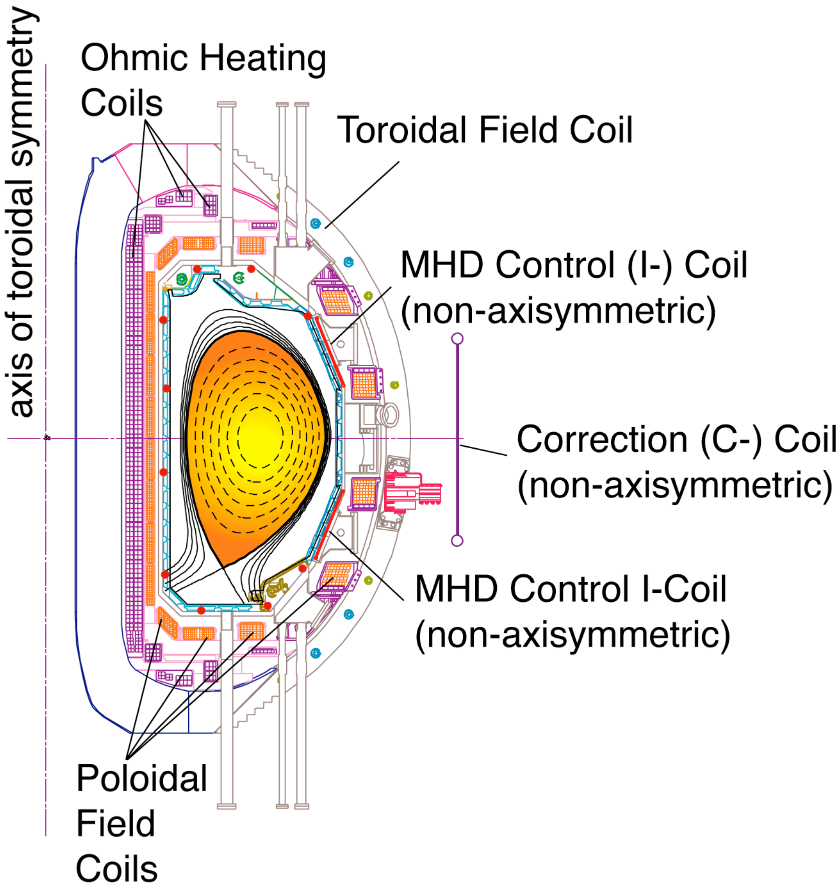
3D edge issues in tokamaks



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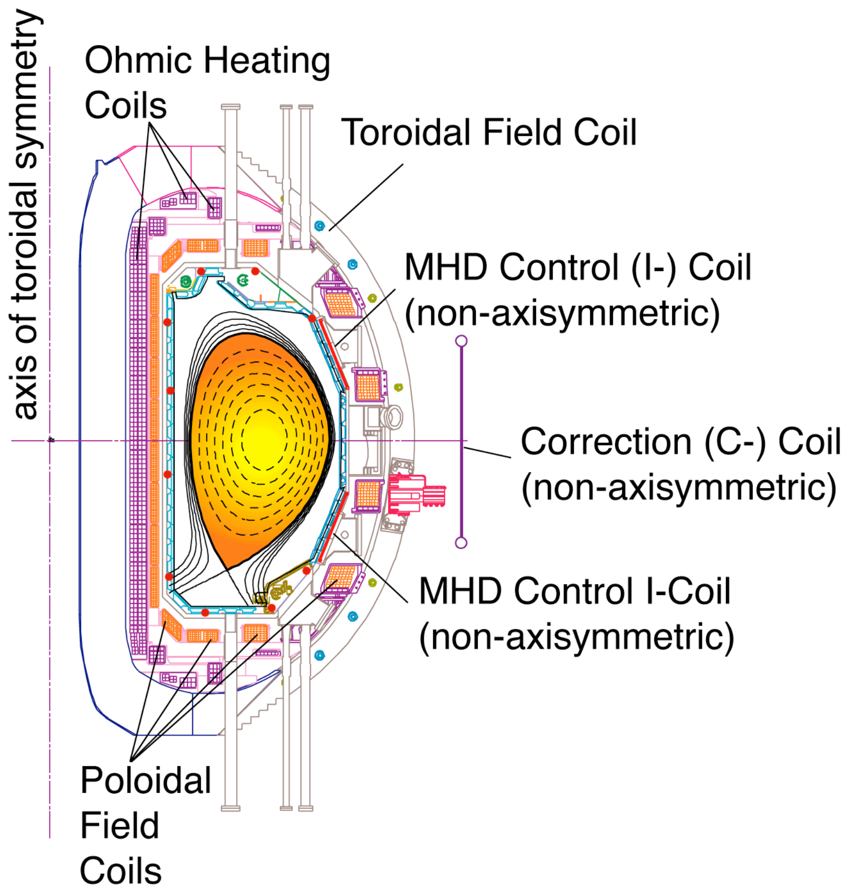
Why are 3D edge issues important in tokamaks?

- Edge confinement and stability is known to be strongly tied to magnetic geometry (topology?)
  - L-H transition (position, shape, up-down symmetry, etc.)
  - QH-mode, VH-mode, etc. (shape, co- versus counter- NBI)
  - ELM frequency and amplitude (triangulatiy, squareness, etc.)
  - Locked modes, Quasi-Stationary Modes (QSMs), Resistive Wall Modes (RWMs), MARFEs, etc.
- Optimized boundary control (power and particle exhaust, impurity production, etc.) requires good alignment of PFCs with magnetic topology.
- Toroidal magnetic topology is very sensitive to resonant perturbations.

Nominally axisymmetric tokamaks have many sources of non-axisymmetric magnetic perturbations

- External sources include:
  - Field-errors due to confinement, heating, shaping and correction coils
  - MHD control coils (RWM) and boundary layer coils
- Plasma sources include:
  - Plasma (MHD) instabilities
  - edge current filaments



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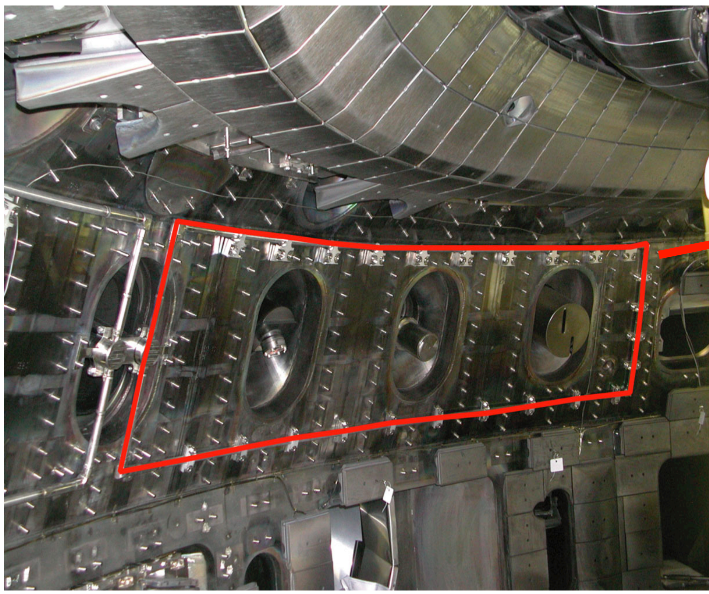
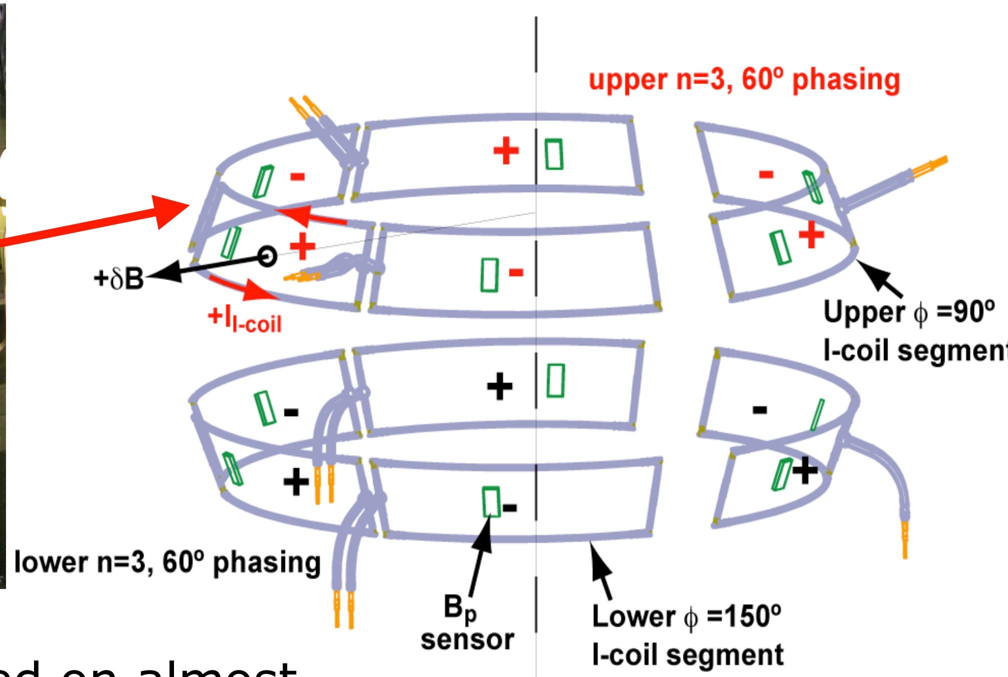
Internal (I-) and external (C-) coils are used for MHD control experiments in DIII-D

- Various I-coil polodial and toroidal mode number configurations, toroidal phases and parities used for RWM and ELM control.





even up-down parity

- The C-coil (not shown) is used on almost every discharge to correct field-errors that cause locked modes and Quasi-Stationary Modes (QSMs).

