3D magnetic geometric effects during RMP application and comparison to measurements in DIII-D

by
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with
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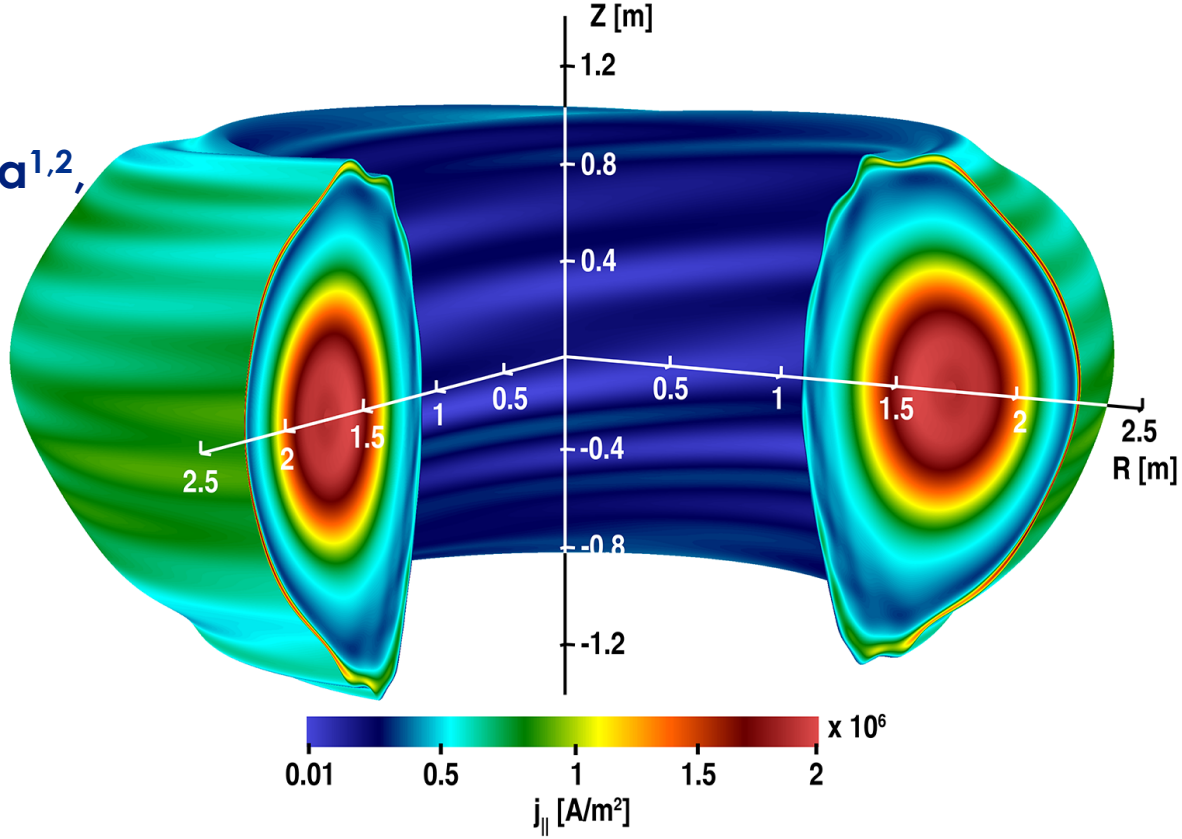
[4]General Atomics
[5]Princeton Plasma Physics Laboratory



Presented at the
ORNL FEST Seminar
June 24, 2015

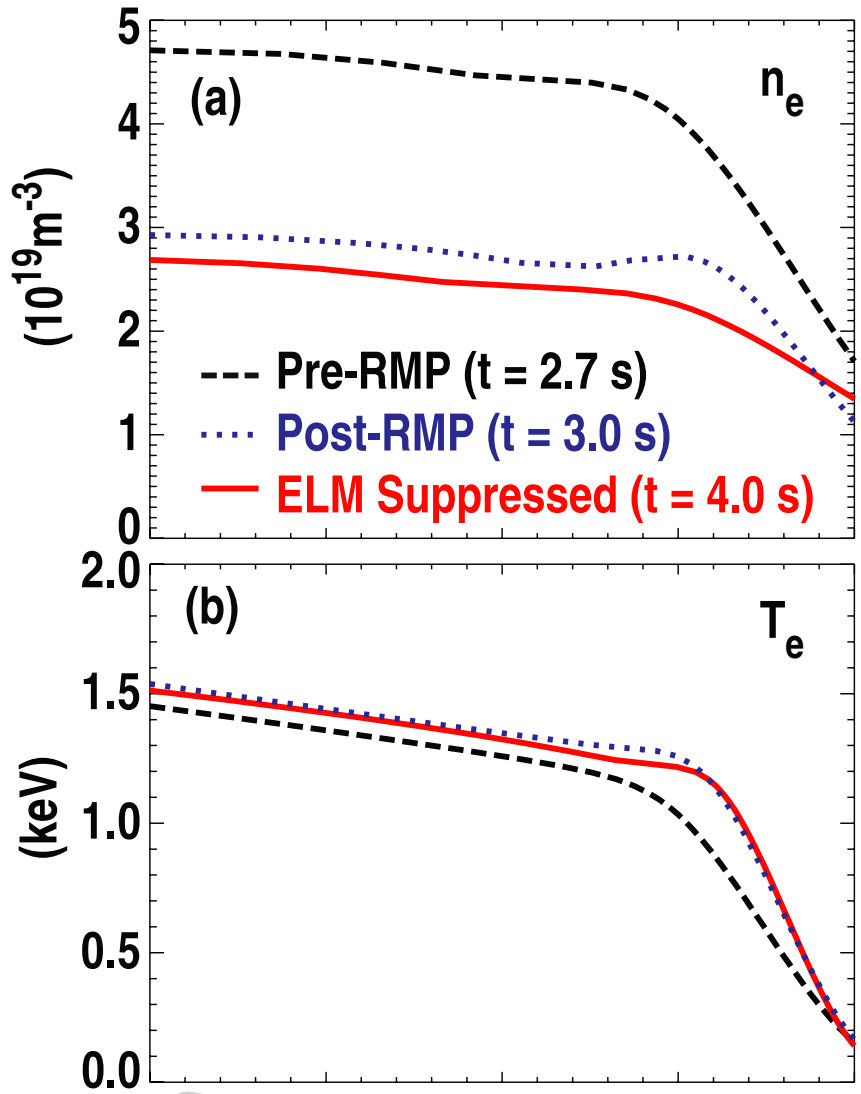
Outline: Tool development and physics goals of 3D equilibrium reconstruction in DIII-D

- **3D equilibrium reconstruction using V3FIT**
  - VMEC assumes closed, nested flux surfaces and enforces radial force balance
    - Ideal non-linear MHD, no islands or rotation
  - Iterate VMEC inputs to find equilibrum with minimized χ^2 given diagnostic measurements

