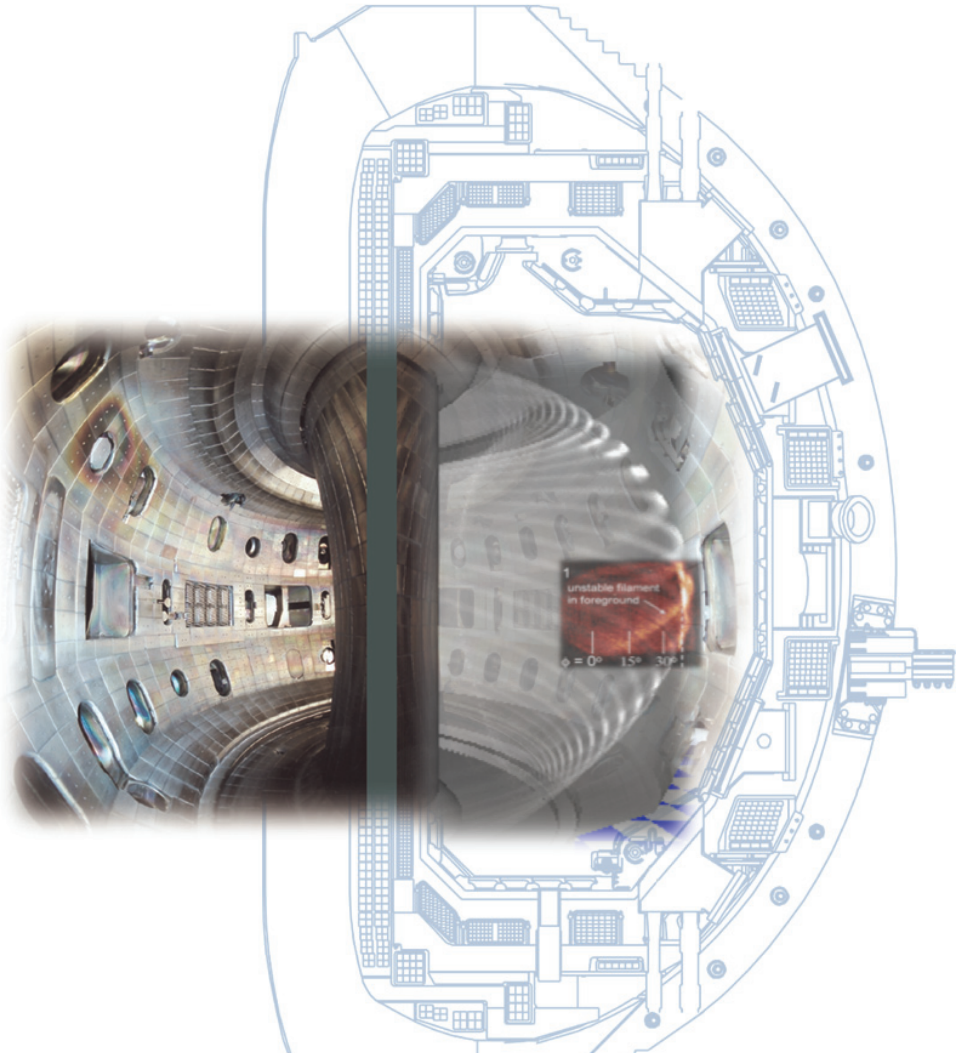
Magnetic Barriers and their Possible Role in ELM Control by Resonant Magnetic Perturbations at DIII-D

Presented by
F. Volpe, Univ. of Wisconsin, Madison

On behalf of
J. Kessler, SE Missouri State University

In collaboration with
T.E. Evans, General Atomics
H. Ali, A. Punjabi, Hampton Univ., VA



ELM images: P. Snyder (GA) and J. Yu (UCSD).

15th Workshop on MHD Stability Control: "US-Japan Workshop on 3D Magnetic Field Effects in MHD Control"
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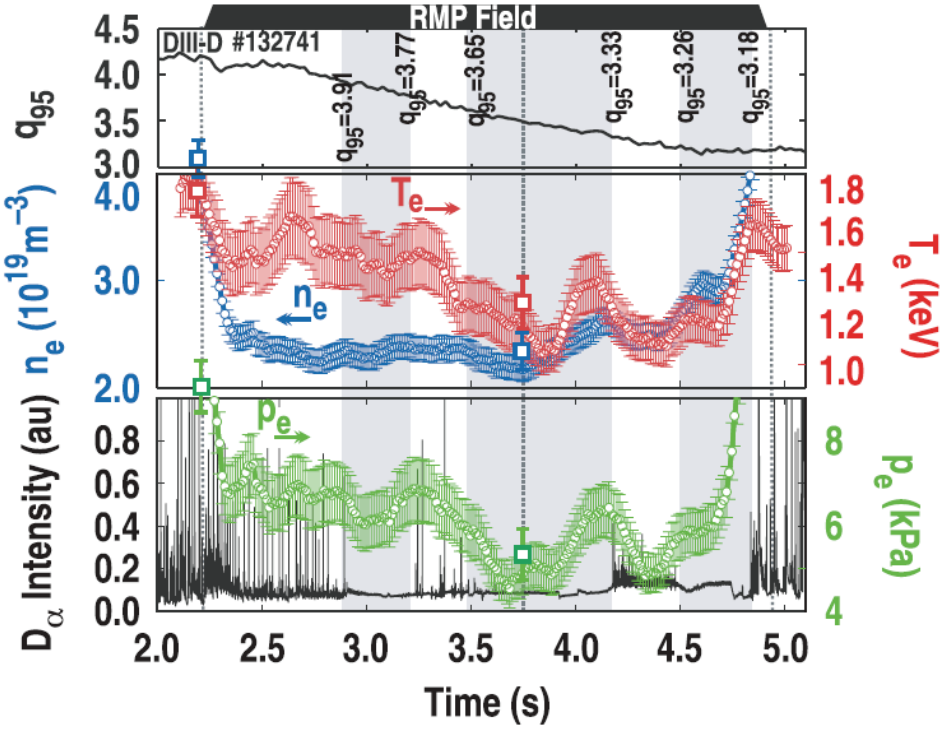
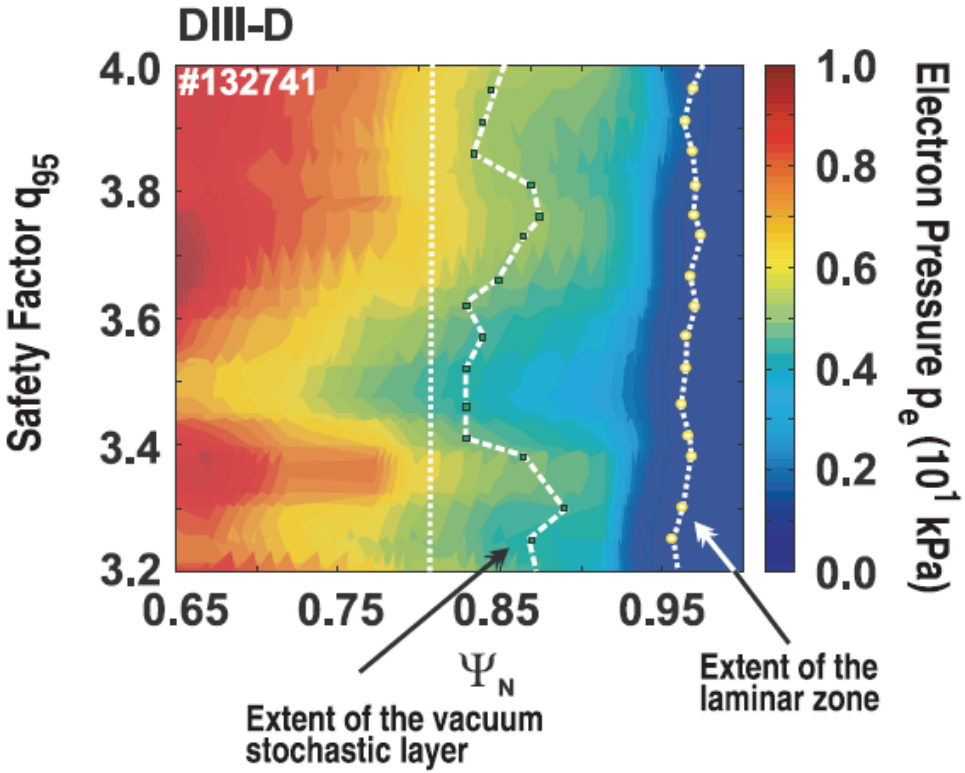
ELMs are Suppressed Only for Values of q_{95} at Which the Stochastic Layer is Broadest





[Schmitz, PRL 2010]

Our hypothesis:
a laminar surface ("magnetic barrier") forms in the middle of the stochastic region for specific values of q_{95}