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Hamilton-Jacobi form of magnetic field is used for the perturbation analysis

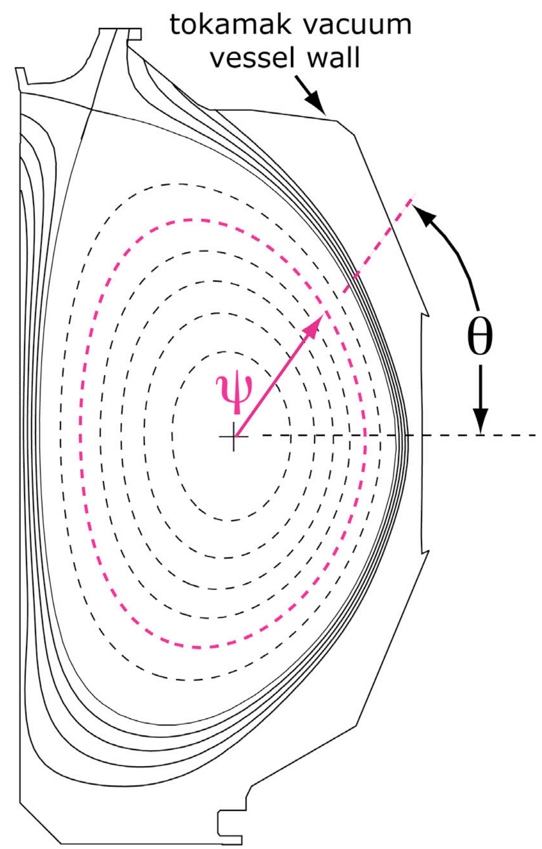
- Represent magnetic field lines in action-angle coordiantes:

$$\frac{d\theta}{d\phi} = \frac{\partial H(\psi,\theta)}{\partial\psi} \quad \text{and} \quad \frac{d\psi}{d\phi} = -\frac{\partial H(\psi,\theta)}{\partial\theta}$$

$$H(\psi,\theta) = H_0(\psi) + \sum_n \varepsilon_n H_n(\psi,\theta)$$

the toroidal angle ϕ is a time-like variable and ε is the perturbation amplitude.

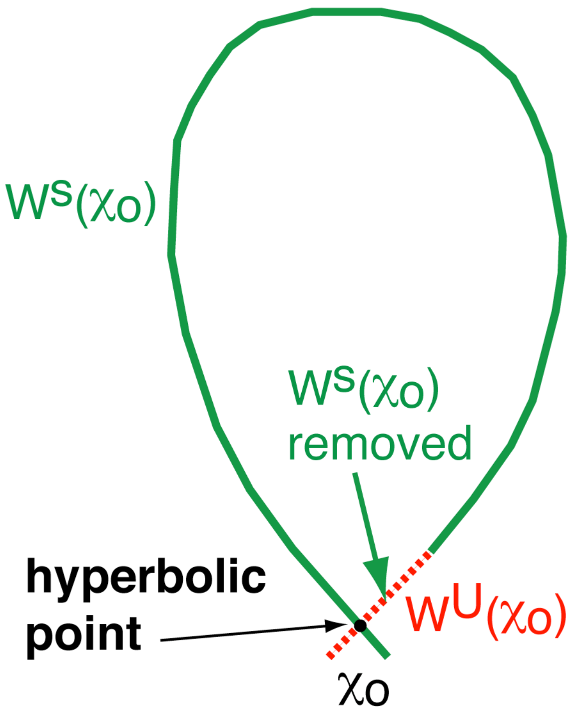
- Standard twist map methods used to study the properties of this conservative Hamiltonian system:
  - Numerical twist maps based on field line integration codes - TRIP_MAP and TRIP3D_MAP



Poloidal cross section of a toroidal magnetic equilibrium in a tokamak

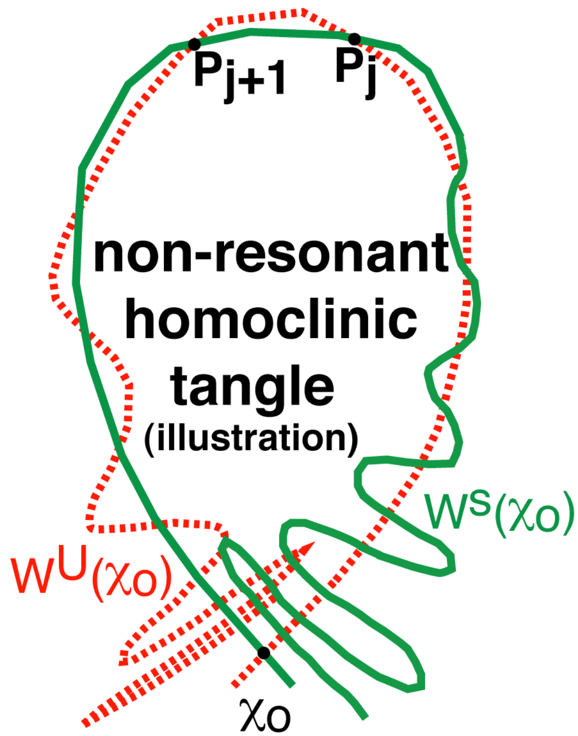
Non-axisymmetric magnetic perturbations produce separatrix splitting resulting in the formation of homoclinic tangles

unperturbed separatrix



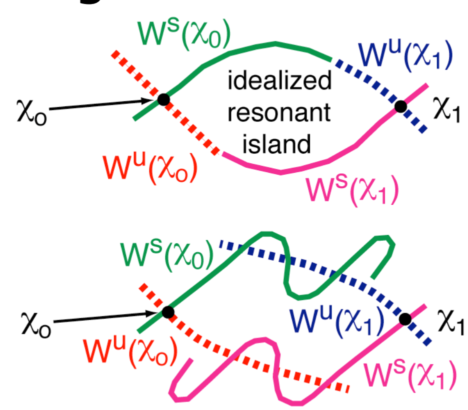
overlapping stable and unstable manifods

perturbed separatrix



splits into a stable and unstable manifold

Stable and unstable manifolds intersect to produce both resonant and non-resonant homoclinic tangles.



resonant homoclinic tangle (illustration)

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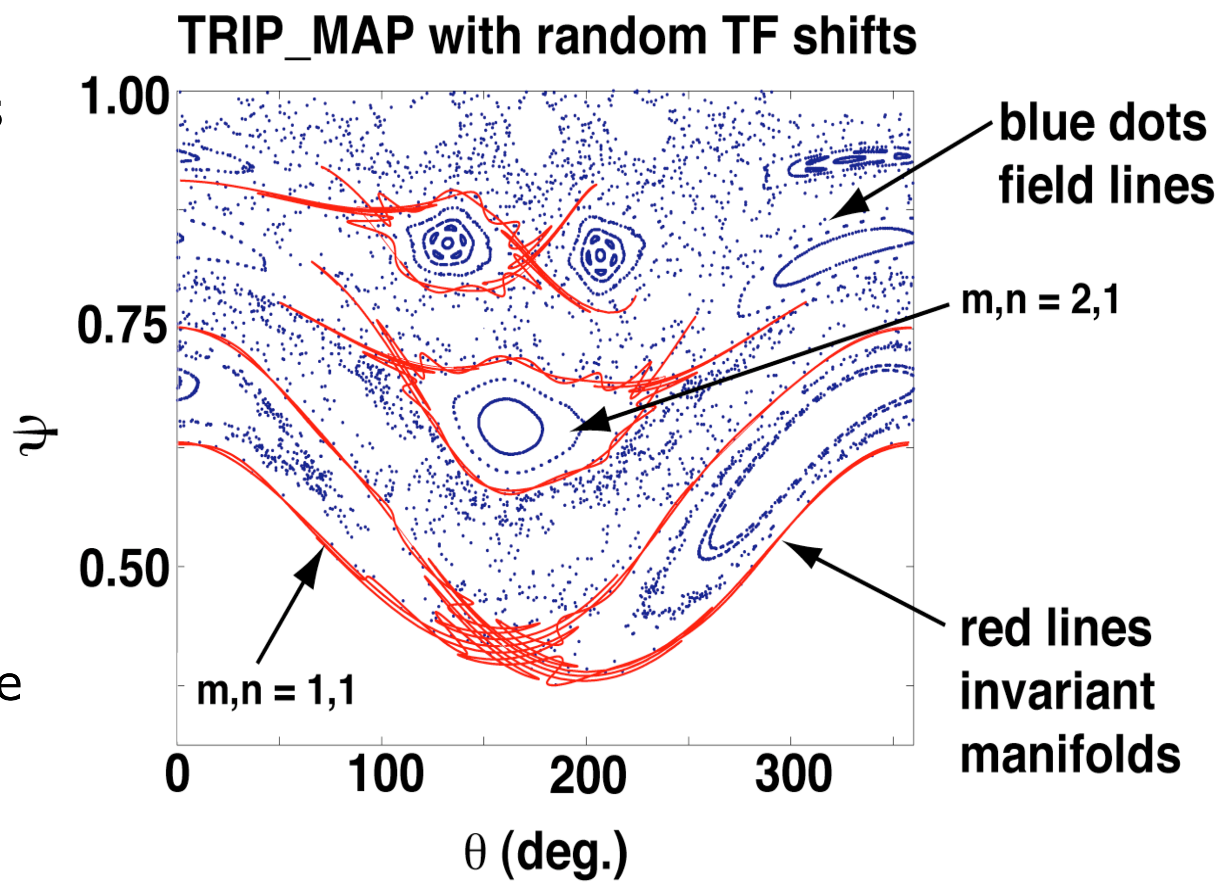
Small random displacements in all the tokamak coils can create stochasticity

- Invariant manifolds around resonant islands (red) separate classes of field line trajectories.
  - Field lines move toward (away) from hyperbolic points along stable (unstable) manifolds.