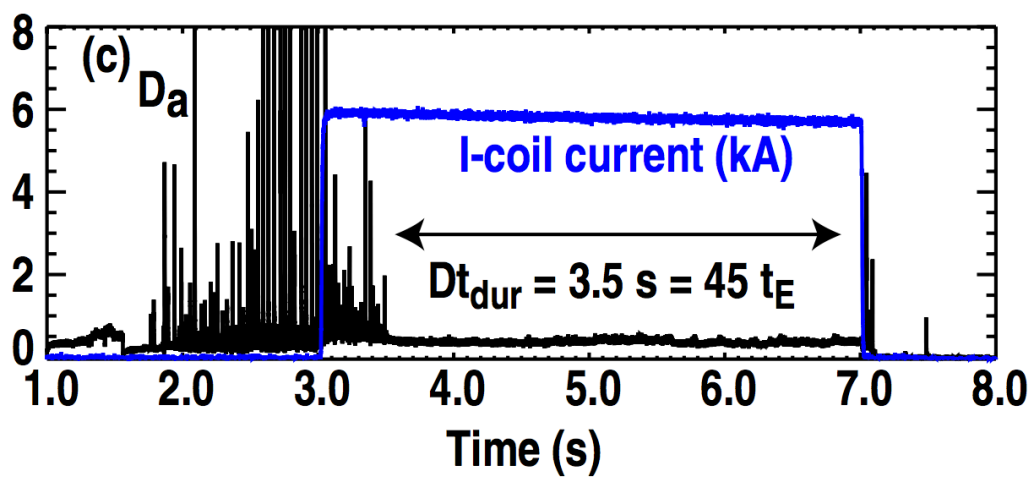
- **Multi-stage approach to reconstruction**
  - Start with kinetic EFIT
  - Constrain some degrees of freedom as more are added to make χ^2 minimization tractable

- **Equilibrium changes to be studied**
  - Geometric quantities relevant for microturbulence
  - 3D microstability, transport proxy functions
  - Differenced SXR images with phase flips

The application of 3D fields under certain conditions in H-mode tokamaks leads to density pumpout and ELM suppression



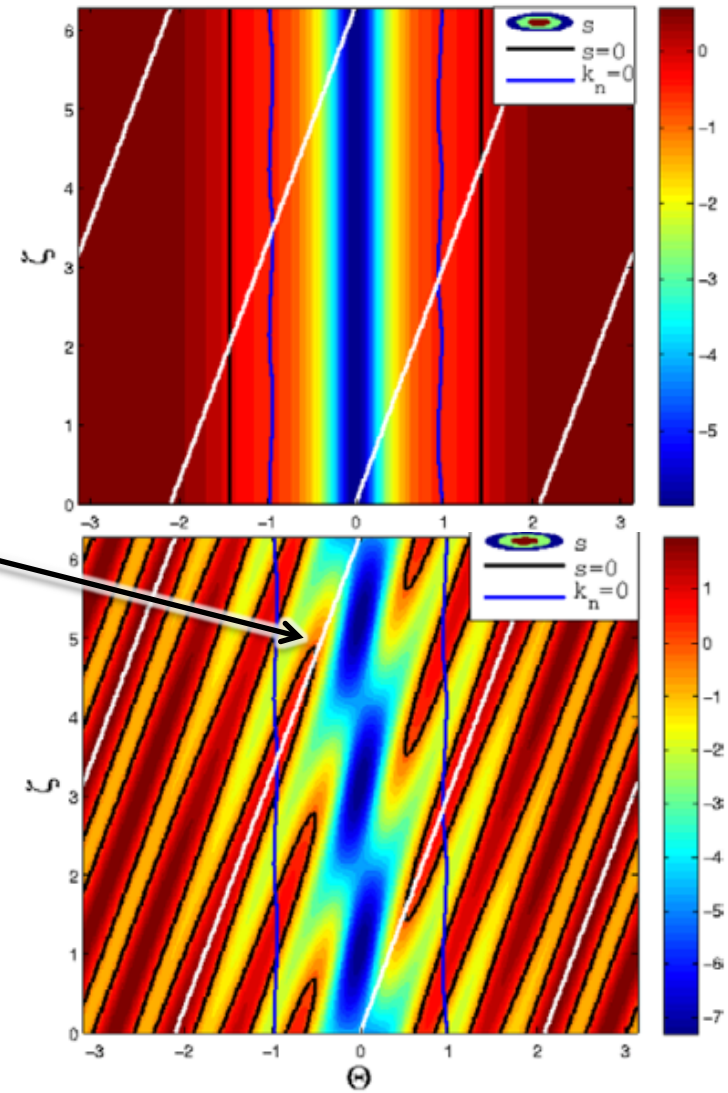
- Application of small fields lead to large global changes
- Density pumpout fraction is larger for lower collisionality
- ELM suppression with certain ranges of q_{95}



M.R. Wade et al., Nucl. Fusion ***55*** *(2015) 023002*

Equilibrium changes in DIII-D may be leading to increased turbulent transport, especially near resonant surfaces

- **3D Pfirsch-Schlüter currents cause changes in the local magnetic shear →**
- **Near rational surfaces, zero local shear overlaps with bad curvature region**
  - Linearly destabilizes turbulence near rational surfaces
- **Analytic simulation based on local Miller equilibria**



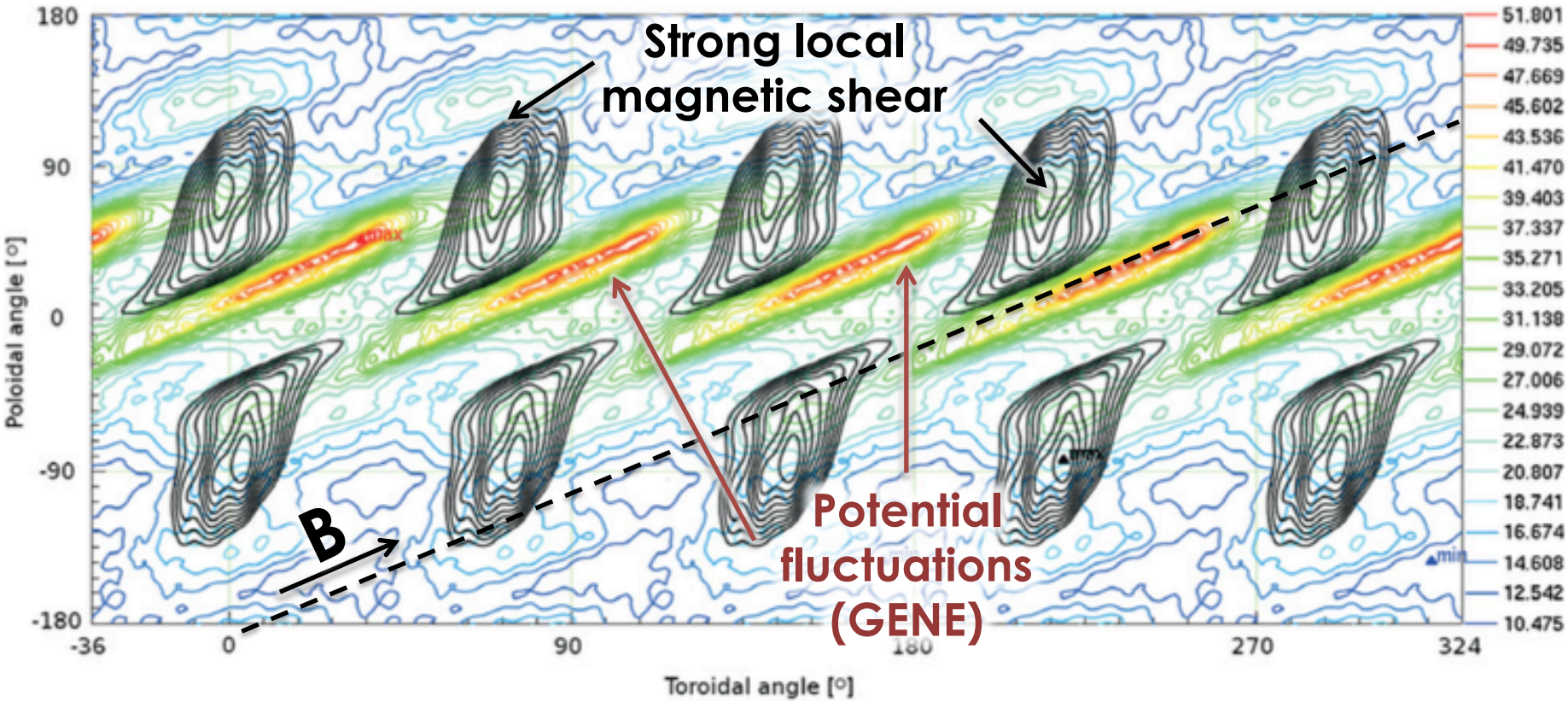
Axisym.

