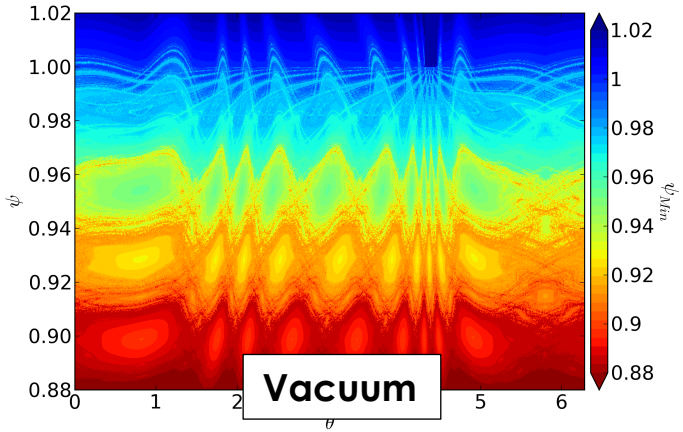
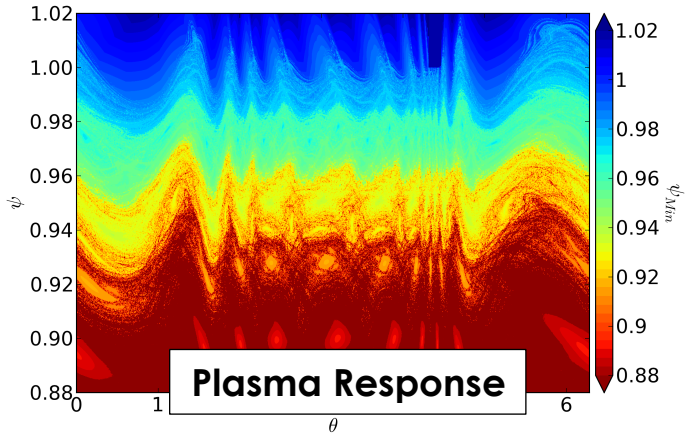
Impact of plasma response on plasma displacements in DIII-D during application of external 3-D perturbations

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

[1] ORNL, [2] GA





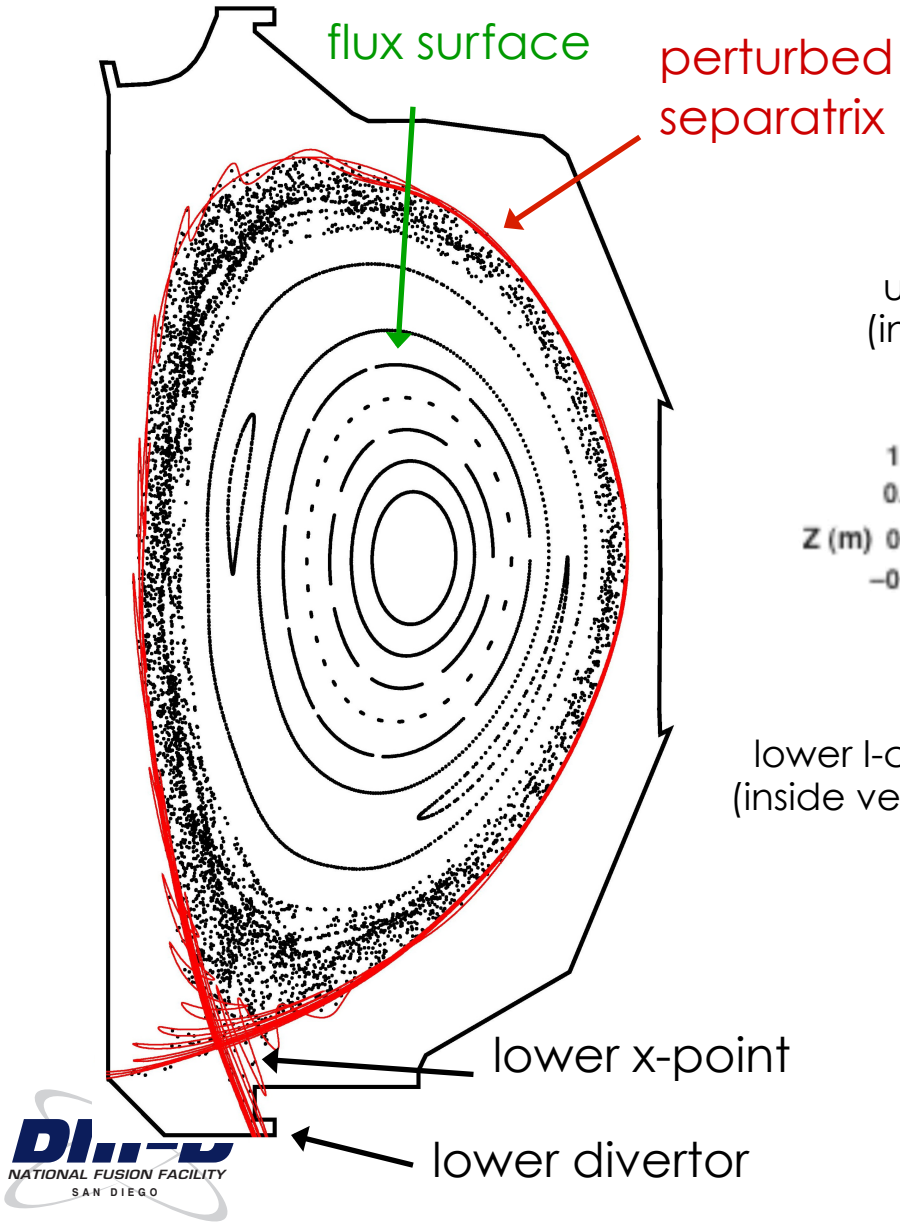
presented at:
ORNL

May 2013

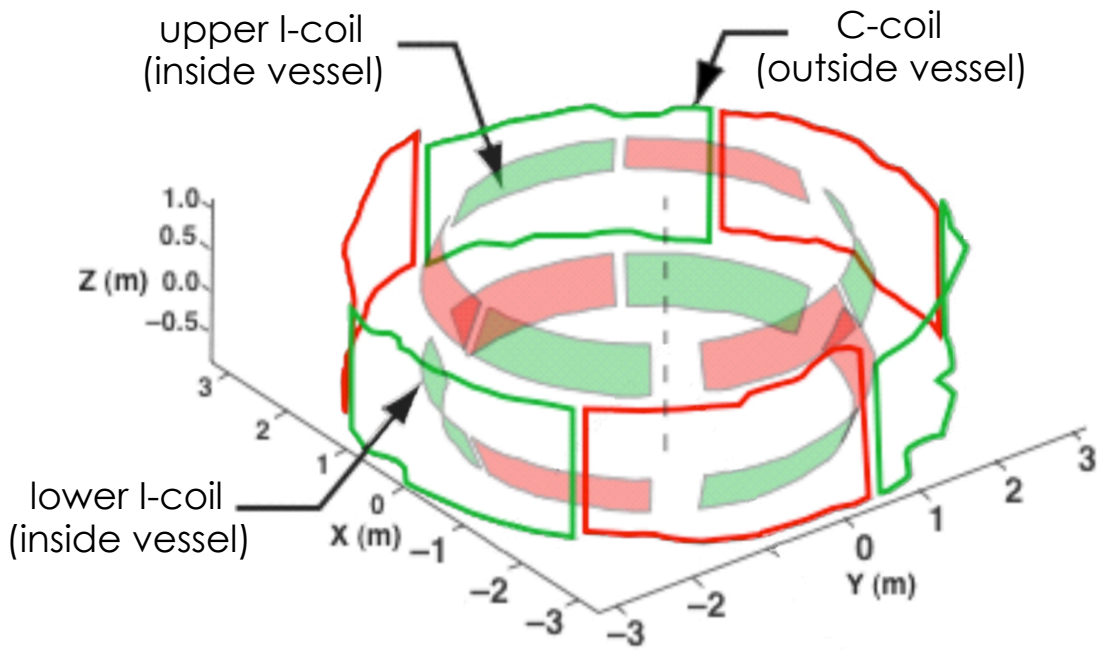
Content

- **Motivation and Introduction**
- **Plasma response based on the M3D-C1 code**
  - modified magnetic structure
  - perturbation spectrum
- **Modeling of soft X-ray emission in the plasma edge**
  - Soft X-Ray Imaging System
  - magnetic approach
  - fluid approach
  - displacements
- **Plasma response drive**
  - response sensitive to electron rotation
  - Kink vs. Islands
  - Hypothesis: Impact of plasma response on ELM suppression
- **Outlook & Conclusions**

External perturbations in the DIII-D tokamak modify magnetic topology in edge region



Resonant Magnetic Perturbation (RMP) **off**



→ **large stochastic layer formation**

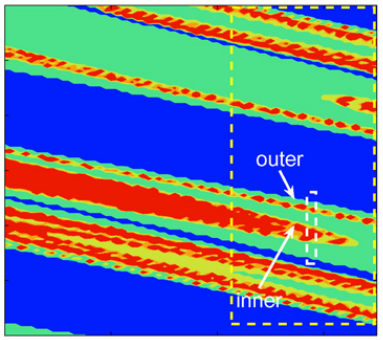
referred to as: Vacuum case

How does the plasma respond to 3D RMP fields?

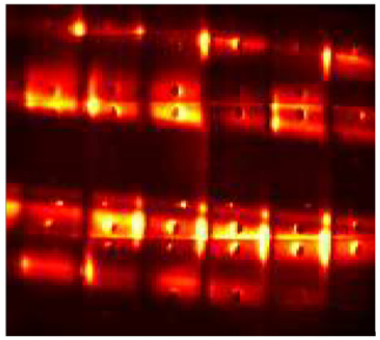
Past measurements agree with vacuum modeling

- Islands imaged in Ohmic discharges (Tore Supra) T.E. Evans *et al.*, PoP **9**, 4957 (2002)
- strike point splitting, heat/particle flux footprints in L-mode plasmas (TEXTOR) →

Connection length



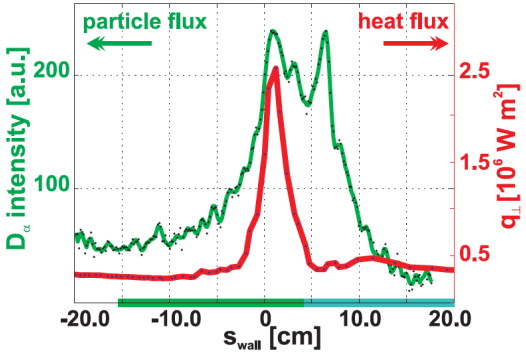
IR Camera



M.W. Jakubowski *et al.*, PPCF **49**, S109 (2007)

In H-mode, plasma response becomes important

- e.g. heat flux shows no splitting, but particle flux & vacuum modeling does (low collisionality only)



O. Schmitz *et al.*, PPCF **50**, 124029 (2008)

New diagnostics and new codes become available

- here: Soft X-Ray Imaging System
- here: M3D-C1 + MAFOT

Understanding of topology and plasma response in H-mode needed for predictions in future devices

