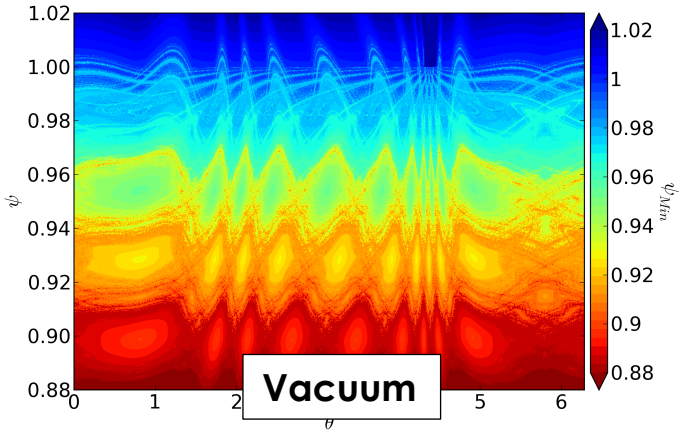
Impact of plasma response on RMP ELM suppression in DIII-D

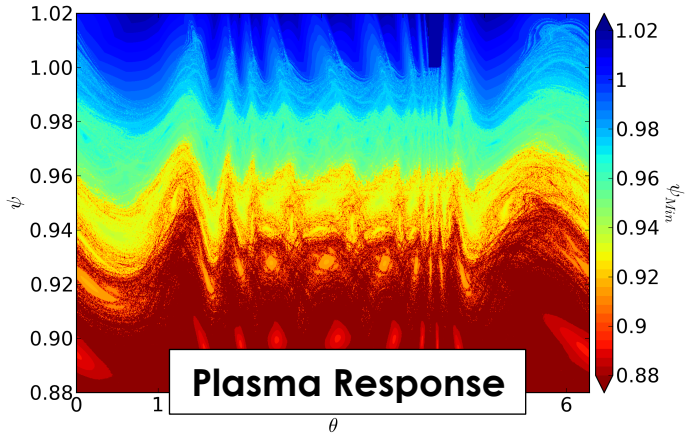
A. Wingen[1], M.W. Shafer[1], E.A. Unterberg[1], N.M. Ferraro[2], T.E. Evans[2], P.B. Snyder[2] and D.L. Hillis[1]

[1] Oak Ridge National Laboratory
[2] General Atomics

Presented at
ORNL

July, 2014





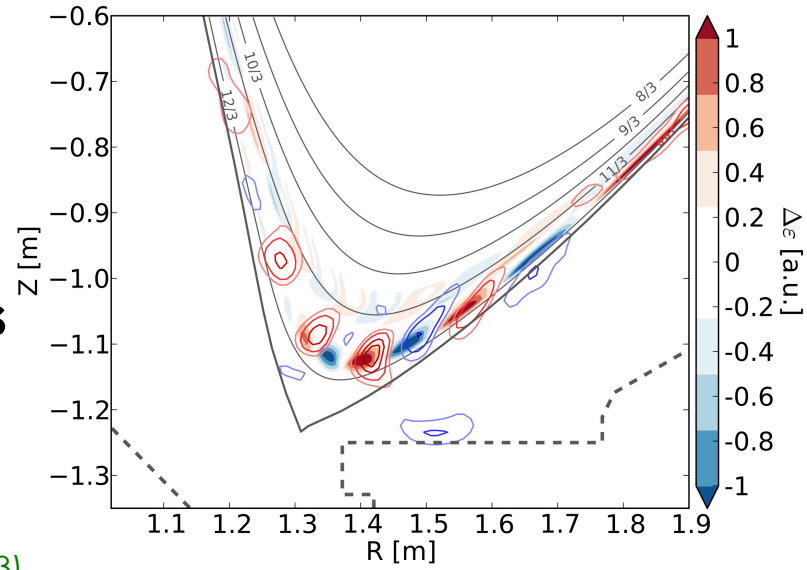
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

OAK RIDGE National Laboratory

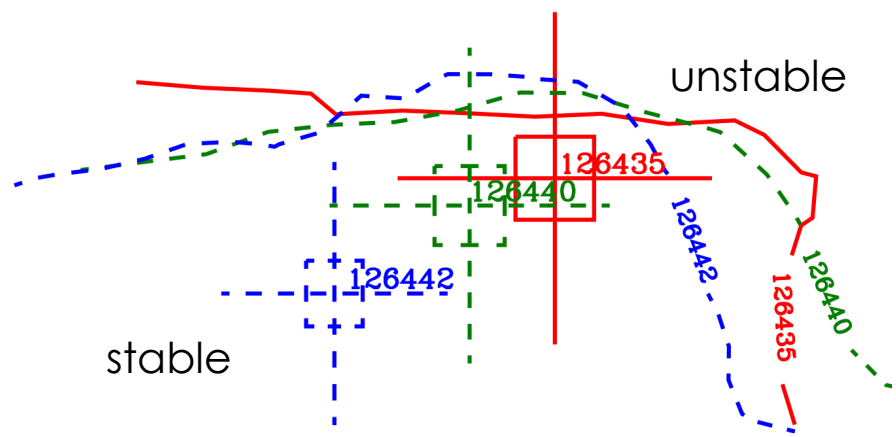
How does the plasma respond to 3D RMP fields?

- **L – mode measurements agree with vacuum modeling**
  - Islands imaged in Ohmic discharges (Tore Supra) T.E. Evans *et al.*, PoP **9**, 4957 (2002)
- **In H – mode plasma response becomes important**
  - DIII-D soft X-ray imaging system & synthetic diagnostic

