3D edge issues in tokamaks

Presented by:
T. E. EVANS
General Atomics, San Diego, CA

With contributions by:
R. K. W. Roeder,
Cornell University, Ithaca, NY

J. A. Carter,
University of North Carolina, Chapel Hill, NC

B. I. Rapoport,
Oxford University, Oxford, UK

M. E. Fenstermacher and C. J. Lasnier
Lawrence Livermore National Laboratory, Livermore, CA

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

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

- The C-coil (not shown) is used on almost every discharge to correct field-errors that cause locked modes and Quasi-Stationary Modes (QSMs).
Hamilton-Jacobi form of magnetic field is used for the perturbation analysis

- Represent magnetic field lines in action-angle coordinates:

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

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

the toroidal angle $\phi$ is a time-like variable and $\varepsilon$ 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
Non-axisymmetric magnetic perturbations produce separatrix splitting resulting in the formation of homoclinic tangles.

Stable and unstable manifolds intersect to produce both resonant and non-resonant homoclinic tangles.
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.
Field lines in tangles exhibit chaotic trajectories due to:
- Stable-unstable manifold intersections produced by Homoclinic tangles from single or opposing hyperbolic \( \chi \) points.
- Stable-stable and unstable-unstable manifold intersections are forbidden.
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 $2 \times 10^4$ gauss)
    - $\sim 30 \times$ 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

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

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.

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
  - 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.

\[ r^* = 0.327 \text{ m} \]
\[ z = 1.100 \text{ m} \]

\[ r^* = R - 1.0 \text{ m} \]

\[ z = 1.349 \text{ m} \]

Upper baffle radius @ \( z = 1.100 \text{ m} \)

\[ \text{unperturbed upper strike point at} \]

\[ \text{Reminiscent of spirals in N. Pomphery, A. Reiman,} \]

\[ \text{Phys. Fluids B 4, 938 (1992)} \]
The topology of non-resonant tangles is sensitive to changes in the up-down equilibrium symmetry

- Tangles protrude near both $\chi$-points in balanced ($dR_{\text{sep}} \sim 0$) equilibria
  - Dominate $\chi$-point has a double lobe structure
  - Secondary $\chi$-point lobes shadow lobes from the primary $\chi$-point
- The exact structure of the tangles is sensitive to shape parameters like up-down balance ($dR_{\text{sep}}$), triangularity, etc and perturbation amplitude.

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

- 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.
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
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 induced by a homoclinic tangle
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.
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.
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 stochastic 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