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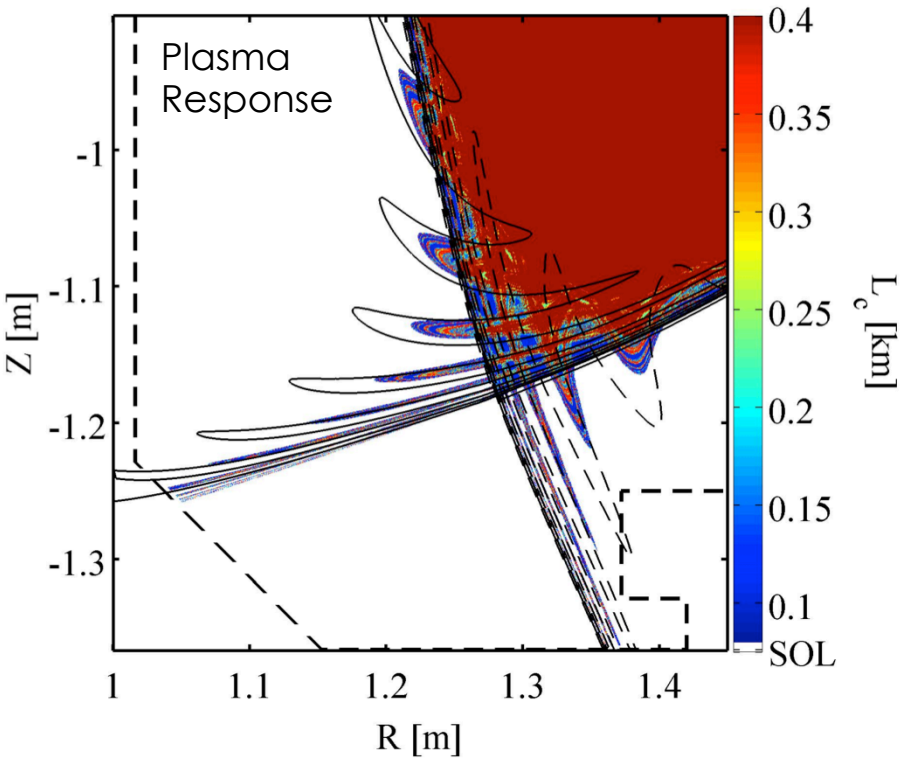
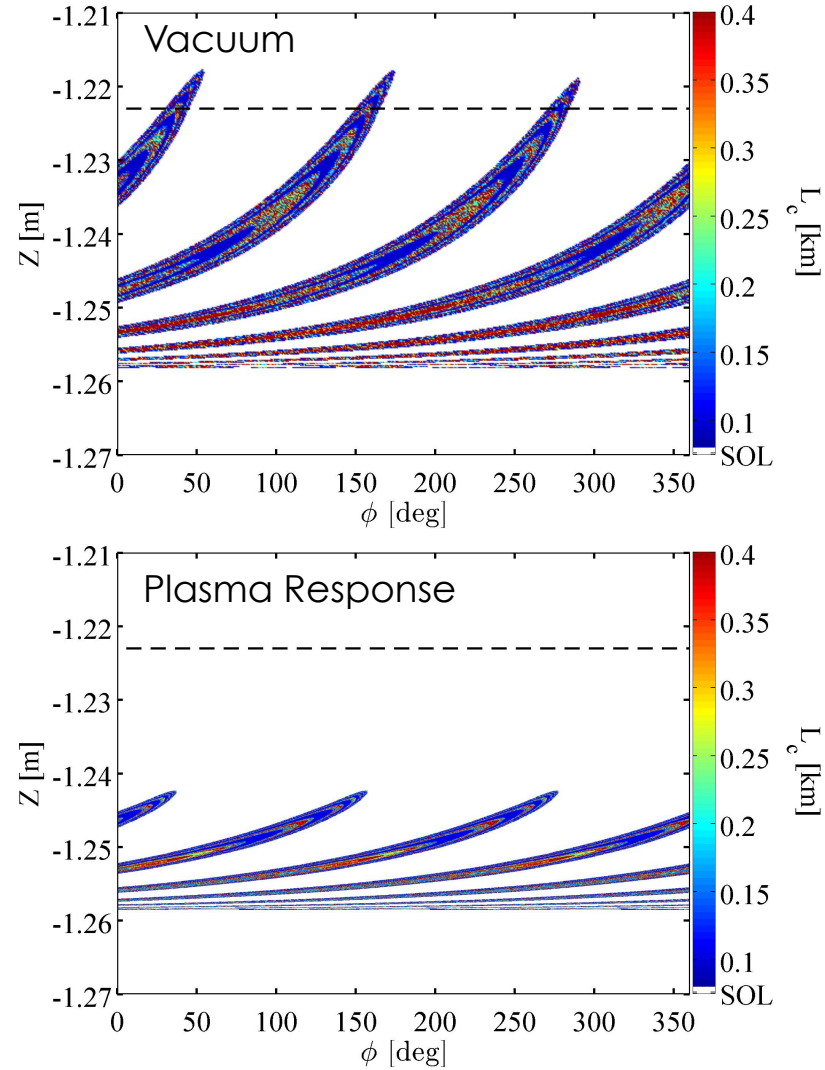
M3D-C1, a linear resistive two fluid MHD code, calculates a plasma response

- uses an idealized (sinusoidal) I-coil perturbation only, pure n = 3
- Discharge: 126006 @ 3600 ms
- color = connection length



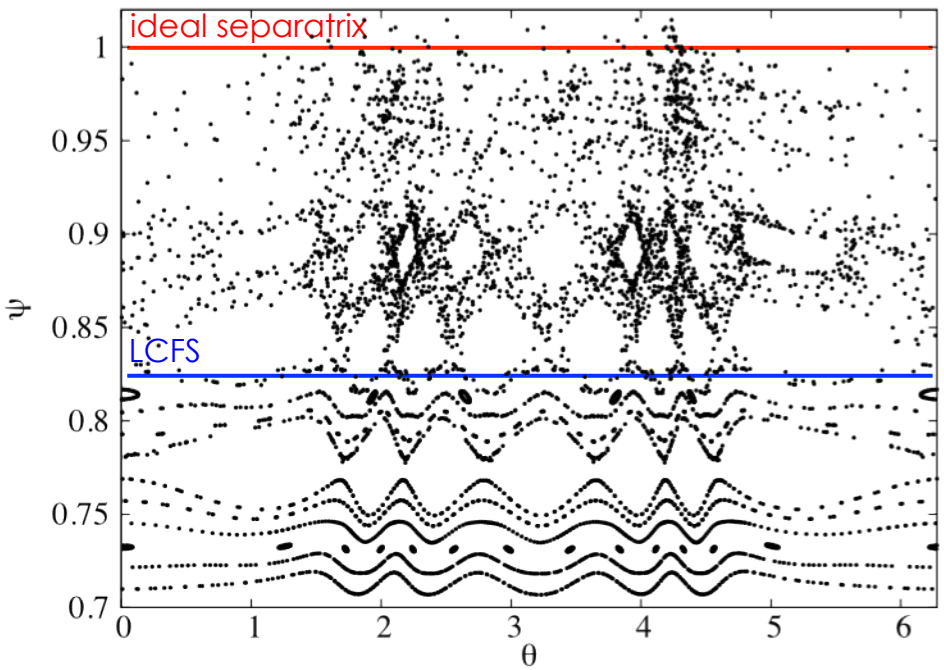


Plasma response can shrink magnetic structures

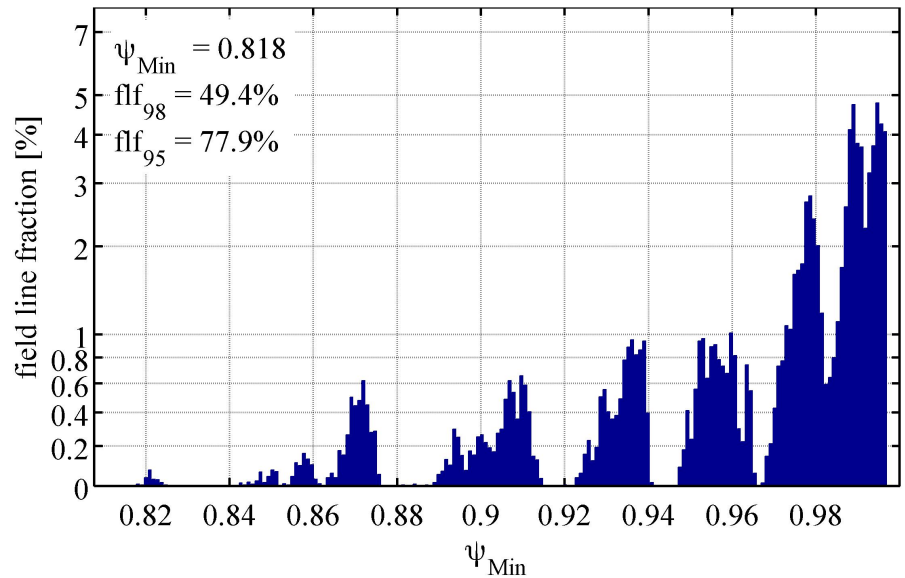
Plasma response can change stochasticity

Discharge: 126006 @ 3600 ms

Vacuum



Penetration statistics of field lines entering from outside of ψ = 1



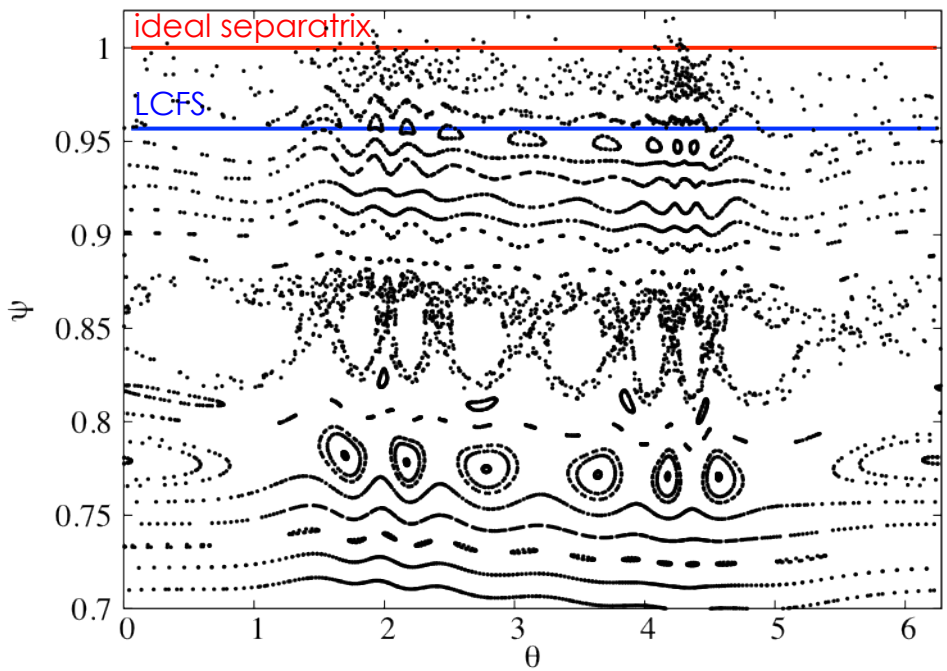
- large stochastic areas
- significant island chains

- field lines get stuck around islands
- large area open to wall
  LCFS at about ψ = 0.818

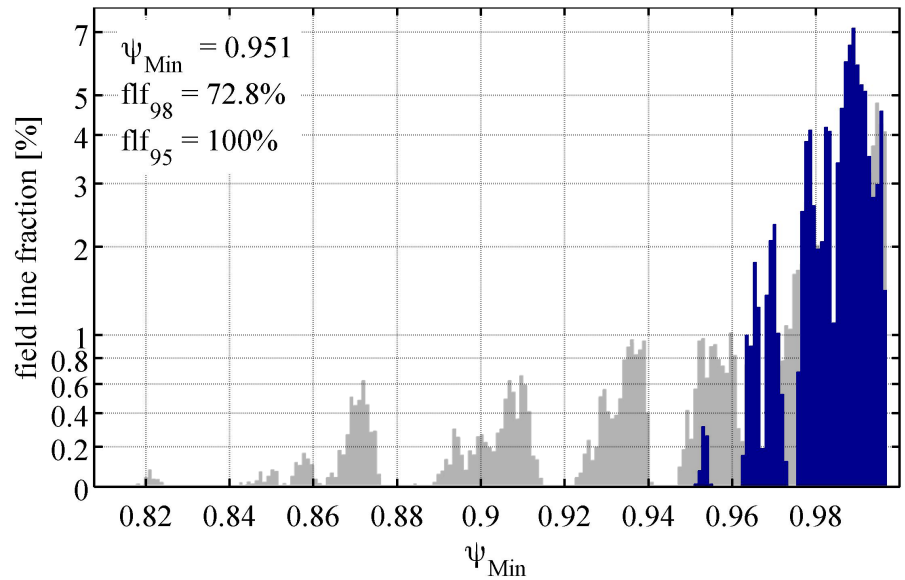
Plasma response can change stochasticity