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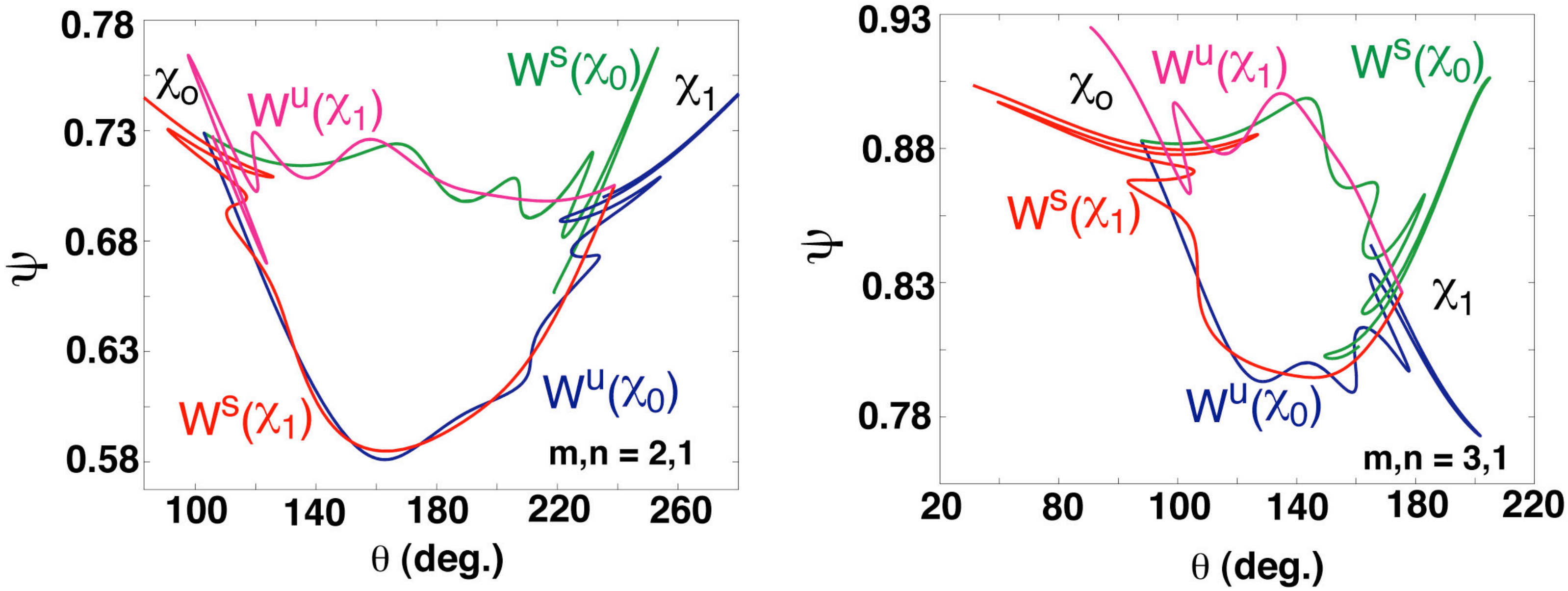
A complex web of tangle intersections near χ-points produces local island stochasticity

Expanded views of TRIP_MAP islands due to random TF shifts



- Field lines in tangles exhibit chaotic trajectories due to:
  - Stable-unstable manifold intersections produced by
    - Homoclinic tangles from single or opposing hyperbolic (χ) points.
- Stable-stable and unstable-unstable manifold intersections are forbidden

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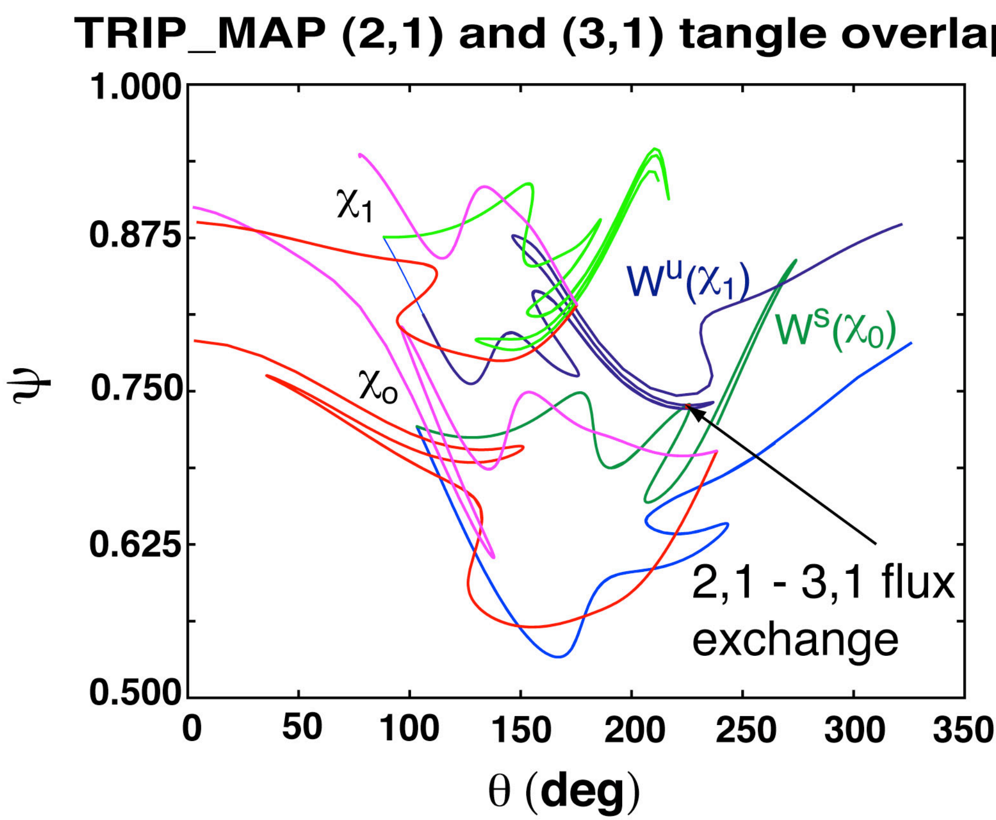
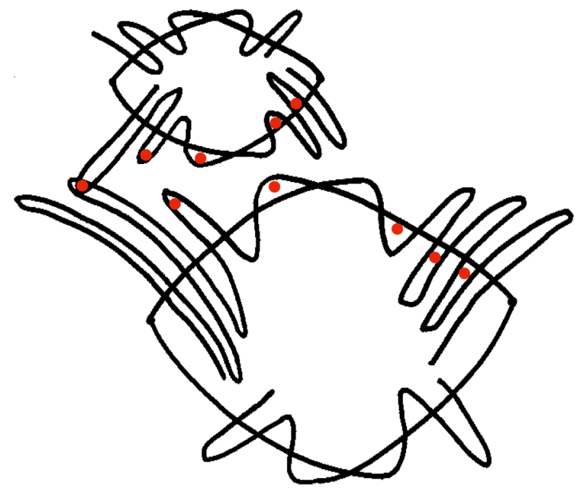
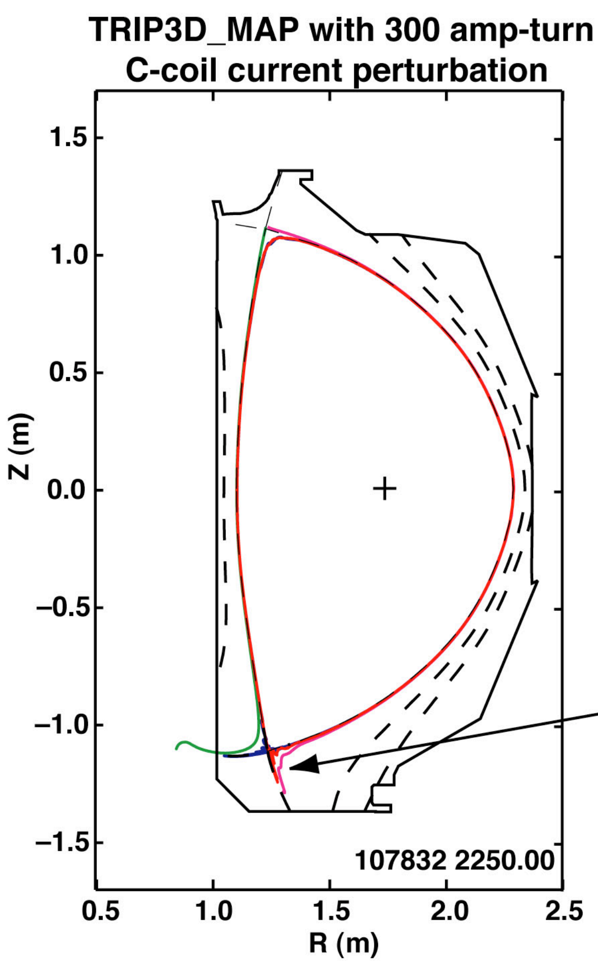
Tangle intersections between neighboring islands produce global stochasticity



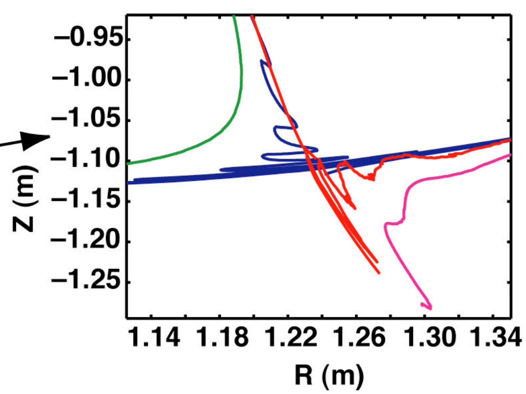


- Island-to-island intersections result in large scale non-diffusive field line transport

Homoclinic tangles appear in the DIII-D separatrix at very low perturbation amplitudes



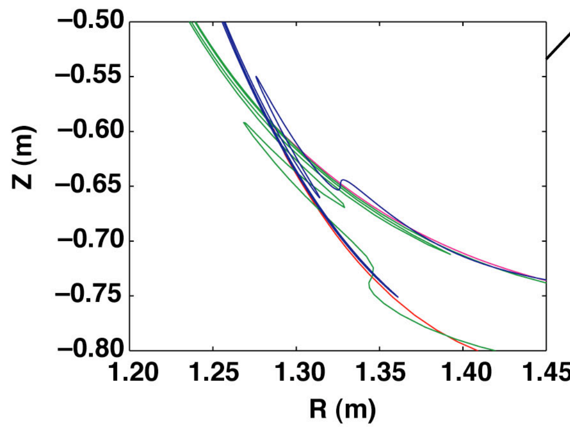
- Non-resonant separatrix splitting is produced by small magnetic perturbations:
  - Tangles appear with C-coil perturbation fields of ~ 0.8 gauss at plasma surface (the toroidal field is 2×10^4 gauss)
    - ~30x below the field-errors correction current
  - Each perturbation source contributes



