superposition of both upper invariant manifolds
- Multiple footprint stripes observed during I-coil operation

The magnetic footprint can be used to validate the TRIP3D magnetic field model

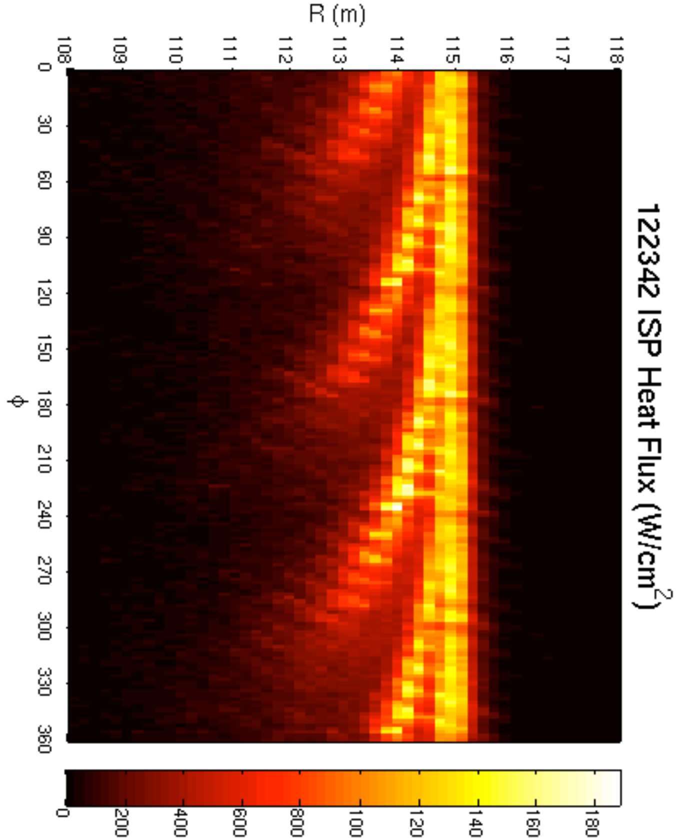
Xpt-TV: filtered D_α



TRIP3D ISP: field lines



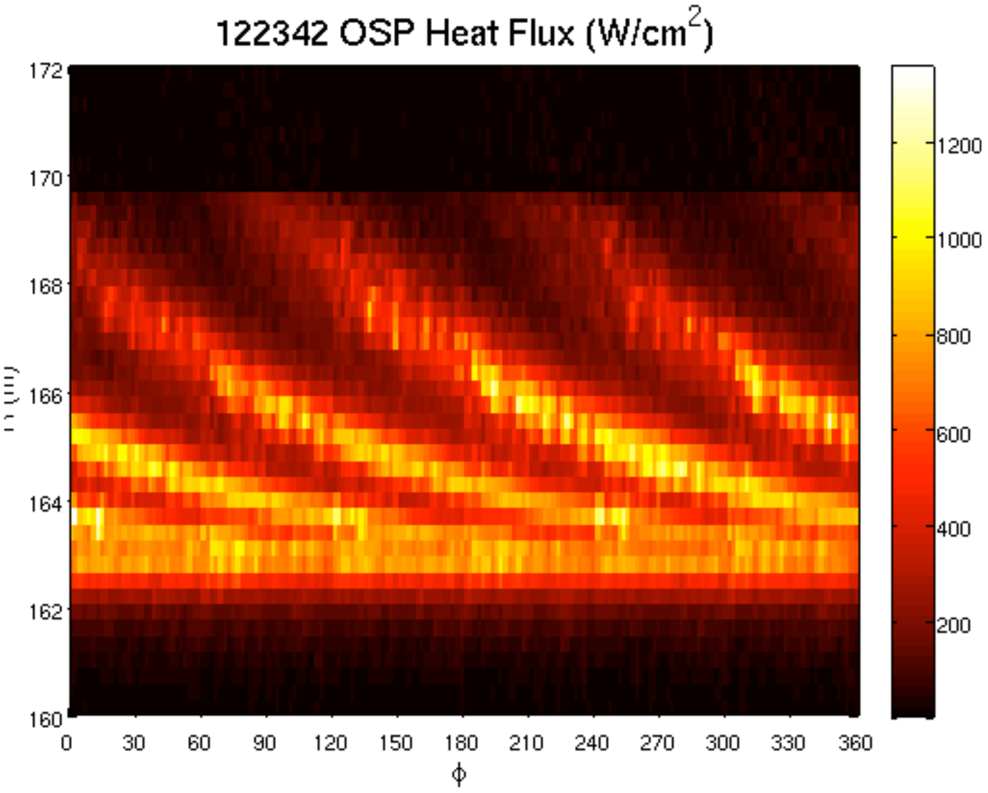
E3D ISP: heat flux



