Strike point splitting: a tool for error field analysis

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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?

Shot 115467 during I-coil pulse
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 …?
I-coil $n = 3$ odd parity
low stochasticity for $q_{95} \sim 3.5$

- Parity (even/odd) controls magnetic spectrum
- Weak edge resonant perturbation spectrum ($\delta B_{nm}^{\text{res}} \sim 0.8 \, \text{G}$)
- 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 ($\delta B_{nm}^{\text{res}} \sim 6.0$ G)
- Full ELM suppression
TRIP3D superimposes external coil fields (Biot-Savart) with Grad-Shafranov axisymmetric equilibrium (EFIT)

- Resonant harmonics of $\delta b_{mn}$ determine the widths of the islands that form in the vacuum approximation
Vacuum approximation generates strong stochasticity

- Vacuum approximation often believed to be sufficient for 0th order magnetic topology in L-mode plasmas: TEXT, TEXTOR, Tore-Supra, stellarators
- Considering amplification and shielding, can this really be true in H-mode?
Strike point structure can be used to probe upstream magnetic field topology

• 5 cm width qualitatively matches TRIP3D field line tracing

• Width scales as $\sim (\delta b/B)_{res}$

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

• Inspired transport simulations and an additional IR cameras
E3D Braginskii fluid transport code developed for stochastic 3D fields

Assumes anomalous $\perp$ transport in static background field

- **Energy equation:** (only energy equations used in this study)
  \[
  \frac{3}{2} n (\partial_t T + u_\parallel \nabla_\parallel T) = \nabla_\parallel \kappa_\parallel \nabla_\parallel T + \nabla_\perp \kappa_\perp \nabla_\perp T + Q_{ei}
  \]

- **Parallel momentum**
  \[
  mn \left( \partial_t u_\parallel + \nabla_\parallel \left( \frac{1}{2} u_\parallel^2 \right) \right) = qnE_\parallel - \nabla_\parallel p - \nabla \cdot \Pi_\parallel
  \]

- **Quasineutral continuity**
  \[
  \partial_t n + \nabla_\parallel nu_\parallel = \nabla_\perp D_\perp \nabla_\perp n
  \]

- **Nonlinear sheath BC’s** (R. Chodura)
  \[
  Q = \beta nTC_s \cos \theta_w \sim nT^{3/2} \quad \Gamma = nC_s \cos \theta_w \sim nT^{1/2}
  \]
E3D uses *Monte-Carlo* fluid elements & field aligned grid to accurately solve anisotropic fluid equations

- Heat transport highly anisotropic \[ \frac{\kappa_{\parallel}}{\kappa_{\perp}} = \frac{\chi_{\parallel}}{\chi_{\perp}} \sim 10^8 - 10^{10} \]

- Stochasticity can generate small scales

- 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.
E3D simulations show large effect on $T_e$ and $T_i$ due to change in connection length structure

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

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

2 unstable branches enter the X-point as $\phi \to \infty$
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
  \[ B \cdot \nabla \psi_\pm = 0 \]
- Field lines can only escape along the tangle
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.
The dynamics of tangle transport can be observed by traveling around the torus.
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$_{95}$
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
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 \( T_e \) and \( T_i \) at target
- Rotating tearing activity should produce equivalent toroidally averaged profile
However, measured heat & particle fluxes are quite different!

129194   inner strike point  3.0-3.2 sec

- Heat flux appears to be axisymmetric?
  - Neither IR camera shows significant strike point splitting

129752   outer strike point  3.2-3.6 sec

- TEXTOR IR camera placed at 165°
- DiMES camera (filtered Dα) at 157°
(M Jakubowski & O Schmitz, FZ-Julich)
The outer lobes are thermally isolated from the interior except during radial transport events (M Jakubowski & O Schmitz, FZ-Julich)
When a large $n=1$ mode appears heat flux splitting is observed!

- 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)
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
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

\[
\Delta'_{\text{layer}} = \Delta'_{\text{tear}} + \Delta_{\text{ext}} \frac{b_{\text{vac}}}{b_{\text{tear}}} \Rightarrow \frac{b_{\text{tear}}}{b_{\text{vac}}} = \frac{\Delta_{\text{free}}}{-\Delta'_{\text{tear}} + \Delta_{\text{layer}}} \sim \frac{1}{1 - (-i\omega\tau_{\text{layer}})^{\alpha}}
\]

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

\[
\delta_{\text{layer}} \sim S^{-1/3} P^{1/6} r \sim 1 \text{mm} \\
\tau_{\text{layer}} \sim S^{-1/3} P^{1/6} \tau_R \sim 10 - 100 \text{ms}
\]
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.