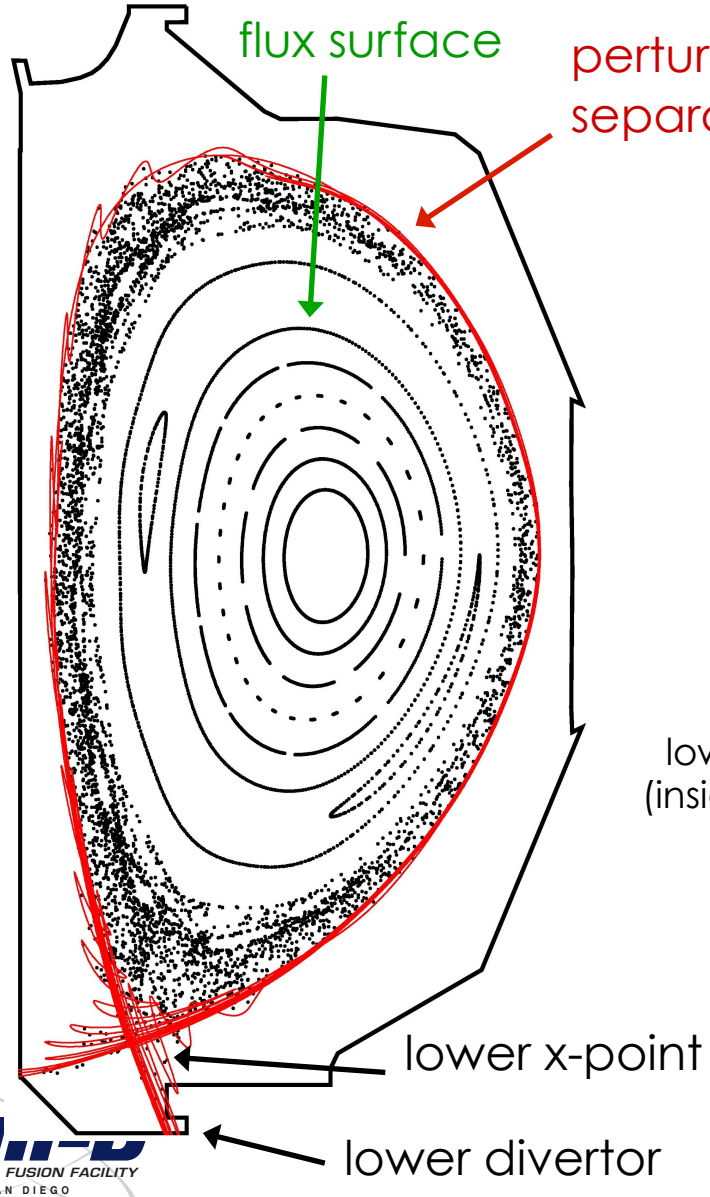
A.Wingen *et al.*, 6. SFP & Nucl. Fusion (2013)



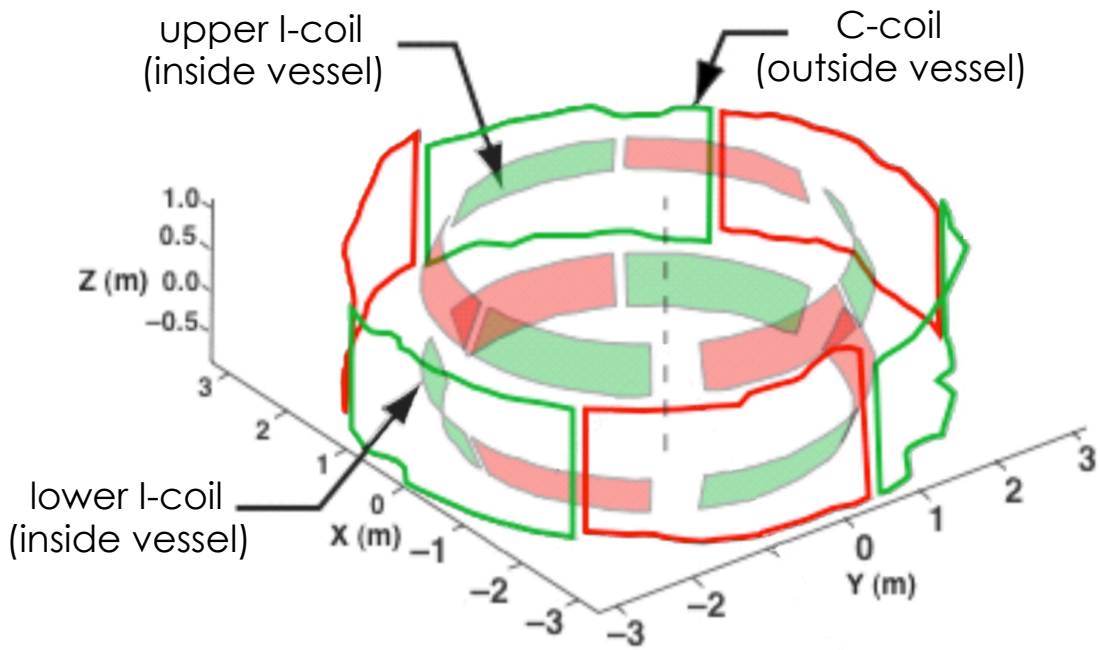
Hypothesis:
Discharges with stronger Kink response are closer to peeling ballooning stability threshold



Vacuum approximation: 3D fields created by coils



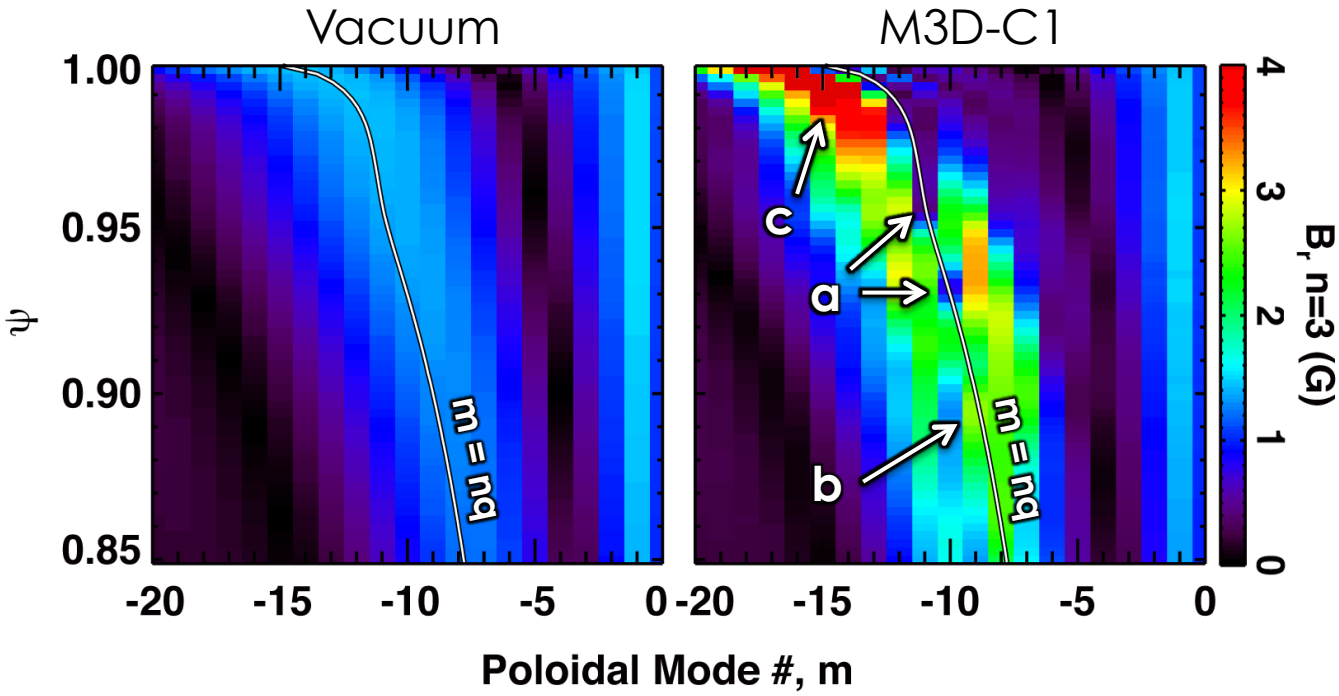
Resonant Magnetic Perturbation (RMP) through applied fields