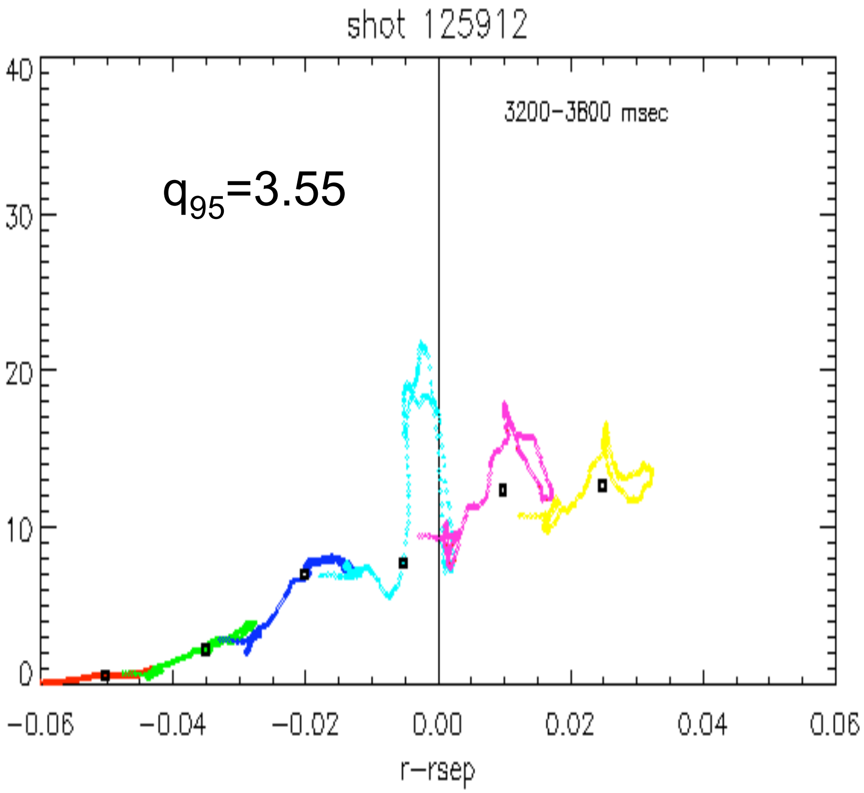
- **Field-errors destroy n = 3 symmetry & verify non-axisymmetric structure**
  - Only 1 strike point observable at 60^o IR-TV, but 3 stripes observable near 180^o Xpt-TV
- **Axisymmetric striations would indicate rotating MHD/tearing activity**

Detailed footprint captured via hi-res simulation and strike point sweep of Langmuir probe array