q=3.01

*T.M. Bird and C.C. Hegna, Nucl. Fusion **53** (2013) 013004*

In 3D geometries, every flux tube is different → full surface must be simulated for gyrokinetic calculations

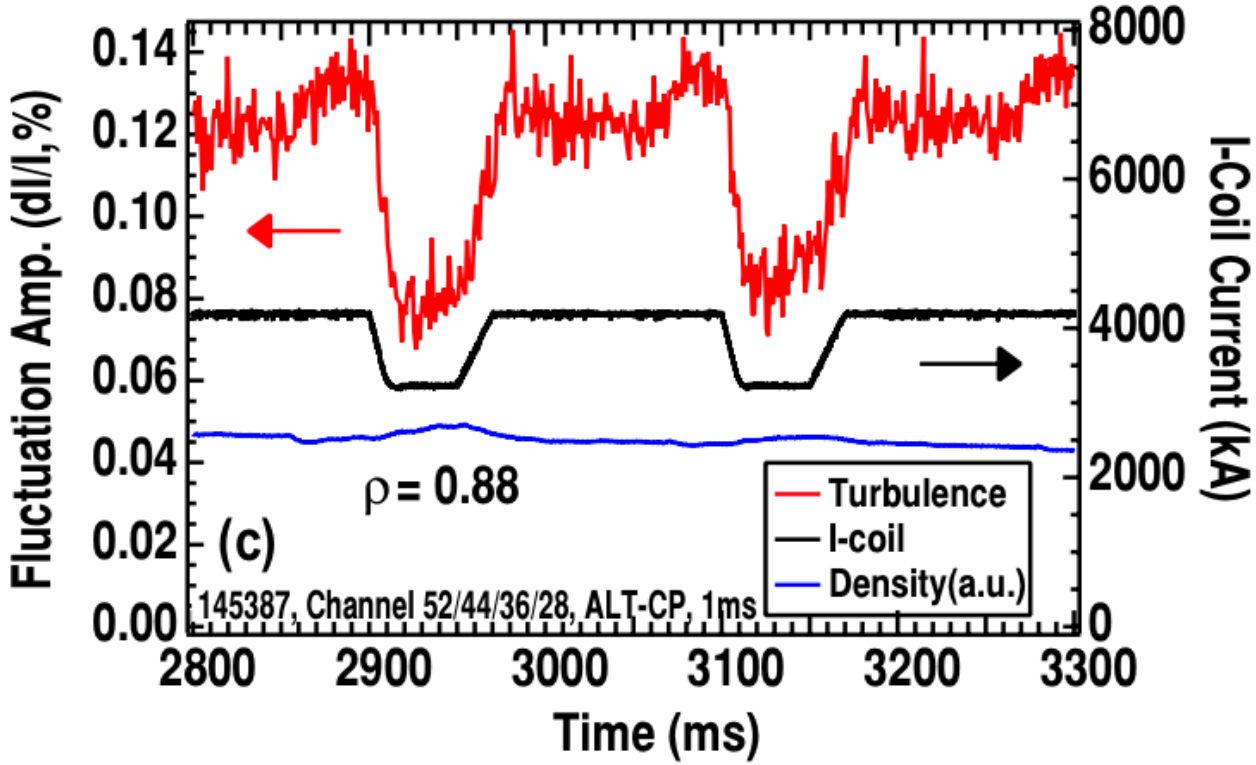
- W7-X potential fluctuations are calculated to be localized away from strong local magnetic shear ($|\nabla\alpha|^2$), despite small global shear



P. Helander et al., PPCF ***54*** *(2012) 124009*

In DIII-D, turbulence changes on a fast time scale with the addition of 3D fields

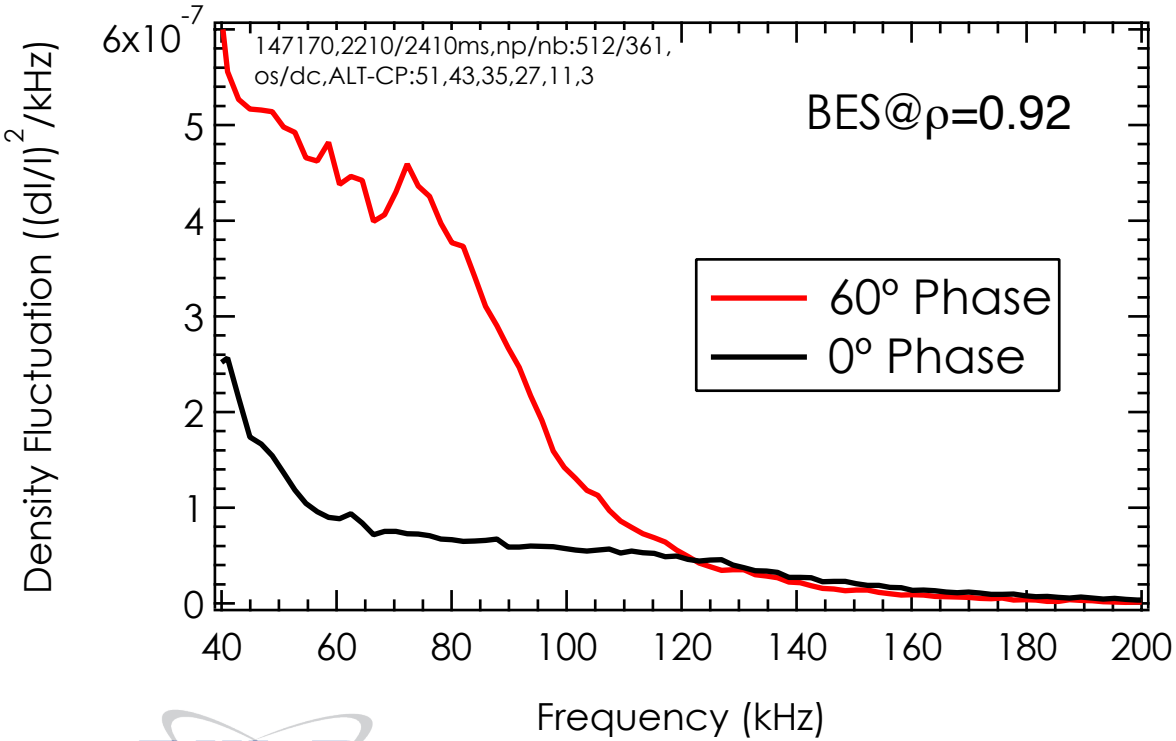
- **Change in fluctuation magnitudes lead changes in density and rotation**
- **Turbulence stability is influenced directly by application of 3D fields, rather than by profile changes**