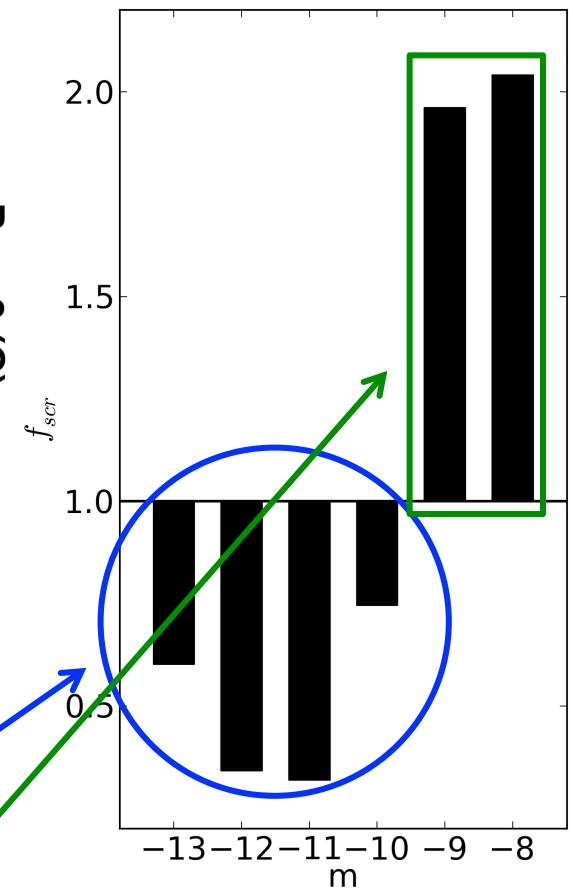
→ **large stochastic layer formation**

M3D-C1: linear, resistive, two-fluid MHD code calculates a plasma response to 3-D fields

Poloidal mode spectrum for 148712



$$f_{\rm scr} = B_{r,\rm pr}/B_{r,\rm vac}$$



Three main effects

- **a:** resonant screening → Islands shrink
- **b:** resonant amplification → Islands grow
- **c:** non-resonant amplification → kinking of flux surfaces

N.M. Ferraro, PoP **19**, 056105 (2012)

Two-fluid resistive MHD plasma response sensitive to rotation

edge/SOL

- low rotation, high resistivty
- vacuum model works well

steep pressure gradient

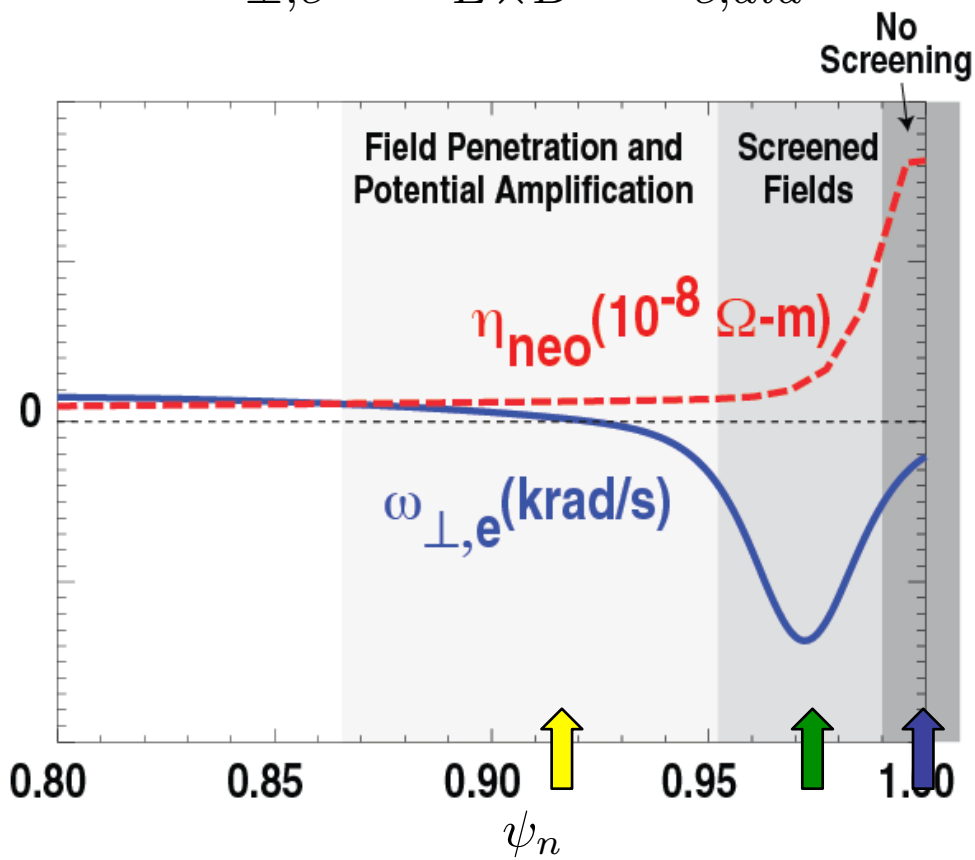
- high rotation, low(er) resistivity
- applied field shielded by image currents on rational surfaces
- non-resonant amplification

top of pedestal

- low rotation, low resistivty
- fields can penetrate
- resonant amplification

perpendicular electron rotation:

$$\omega_{\perp,e} = \omega_{E\times B} + \omega_{e,dia}$$



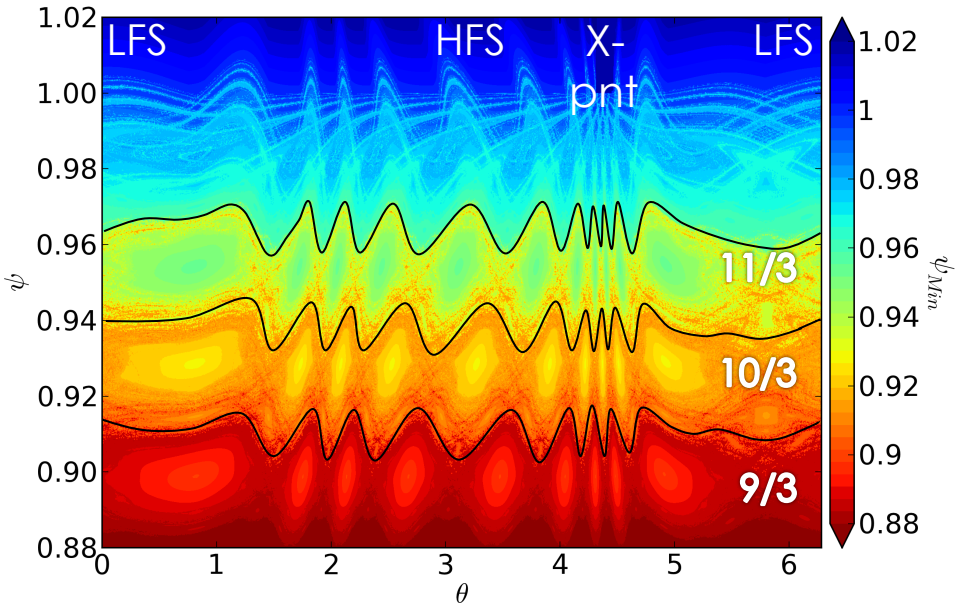
N.M. Ferraro, PoP **19**, 056105 (2012)

Plasma response significantly modifies magnetic topology: simulation shows all three effects