E3D simulation 6MW



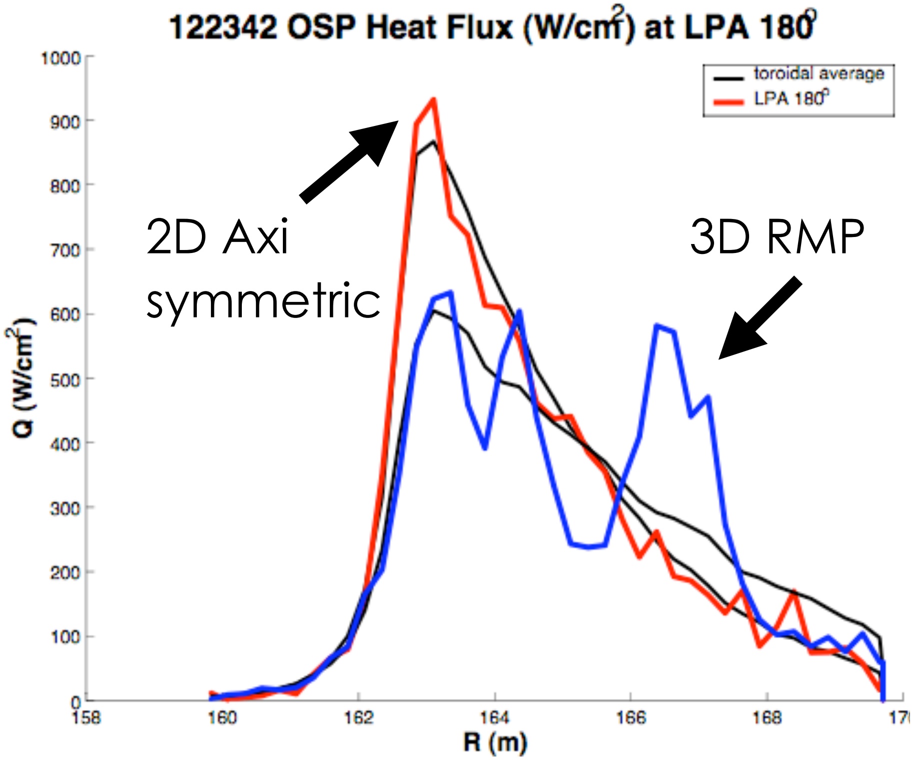
LPA J_{sat} at $\phi_{DIII-D}=180°$
125912 3200-3800 ms



- High resolution **E3D** thermal footprint qualitatively matches measured fluxes
- Quantitative treatment requires particle continuity, neutrals, etc.
- New poloidal mesh efficiently distributes resolution near divertor

Plasma wetted surface area predicted to increase: peak heat flux reduced at fixed input power