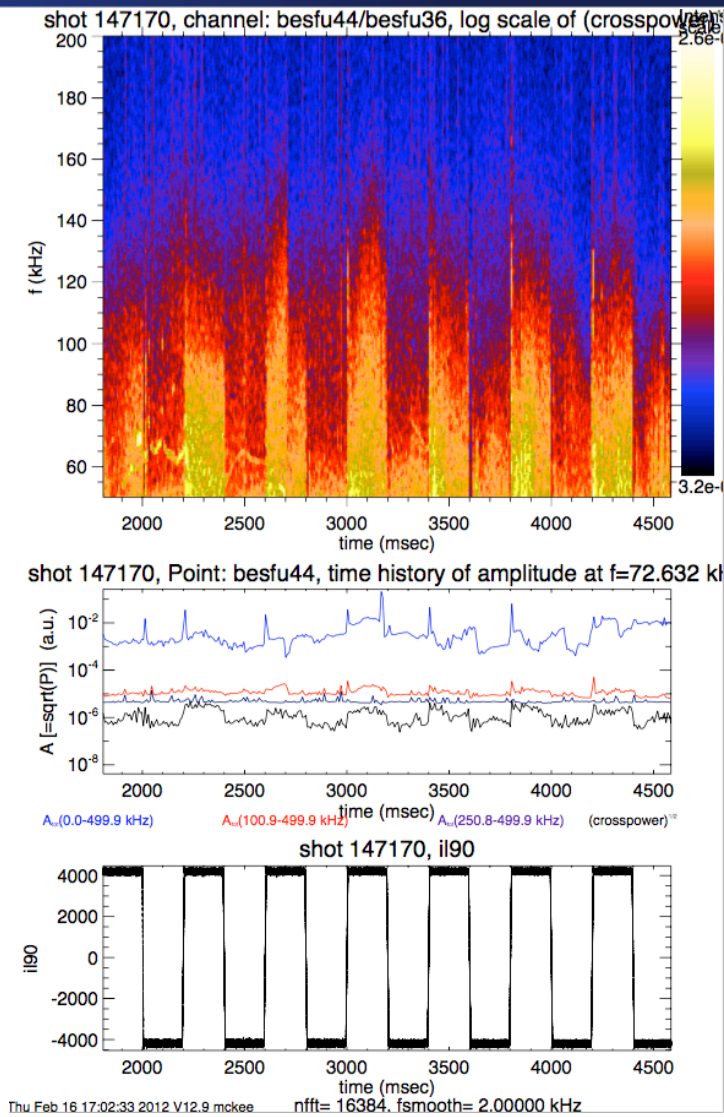


*G.R. McKee et al., Nucl. Fusion **53** (2013) 113011*

Locally measured turbulence changes with phasing of I coils in DIII-D

- **BES in the edge shows fluctuation magnitude dependence on I-coil phase for n=3 phase flips**
  - Possible contribution due to n=3 offset, but offset is much smaller than applied





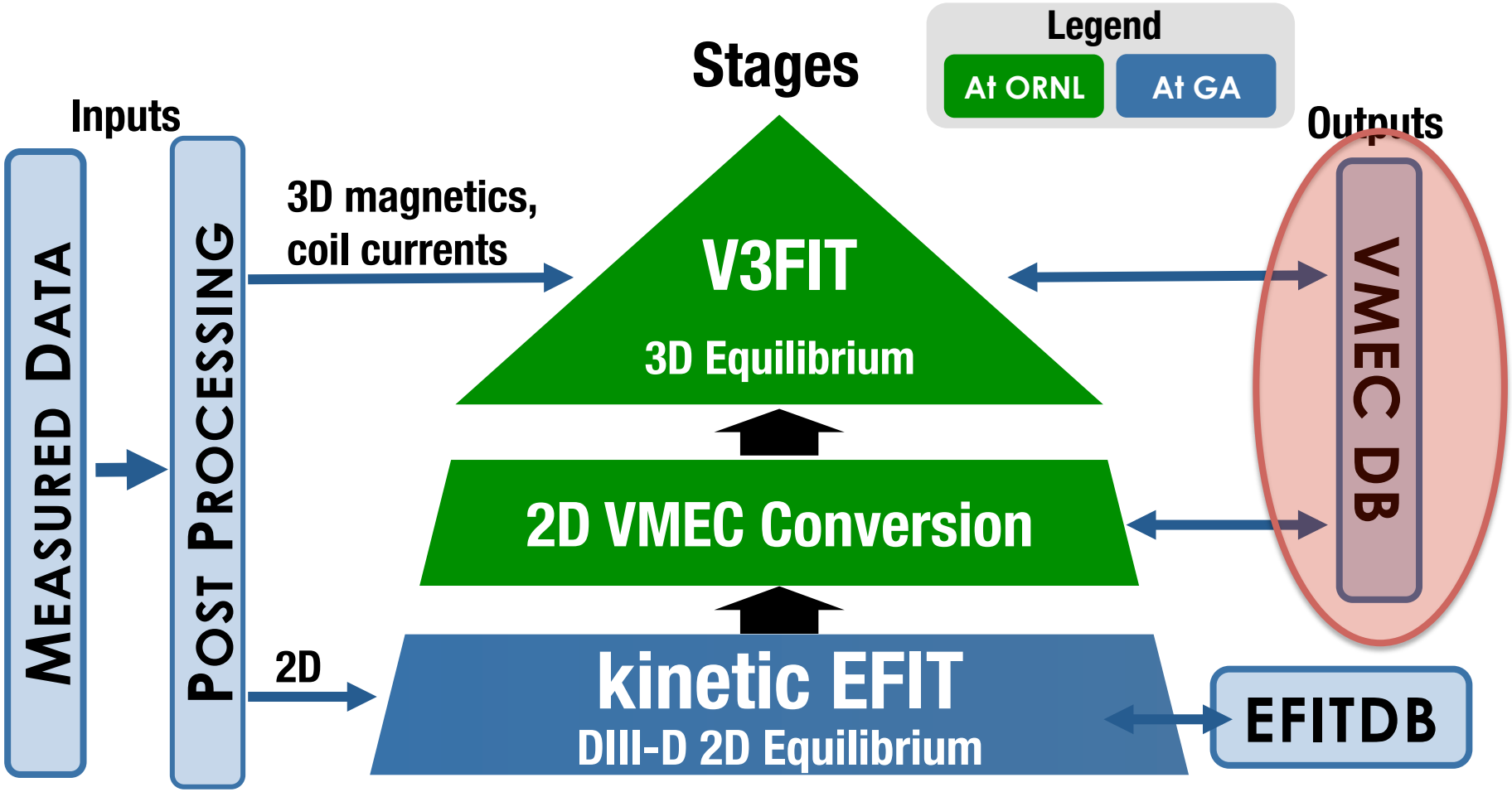
Courtesy G. R. McKee

An accurate equilibrium is necessary to quantify local microstability

- **Need equilibria of real, experimentally relevant plasmas**
  - Ideally a reconstruction of an experiment
- **V3FIT – Mark Cianciosa, Jim Hanson et al.**
  - Iterate on VMEC equilibria, use synthetic diagnostics and compare to measurements to find modeled equilibrium with minimized global χ^2
- **Gyrokinetics required for quantitative study of turbulence stability**
  - Very computationally expensive (many flux tubes, fully non-linear, etc.)
  - GENE / GTC require stellarator symmetry
    - GTC developing a non-SS version
  - Mechanism: Linear growth rate vs zonal flow response?
  - Simulations not available in the short term, use some proxy function for linear growth rate as a first step