Discharge: 126006 @ 3600 ms

Plasma Response



Penetration statistics of field lines entering from outside of ψ = 1

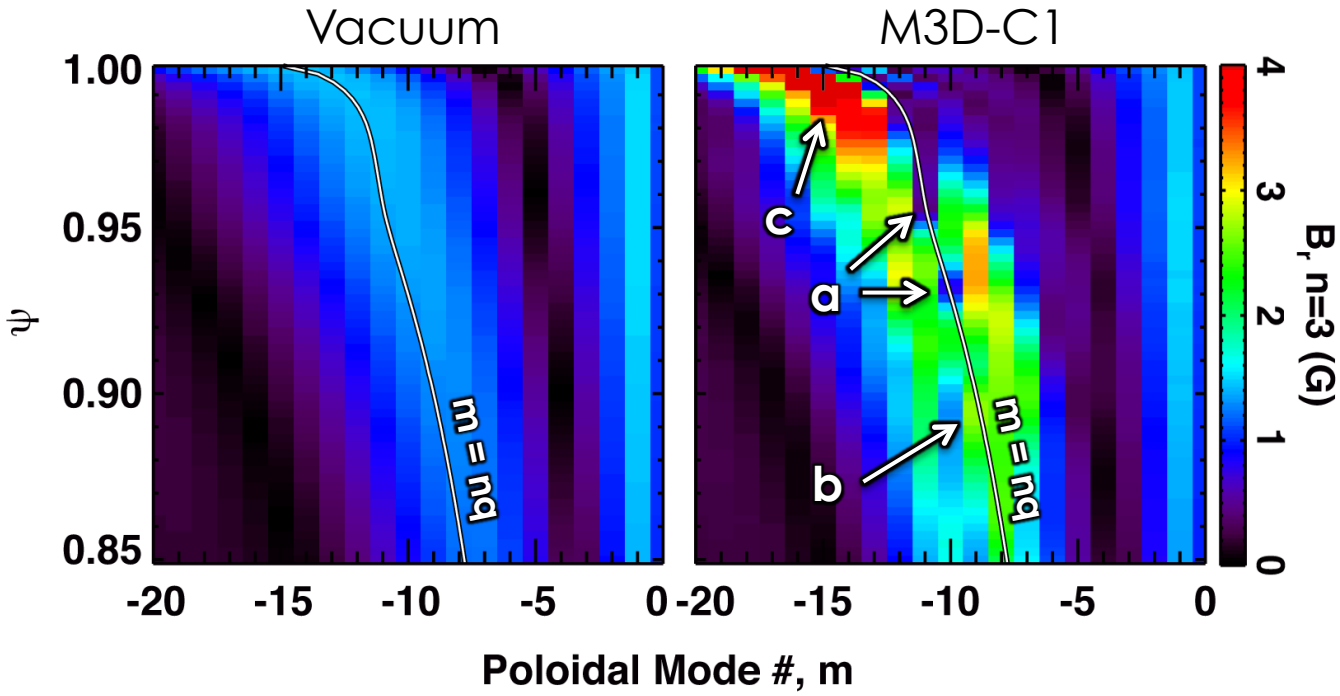


- smaller stochastic areas
- more intact flux surfaces
- **still significant islands present**

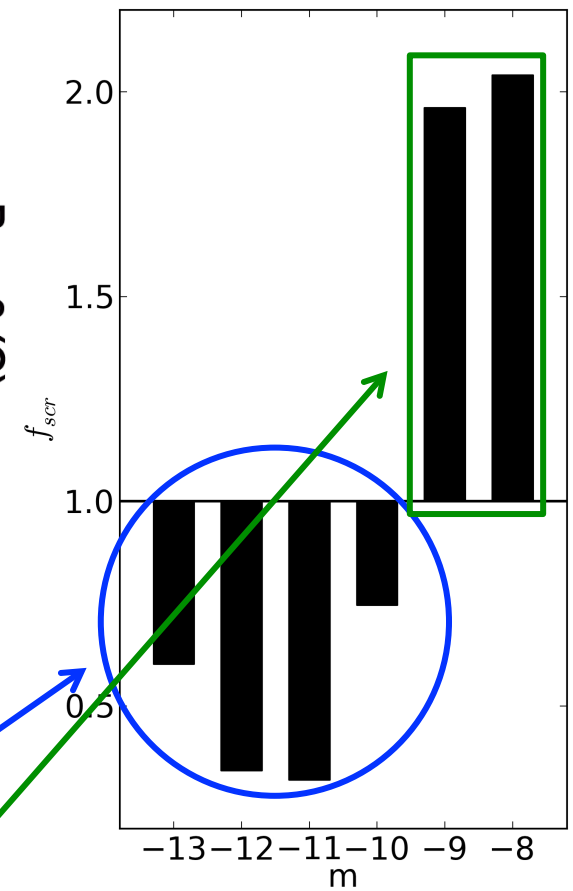
- reduced penetration
- here: only small area open to wall LCFS at about ψ = 0.951

Perturbation spectrum shows amplification and screening of various poloidal modes

Poloidal mode spectrum for 148712



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



Three main effects

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

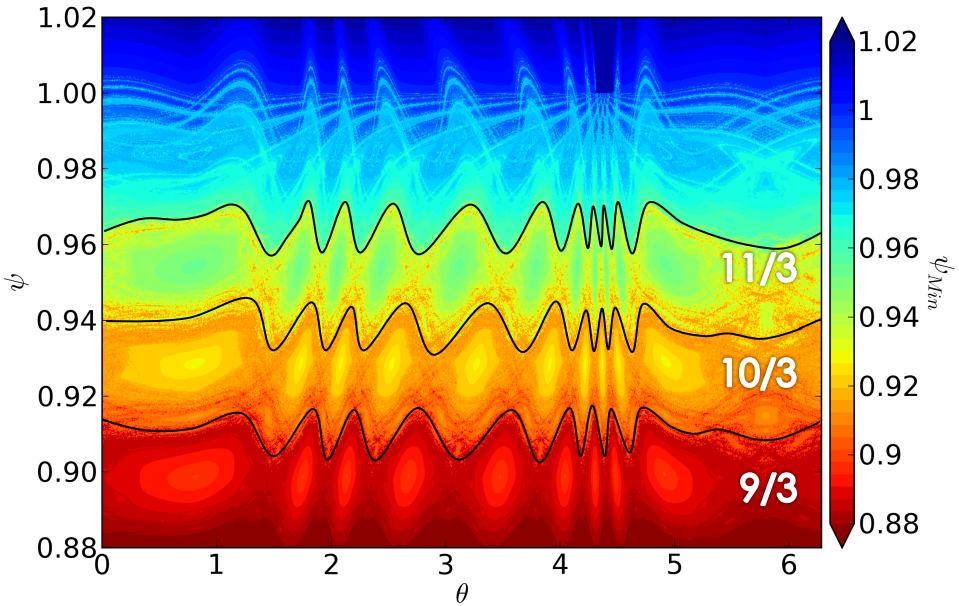
N.M. Ferraro *et al.*, PoP **19**, 056105 (2012)

Plasma response can create magnetic kink, that dominates edge structure

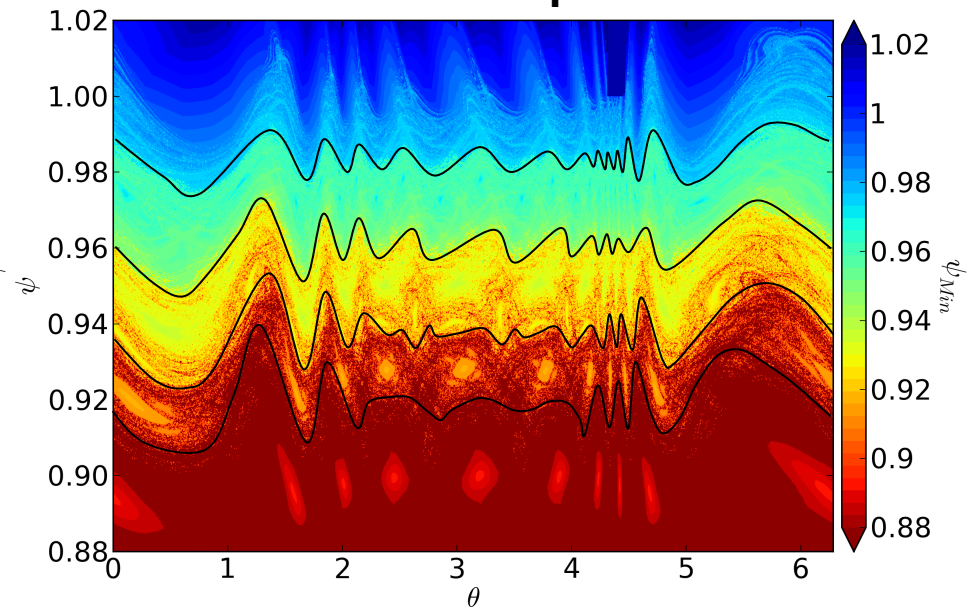
Discharge: 148712 @ 4150 ms

color = penetration depth

Vacuum



Plasma Response



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

- more stochasticity, islands smaller
- radially aglined pertrubation: **kink** with interstitial islands
- local change of periodicity with m, bifurcation at x-point

Kink pushes islands away

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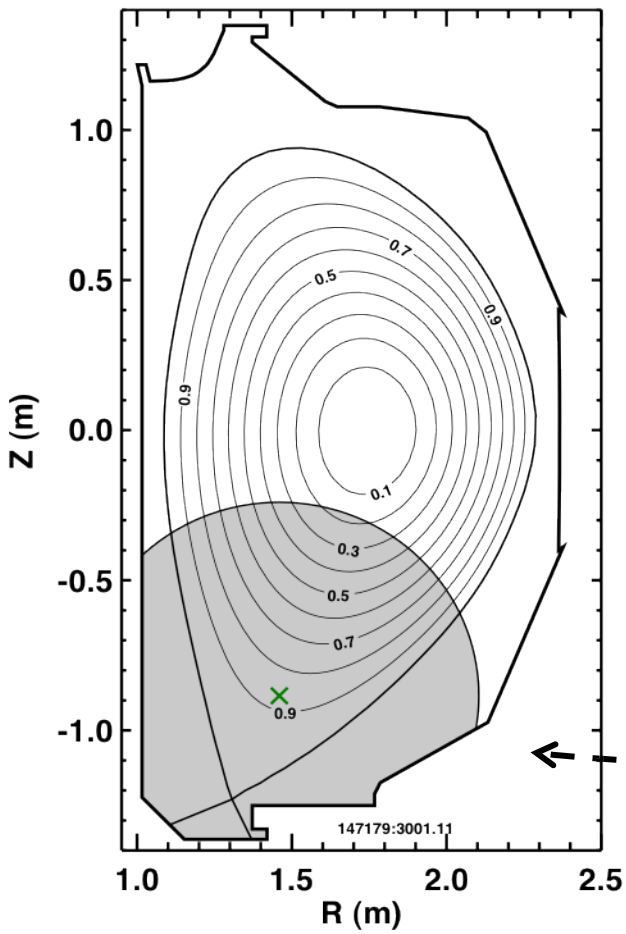
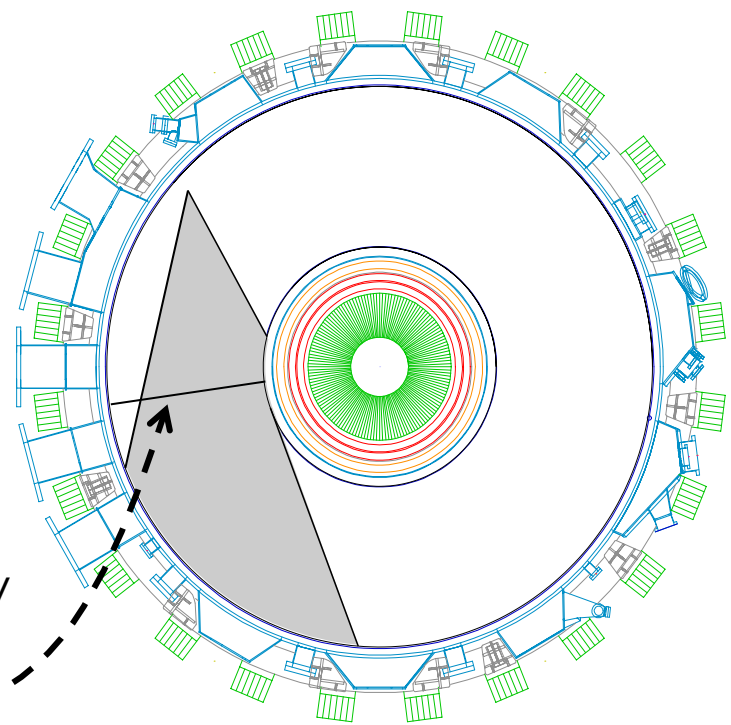
Soft X-Ray Imaging System (SXRIS) view centered above X-point to exploit flux expansion