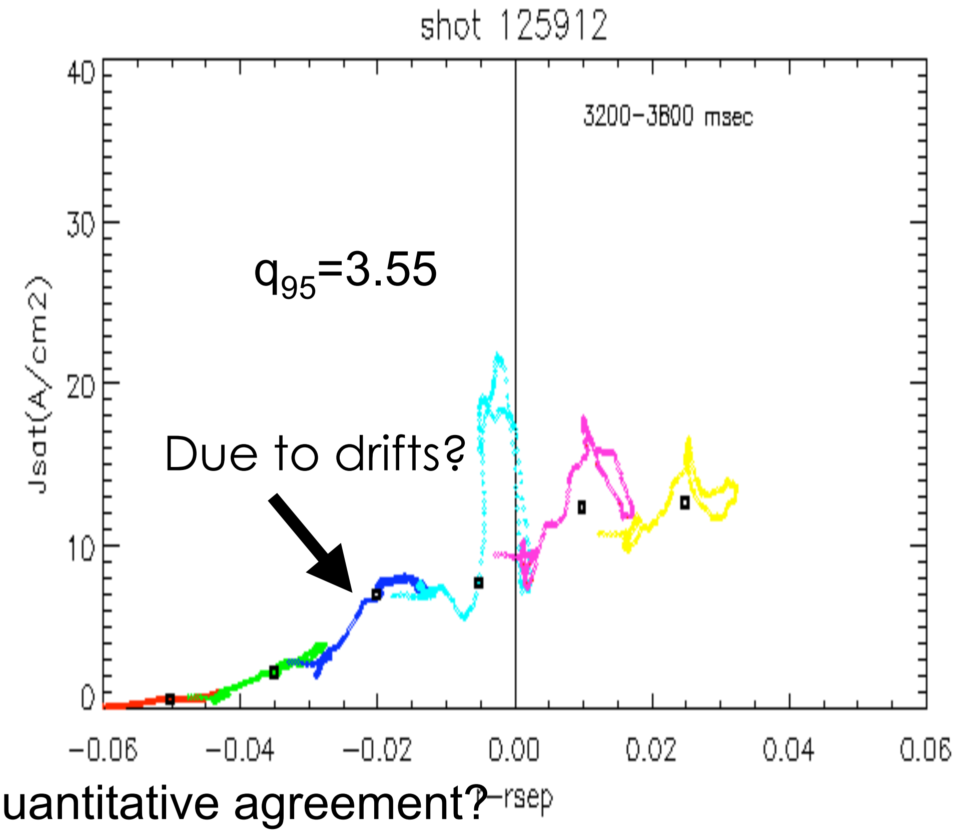
E3D:122342 4650



2D Axi symmetric

3D RMP

LPA: 125912 3200-3800 ms



q_{95}=3.55

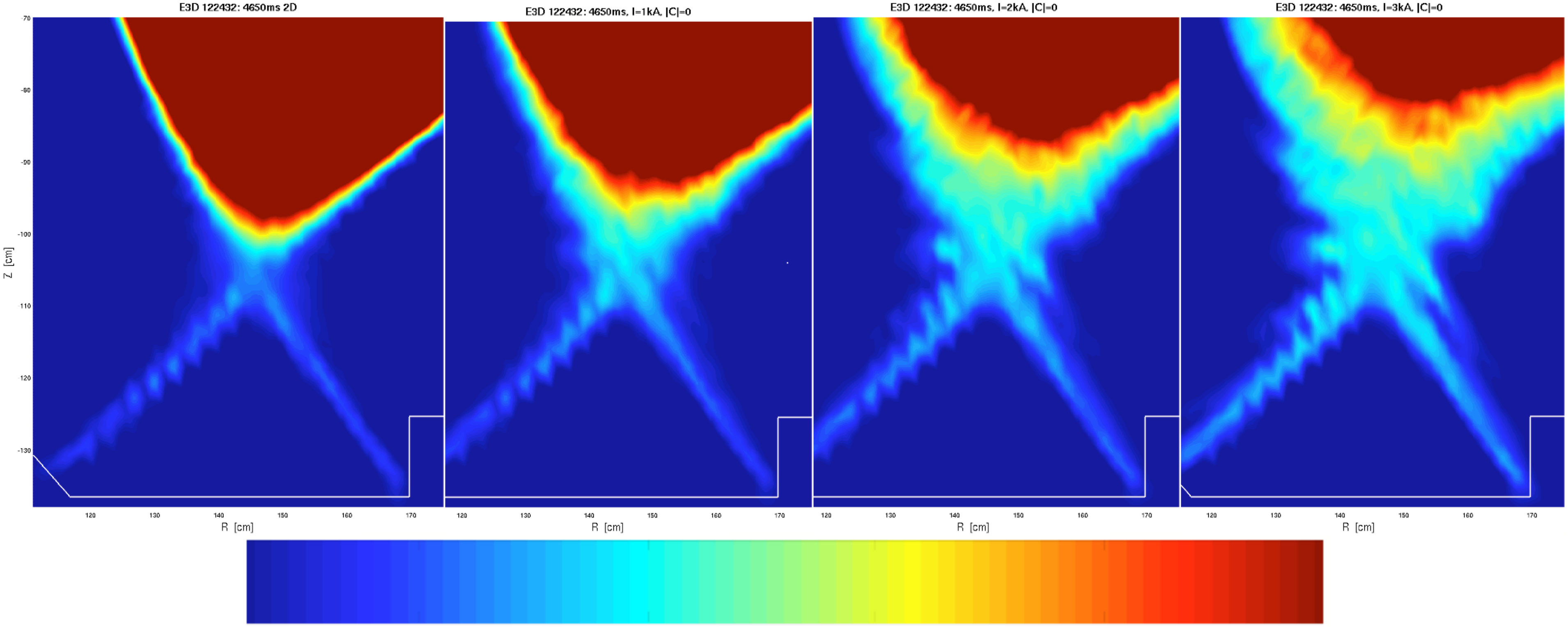
Due to drifts?