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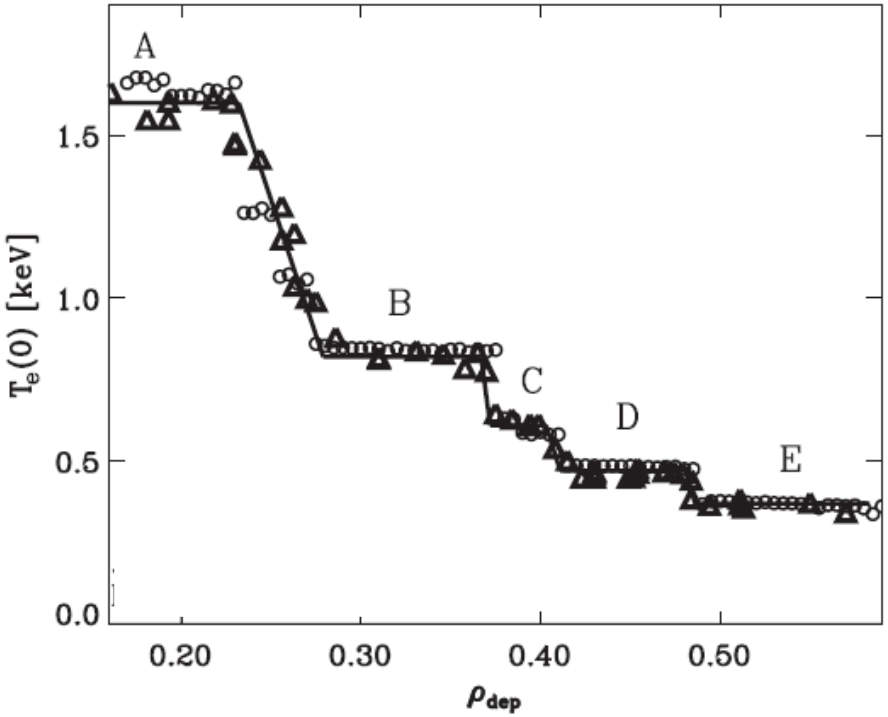
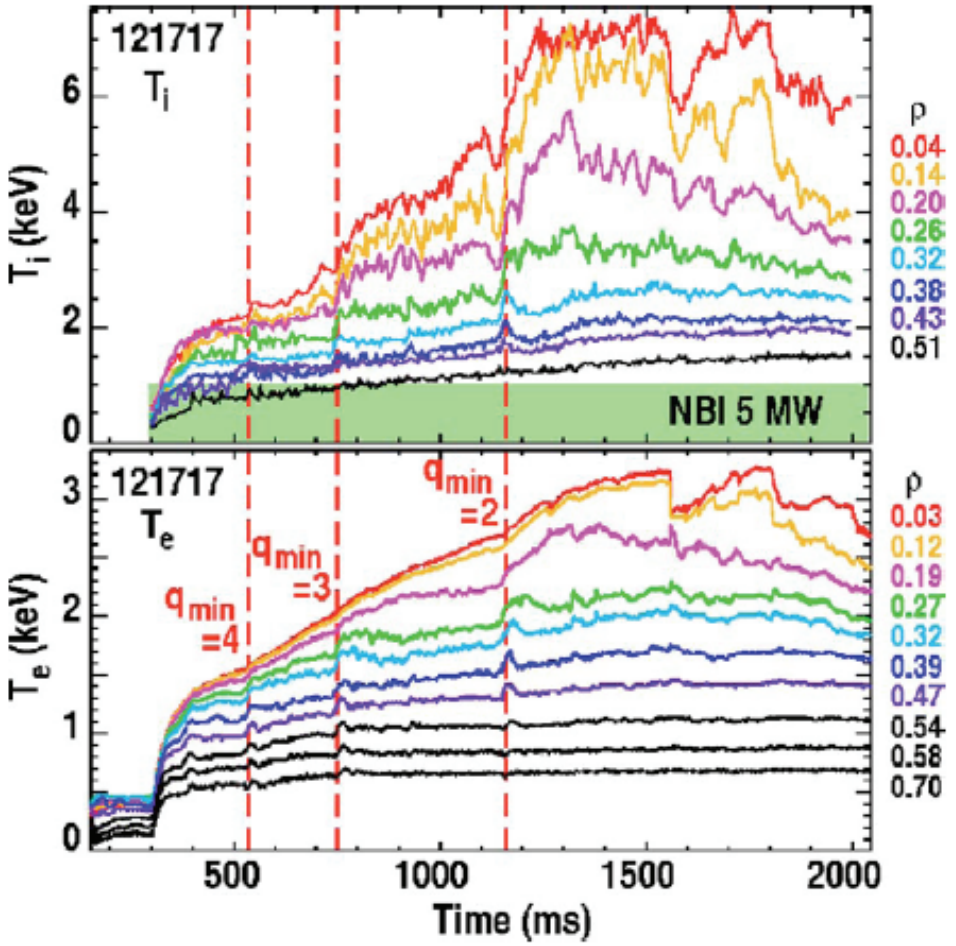
Magnetic Barriers Might also Explain a Class of Internal Transport Barriers forming at Rational q and q_{min}



↑ RTP [Hogeweij 1998]

DIII-D [Austin 2006] →



Attributed to magnetic barriers at special irrational values of q in the immediate vicinity of observed rational q's [Schilam, 2002]

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Outline

- **What are Magnetic Barriers and how we mathematically "construct" them**
- **How we can numerically detect barriers in a realistic, experimental configuration**
  - Criteria defined on idealized geometries, then extended to EFIT +trip3d results
- **n=1 magnetic barriers can form (have formed?) at DIII-D**
- **n=3 semi-permeable magnetic barriers can also form**
  - Intermittent in q_{95} → possible explanation of q_{95} dependence of ELM control by Resonant Magnetic Perturbations (RMPs)?

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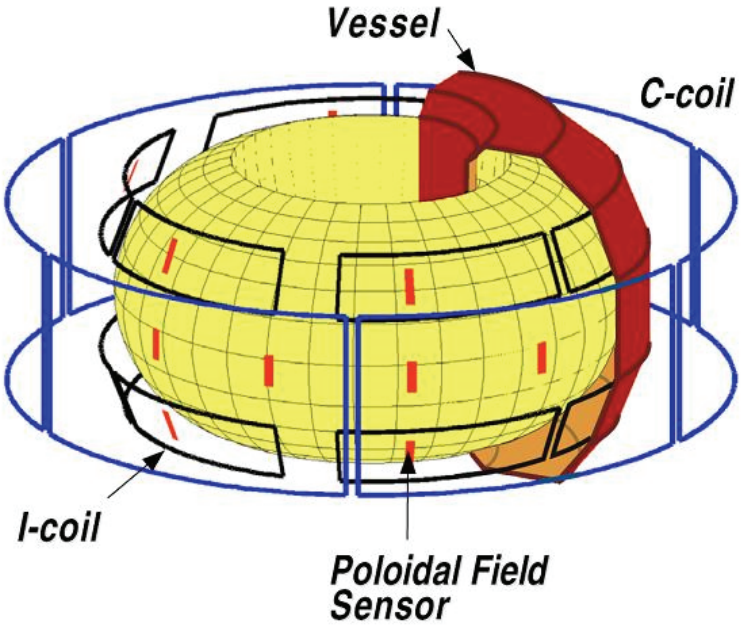
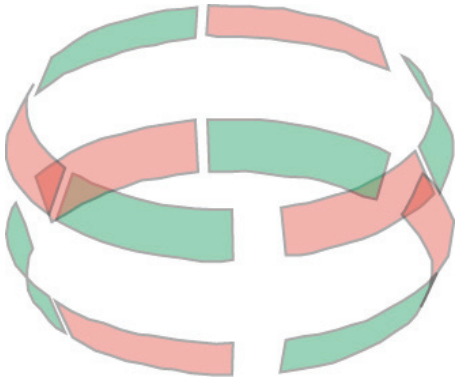
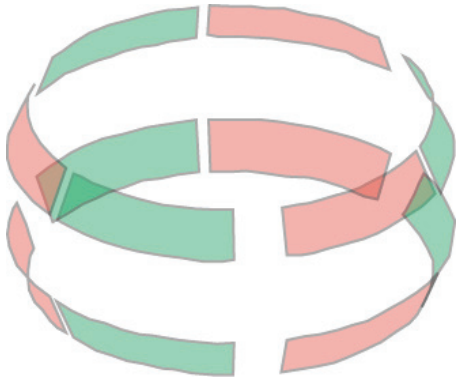
Magnetic Field Lines were Traced and 'Puncture Plots' Generated in Search for Barriers

- EFIT equilibrium field
- Super-imposed *vacuum* field from I-coils, via trip3d code
- *n*=1, for comparison with [H. Ali and A. Punjabi, PPCF 2007]
- *n*=3 as in ELM experiments

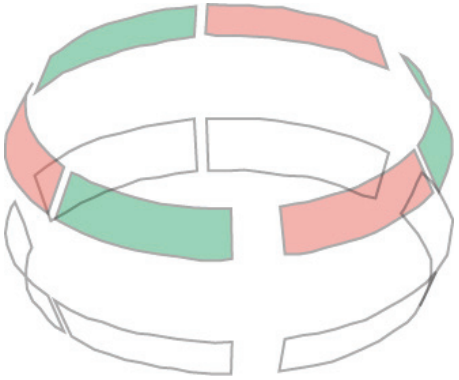




Odd parity



Even parity



Single row (upper)

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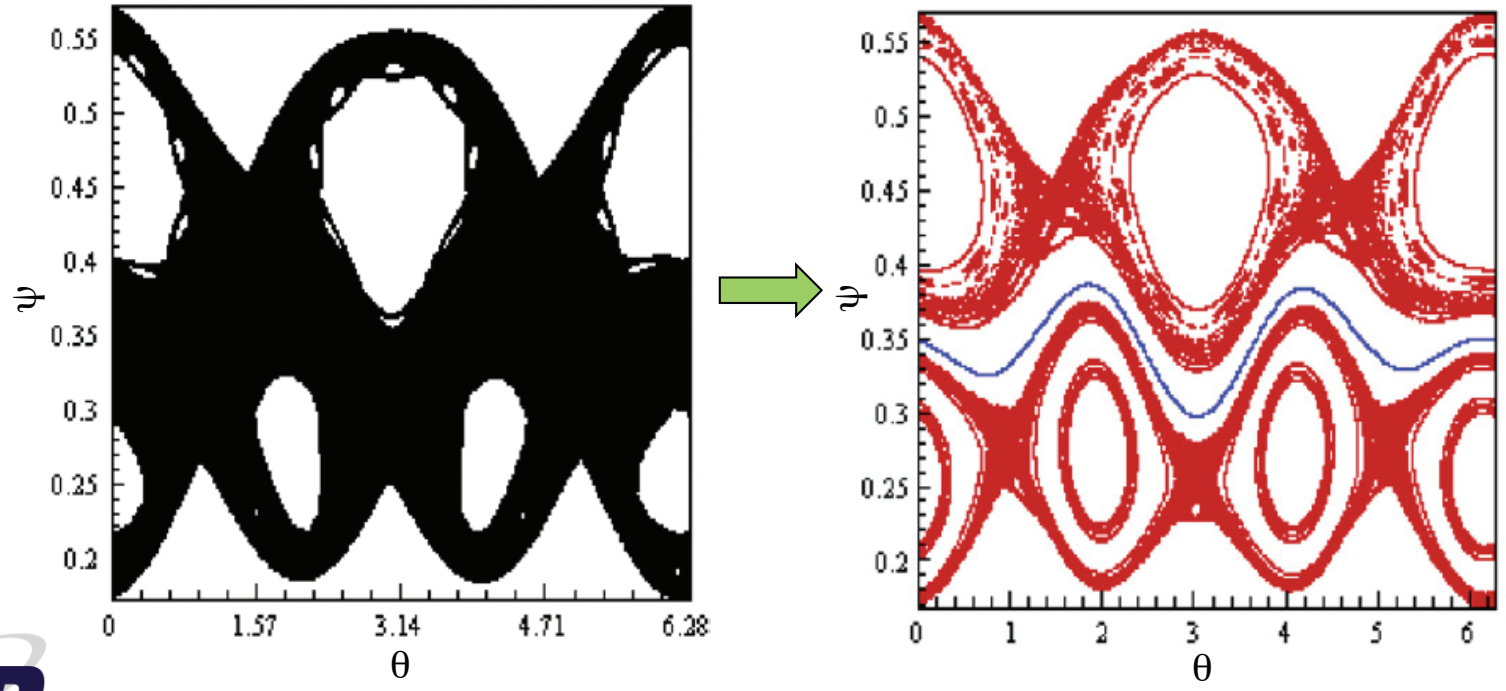
Large Coalescing Islands Generate Chaos but also Magnetic Barriers