Poloidal cross section with area seen by SXR camera



Top view with pinhole view cone



tangency plane

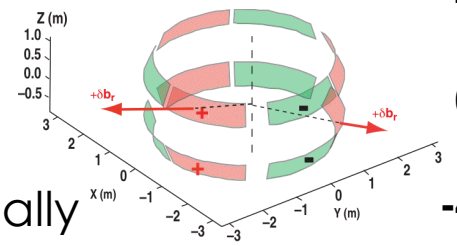
SXRIS measures line-integrated emission within view cone

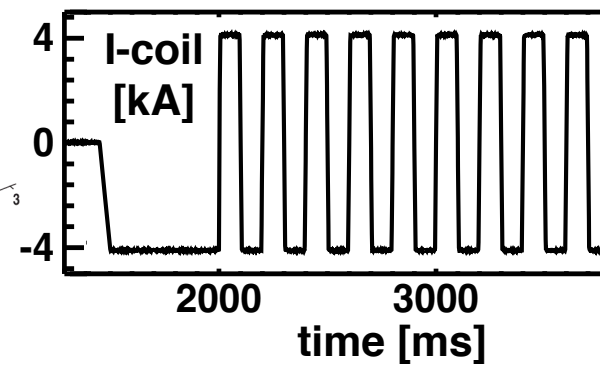
M.W. Shafer *et al.*, Rev. Sci. Instrum. **81**, 10E534 (2010)

n = 3 RMP phase modulation isolates response by increasing signal contrast via differencing

Experimental setup

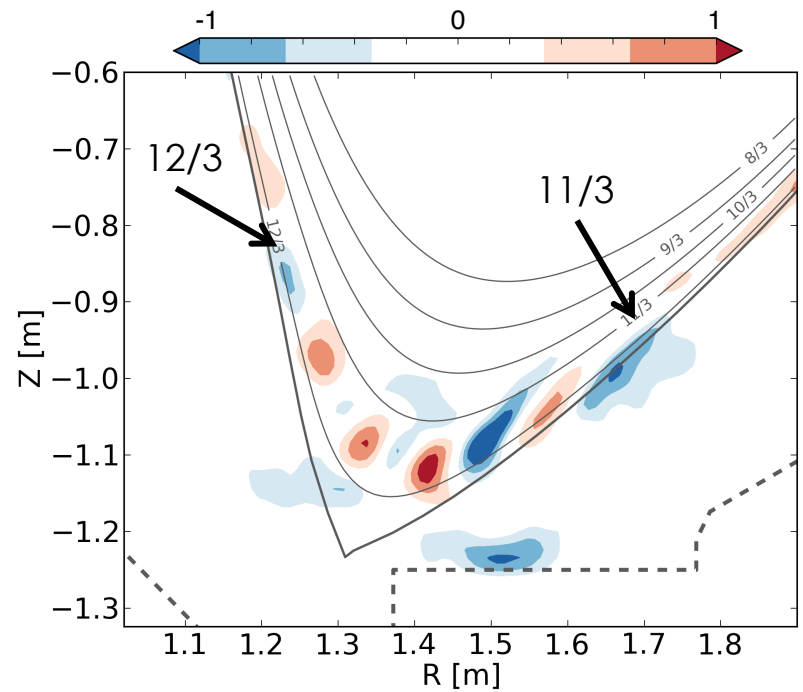
- standard RMP ELM-suppression plasmas
- I-coil currents are flipped periodically
- magnetic structure shifts 60° back and forth toroidally
- thick filter blocks low-energy SXR from SOL





Differenced emission

- Imaging inverted to give local emission
- subtract local SXR emission for both I-coil phases
- differenced image shows helical SXR displacements between the 11/3 and 12/3 rational surfaces, with apparent $m \approx 11 \pm 1$



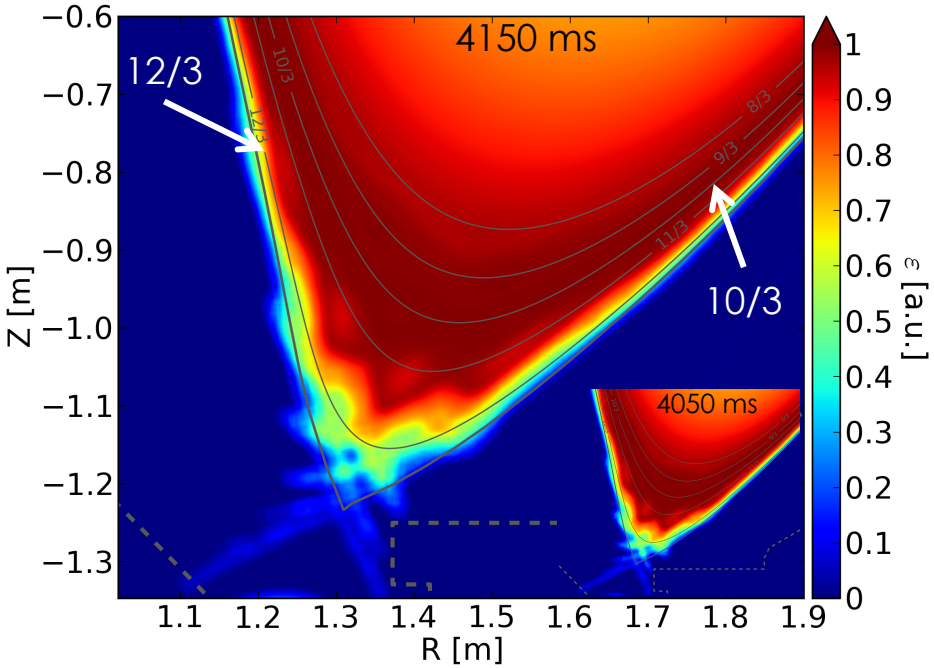
M.W. Shafer *et al.*, APS 2012 M.R. Wade *et al.*, IAEA 2012

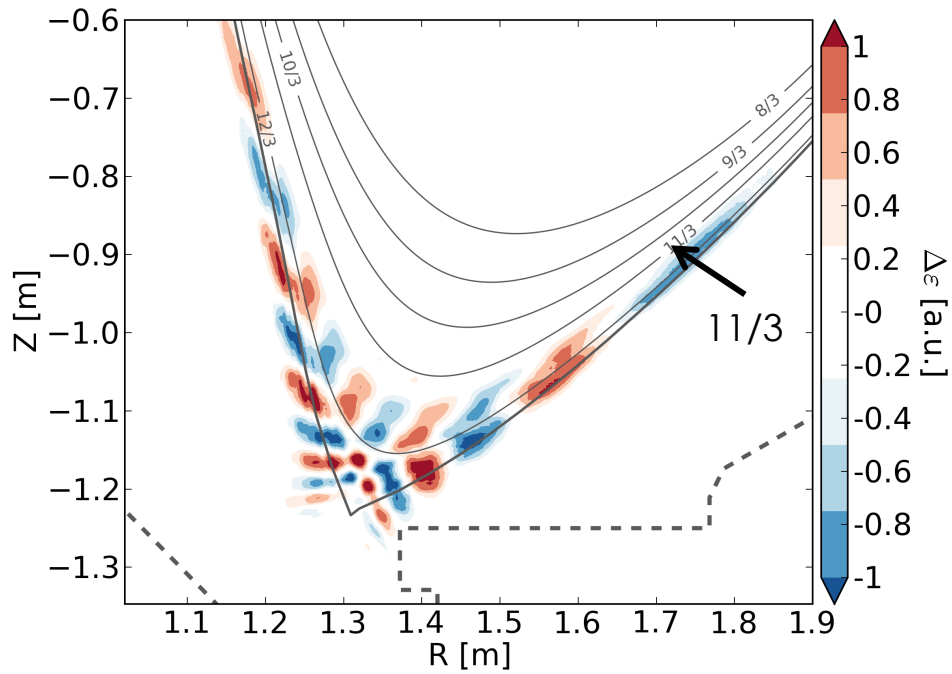
Overview of different modeling procedures

Case \ Approach	Magnetic (MAFOT)
Vacuum	• field line tracing $\vec{B}_V = \vec{B}_{EQ} + \vec{B}_{RMP}$ → ψ_{Min} = penetration • **assume:** emission is constant on field line • assign emission to ψ_{Min} ← profile $\varepsilon(\psi)$ derived from SXR data • apply smoothing filter ✓ works well with thin filter to explain lobe emission in SOL → M.W. Shafer *et al.*, NF **52**, 122001 (2012) (Editors's choice 2012)

Magnetic approach: overestimates lobes relative to internal structure with thick filter

Vacuum





- emission peaks between 10/3 and 12/3 surfaces
- I-coil flips cause emission structure to move poloidally → **subtract**

- strong emission from lobes → largest displacements outside of separatrix
- displacements up to 11/3 surface

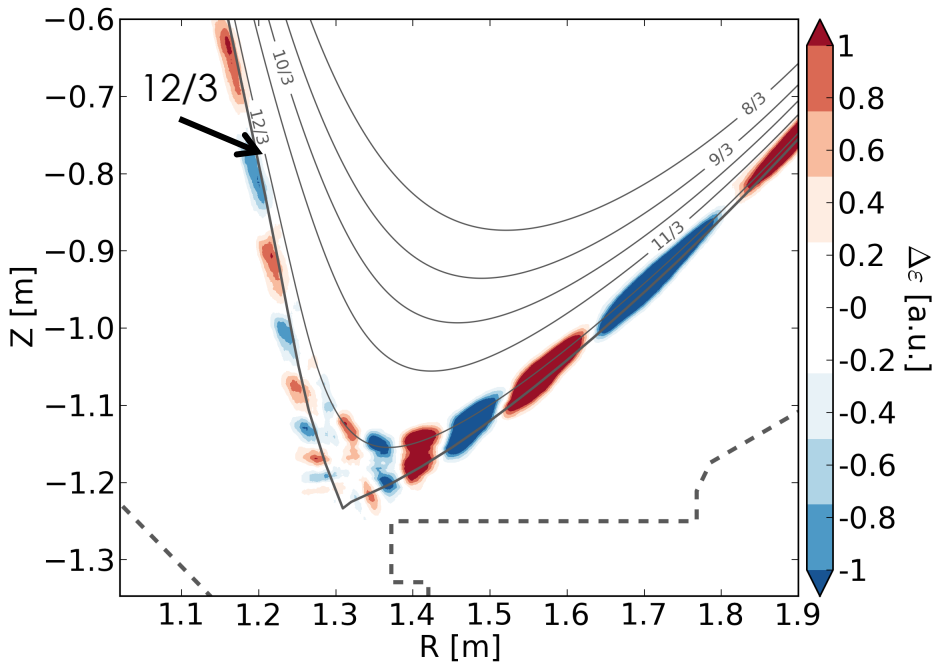
plasma response needs to be included

Overview of different modeling procedures, part II

Case \ Approach	Magnetic (MAFOT)
Vacuum	• field line tracing $\vec{B}_V = \vec{B}_{EQ} + \vec{B}_{RMP}$ → ψ_{Min} = penetration • **assume:** emission is constant on field line • assign emission to ψ_{Min} • apply smoothing filter
Plasma response (M3D-C1)	• $\vec{B} = \vec{B}_V + \vec{B}_{PR}$ • $\vec{B}_{PR}$ from M3D-C1, self-consistent • same procedure as above

Plasma response alters the magnetic structure → displacement pattern changes

Plasma Response



- emission from lobes much weaker, but lobes still overestimated
- very large displacements at separatrix and 12/3 on low-field side
- differenced image shows only minor agreement with data

Overview of different modeling procedures, part III

Case \ Approach	Magnetic (MAFOT)	Fluid (M3D-C1)
Vacuum	• field line tracing $\vec{B}_V = \vec{B}_{EQ} + \vec{B}_{RMP}$ → ψ_{Min} = penetration • **assume:** emission is constant on field line • assign emission to ψ_{Min} • apply smoothing filter	X
Plasma response (M3D-C1)	• $\vec{B} = \vec{B}_V + \vec{B}_{PR}$ • $\vec{B}_{PR}$ from M3D-C1, self-consistent • same procedure as above	• electron temperature & electron density • Emissivity: $\varepsilon \sim n_e^2/\sqrt{T_e}$ • remap to experimentally obtained emissivity