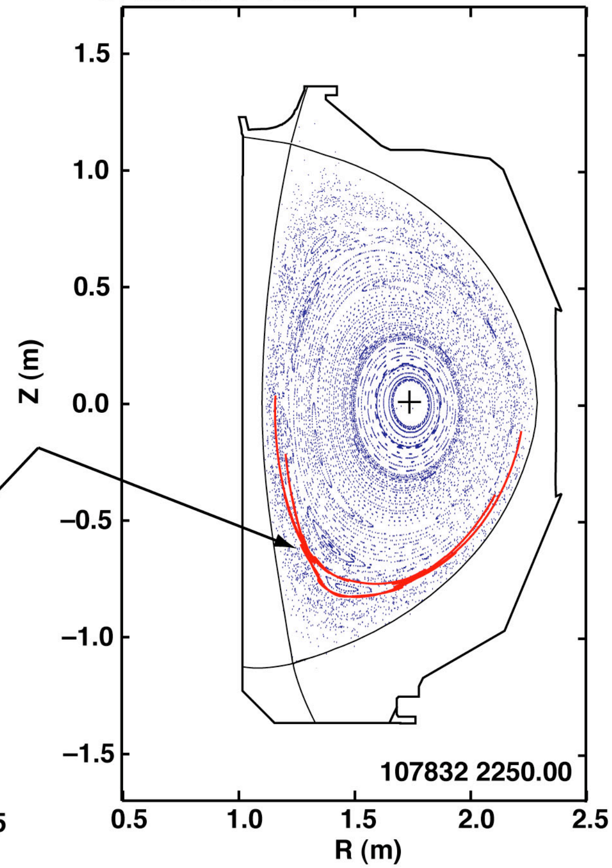
- Size and structure of non-resonant tangles sensitive to:
  - up-down symmetry, triangularity and other shape parameters

Complex webs of resonant homoclinic tangles are responsible for the onset of global stochasticity in the edge of the DIII-D tokamak

- The edge of a diverted tokamak is very sensitive to the onset of global stochasticity[1]
  - Neighboring resonant island tangles intersect across the high edge magnetic shear region
  - Resonant tangles intersect non-resonant tangles producing escape trajectories into the scrape-off layer
- The exact details of the escape trajectories depend on properties of the sources and the shape of the plasma

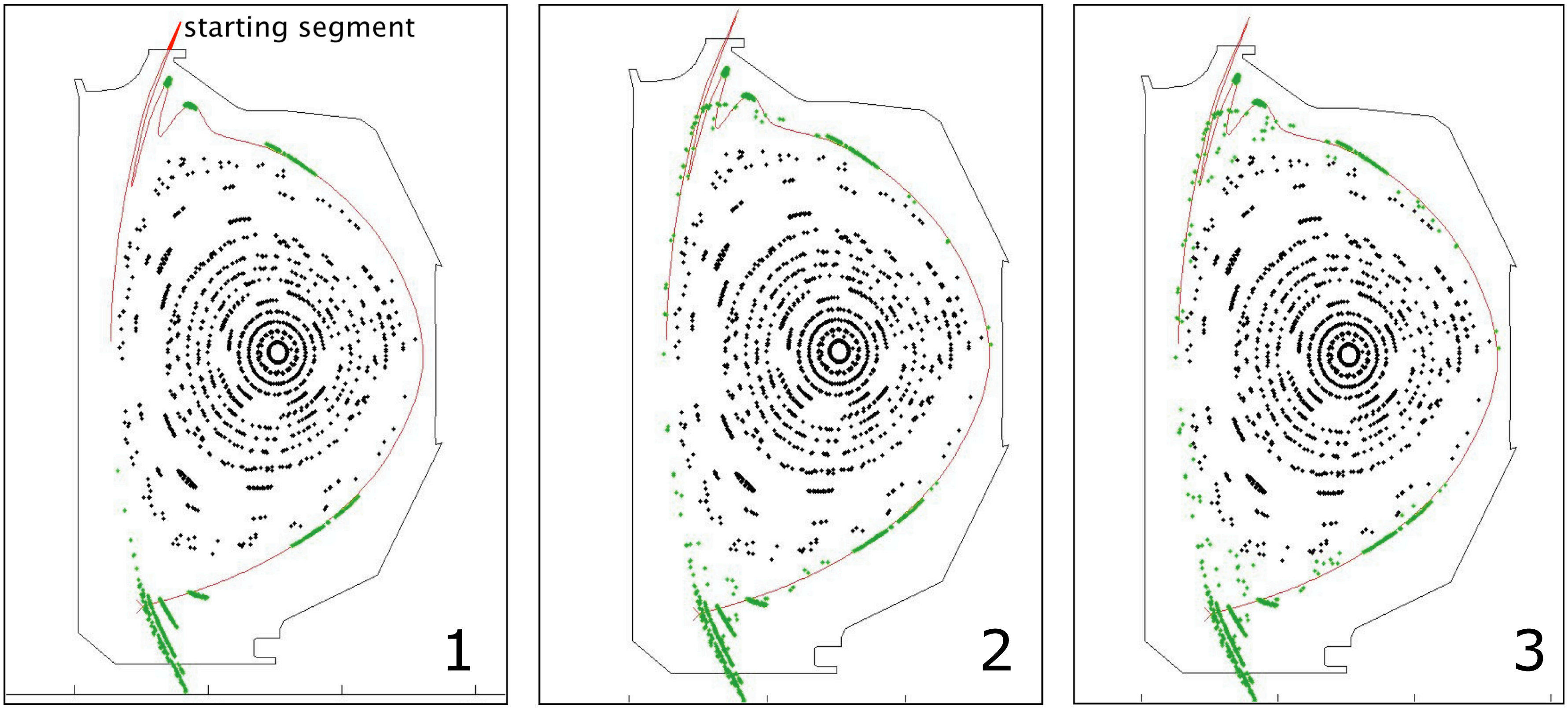


TRIP3D m,n=4,1 tangle with 10kA-turns in the DIII-D C-coil



[1]T. E. Evans, R. A. Moyer, P. Monat, Phys. Plasmas **9**, 4957 (2002)

Large regions of the edge plasma are connected to material surfaces by flux exchange through resonant and non-resonant tangle intersections



- Following part of a lobe that intersects the upper divertor backwards several iterations shows how field lines mix and escape from the edge plasma.

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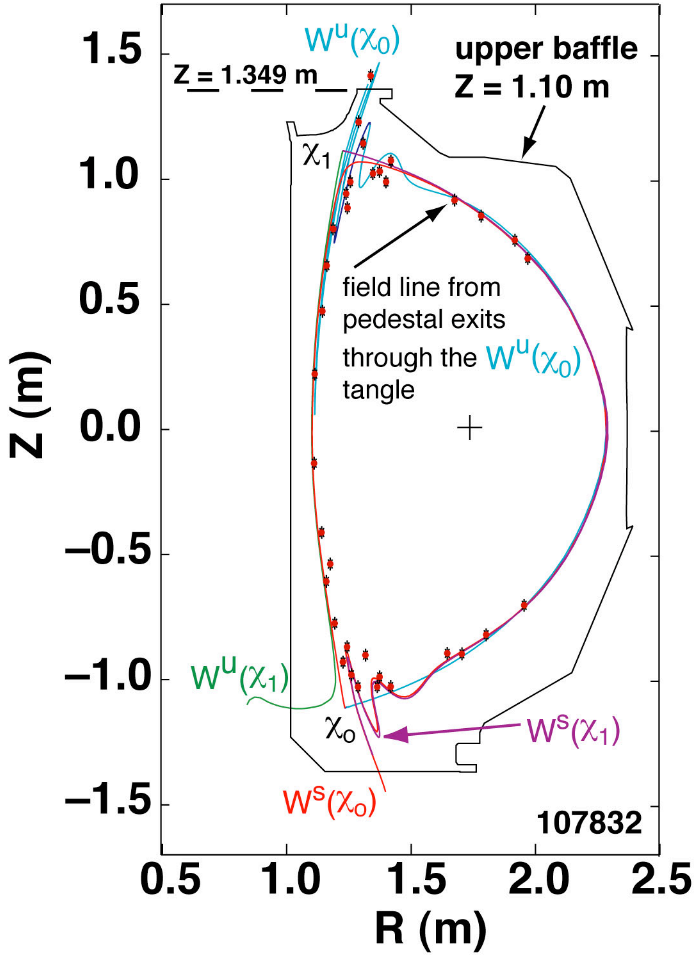
Heat and particles follow stochastic field lines that escape through non-resonant tangles

TRIP3D_MAP tangles with 10 kA-turns of C-coil current



- Heat and particles from deep inside the plasma escape through non-resonant homoclinic tangles and strike material surfaces in the divertors or other protruding structures[2]
- Patterns created by the escaping heat and particle flux can be related to topology of the non-resonant tangles

[2] R. K. W. Roeder, B. I. Rapoport, T. E. Evans, Phys. Plasmas **10**, 3796 (2003)