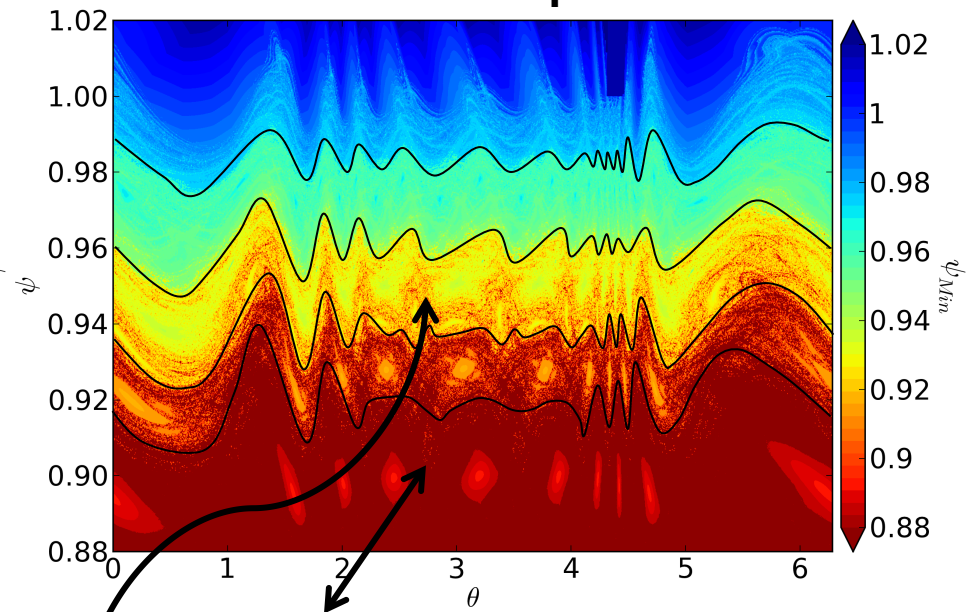
H-mode discharge with n = 3 RMP

color = penetration depth

Vacuum



Plasma Response

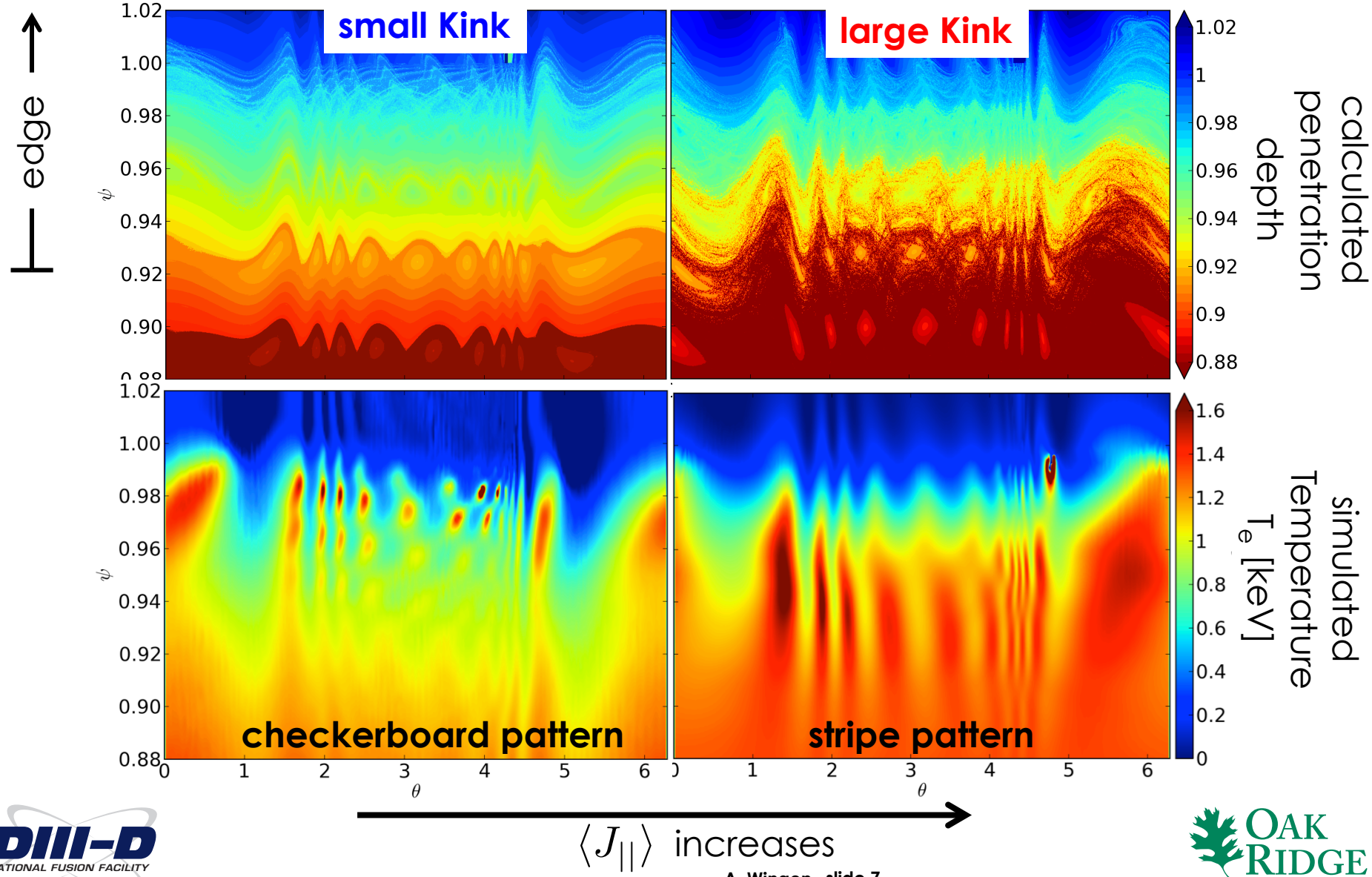


- island chains dominate structure
- stochastic regions → fractal
- radial phase inversion across islands

- **resonant amplification**, islands grow
- **resonant screening**, islands shrink
- **bended surfaces,** radially aligned → Kink response

Bending pushes islands away

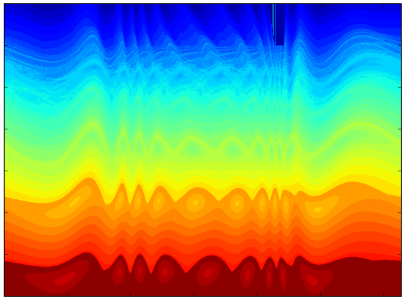
Resonant response is correlated to electron rotation, Kink response is correlated to edge current density



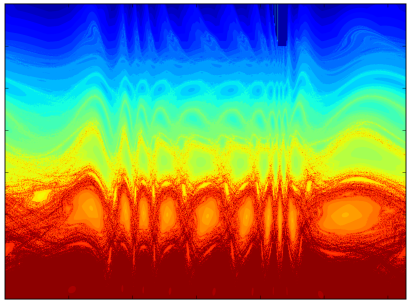
Hypothesis:

Discharges with stronger Kink response are closer to peeling ballooning stability threshold → **ELMs eventually return**

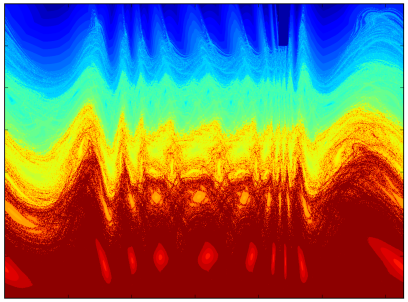
- **small Kink response**
  - well suppressed over entire I-coil phase, $I_{I\text{-}coil} \sim 4kA$
  - 126006 & 126442



- **moderate Kink response**
  - good ELM suppression, but at generally higher I-coil current, $I_{I\text{-}coil} \sim 5kA$
  - 126439, 126440 & 146626



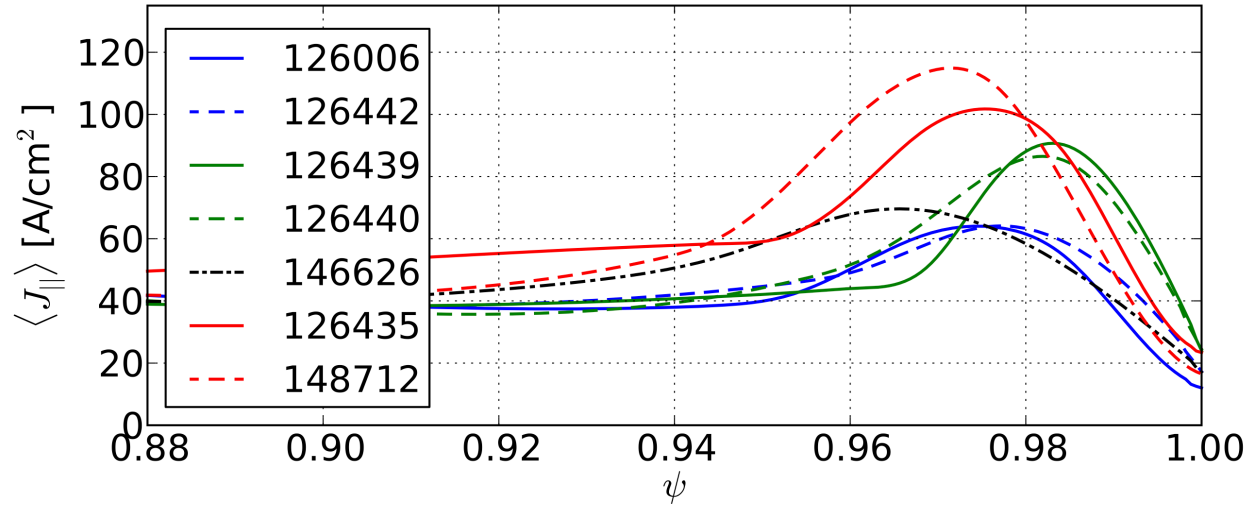
- **large Kink response**
  - ELMs are only mitigated or return during second half of the discharge, $I_{I\text{-}coil} = 4kA$
  - 126435 & 148712