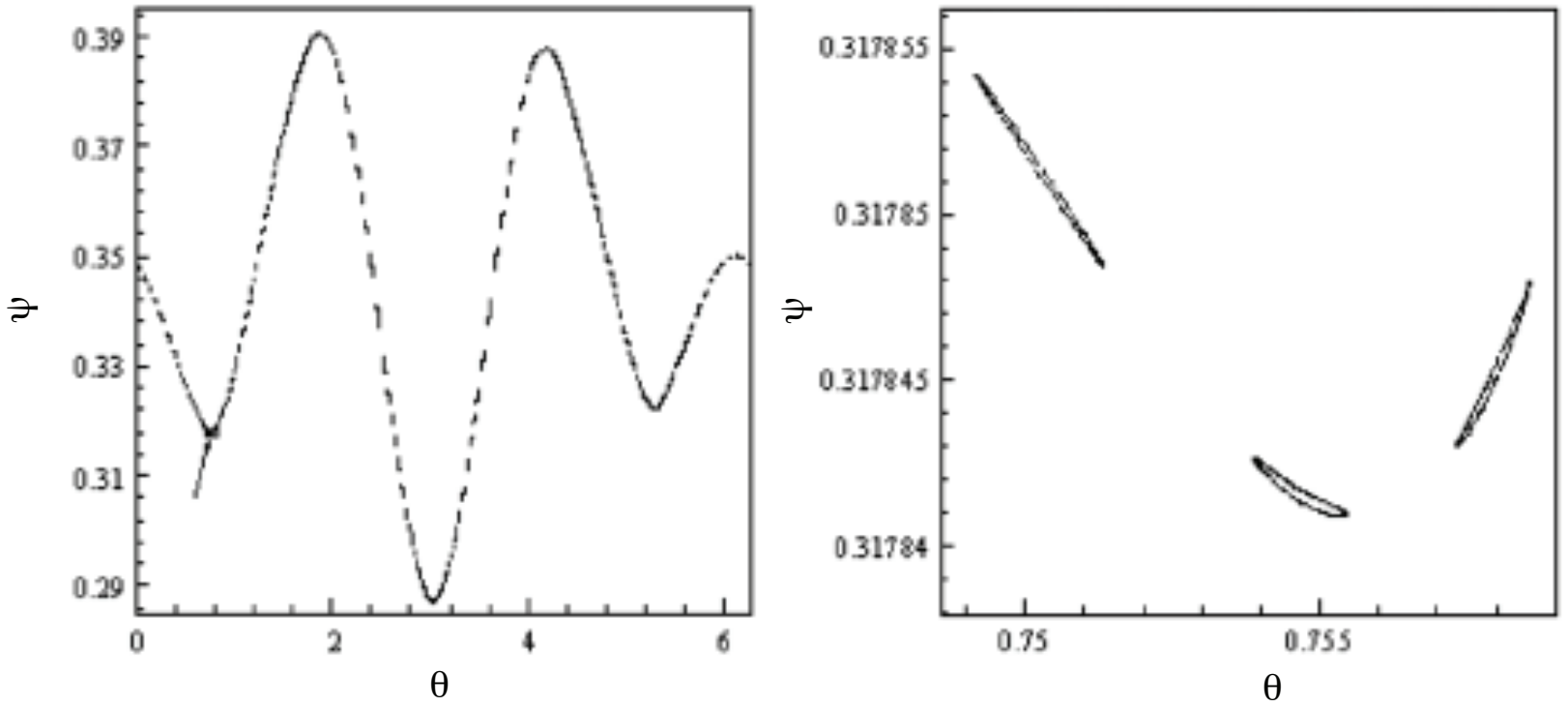
- Islands can form where q(ψ) = m/n
- Overlapping islands form chaotic regions
- Laminar "barrier" can form amongst chaos[1] at irrational values of *q*
- Ali and Punjabi construct barriers between 3/2 and 2/1 at DIII-D by assuming second order perturbation to the poloidal flux:

$$\chi_C^{(2)}(\theta,\phi) = -\frac{1}{2}\delta^2\left[\frac{\mathrm{d}}{\mathrm{d}\psi}\left(\frac{1}{q(\psi)}\right)\right]_{\psi=\psi_b}\left[\frac{3}{3\omega-2}\cos(3\theta-2\phi)+\frac{2}{2\omega-1}\cos(2\theta-\phi)\right]^2$$



[1] H. Ali and A. Punjabi, 2007 *Plasma Phys. Control. Fusion* **49** 1565.
[2] *Stat. Phy. & Chaos in Fusion Plasmas.* ed. Horton and Reichl (1984)

Barriers do not "Form"
They are the Last Laminar Surfaces to be Destroyed



- **Sufficiently strong RMP →**
  barrier breaks into cantori or chain of small islands

- **Most robust barrier at most irrational *q* ("golden ratio"), q=1.618…**

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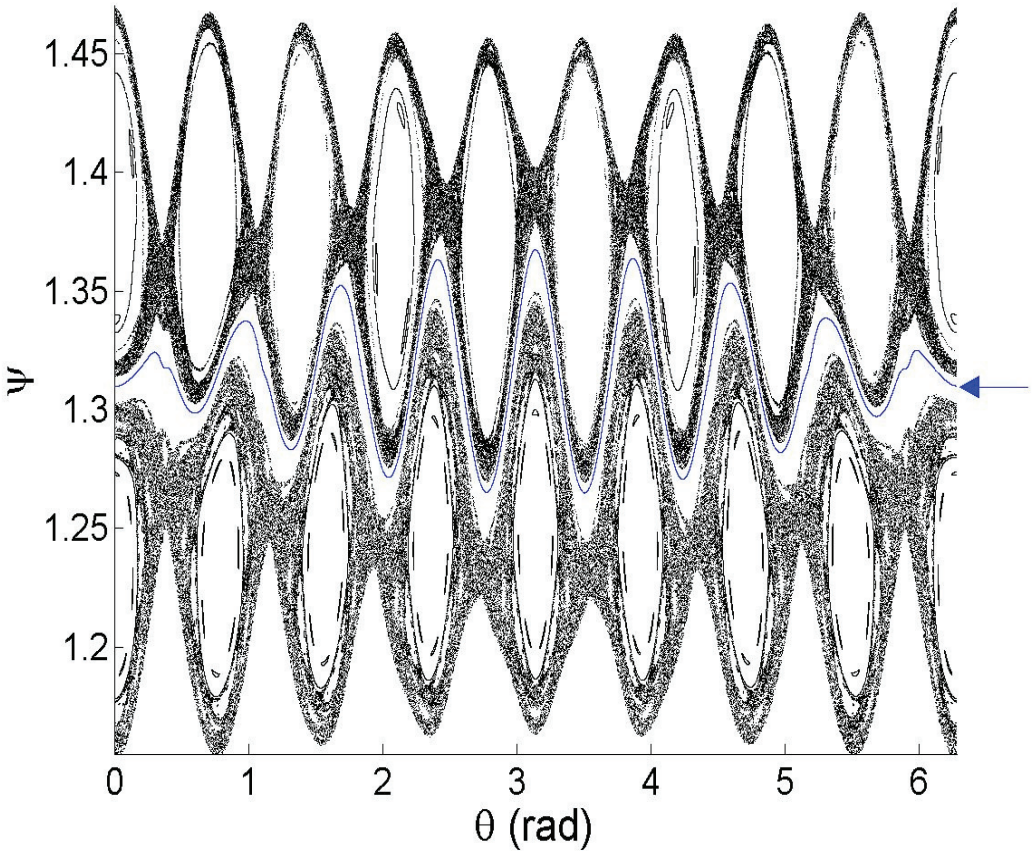
An *n*=3 Barrier was "Constructed" to Formulate and Test Barrier (and Island, and Chaos) Recognition Criteria

- **Barrier between 8/3 and 9/3 overlapping islands**
- **Ψ - θ map of 10 initial points of constant magnetic flux**
- **Sometimes barrier obvious by visual inspection**
- **Typical sequence: island, chaos, barrier, chaos, island**



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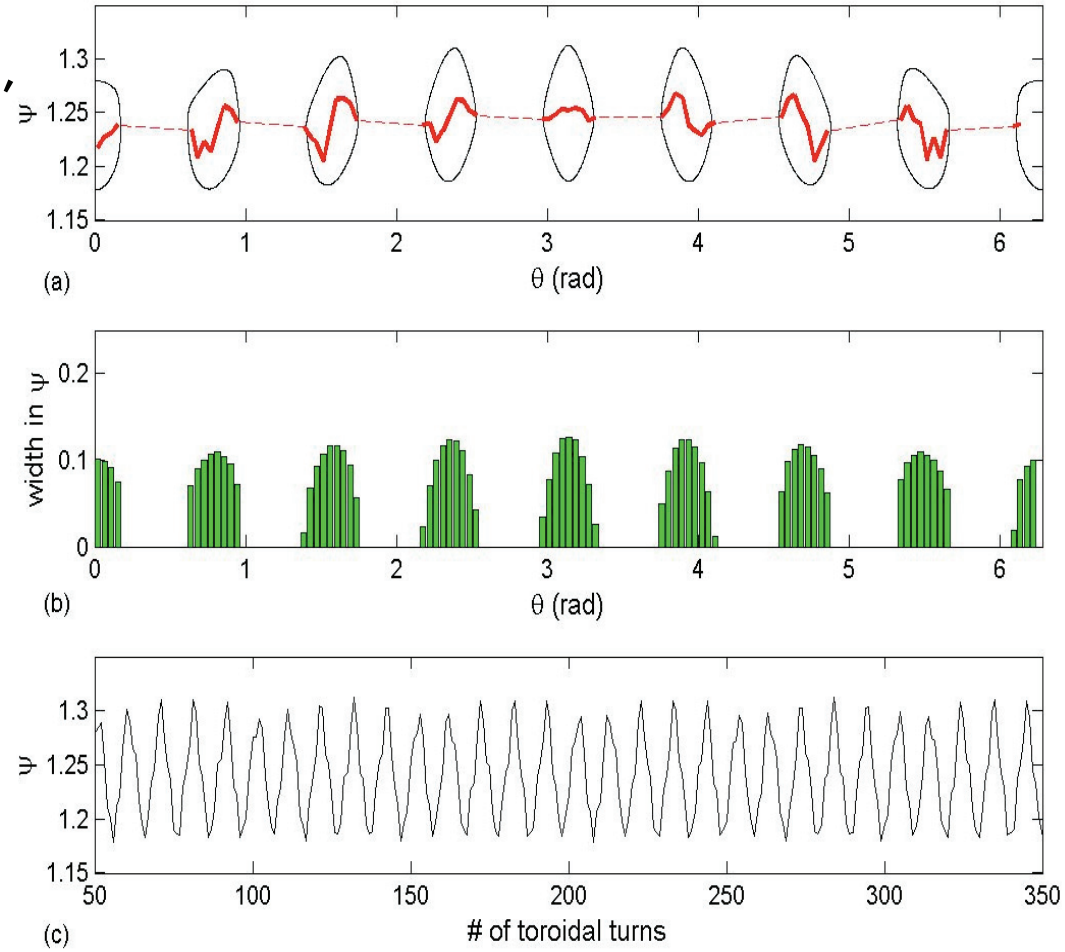
Islands are Easily and Uniquely Identified from Poloidal Gaps