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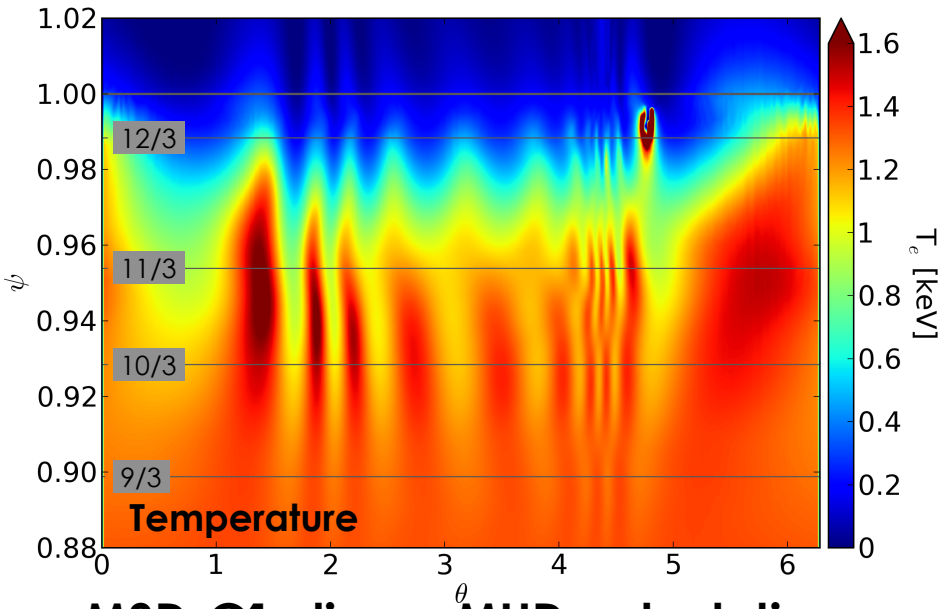
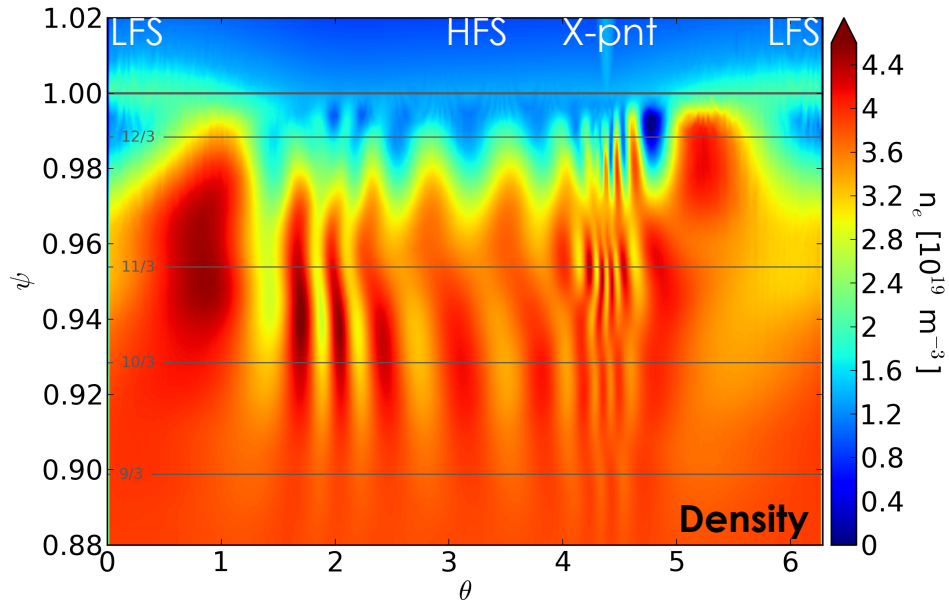
Fluid approach: use temperature and density from MHD simulation to model SXR emission





M3D-C1: linear MHD calculation

- I_{pert} = 3 kA → one small region of non-physical data
- no non-linear effects → stochastic B-field not reflected here

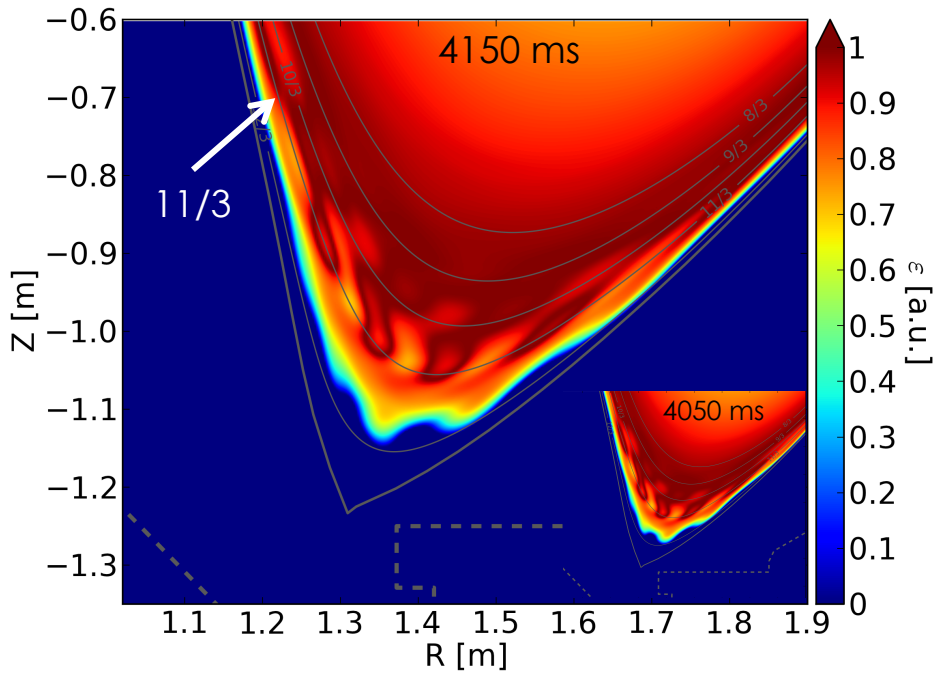
Perturbed structure shows kink like oscillations

- T_e and n_e structures are alike, but out of phase
- periodicity changes locally with *m*, bifurcation at x-point

Similar to kink in magnetic structure (later more)

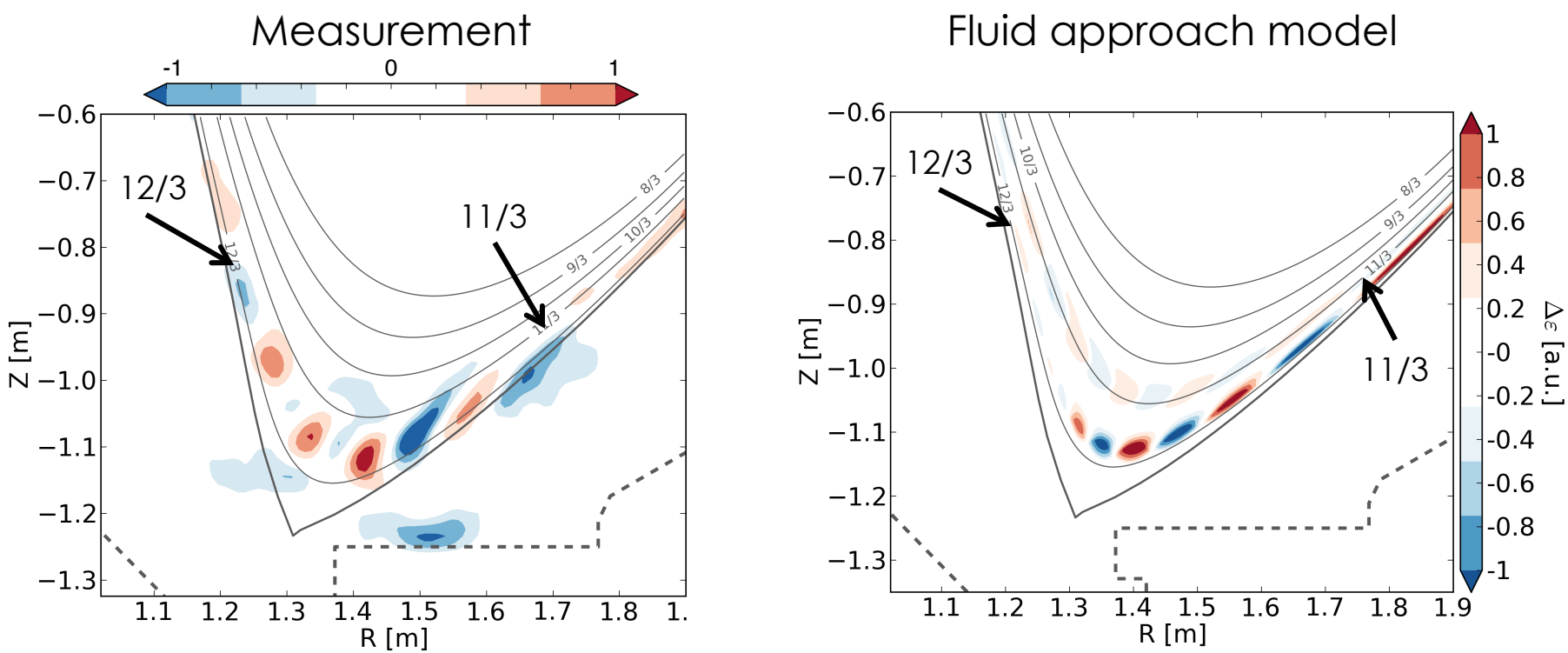
Lokal SXR emission peaks around 11/3 surface, almost no emission from lobes

- from 1D profiles, get $\varepsilon(\psi) := n_e^2(\psi)/\sqrt{T_e(\psi)}$ → invert → $\psi(\varepsilon)$
- calculate $\varepsilon(R,Z)$, using the 2D perturbed $n_e(R,Z)$ and $T_e(R,Z)$ from M3D-C1
- get emission based on experimental profile $\varepsilon_{\text{fit}}(\psi(\varepsilon(R,Z)))$



- stripes in n_e and T_e adjusted by ε_{fit} → **emission structure comes from kink**

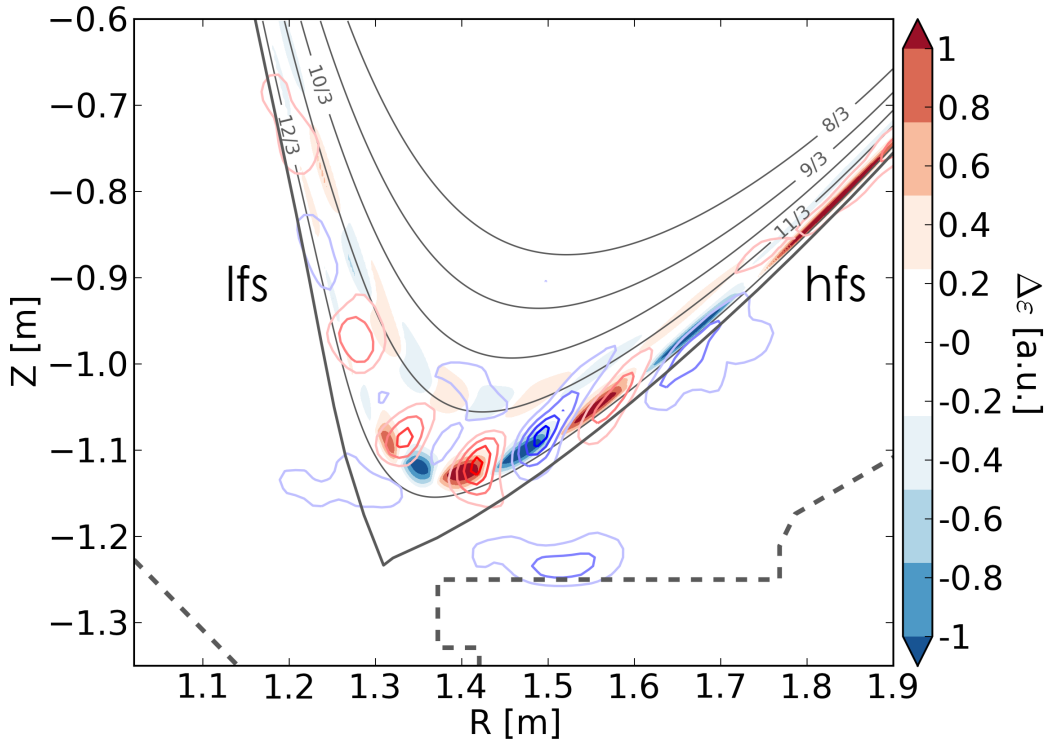
M3D-C1 fluid approach shows good agreement with measurement