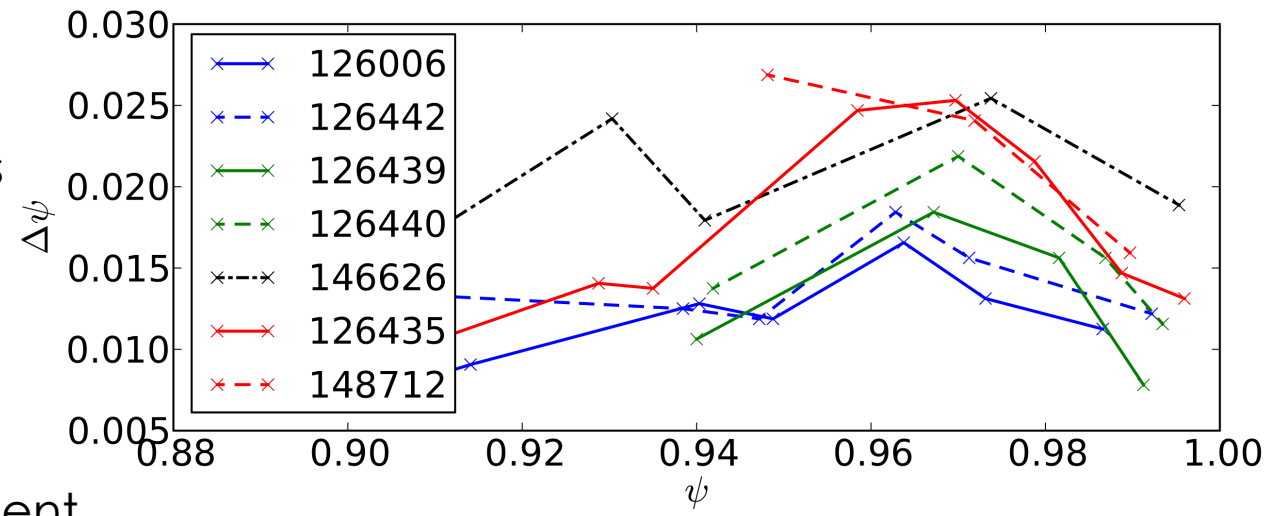


Kink displacements follow current density

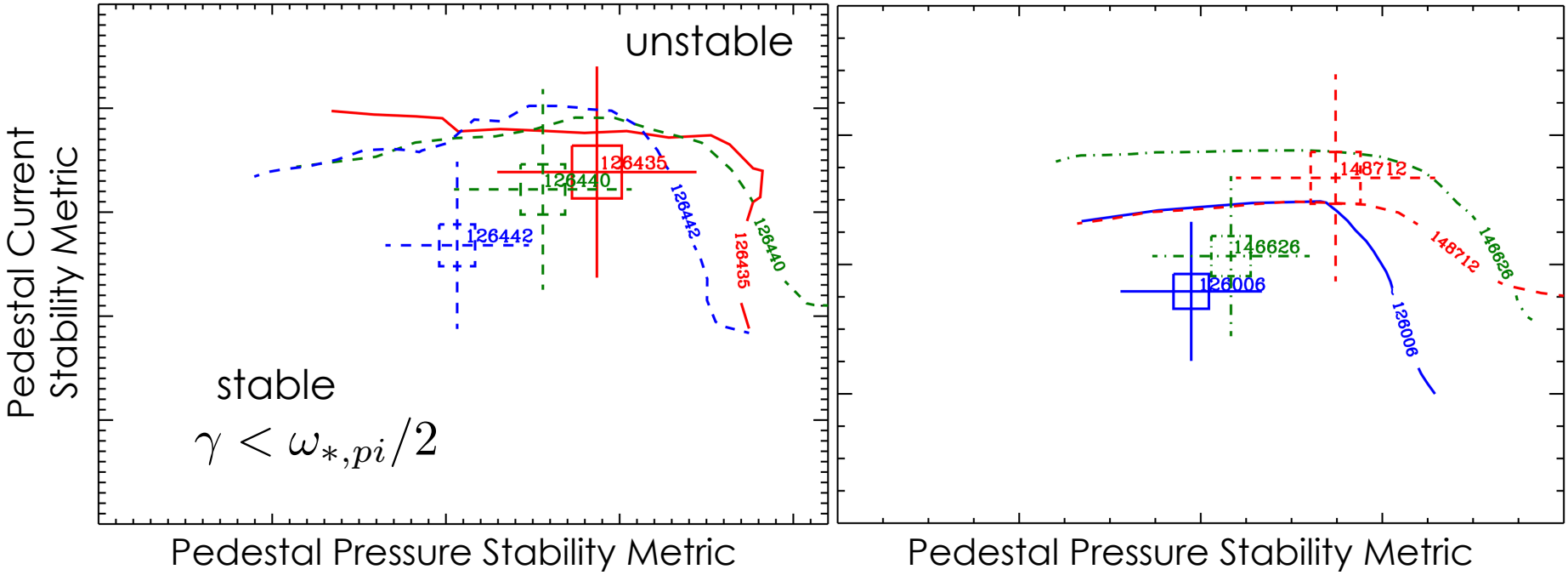
- **low edge current**
  - small displacements
  - Island like
  - **well suppressed**
- **moderate current**
  - intermediate
  - **suppressed, but at stronger I-coil**
- **strong current**
  - large displacements
  - Kink like
  - **ELMs return**
- **exception?**
  - moderate current, but large displacement

← **large islands, different q_{95}**





ELITE simulations confirm ELM stability



P. B. Snyder *et al.*, Nucl. Fusion **49**, 085035 (2009)

- **far inside the stability region**
- **well inside but further towards instability**
- **close to stability boundary, but still inside** → only ELM mitigation
- **just outside** → marginally peeling ballooning unstable