- Each "Structure" (stochastic region, laminar surface or, in this case, island) is interpolated
- Difference between max and min Ψ in each θ interval defines the structure width
- Poloidal pattern (this slide) and poloidal spectrum (slide 11) of interpolation and width help to distinguish different structures



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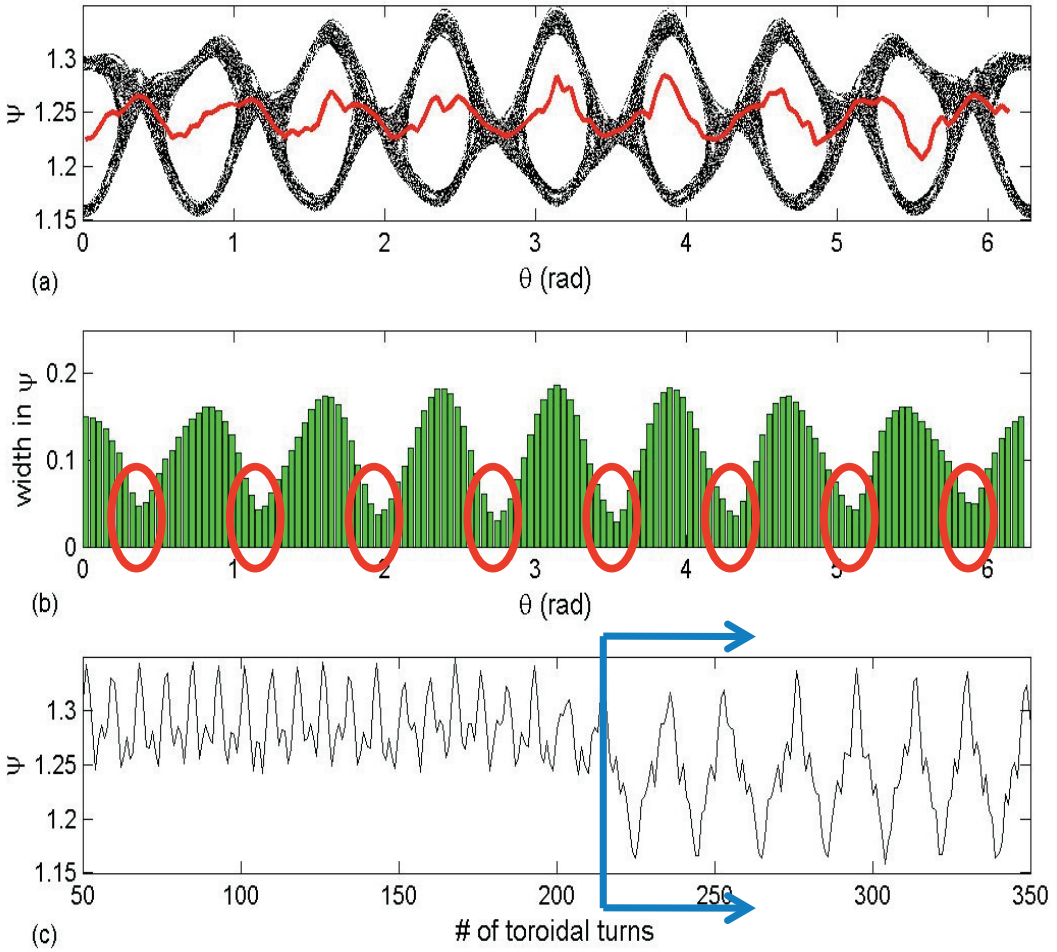
Stochastic Layers have Finite Radial width and no Poloidal Gaps

- Unlike islands, chaotic surfaces have no gaps, neither in the interpolation nor in the width
- Unlike laminar surfaces, chaotic regions have finite width
- Unlike laminar surfaces and islands, Ψ is not periodic in θ. For example, it can exhibit a break in periodicity



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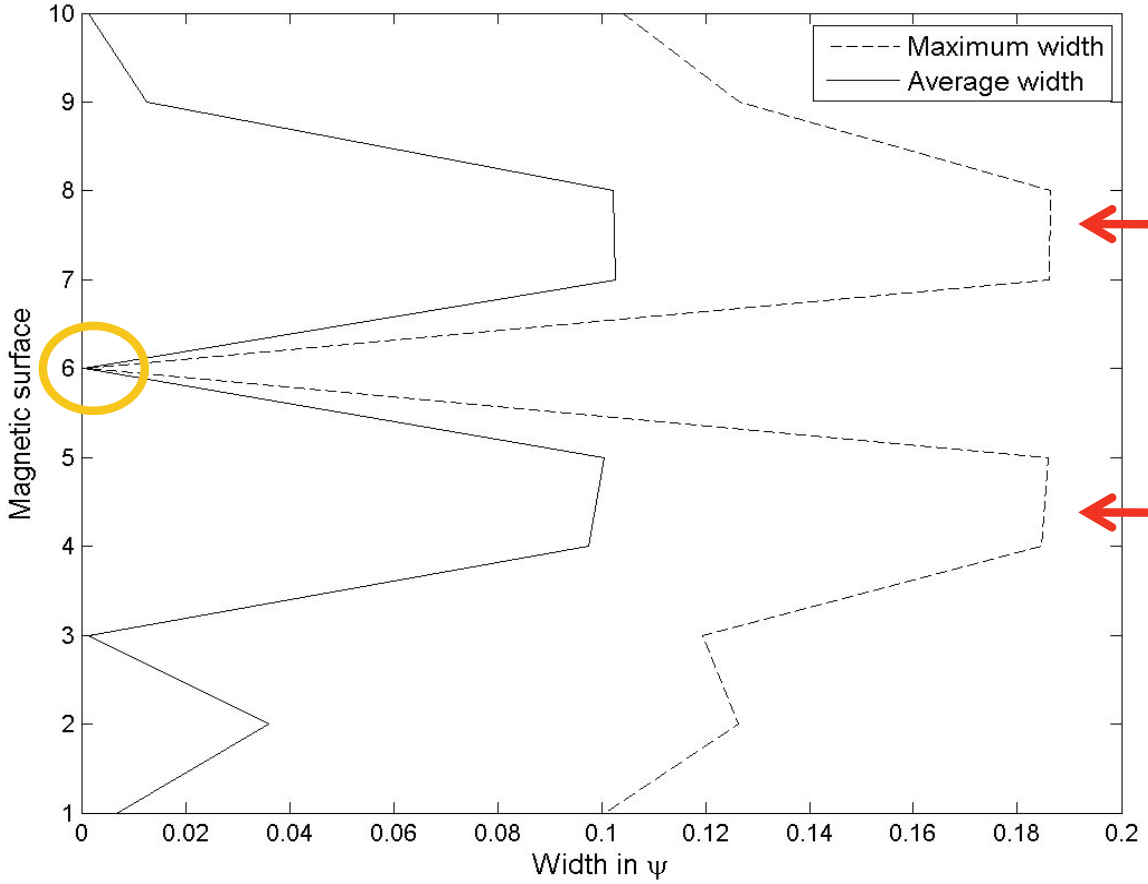
Structure width is a Good Indicator of Barriers



barrier

chaos

chaos

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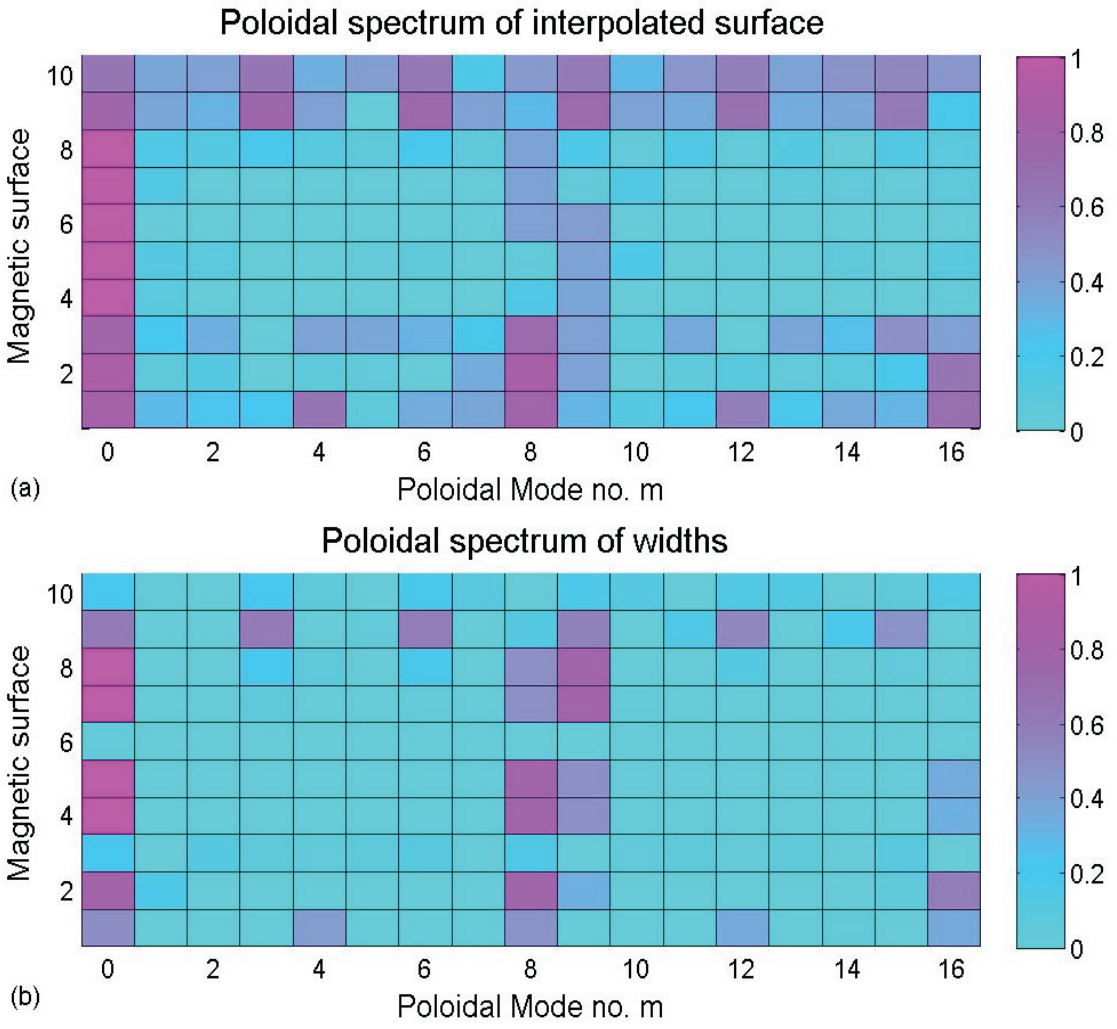
Barriers are Narrow Structures of Narrow Poloidal Spectrum