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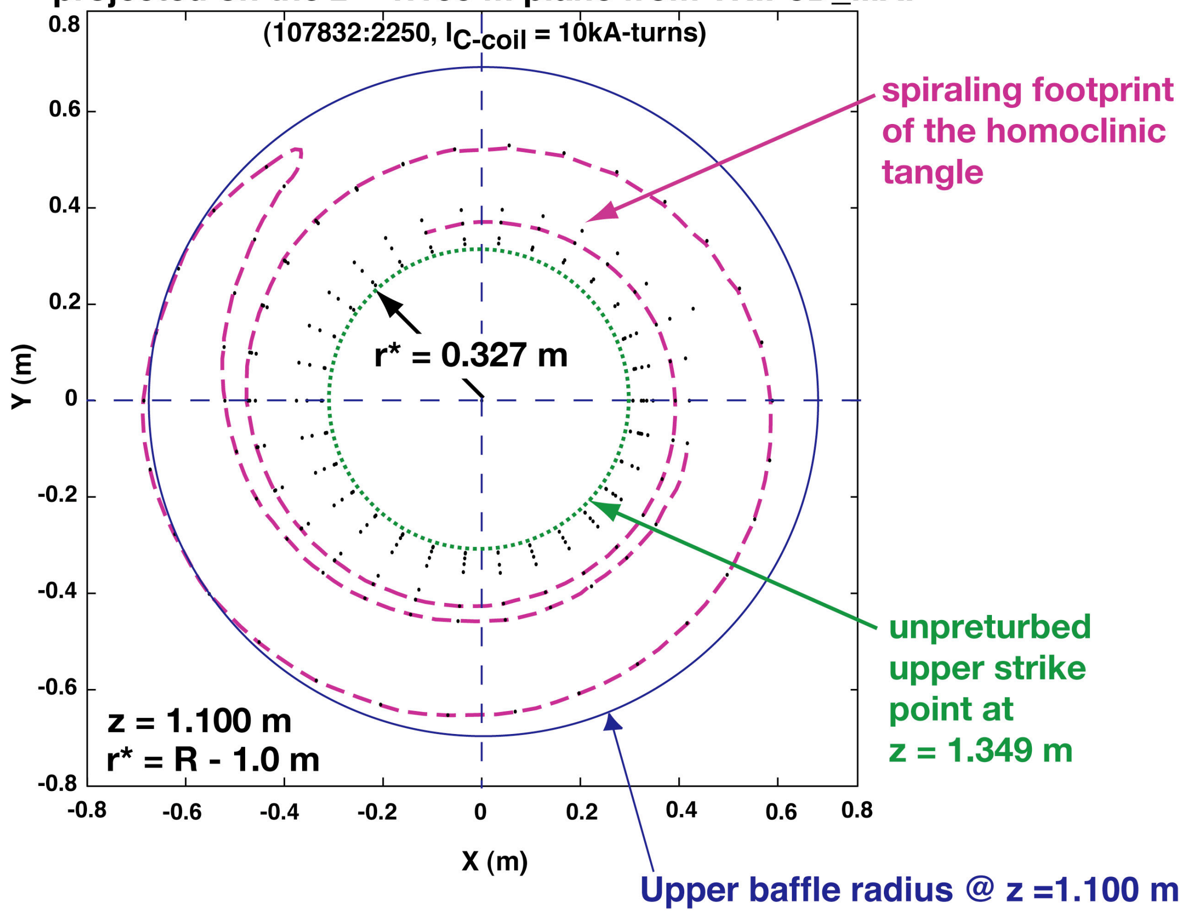
Non-resonant tangles form spiral-like patterns on toroidal surfaces such as divertor targets

- Non-resonant tangles create a unique signatures on plasma facing surfaces:
  - spiraling magnetic footprints on the divertor target plates[3]
  - Toroidally localized hot spots on protruding baffle structures
- At the location of the divertor plates the spiral due to the C-coil is ~1 cm.

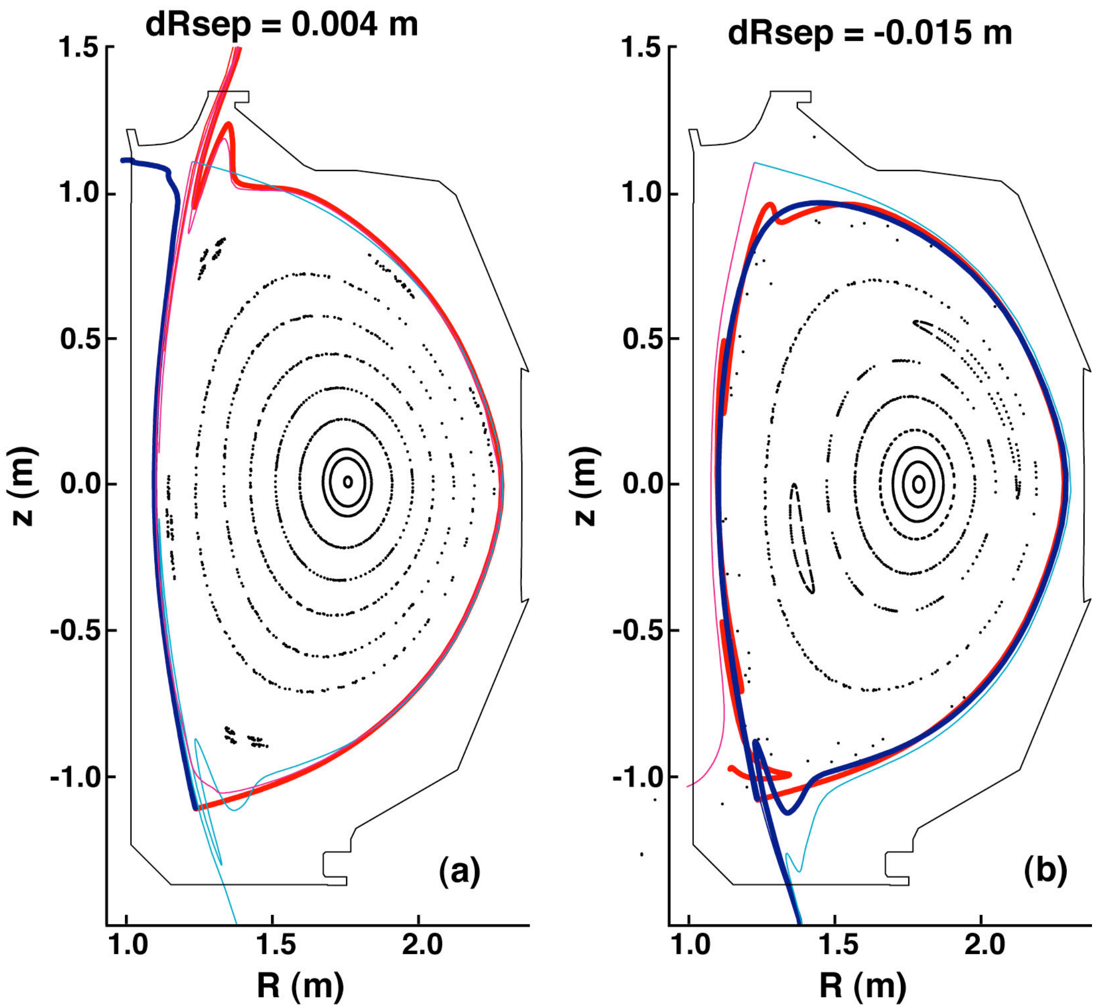
Toroidal pattern of a DIII-D magnetic field homoclinic tangle projected on the z = 1.100 m plane from TRIP3D_MAP



[3]Reminiscent of spirals in N. Pomphery, A. Reiman, Phys. Fluids B **4**, 938 (1992)

The topology of non-resonant tangles is sensitive to changes in the up-down equilibrium symmetry

- Tangles protrude near both χ-points in balanced (dRsep ~ 0) equilibria
  - Dominate χ-point has a double lobe structure
  - Secondary χ-point lobes shadow lobes from the primary χ-point
- The exact structure of the tangles is sensitive to shape parameters[4] like up-down balance (dRsep), triangularity, etc and perturbation amplitude.



[4]T. E. Evans, R. K. W. Roeder, J. A. Carter, B. I. Rapoport, Contrib. Plasmas Phys. **44**, 235 (2004)