- Qualitative agreement looks promising, quantitative agreement?
- Toroidal rotation ➔ linearly decreasing toroidally averaged profile
- Extra bump in private flux zone? Parallel flow? Drift effects?
- Proper in-out asymmetry will probably require asymmetric D_{anom}

Tangle predicted to grow & heat with RMP strength

122342 at 4650 ms BC's: $T_e = 1.6\ keV,\ T_i = 2.6\ keV$ at $\psi_n = 77\%$

I-coil (kA): *0 (2D)* *1* *2* *3*



Te (eV): *50* *100* *150* *200*

$$D_\perp = 0.2 m^2 / s \quad n_{sep} = 4 \times 10^{18} m^{-3}$$

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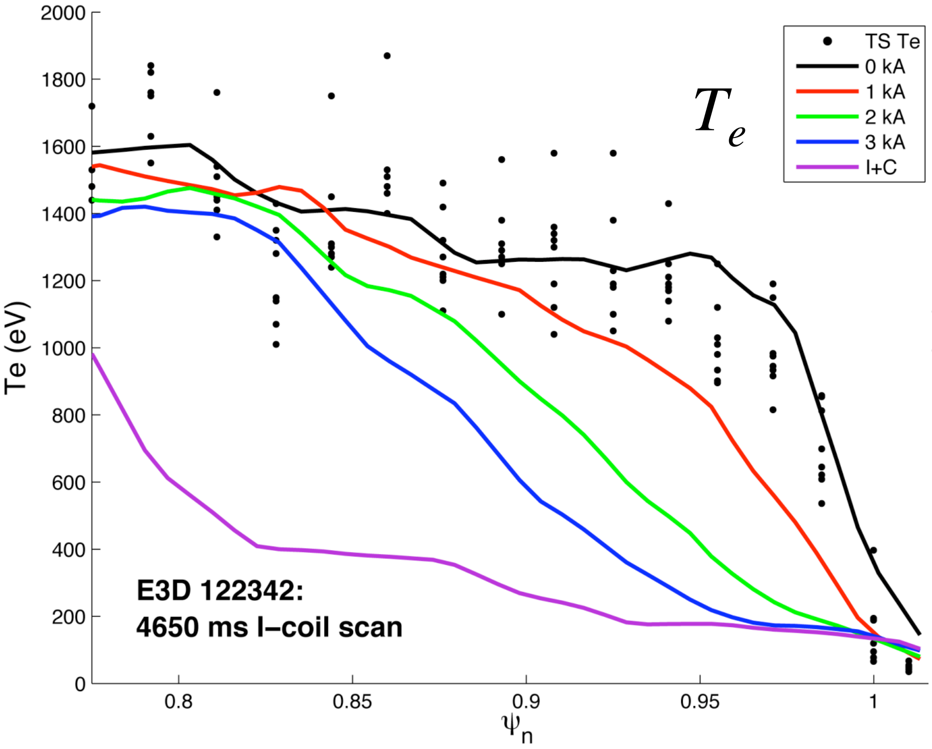
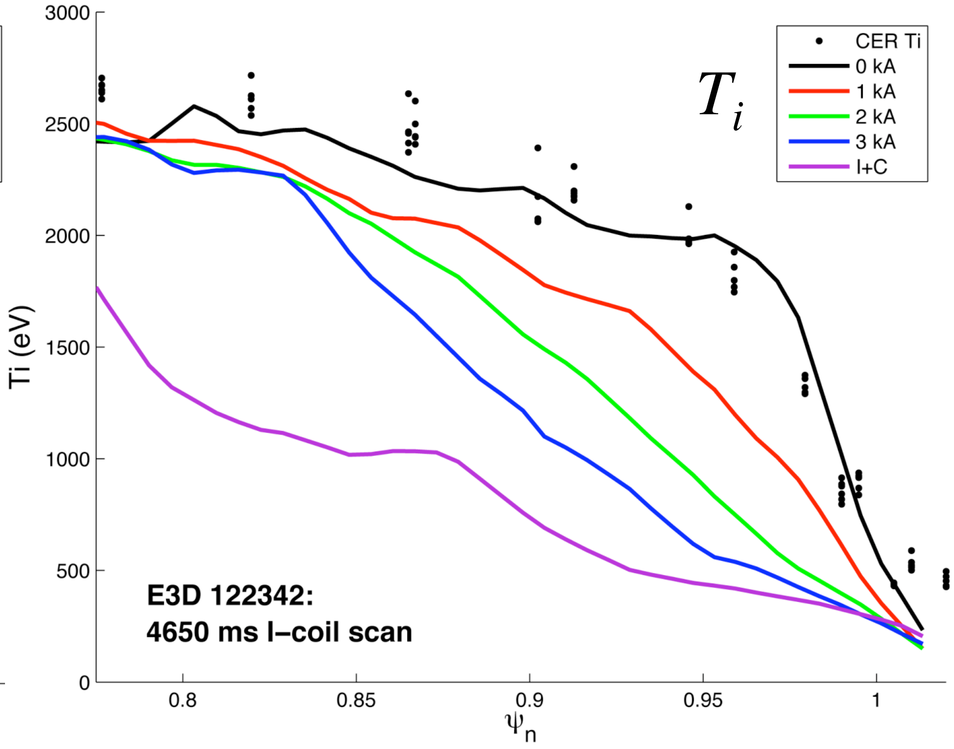
Pedestal T_e and T_i predicted to cool with RMP strength