- Peaked at m=3 (9/3) and m=8 (8/3)
- High m=0 peak for stochastic surfaces
- Peaks at m=8 and m=9 indicate barrier
- Poloidal spectrum of width, low broad spectrum for all m



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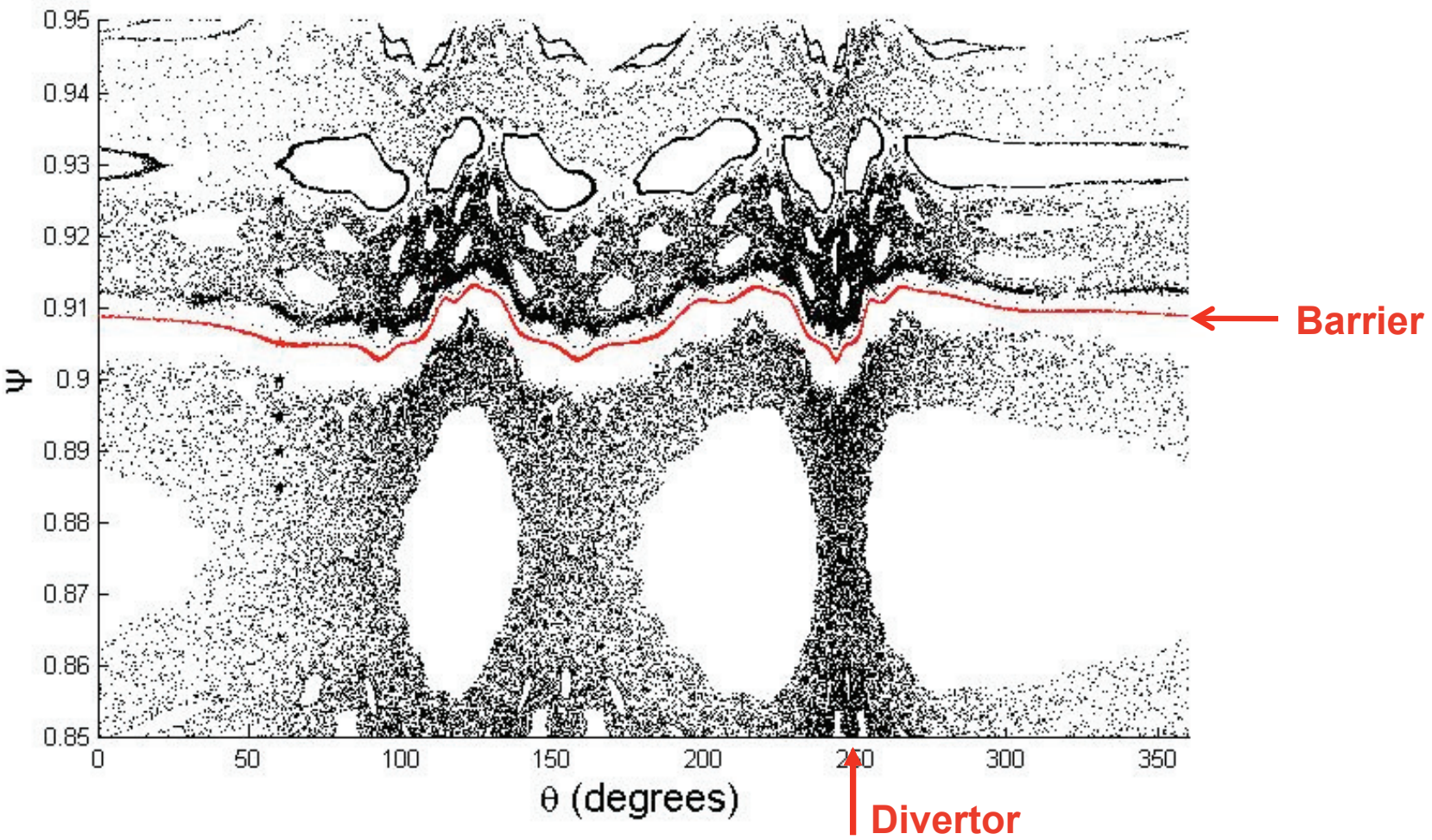
Robust Barrier forms in Numerical Modeling of DIII-D Discharges with Relatively Modest *n*=1 Perturbation



- $I_{I\text{-}coil}$ = 1.45 kA → perturbation comparable with residual EF

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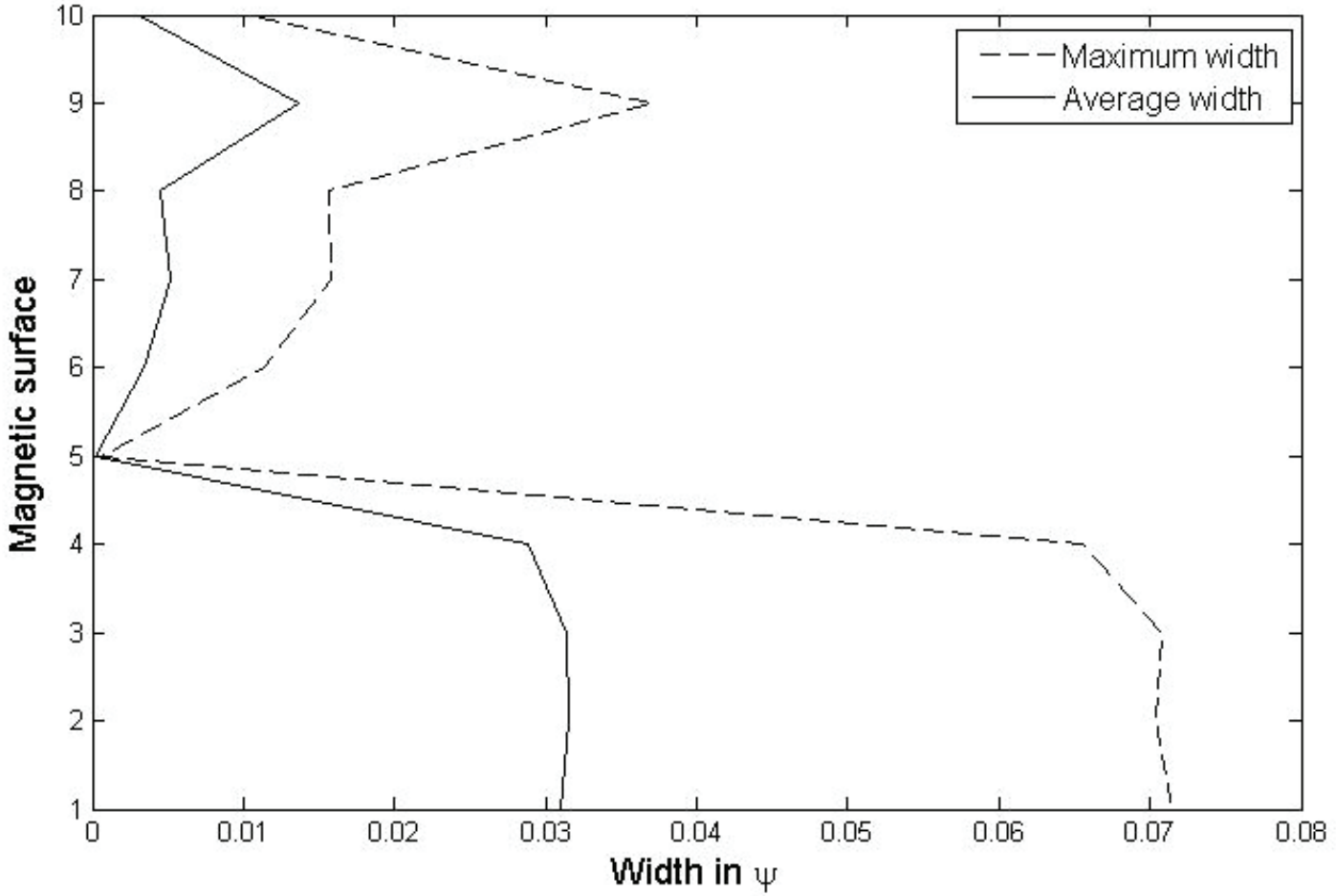
Barrier is Confirmed by Zero Width



- **Narrow maximum width indicates barrier**

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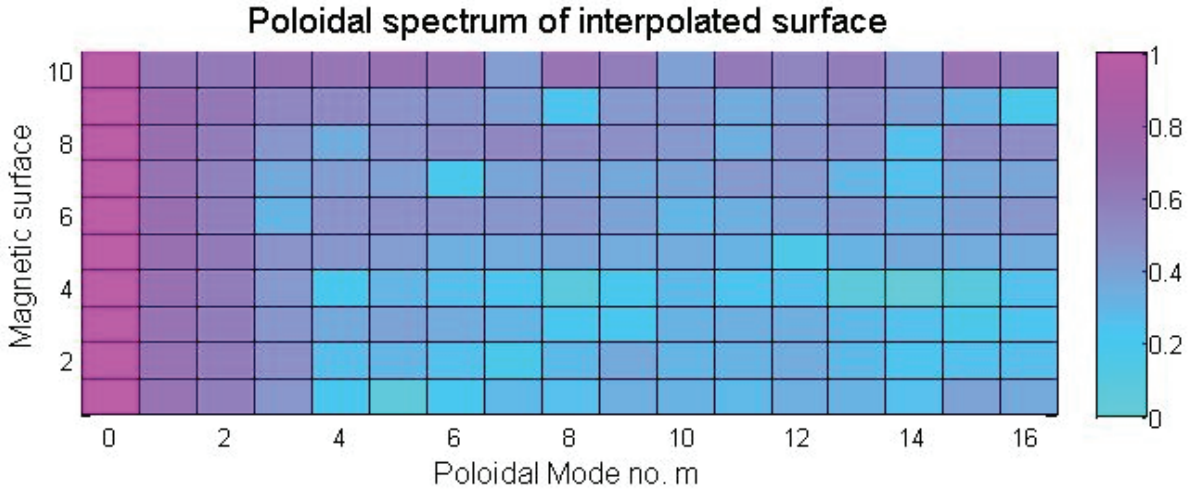
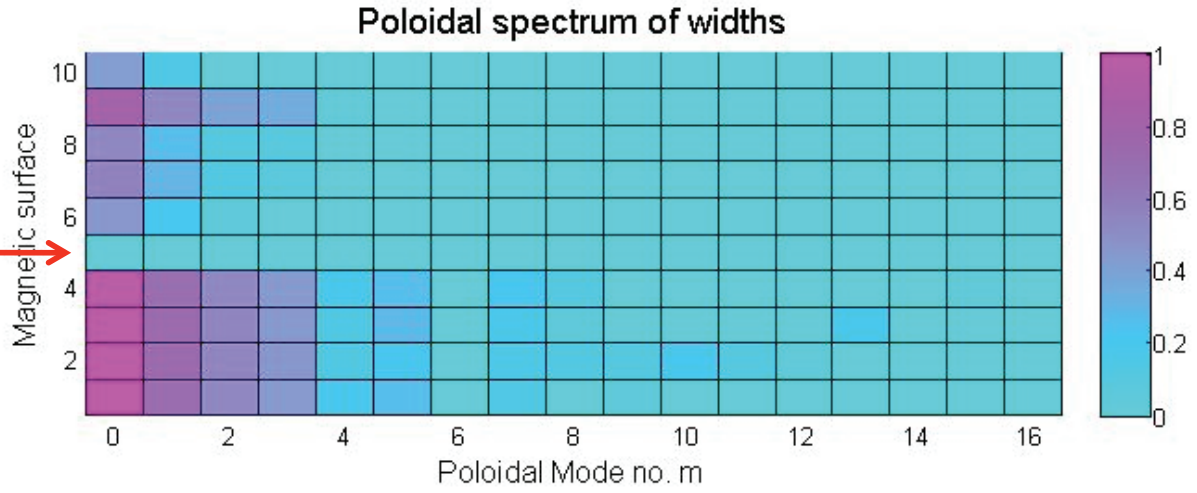
Poloidal Spectrum of Radial Width is a Good Indicator of Barrier Formation within Experimental Data