V3FIT: J.D. Hanson *et al* 2009 *Nucl. Fusion* **49** 075031

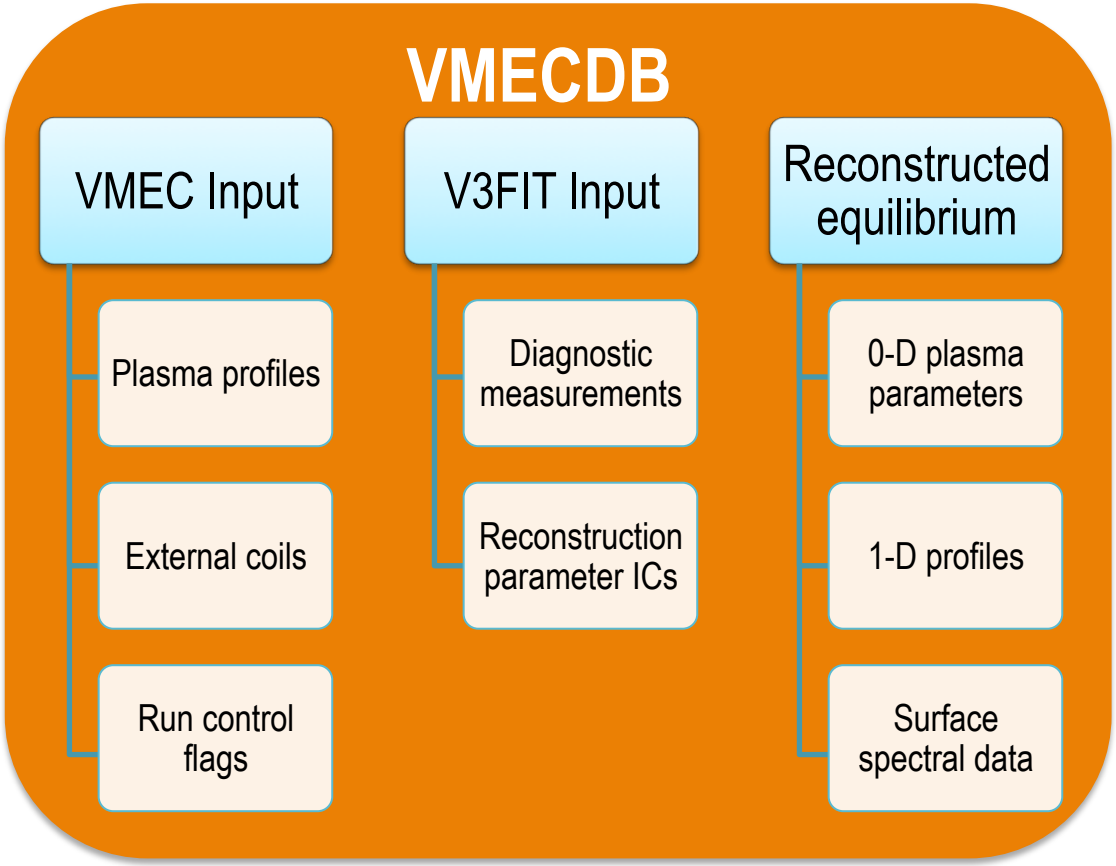
A "multi-stage" workflow is being developed based on established DIII-D reconstruction workflow



- V3FIT may become more than 1 stage
  - Constrain some parameters as new ones are reconstructed

Centralized database for DIII-D VMEC and V3FIT runs has been developed

- **Based on MDSplus**
- **Repository contains all data from workflow**
  - Centralized database removes confusion over file versions
  - Eliminates the need for storing, passing many individual files
- **Access to repository (at DIII-D) enabled from ORNL**
  - First V3FIT reconstruction completed on SWIM



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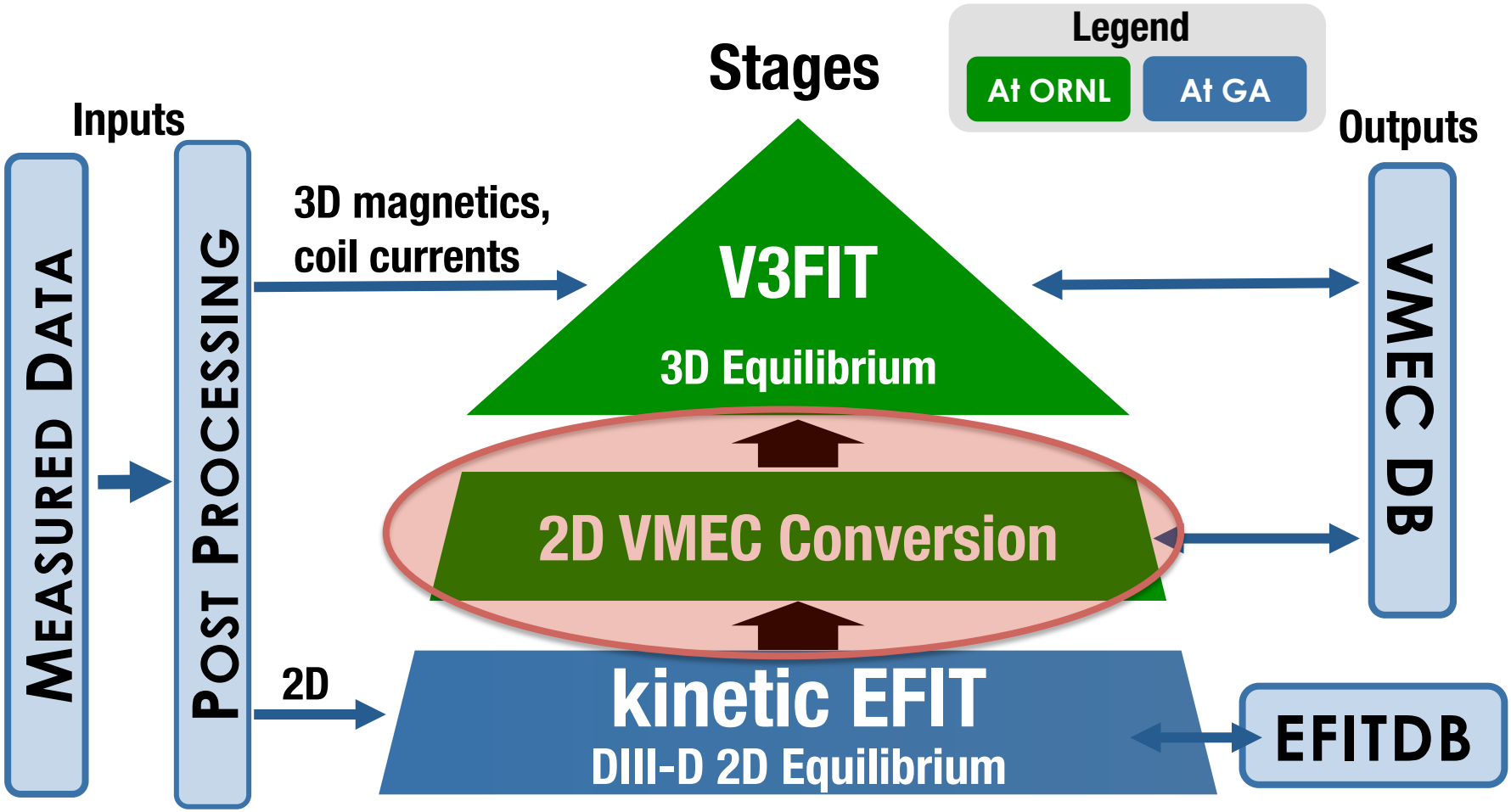