- measured displacements located between 11/3 and 12/3 rational surfaces
- modeled displacements very similar, but also some on 11/3 surface
- poloidal mode number agrees in both cases: ***m* = 12**

M3D-C1 fluid approach shows good agreement with measurement

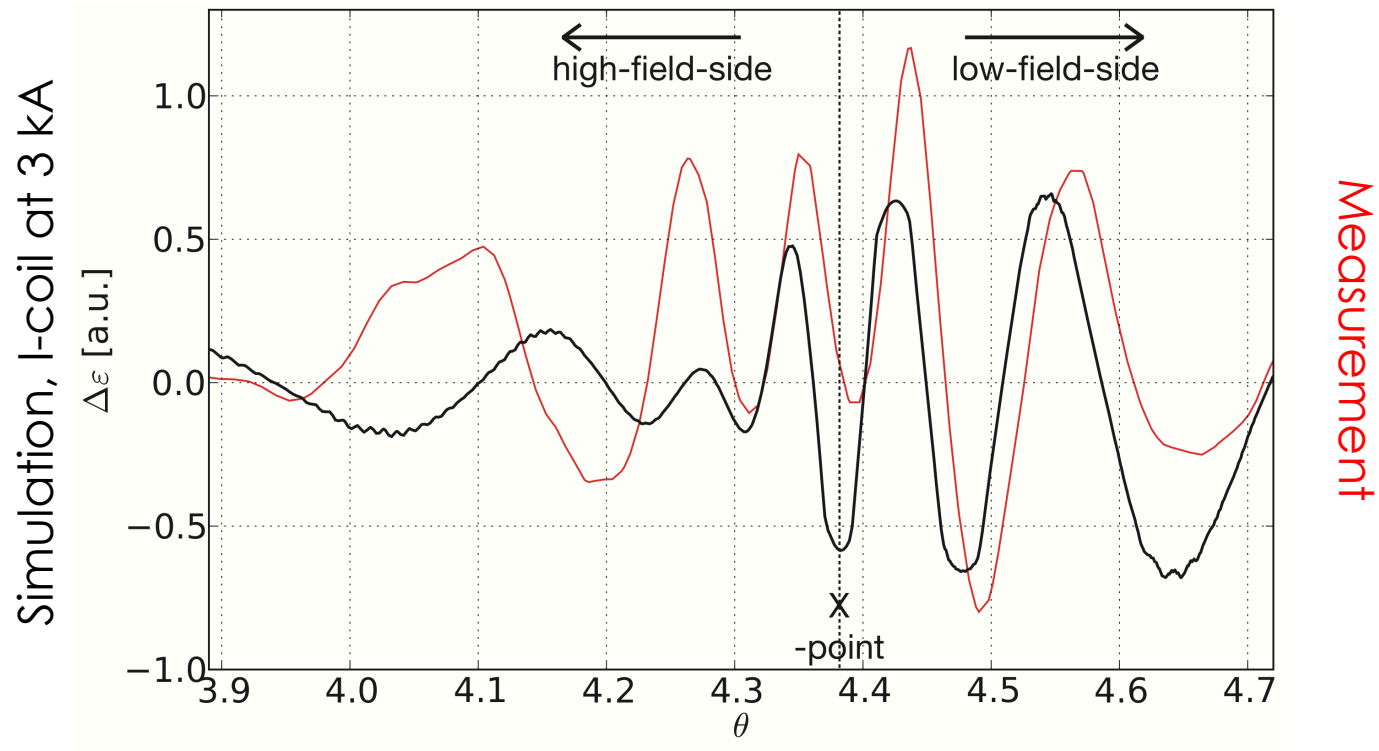
Overlay: contour lines = Measurement ←→ filled contours = Model



- weak displacements on 11/3 surface also show agreements
- modeled displacements show a phase shift on low-field-side (lfs) good agreement on high-field-side(hfs) and at X-point
- wall interaction not included in model

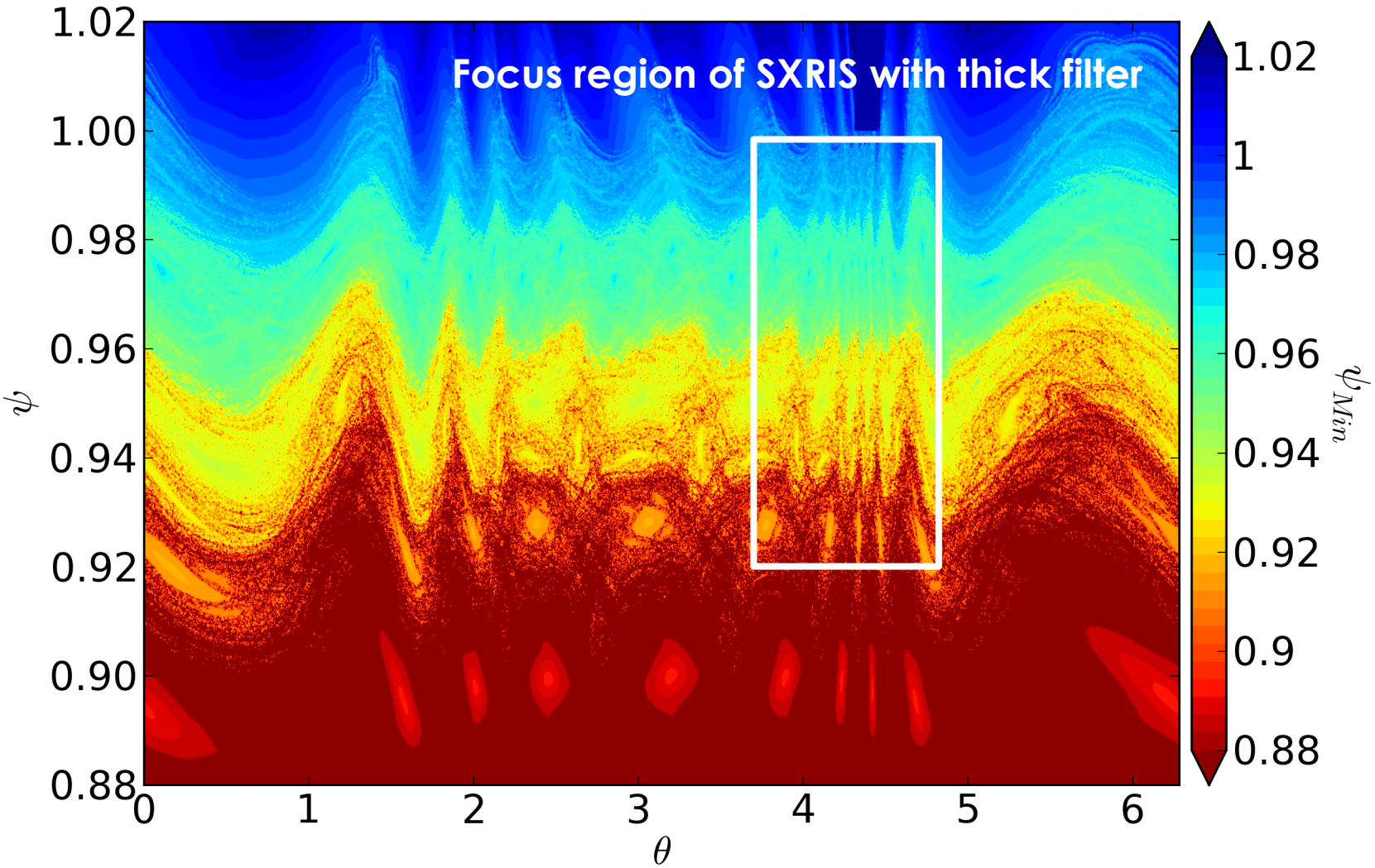
Measured SXR displacements agree with modeld ones

- Fluid approach model: differenced emission along 0.98 surface
- SXR data: differenced emission profile along 0.98 surface
- **both show the very similar oscillation pattern**



SXRIS measurements consistent with M3D-C1 plasma response

T_e aligned with kinked magnetic structure due to large anisotropy in thermal conductivity



The SXR diagnostic measures the kink, as shown in T_e and ψ_{Min}

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Two-fluid resistive MHD plasma response sensitive to $\omega_{\perp,e}$

Edge/SOL

- low rotation, high resistivty
- vacuum model works well

Steep pressure gradient

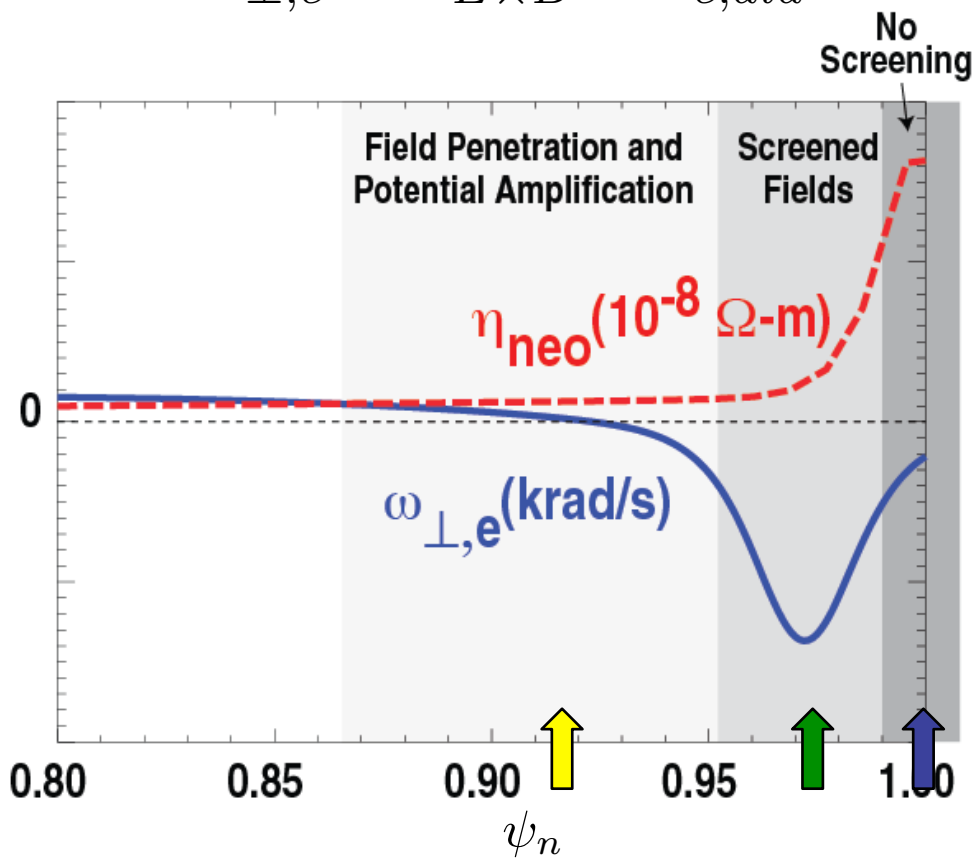
- high rotation, low(er) resistivity
- applied field shielded by image currents on rational surfaces
- non-resonant amplification

Top of Pedestal

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

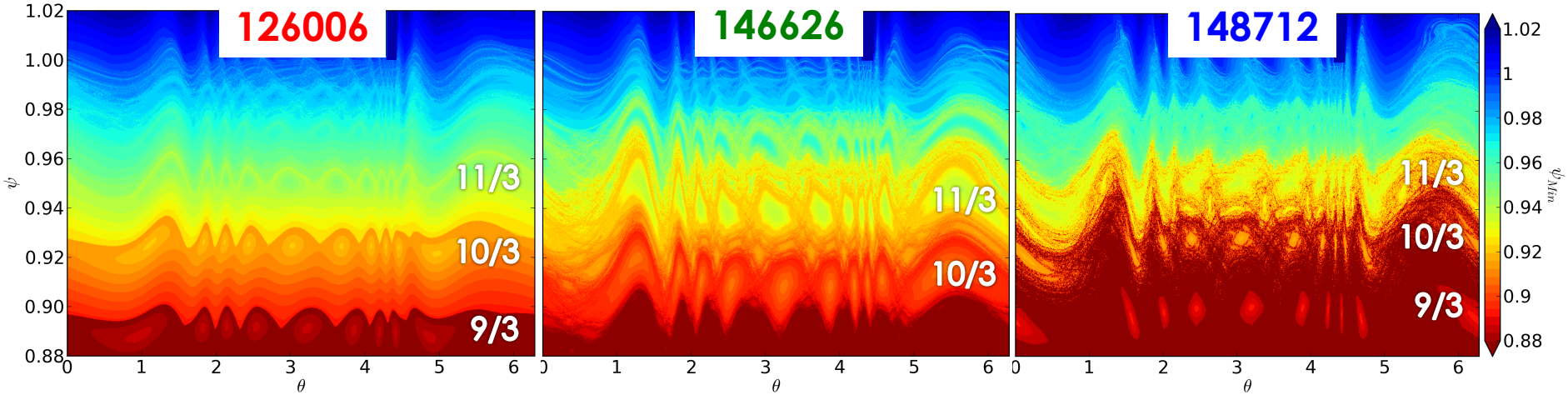
perpendicular electron rotation:

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



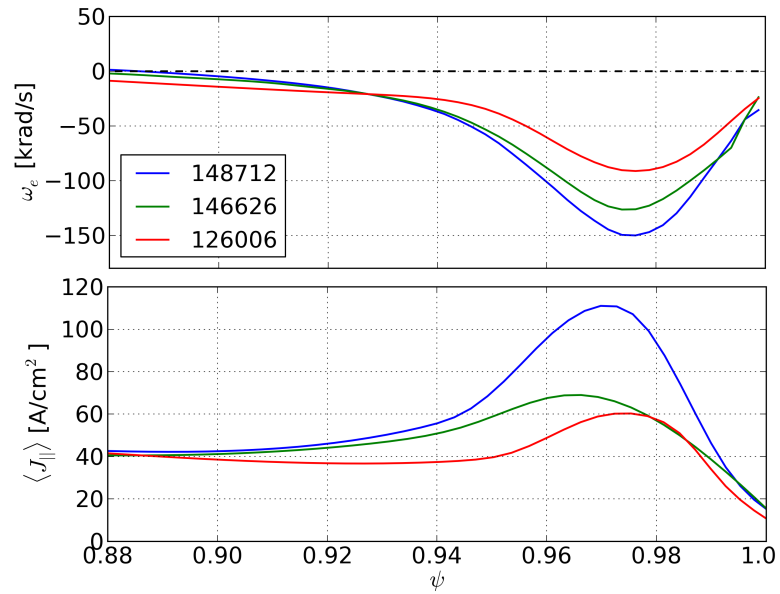
N.M. Ferraro, PoP **19**, 056105 (2012)

Plasma response gets stronger with increasing electron rotation and edge current density



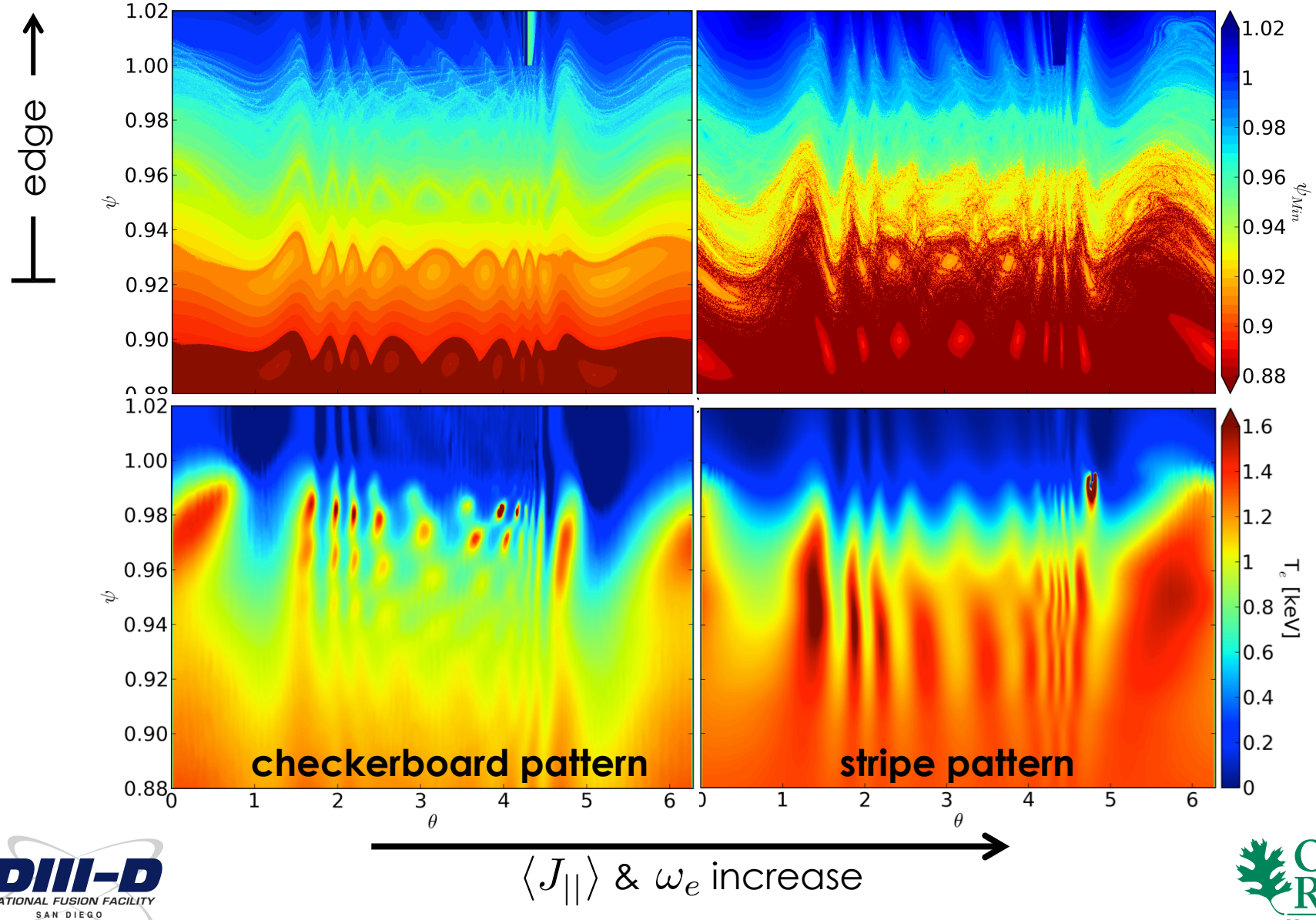
All effects increase:

- resonant amplification
  - → islands grow, e.g. 9/3, 10/3
  - → more stochasticity
- resonant screening (everywhere else)
  - → islands shrink
  - → closed flux surfaces
- non-resonant amplification
  - → kinking



Combination of rotation and edge current density influences plasma response

Island dominated edge ←→ Kink dominated edge



Hypothesis: discharges with stronger kink are closer to peeling ballooning stability threshold → ELMs

- **126006: a well ELM suppressed discharge**
  - steady suppression throughout the entire I-coil phase
  - $I_{\text{I-coil}}$ = 3.9 kA
  - island dominated, very small kink
- **146626: good ELM suppression throughout the shot at higher I-coil current**
  - $I_{\text{I-coil}}$ = 5.1 kA
  - intermediate case: larger kinking but still significant islands
- **148712: marginal ELM suppression**
  - first suppressed, but ELMs return at higher density (still below empirical limit)
  - 0° I-coil phase still ELM free, 60° phase ELMing
  - strong kinking, islands small, larger stochasticity
- **all discharge parameters well within empirical limits for suppression**

to be investigated in the future...

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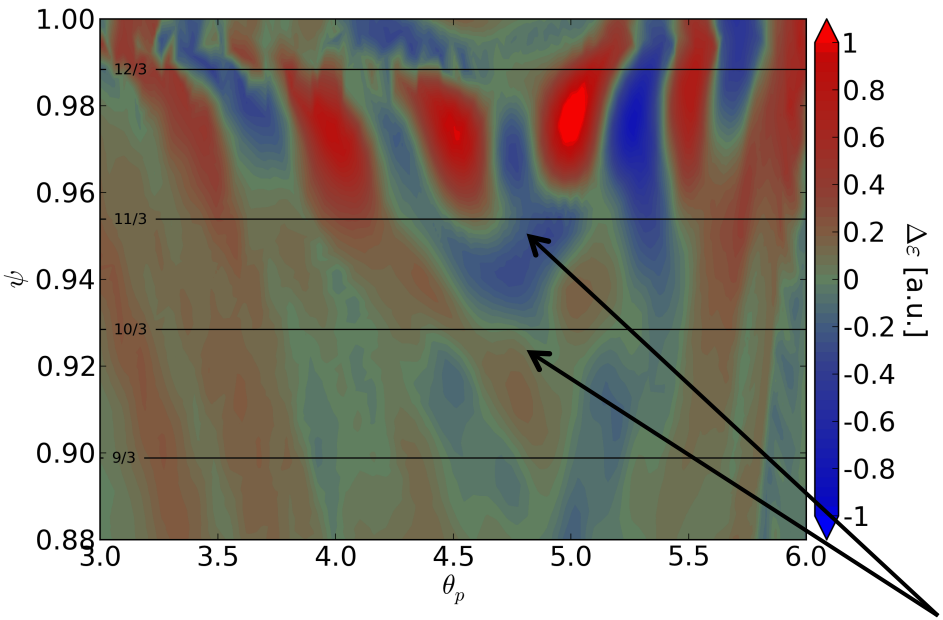
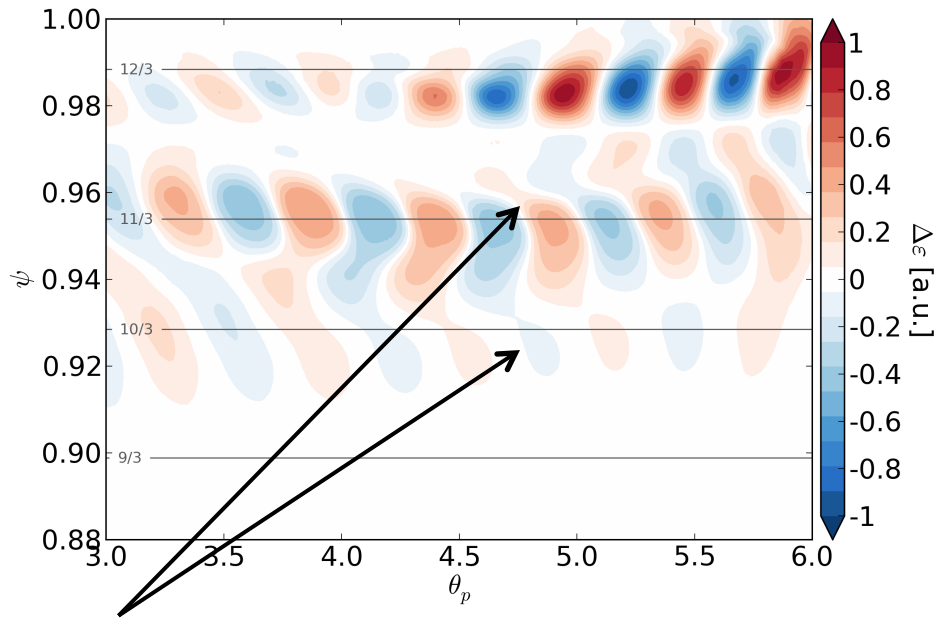
Outlook: Island structures further inside?