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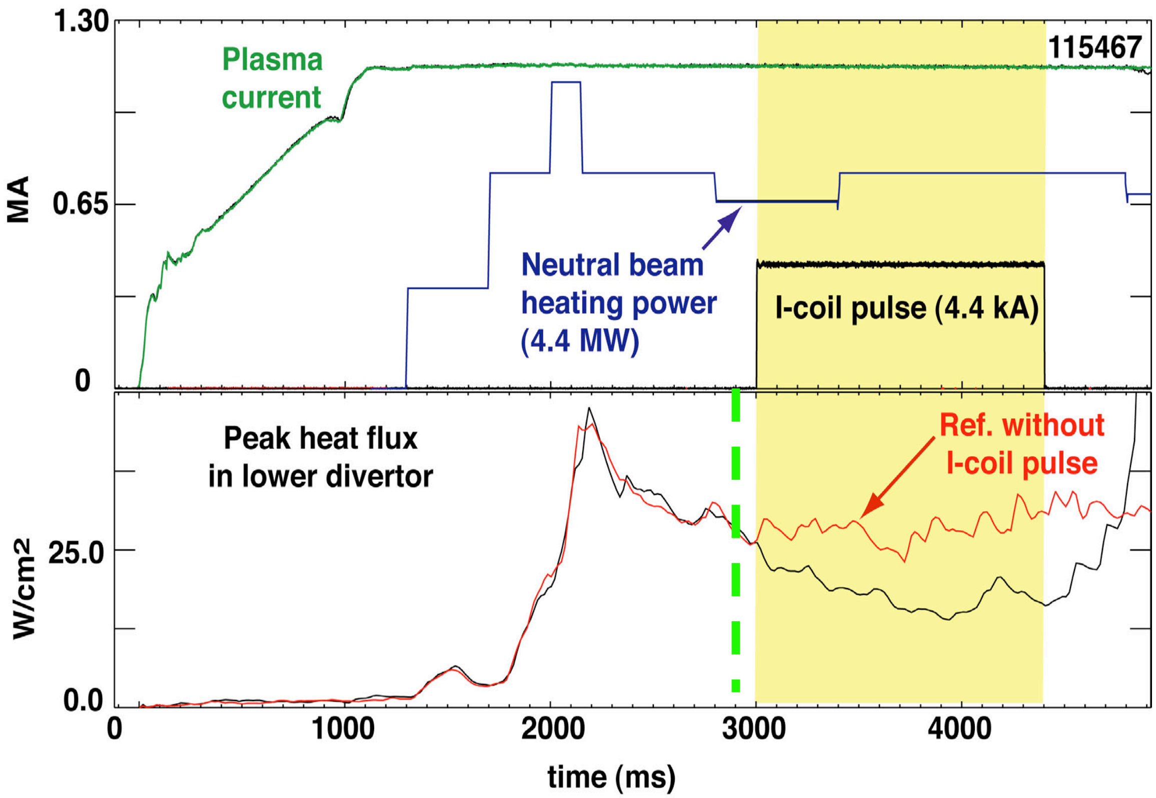
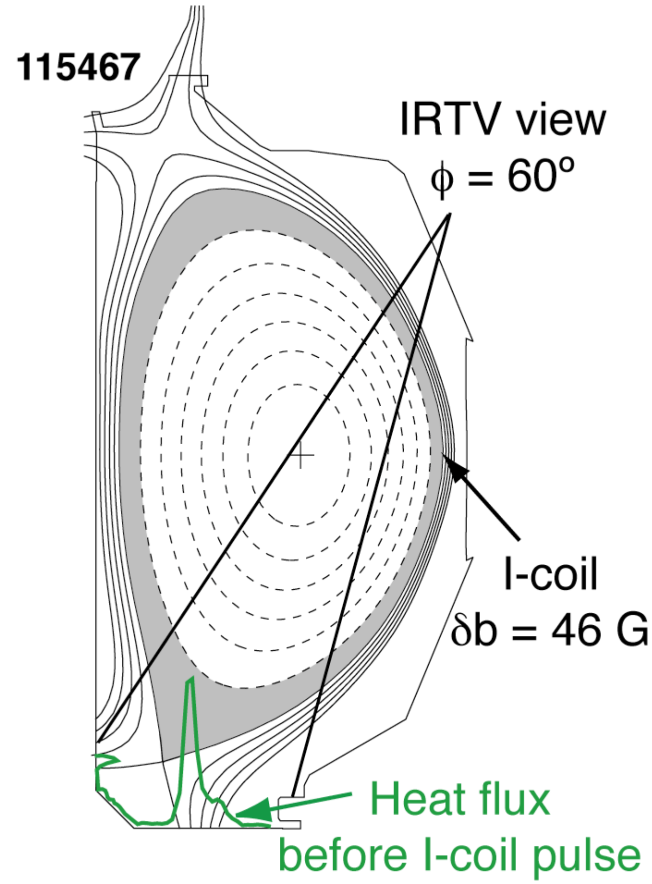
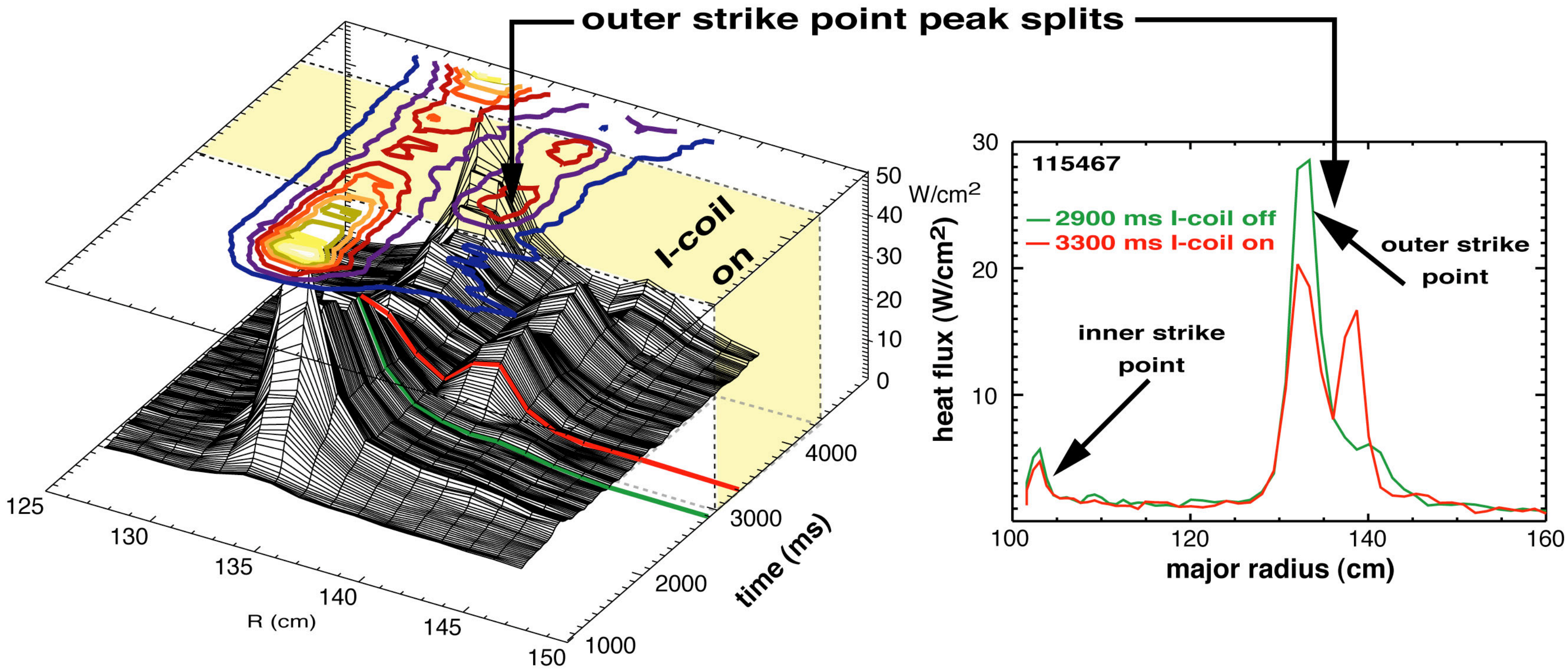
The divertor heat flux changes during magnetic perturbations from the I-coil





- The 4.4 kA I-coil pulse introduces a 46 gauss magnetic perturbation at the plasma surface.

The peak in the divertor heat flux slowly splits during I-coil perturbation



- Split heat flux peaks are consistent with divertor plate homoclinic tangle intersections
  - Correlated with I-coil pulse
  - Larger than modeling predicts and time dependent
    - Plasma response (evolution/amplification) is important

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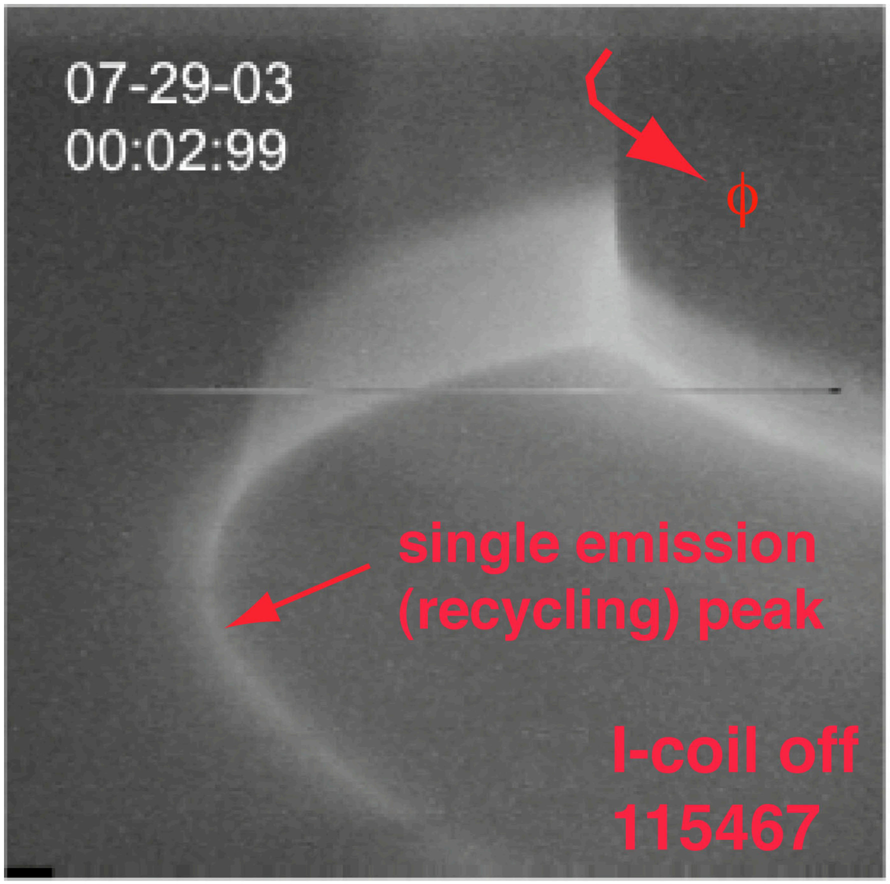
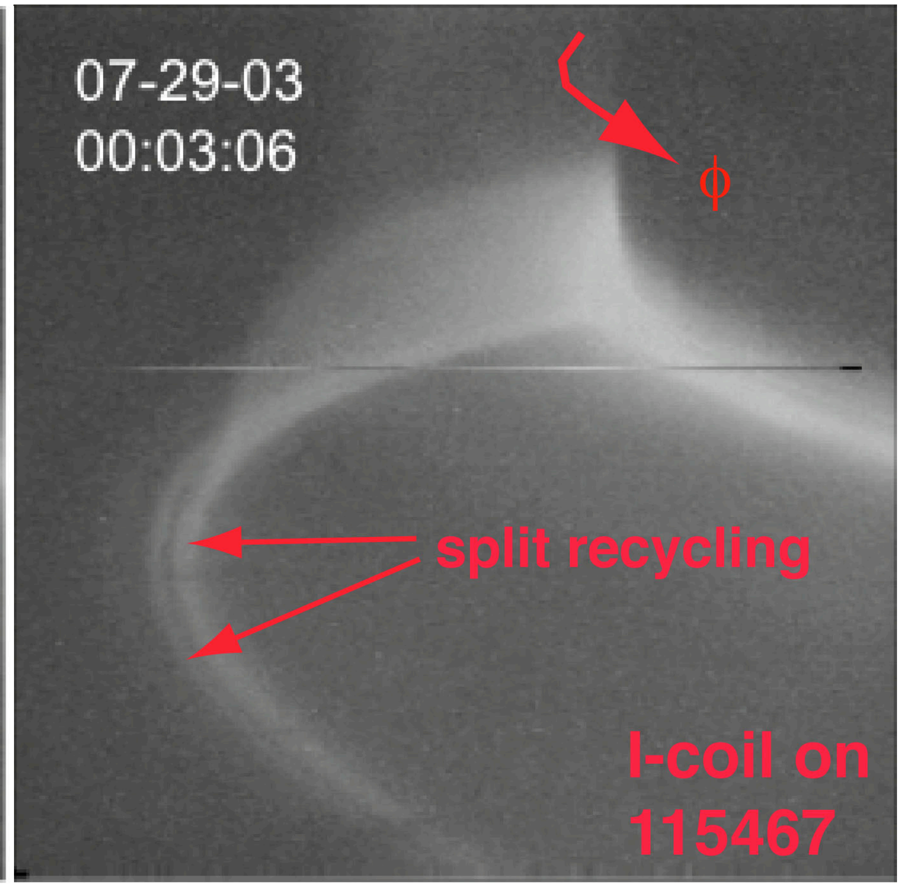
Plasma emissions in the lower divertor also splits during I-coil perturbation





- Tangentially viewing camera looking at plasma emissions in the lower divertor sees a splitting of the strike point recycling when the I-coil is pulsed.