Same ordering as edge current density

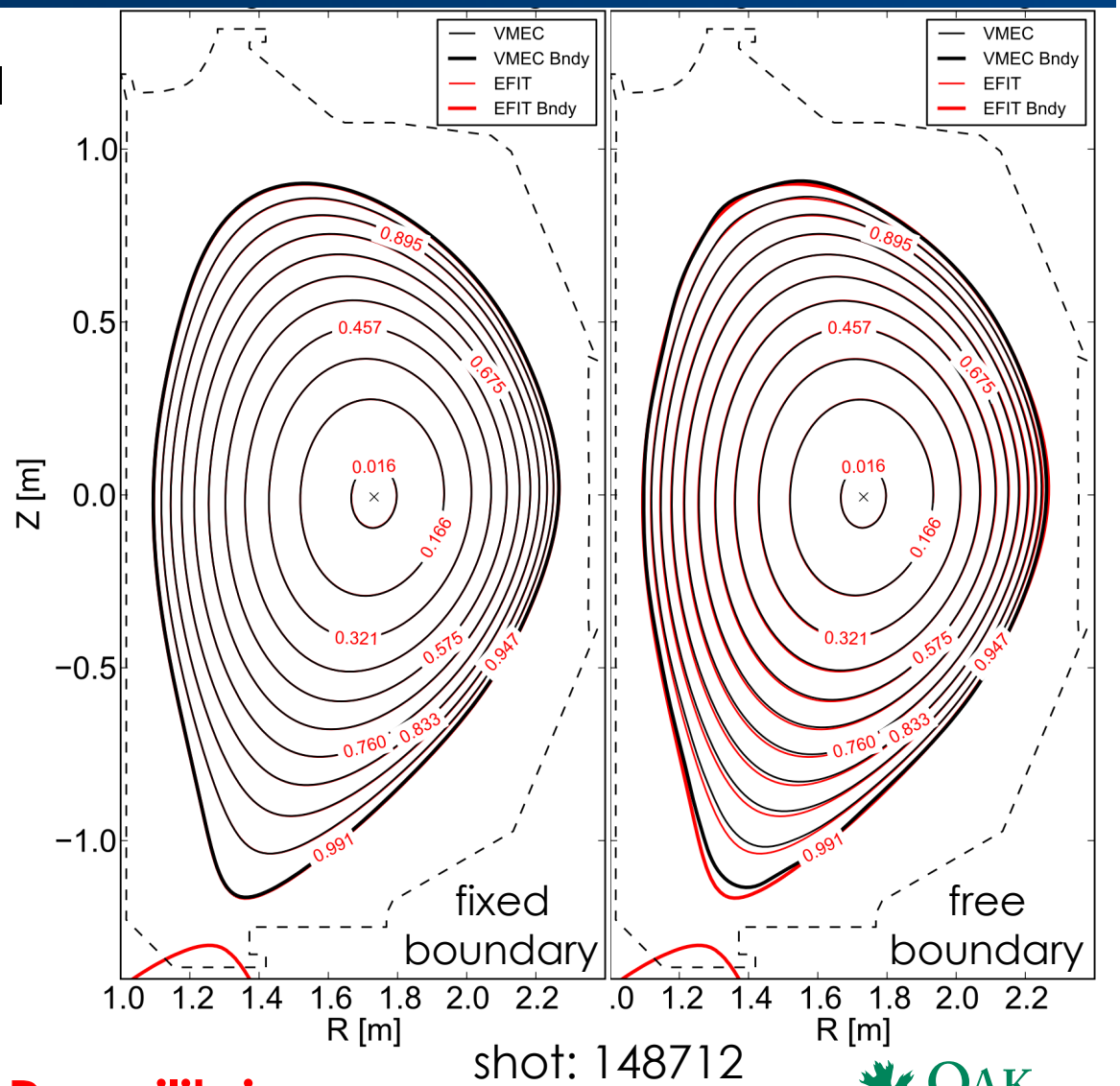
Results using linear resistive MHD (M3D-C1)

- **plasma response changes islands and introduces bending of surfaces**
  - resonant response sensitive to rotation
  - surface bending also forces islands to bend the same way
- **kink displacements correlate with edge current density**
  - displacements follow the profiles
  - displacement profiles are in the same order as current density profiles
  - no correlation with pressure found
- **ELITE simulations confirm that ELM stability follows the same order as current density**
  - well in support of Hypothesis

compare to non-linear ideal code: VMEC

Cross-check kink response with ideal, non-linear MHD, here: VMEC

- **use kinetic EFIT as initial condition**
  - VMEC cannot reach separatrix
    → truncate
- **use: n = 3, 3kA I-coil**
  - n = 4, m = 32, ns = 385
- **fixed boundary mode**
  - force current profile
  - extract iota profile
- **free boundary mode**
  - force iota profile
  - use iota from fixed boundary run