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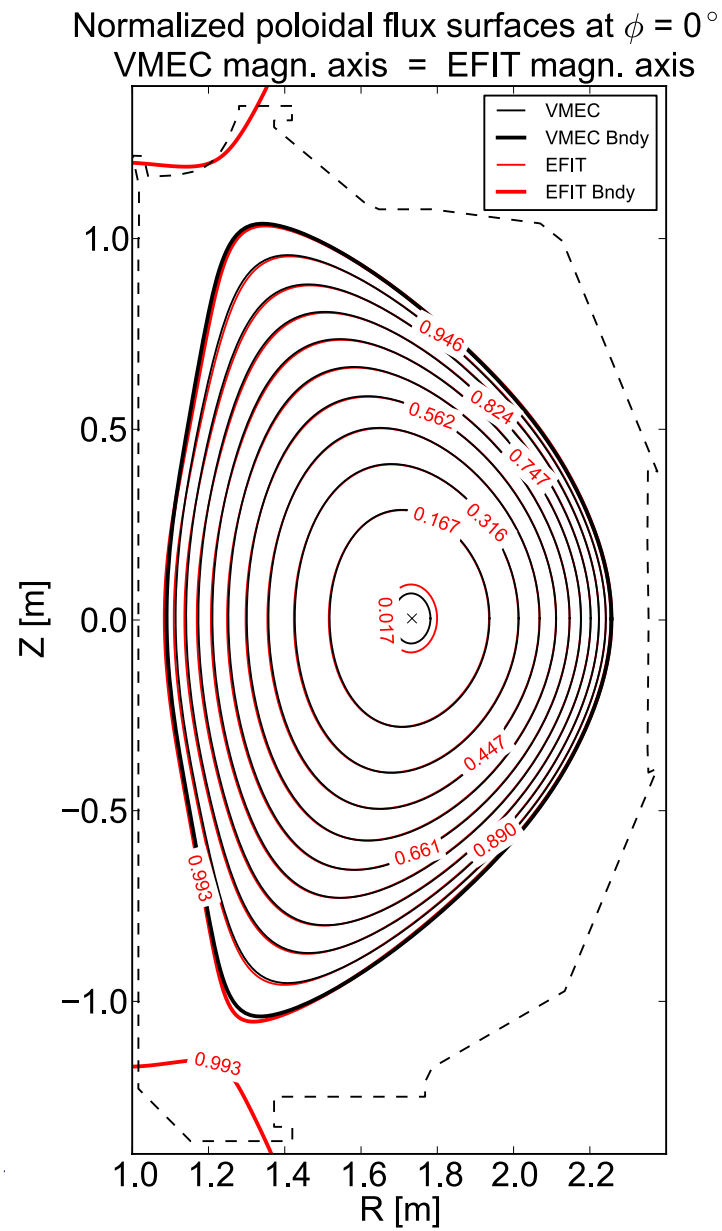
Unique challenges of calculating VMEC equilibria for an H-mode tokamak have been addressed

- **Spectral resolution of X-point geometry**
  - Truncate boundary near separatrix between rational surfaces
- **Weakly 3D**
  - Use 2D EFIT equilibrium as initial boundary condition
  - High resolution, low force tolerance required to resolve subdominant n ≠ 0 component
    - PARVMEC provides significant speed-up
- **Large edge gradients and plasma currents**
  - Non-linear mapping of surfaces to flux resolves edge gradients with fewer total surfaces (~97 vs 385)



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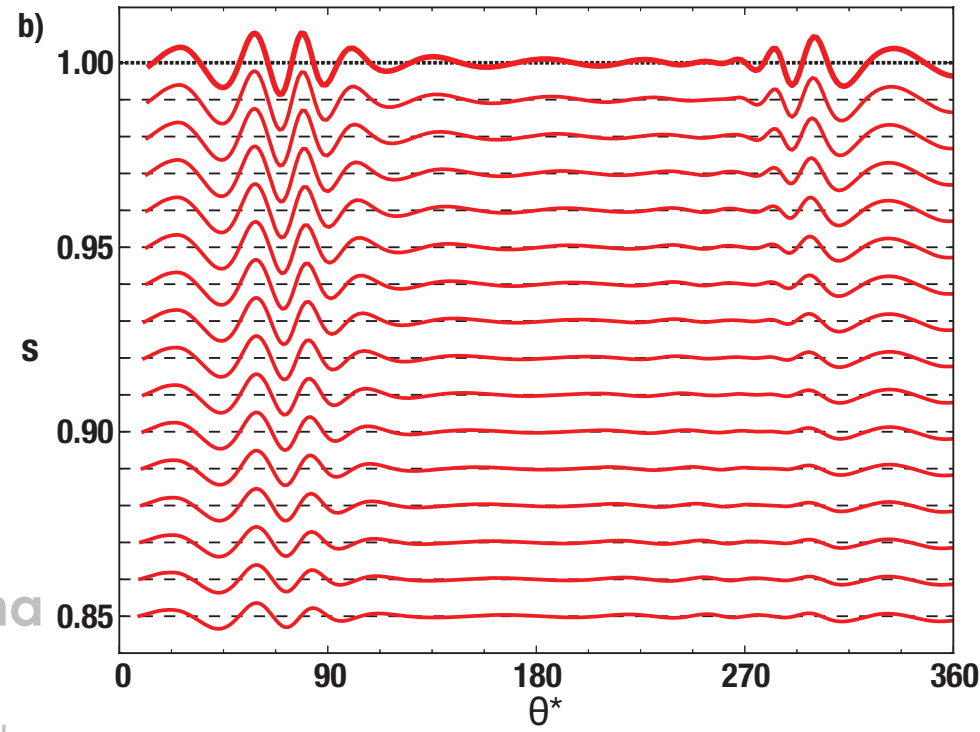