- **Distorted by DIII-D geometry**



- **Poloidal spectrum of width, low broad spectrum**



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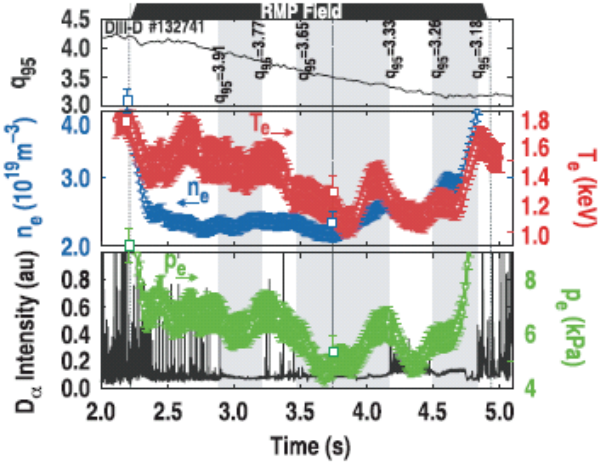
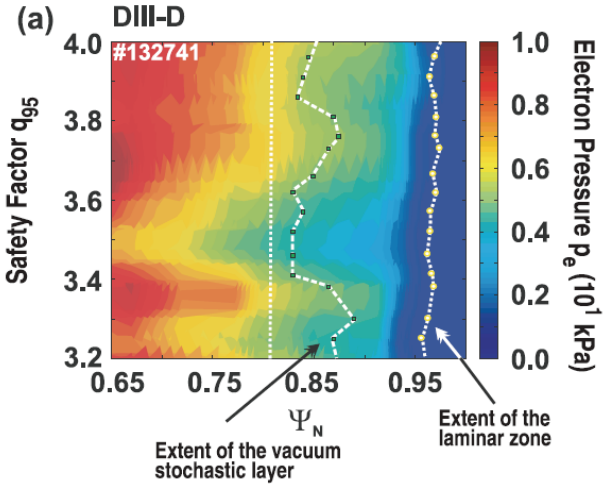
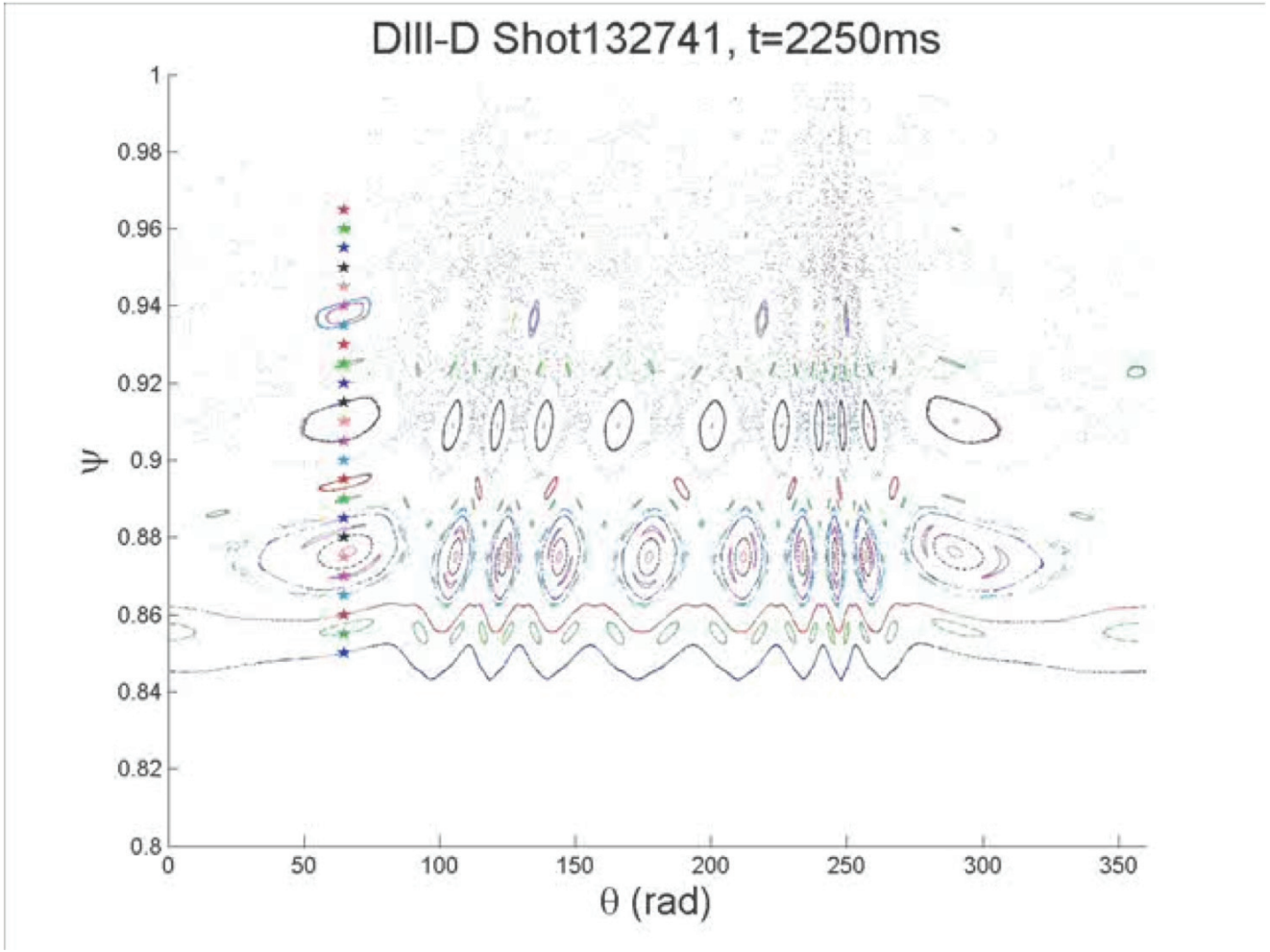
Possible Intermittent Barrier Formation During q_{95} Ramp DOWN in even Parity, n=3 Shot