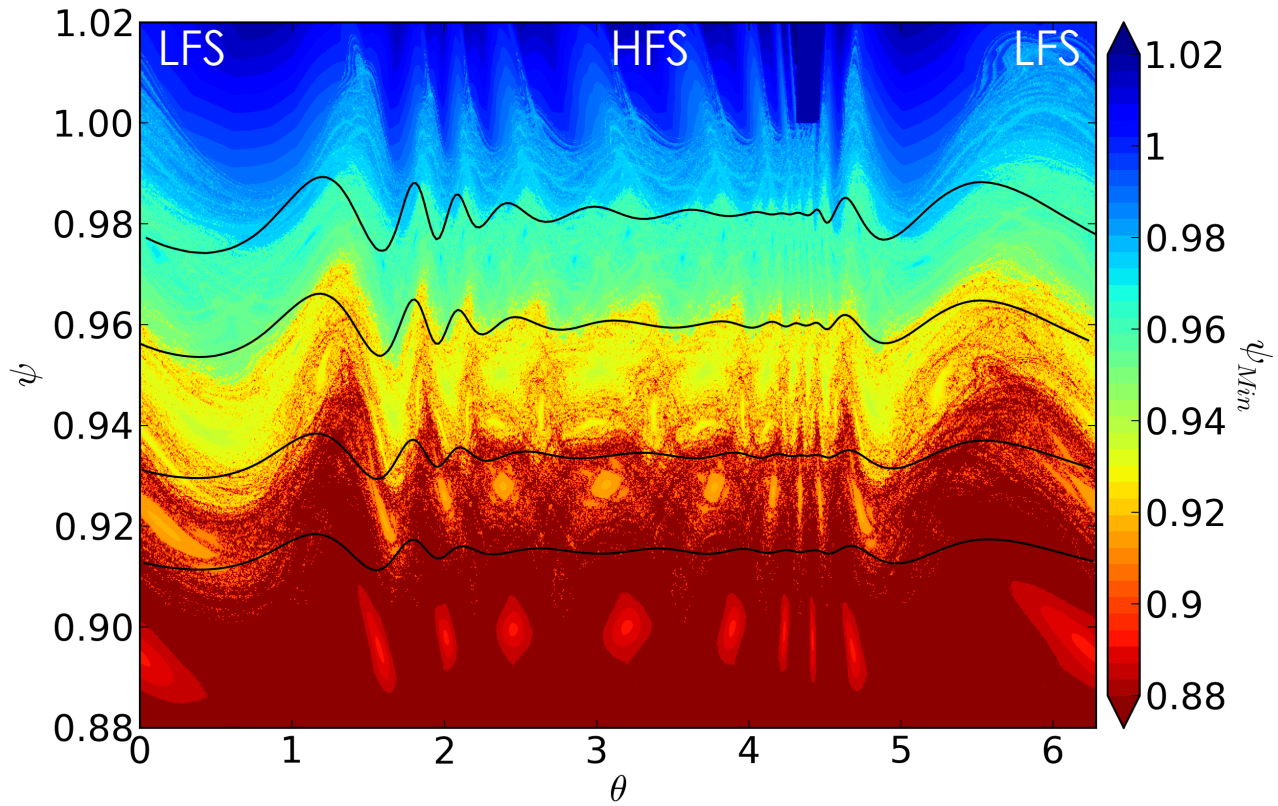
shot: 148712

VMEC finds 3-D equilibrium

VMEC kink response qualitative similar, but displacements are smaller

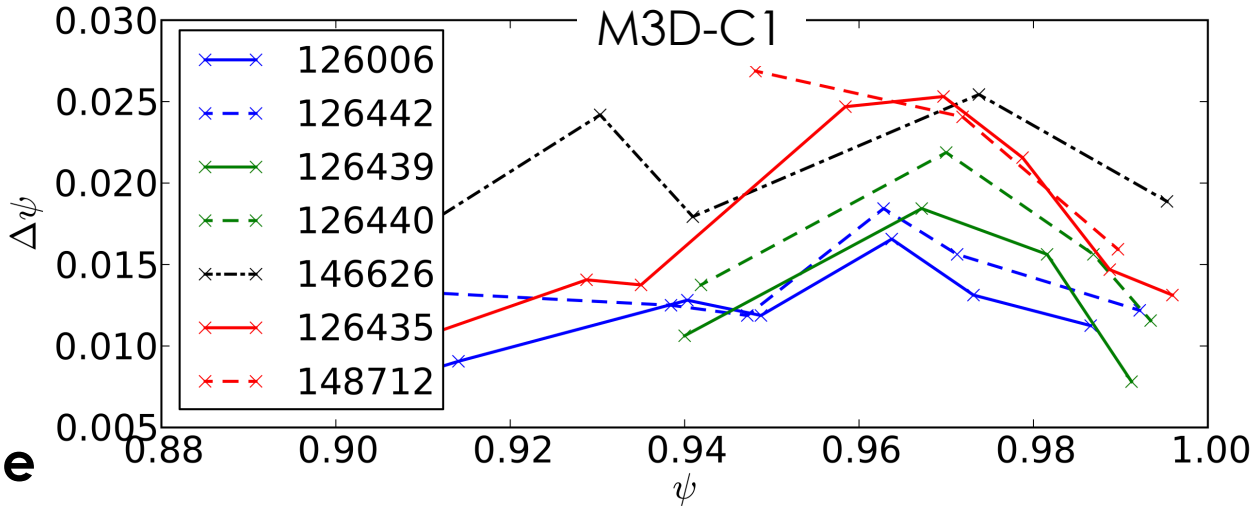
- **basic qualitative agreement**
  - similar corrugation
  - poloidal structure alignment shows small phase shift
- **poor quantitative agreement**
  - high field side: corrugations much smaller in VMEC
  - low field side: $\psi > 0.97$ ok further in VMEC too small

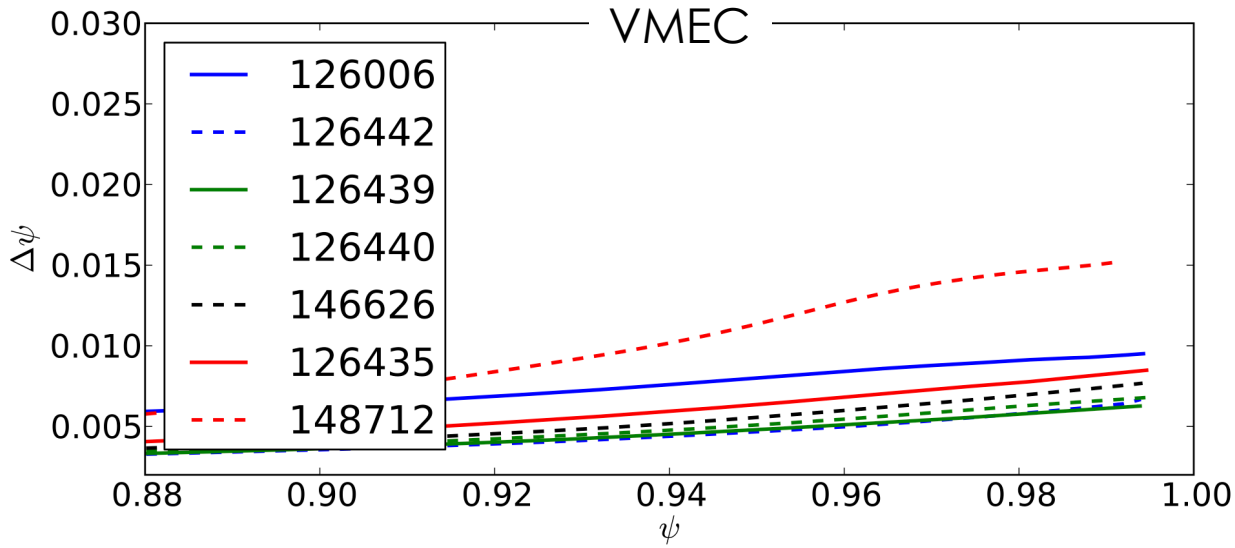
color: magnetic structure from M3D-C1
lines: surfaces from VMEC



VMEC and M3D-C1 dissagreement: ideal vs. resistive MHD?

- **displacements in VMEC increase steadily towards edge**
  - M3D-C1 follows $\langle j_{||} \rangle$ profile
- **discharges are in the same order**
  - 6 of 7 show the same ordering
  - 126006 outlier
    - why?
- **2x to 5x smaller displacements in VMEC**





Results using non-linear ideal MHD (VMEC)

- **successful 3-D equilibrium construction with high resolution**
  - start with 2-D equilibrium: kinetic EFIT
  - truncation within gap of rational surfaces essential
  - final 3-D equilibrium close to EFIT, but with typical n = 3 surface corrugation
- **basic qualitative agreement of surfaces with M3D-C1**
- **no quantitative agreement with M3D-C1**
  - VMEC displacements 2x to 5x smaller than in M3D-C1
- **VMEC displacements do not follow current density profiles**
  - displacements increase steadily towards edge
  - profile ordering matches though (one outlier)

Future work

- **differences in kink response between VMEC & M3D-C1 will be studied further**
  - each code covers different physics
    - M3D-C1: resistive, 2-fluid, rotation effects
    - VMEC: ideal, non-linear
  - each code has restrictions
    - M3D-C1: linear → displacements can be overestimated
      linear validity can be locally violated at the edge
    - VMEC: no rotation → no amplification or screening
      truncation → no description of separatrix or SOL
- **link to diagnostics, especially soft X-ray imaging**
  - M3D-C1 kink response in 148712 agrees with observed structures in position and number, not in size
  - extend VMEC B-fields to the wall and compare with footprints
  - VMEC shows poloidal structure in current density and local shear
    - changes in local transport could create emissivity structures in SXR

more analysis of further discharges needed