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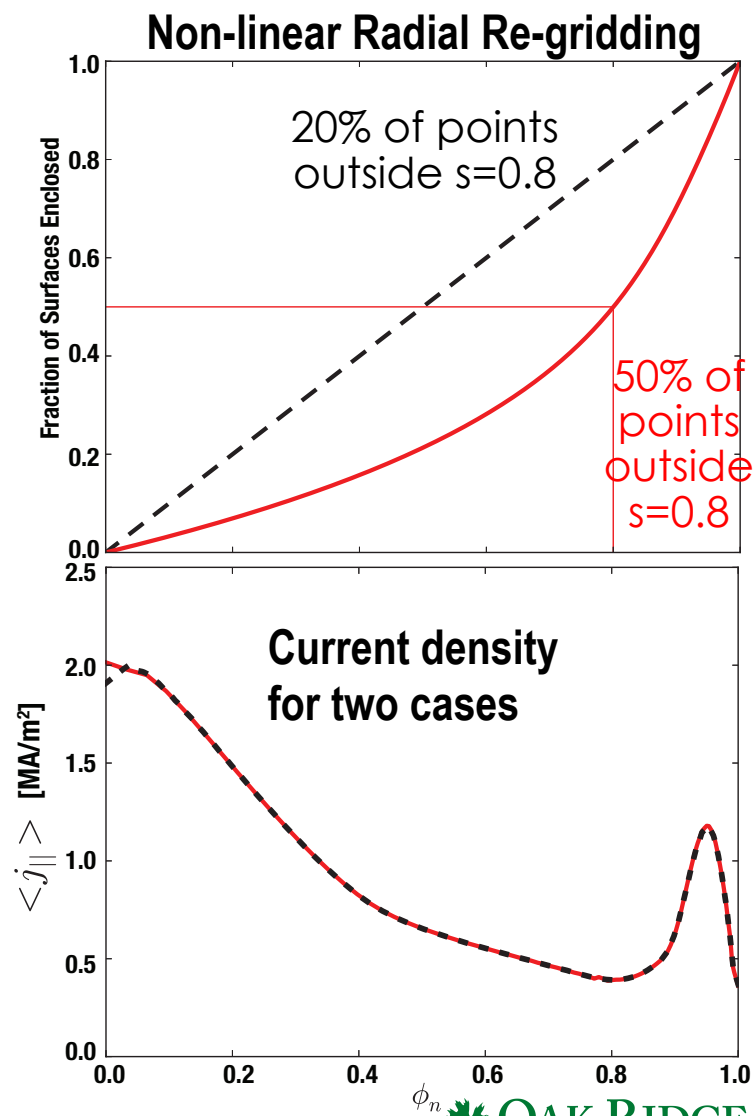

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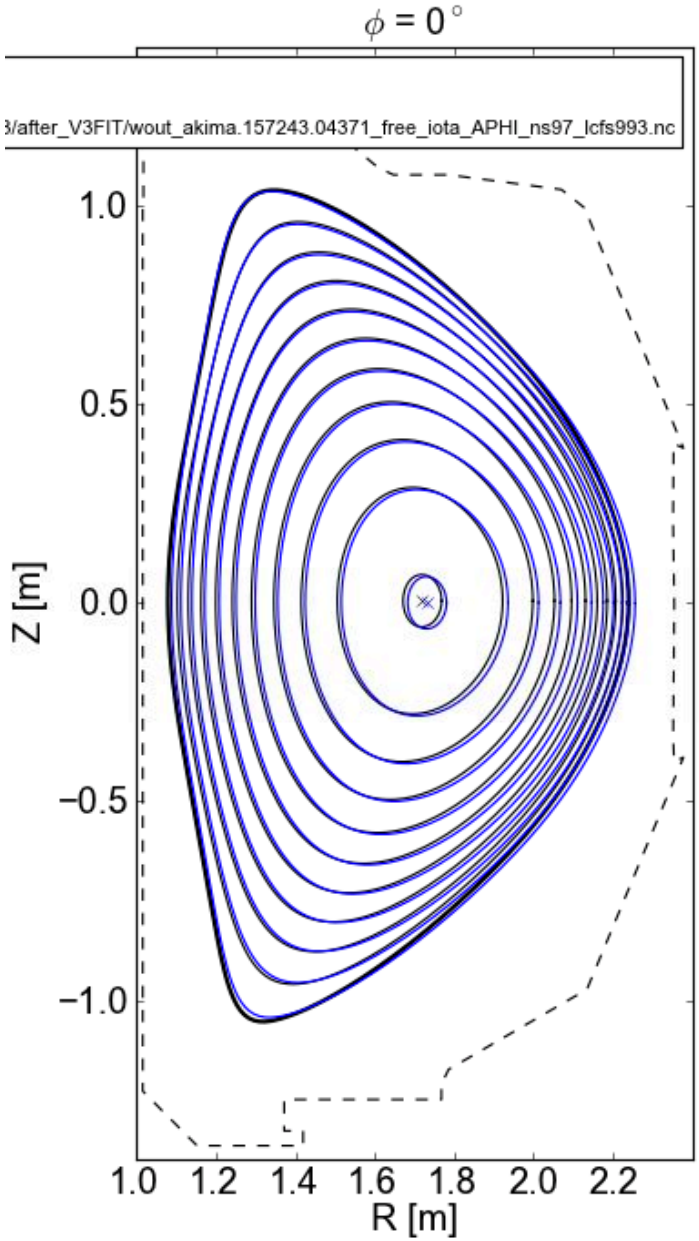
V3FIT reconstruction of axisymmetric equilibrium starting from an EFIT converges with minor modifications



- **Proof of principle: compare axisymmetric reconstruction using V3FIT to a kinetic EFIT**
  - "Blessed" kinetic EFIT from L. Lao
- **Very small n>0 component**
  - 3D diagnostics not yet implemented
- **Axis shifts outward by ~1 cm relative to initial condition (kEFIT)**