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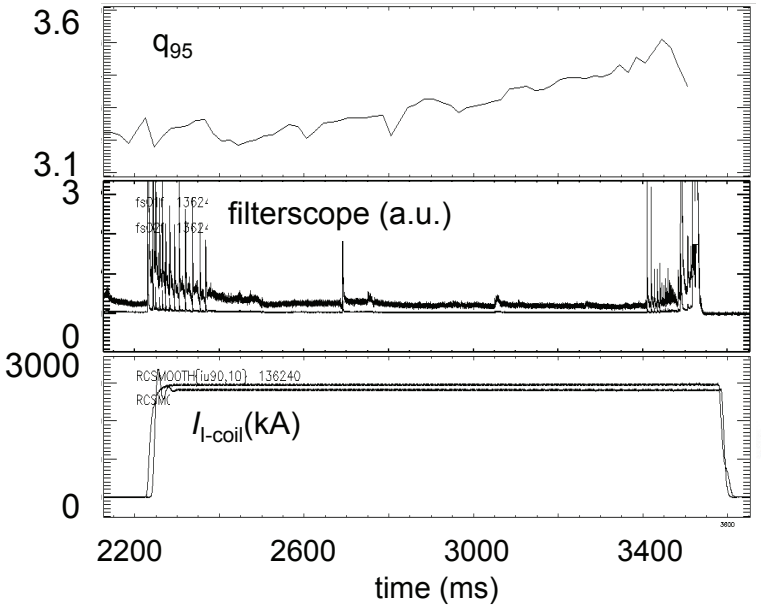
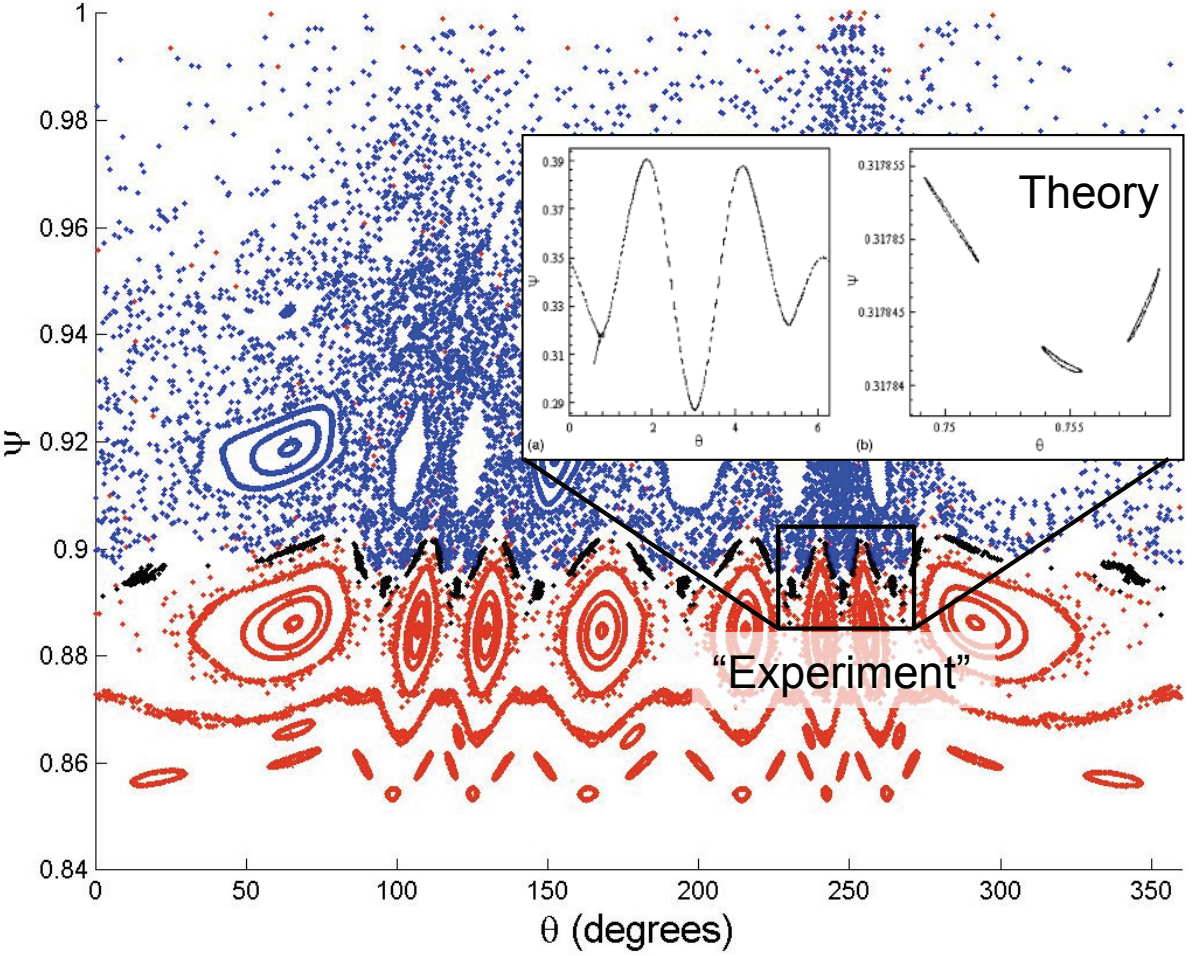
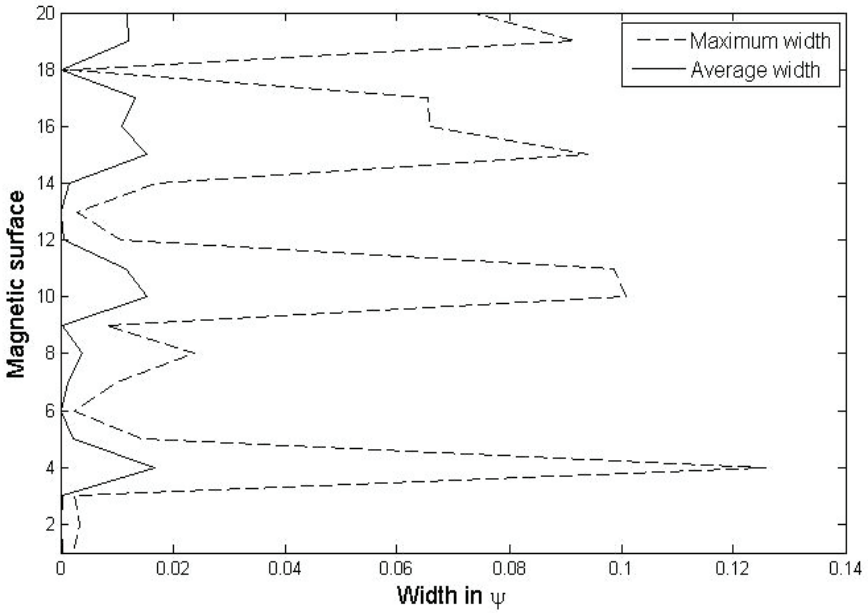
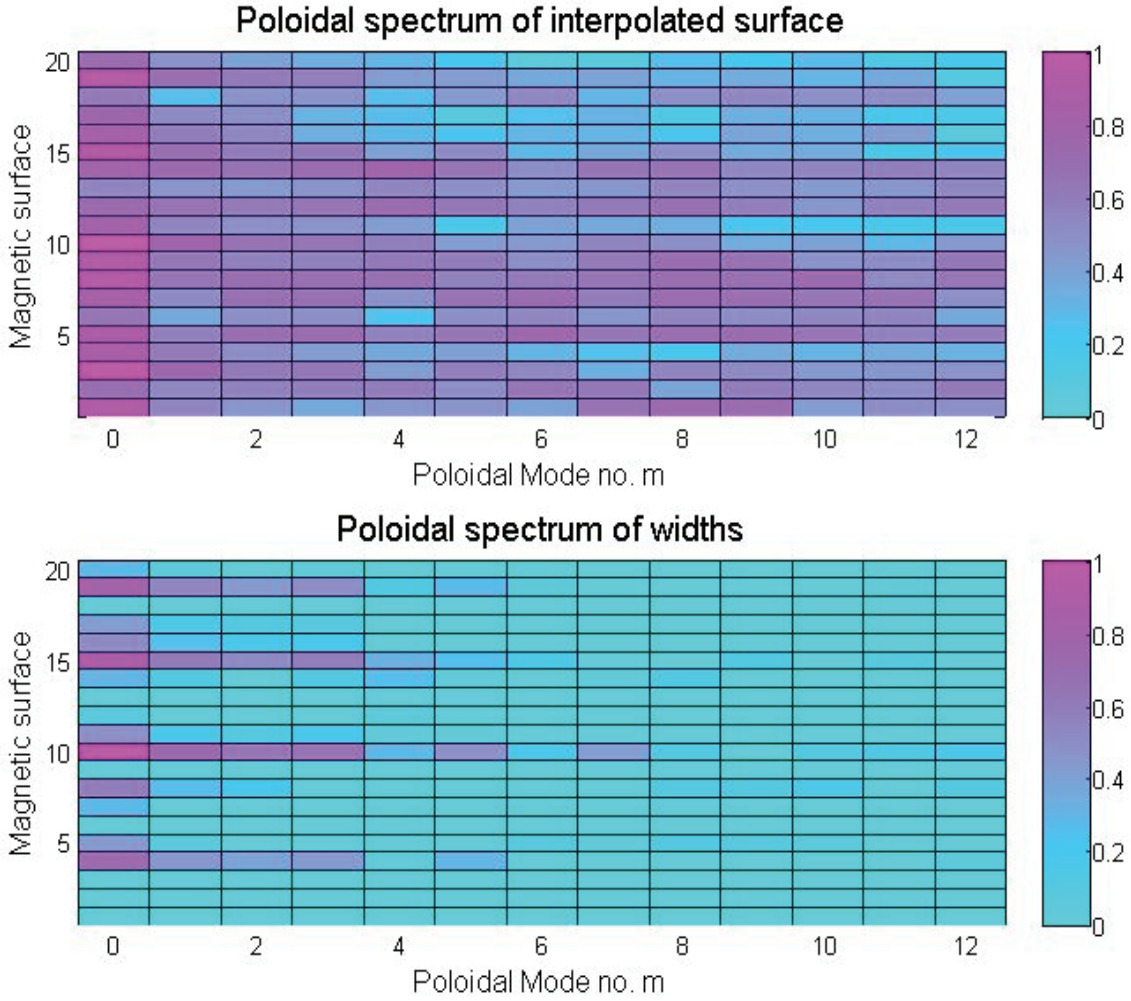
Semi-permeable Barrier Observed During n=3 q_{95} Ramp-down Experiment





Imperfect Barrier not very Obvious from Width and Poloidal Spectrum





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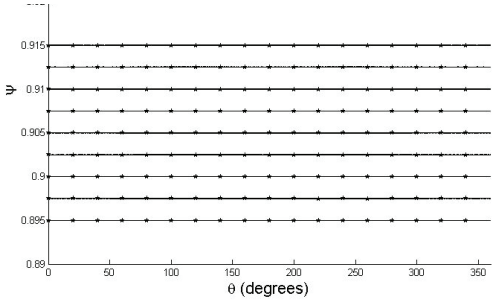
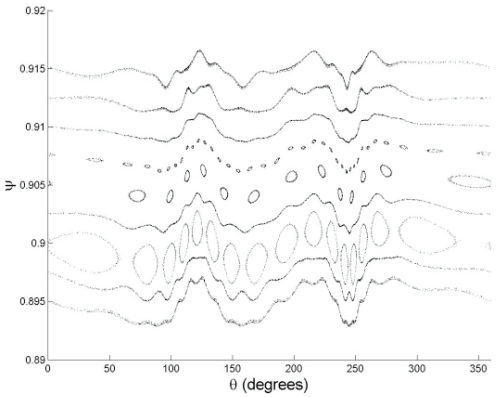
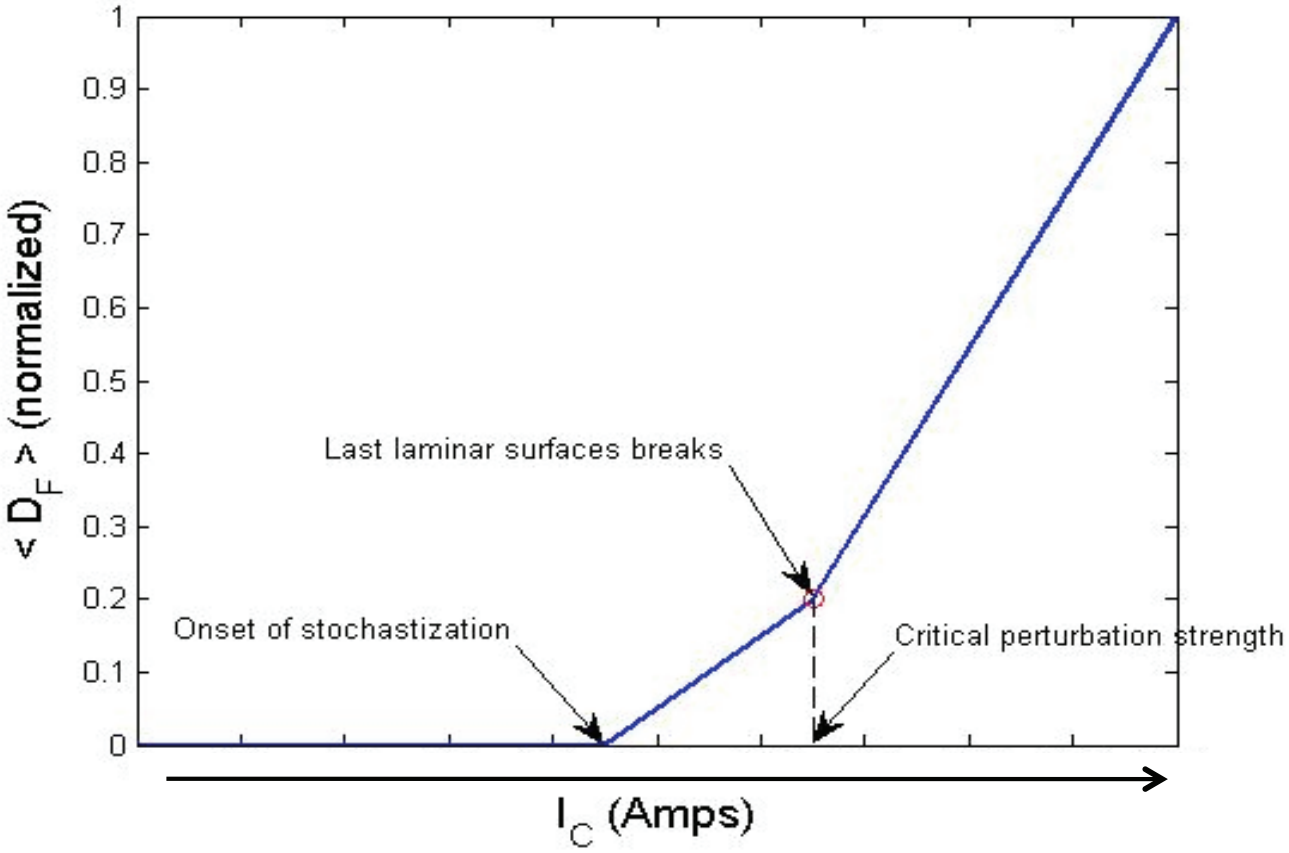
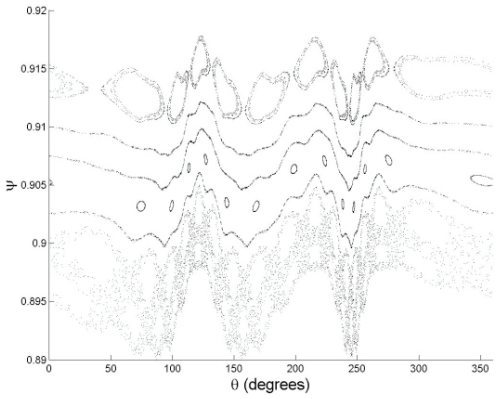
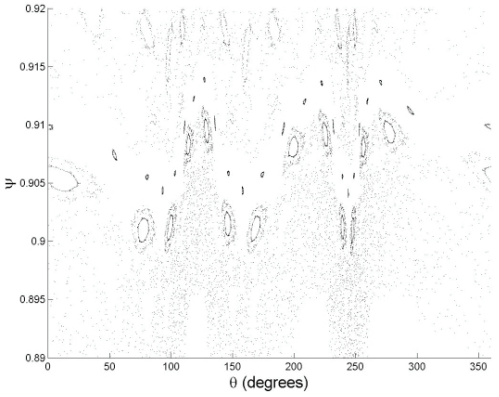
Diffusion Averages Might be a Good Means for Determining Critical I-coil Current