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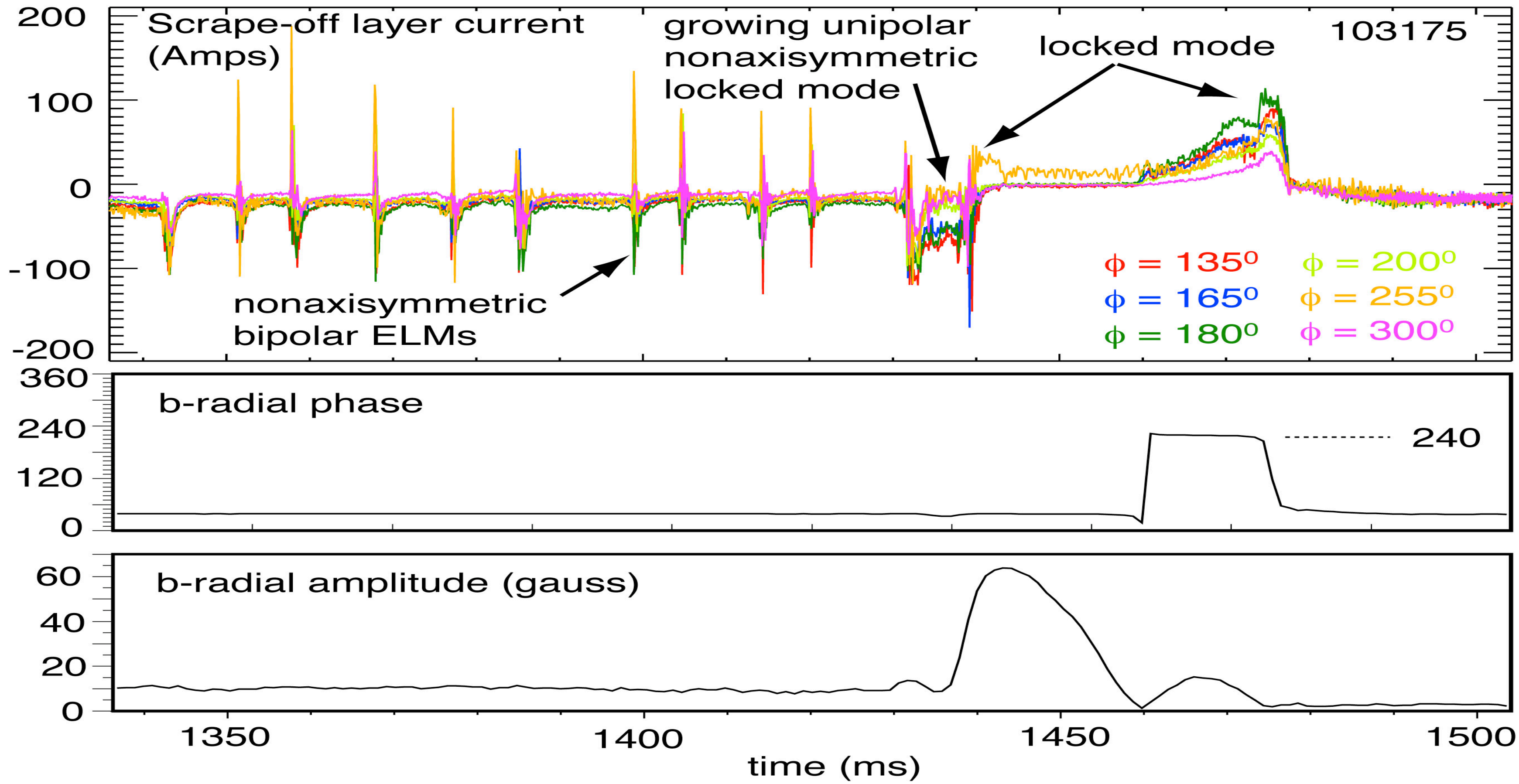
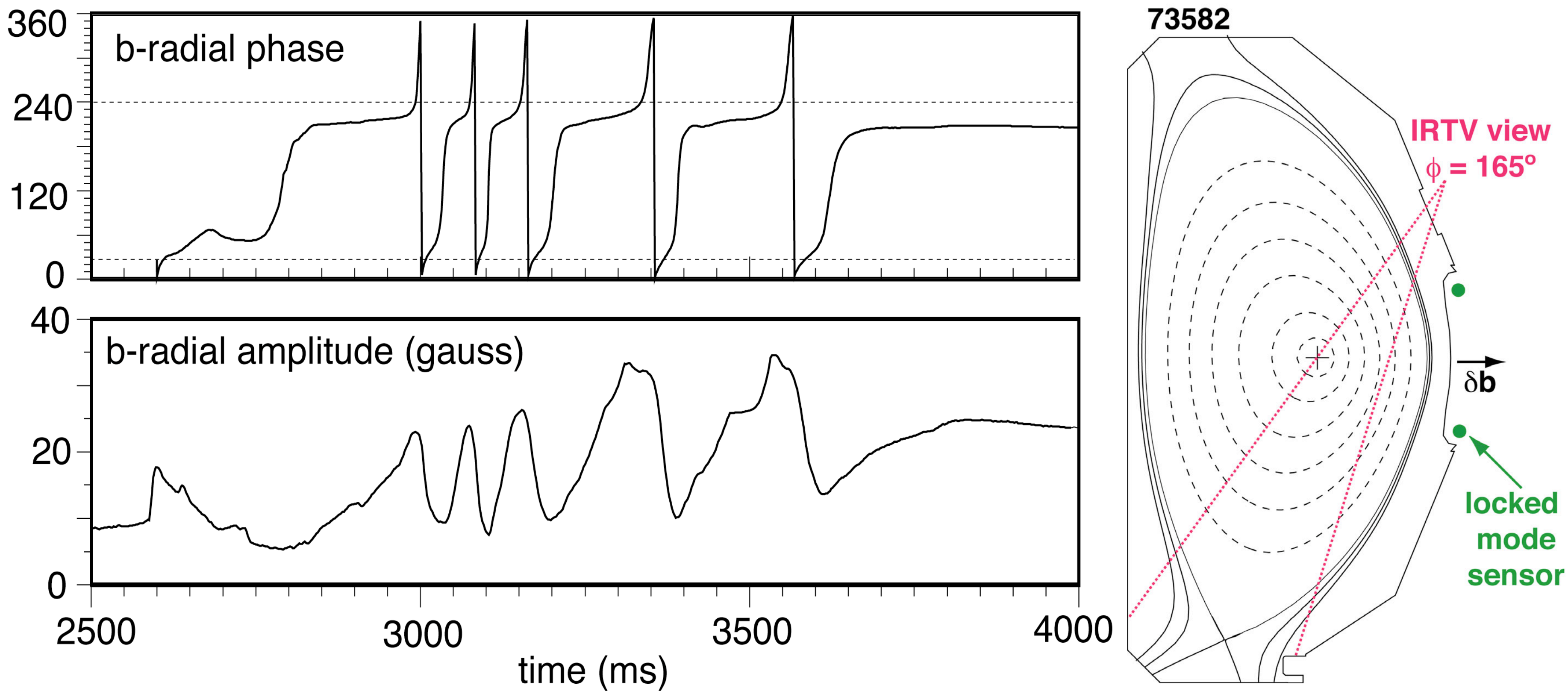
Magnetic perturbations from plasma instabilities also drive homoclinic tangles



- Currents in the scrape-off layer sometimes produce perturbations larger than those due to external coils.

Quasi-stationary modes produce rotating, time dependent, magnetic perturbations



- Rotating magnetic perturbations from Quasi-Stationary Modes (QSM) sweep divertor heat flux profiles past IRTVs viewing the lower divertor:
  - Toroidal mode structure is resolved

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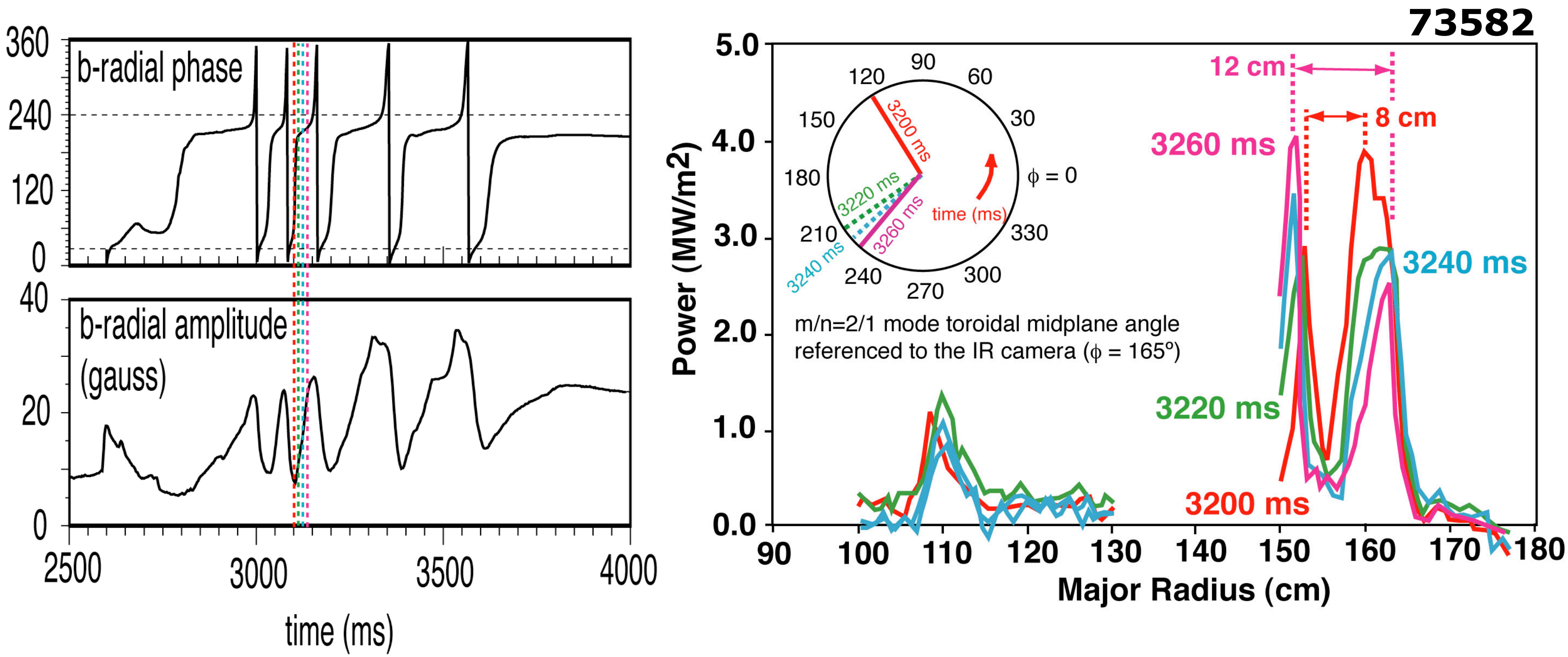
Rotating QSMs produce spiral-like signatures in the divertor heat flux