122342 at 4650 ms **BC's: $T_e = 1.6\ keV,\ T_i = 2.6\ keV$ at $\psi_n = 77\%$**





- Constant temperature BC's
- Edge stochastic layer efficiently cools pedestal
  - remains hot compared to SOL
  - disagrees with experimental results

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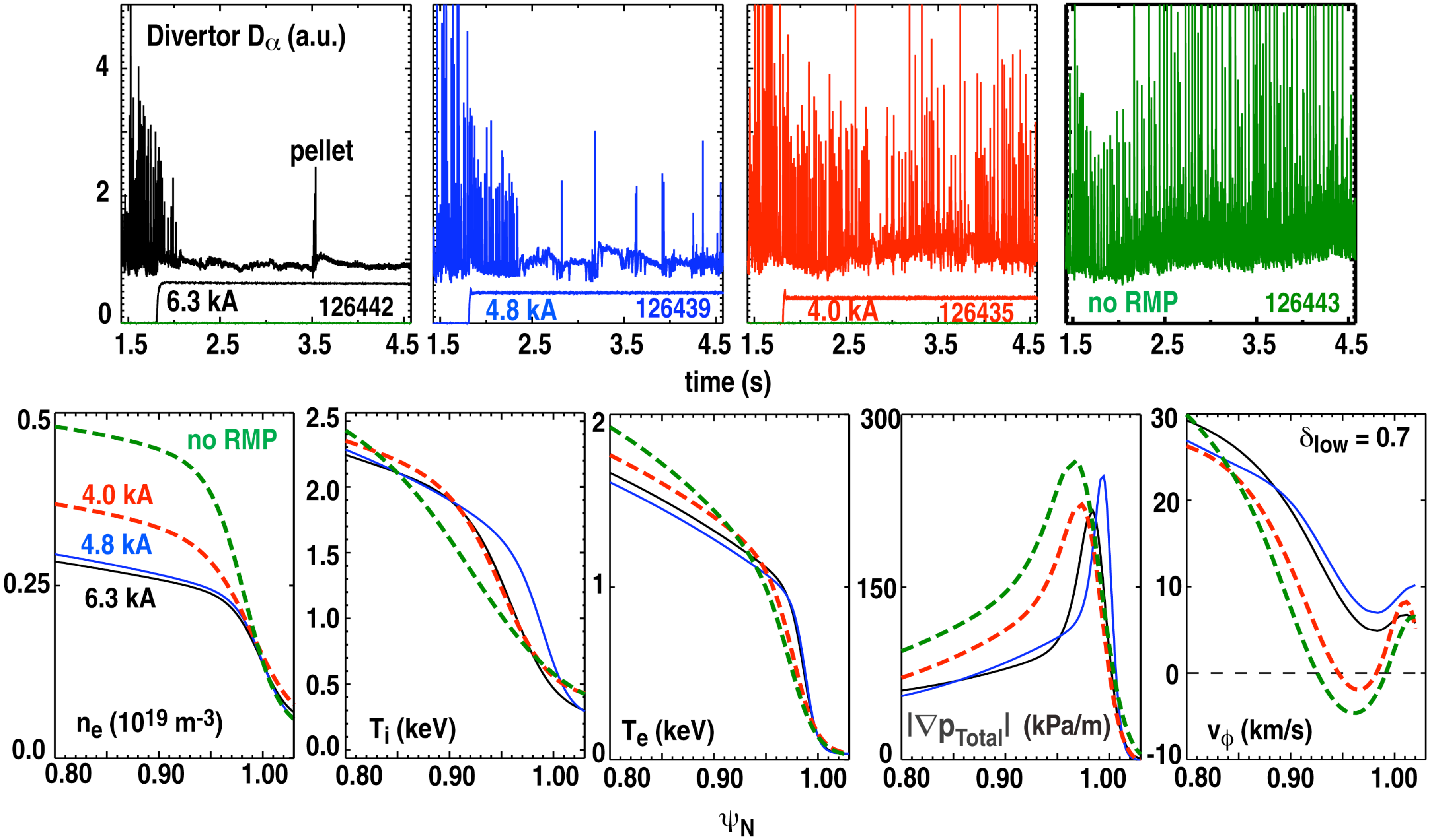
But RMP controls peeling-ballooning stability through particle transport! n_e decreases, not T_e or T_i



Conclusions

- **RMP scenario is a very promising ELM control candidate**

- **Non-axisymmetric thermal footprints predicted by TRIP3D/E3D has been qualitatively confirmed**
  - Strike-point splitting observed on infrared/optical cameras and high-resolution Langmuir probe array sweeps
  - Thermal footprints are guided by the invariant manifolds of the magnetic field line motion
  - Plasma-wetted surface area predicted to increase in size and reduce peak heat fluxes and particle loads

- **Predicted thermal conduction too large to match plasma profile reconstructions … more physics needed?**
  - Collisionless kinetic parallel transport may limit conductive fluxes
  - Plasma rotation should act to shield RMPs from the core requires modeling field penetration physics

References:
I. Joseph, R. A. Moyer, T. E. Evans, *et al.*, *"Stochastic Transport Modeling of Resonant Magnetic Perturbations in DIII-D"*, J. Nucl. Mater., *in press.*

- **Low collisionality experiments**
  - T.E. Evans, K.H. Burrell, R.A. Moyer, et al., "Edge stability and transport control with resonant magnetic perturbations in collisionless tokamak plasmas," Nature Phys. 2(6) (2006) 419.
  - K. H. Burrell, T. E. Evans, E. J. Doyle, *et al.*, "ELM suppression in low edge collisionality H-mode discharges using n = 3 magnetic perturbations", Plasma Phys. Control. Fusion 47 (2005) B37-B52.

- **High collisionality experiments**
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  - R. A. Moyer, T. E. Evans, T. H. Osborne, *et al.*, "Edge localized mode control with an edge resonant magnetic perturbation", Phys. Plasmas 12 (2005) 056119.

- **E3D Code**
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- **Tangles**
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  - T. E. Evans, R. K. W. Roeder, J. A. Carter* *et al.*, "Homoclinic tangles, bifurcations and stochasticity in poloidally diverted tokamaks", Contrib. Plasma Phys. 44 (2004) 235.