- Displacements: Kink = stripes, Islands = checkerboard
  → look for radial phase jump in displacement patterns
- use straight field line coordinates (PEST) for better visualization

Measurement



Fluid simulation



Phase jumps on 10/3 and 11/3 surfaces around X-point

Signs of islands !? → to be investigated

Conclusions

- **Plasma response, as calculated by M3D-C1, has various impacts on magnetic structure**
  - e.g. shrinking of lobes, manifolds and footprints
  - stochasticity changes, but still significant islands present
  - magnetic kink, kink even pushes islands away
- **SXR emission successfully modelled and explained by including plasma response**
  - magnetic approach: lobes too strong
  - fluid approach matches SXR data quite well
  - MHD temperature perturbation agrees well with magnetic structure
  - plasma response includes both kink and island responses, but measured SXR displacements are caused by magnetic kink
- **Combination of electron rotation and edge current density is correlated with plasma response**
  - all effects are increased: screening, amplification and kinking
  - transition from island domination to kink domination

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Relation to ELM suppression? Hypothesis: yes

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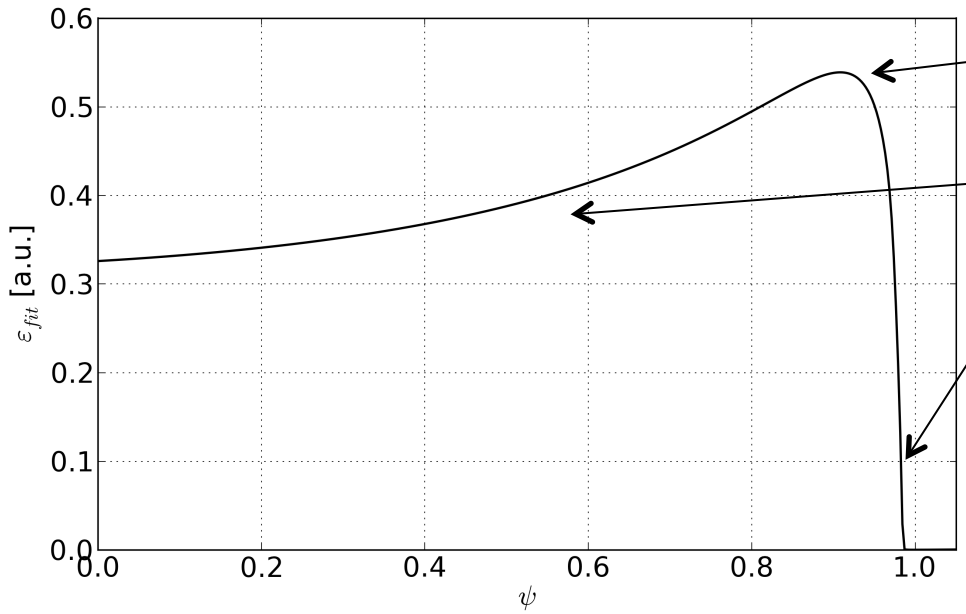
Backups

Experimental emissivity profile

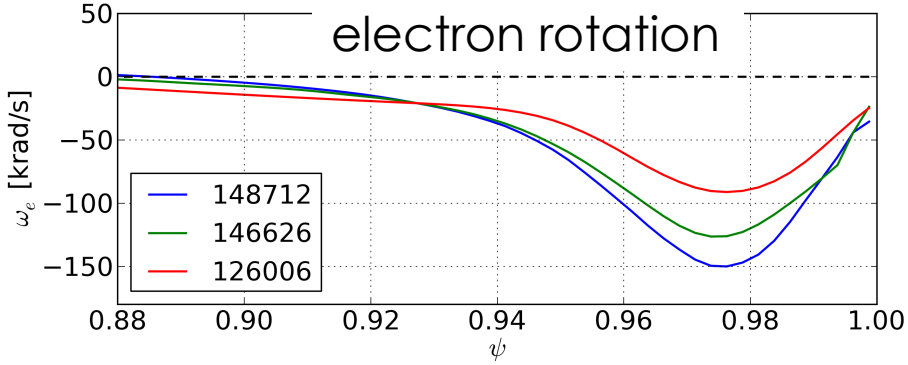
SXR filter: only emission > 500 eV

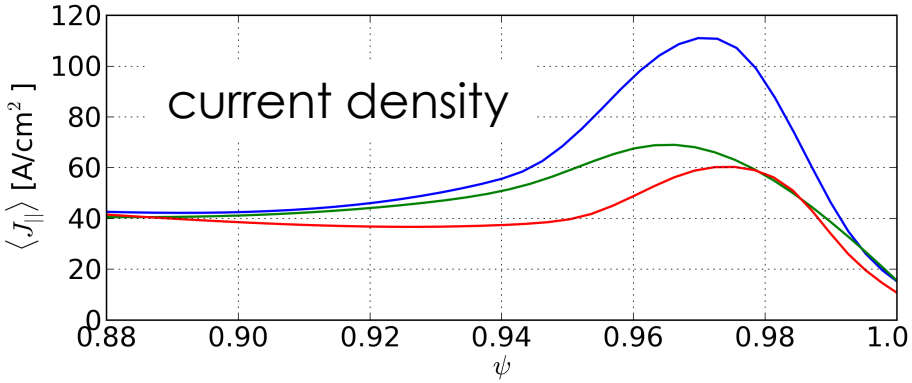


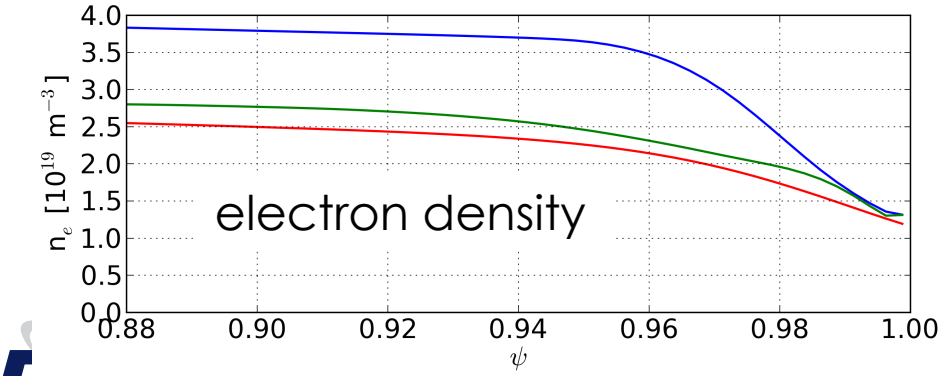
- flux surface averaged SXR intensity
- Emissivity profile includes:
  - line radiation
    → peak at the edge
  - Bremsstrahlung
- extracted directly from measurement by minimization method:
  - use line-integrated SXR image
  - calculate SXR image based on emissivity → subtract
  - change emissivity until residual is minimal

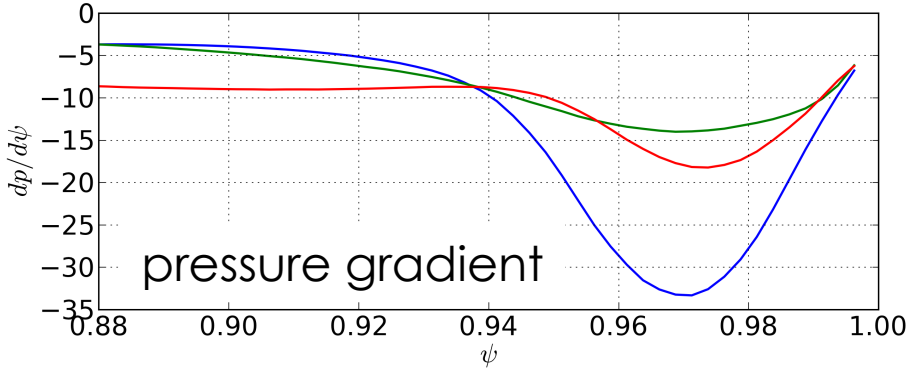
M.W. Shafer *et al.*, NF **52**, 122001 (2012)

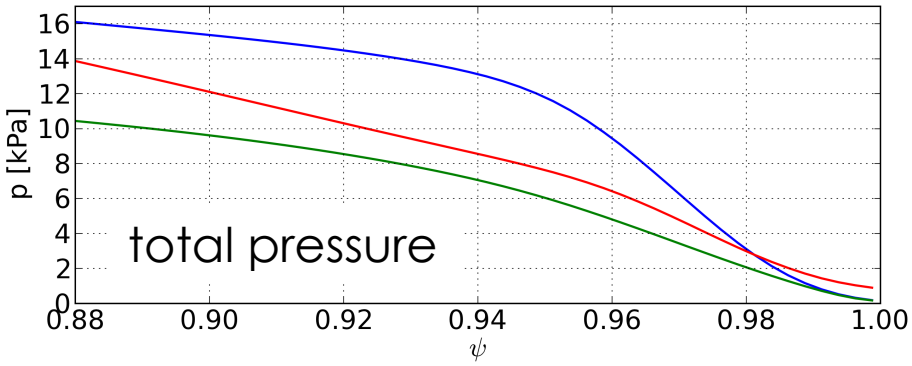
electron density shows same ordering, others do not











Plasma parameters

- **126006 @ 3600 ms**
  I_p = 1.53 MA, B_T = 1.88 T, β_N = 2.5, q_{95} = 3.55, ν^* = 0.188,
  n_e = 3.6x10^{19} m^{-3}, $I_{I\text{-}coil}$ = 3.9 kA @ 60°

- **148712 @ 4150 ms**
  I_p = 1.6 MA, B_T = 1.96 T, β_N = 1.74, q_{95} = 3.38, ν^* = 0.2,
  n_e = 4.8x10^{19} m^{-3}, $I_{I\text{-}coil}$ = 3.9 kA @ 60°

- **146626 @ 2250 ms**
  I_p = 1.43 MA, B_T = 1.85 T, β_N = 1.78, q_{95} = 3.72, ν^* = 0.2,
  n_e = 3.53x10^{19} m^{-3}, $I_{I\text{-}coil}$ = 5.1 kA @ 60°

- **all have similar shape**

- **some empirical limits for ELMs to return**
  $\beta_N < 1.4$, $q_{95} > 3.6$, $q_{95} < 3$, $\nu^* > 0.35$, $n_e > 5\text{x}10^{19}$ m^{-3}

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M3D-C1 Solves Two-Fluid Equations

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{u}) = 0$$ mass conservation

$$n_i m_i \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi$$ force balance

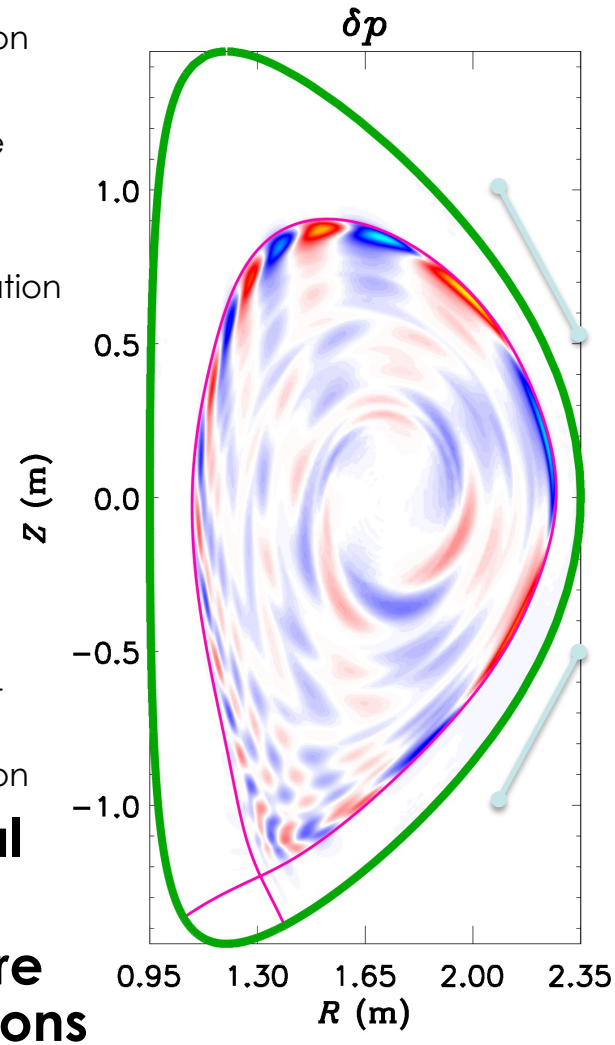
$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\Gamma p \nabla \cdot \mathbf{u} - \frac{1}{n_e e} \mathbf{J} \cdot \left(\Gamma p_e \frac{\nabla n_e}{n_e} - \nabla p_e \right) + (\Gamma - 1)\left(\eta J^2 - \Pi : \nabla \mathbf{u} - \nabla \cdot \mathbf{q} \right)$$ energy conservation

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left[-\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{n_e e} \left(\mathbf{J} \times \mathbf{B} - \nabla p_e \right) \right]$$ generalized Ohm's law

$$\mathbf{J} = \nabla \times \mathbf{B}$$ Maxwell

$$\Pi = -\mu \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right]$$ pressure tensor

$$\mathbf{q} = -\kappa \nabla p - \kappa_{\parallel} \mathbf{b}\mathbf{b} \cdot \nabla T_e$$ heat conduction



- **Boundary conditions: normal B from external coils is held constant at boundary**
- **Here, linear, time-independent equations are solved directly, subject to boundary conditions**

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