- The distance between the heat flux peaks increases as the QSM rotates past the IRTV
  - Consistent with a spiral structure induce by a homoclinic tangle

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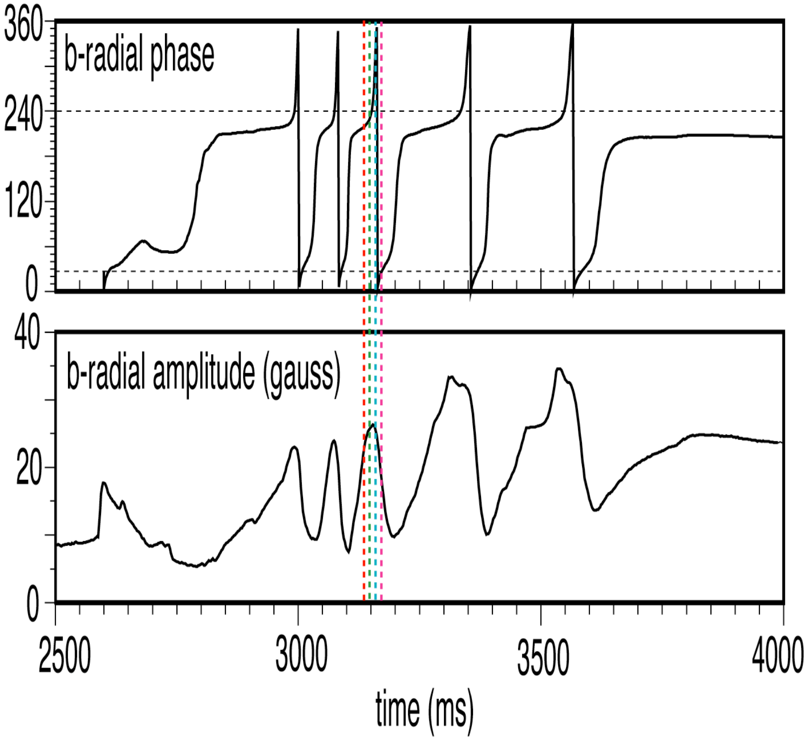
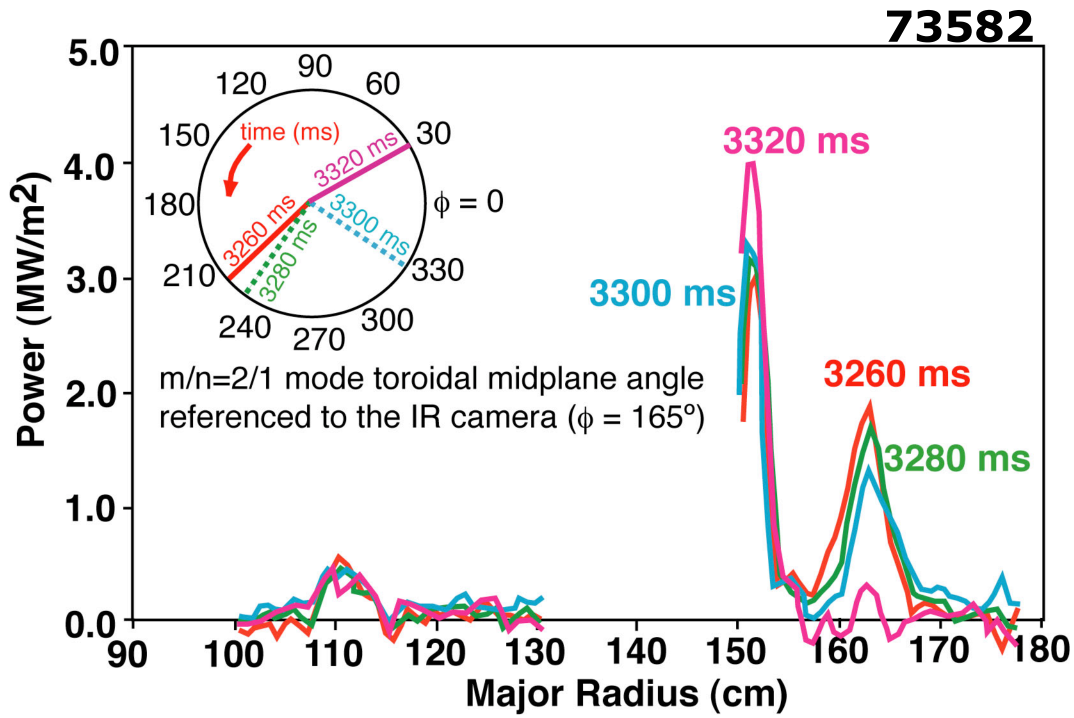
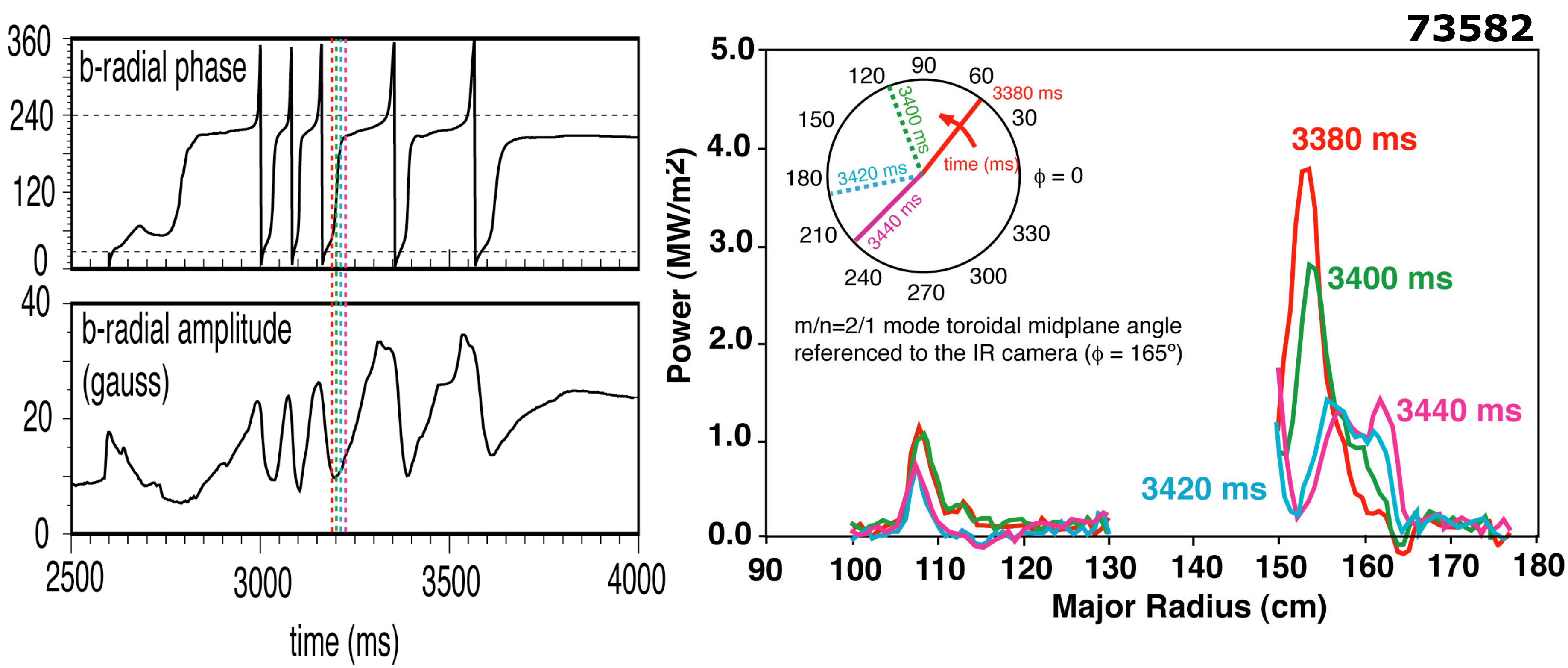
An n=1 toroidal mode structure is observed as a QSM rotates past the IRTV





- As the QSM rotates past the IRTV with relatively constant amplitude an n=1 toroidal mode structure is observed

The mode structure appears to be obscured by a change in the mode amplitude



- Other toroidal modes may also be present but are difficult to resolve with the IRTV data.

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Additional comments and observations

- Experimental signatures of homoclinic tangles are also seen during:
  - Edge Localized Modes (ELMs)
    - toroidal asymmetries in scrape-off layer currents seen in DIII-D
    - Split, spiraling heat flux footprints seen in ASDEX-U
  - Resistive Wall Modes (RWMs) in DIII-D
  - Disruption halo currents in DIII-D
- With increasing tokamak performance levels (higher plasma pressure and confinement) MHD instabilities tend to be more severe implying:
  - A greater need for external control coils
  - Additional complexity in the edge plasma
- Dynamical systems analysis provides a starting point for understanding the topology of the edge plasma (and interactions with material surfaces) but self-consistent plasma models are needed.

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Conclusions

- Modeling results show that two types of homoclinic tangles are involved in determining the edge magnetic topology of poloidally diverted tokamaks:
  - resonant tangles surrounding helical magnetic islands result in global stochatic flux exchange across the plasma edge
  - non-resonant tangles establish escape trajectory pathways to material surfaces
- Experimental measurements demonstrate that tangle-like structures turn on and off with external perturbations
  - Calculations of externally driven spirals and splitting widths in the divertors are too small to match the experimental data
- Time dependent tangle signatures are seen during plasma generated MHD activity
  - Toroidal and radial structure match those calculated with the numerical model
- Plasma effects need to be included in the model and comparisons with experimental data are required