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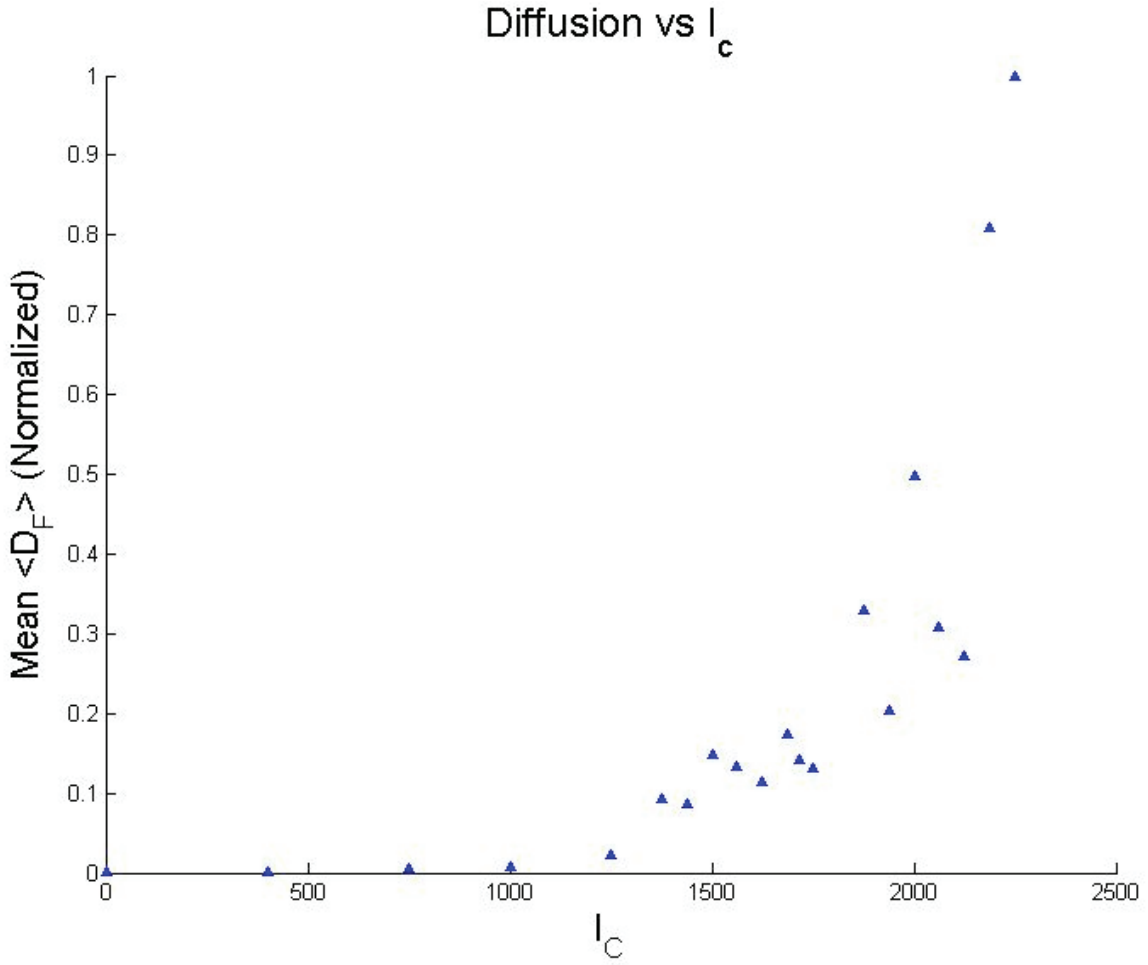
Diffusion Suggests Critical $I_{I\text{-}coil}$≈2.2kA for n=3, Consistent with no Perfect Barrier at $I_{I\text{-}coil}$≥3kA



- **Shielding by rotation and plasma response would increase critical $I_{I\text{-}coil}$ Hence n=3 barriers are not excluded, experimentally, even at $I_{I\text{-}coil}$≥3kA**

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Summary and Conclusions

- Magnetic barriers might explain the q_{95} dependence of RMP control of ELMs
- Confirmed *n*=3 barriers in idealized geometries
- Found criteria for island, chaos & barrier identification
- Observed *n*=1 barriers in realistic geometries (vacuum field from internal coils +plasma equilibrium)
- Observed semi-permeable *n*=3 barriers in realistic geometries
- Barriers clearly depend on q_{95}, although they do not exactly anti-correlate with ELM control, yet

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Future Work

- **Finer radial scans for finer barriers**
- **Include plasma response**

- **Quantify the effects of magnetic barriers on diffusion**
  - Simple gyro radius analysis
  - Monte Carlo

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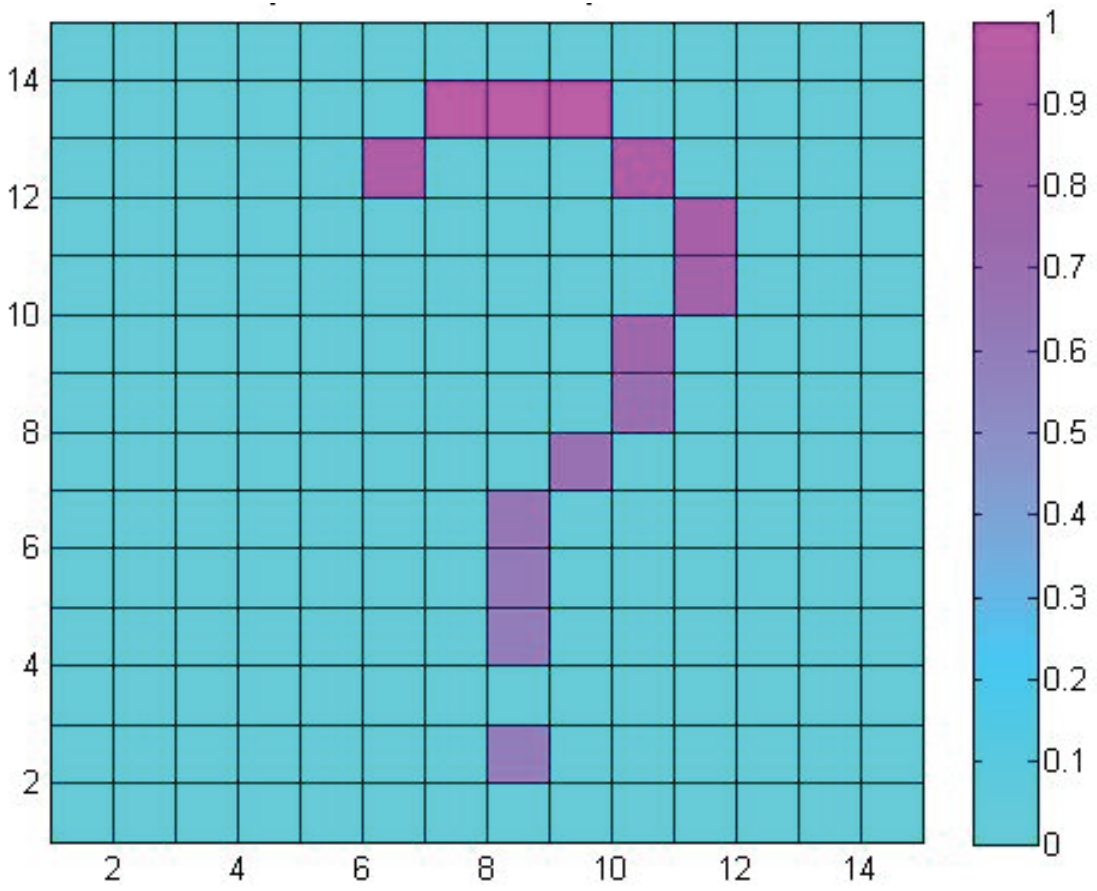
Questions?



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Criteria for Island, Chaos and Laminar Surfaces

	Island	**chaos**	**Laminar Surface**
Radial Width	Finite	Finite	=0
Poloidal Spectrum of Interpolation	Peaked at resonant *m*, harmonics and sub-harmonics	Broad, peaked at *m*=0	Broad, peaked at m=0
Poloidal Spectrum of Width	Peaked at resonant *m*, harmonics and sub-harmonics	Broad, peaked at *m*=0	=0
Toroidal Dependence	Periodic	Non-periodic	Periodic

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