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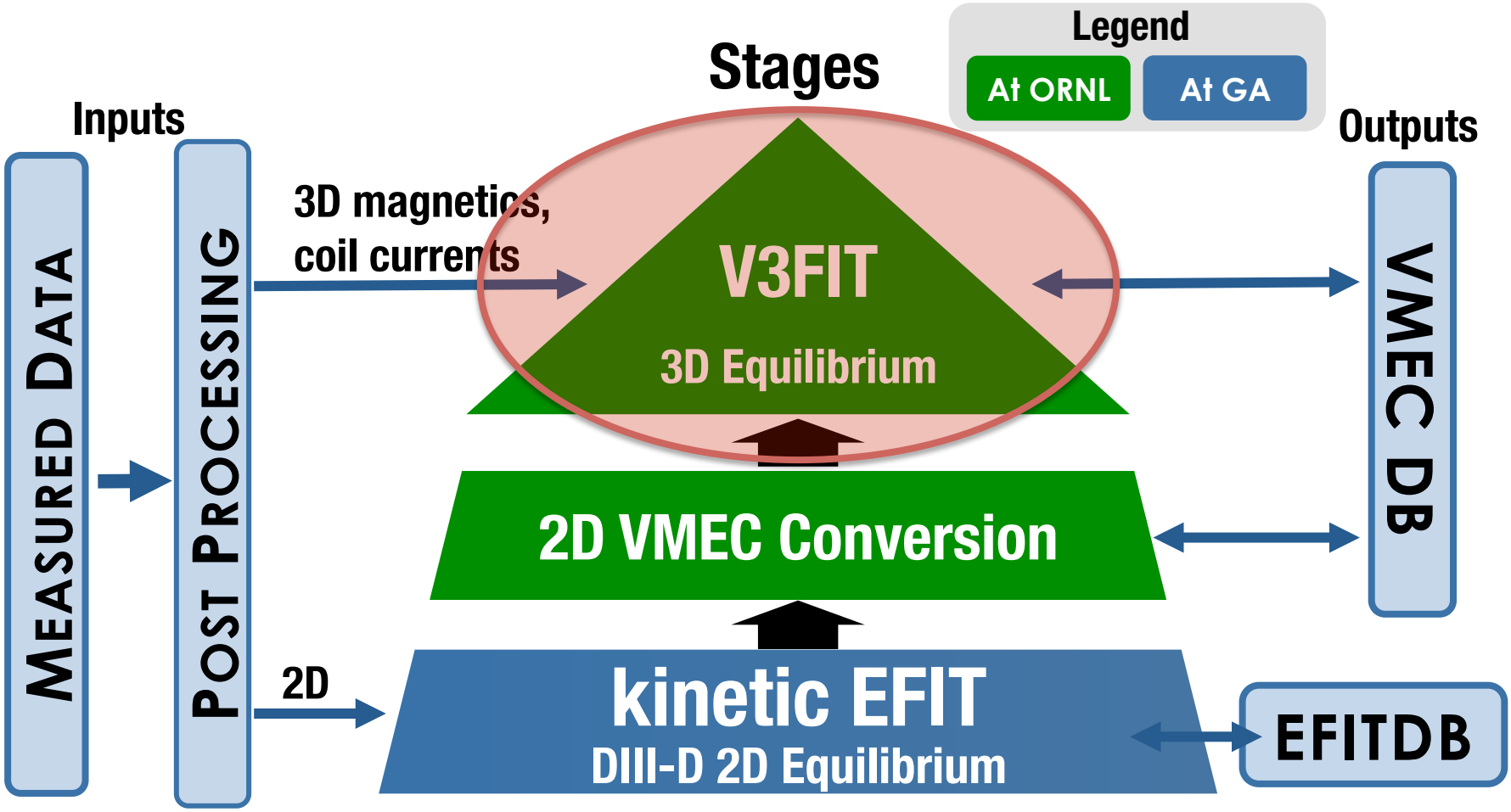
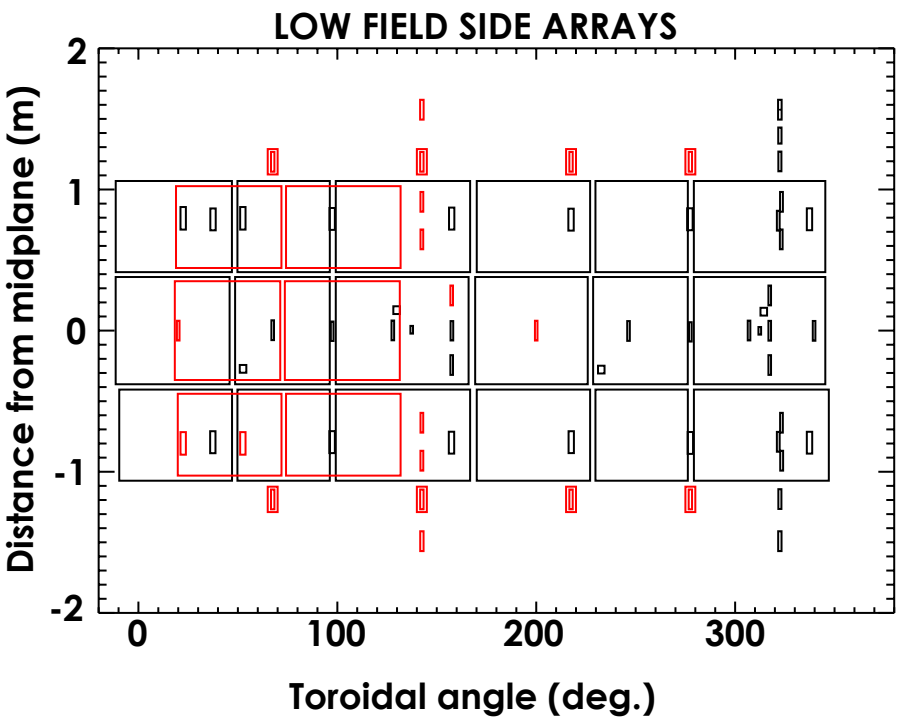
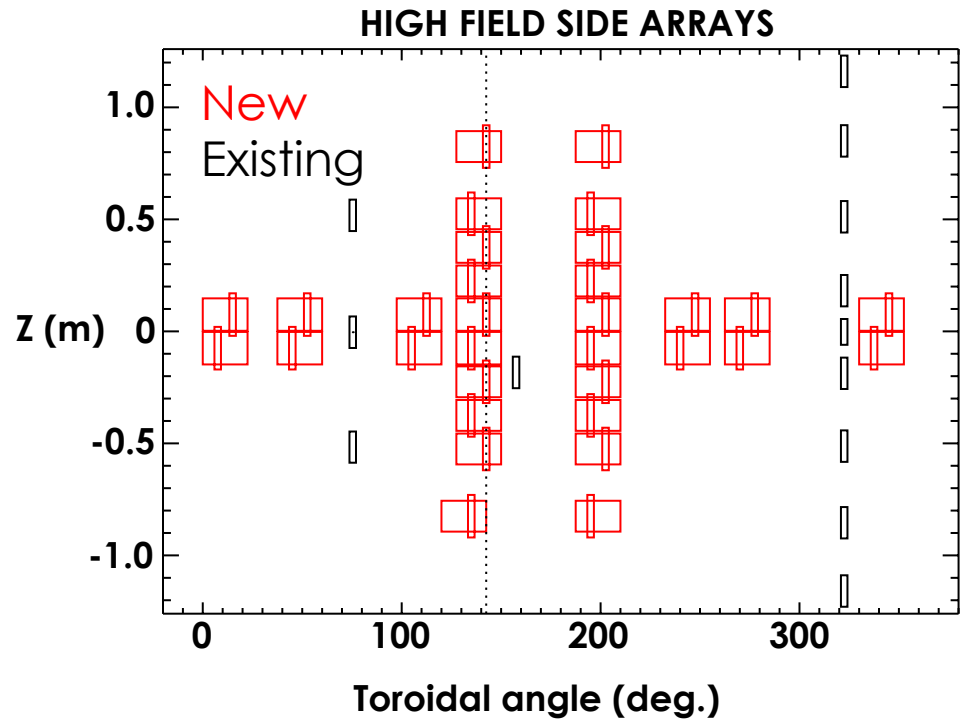
A "multi-stage" workflow is being developed based on established DIII-D reconstruction workflow



- V3FIT may become more than 1 stage
  - Constrain some parameters as new ones are reconstructed

3D differenced magnetic sensor array installed in 2013 greatly improves 3D field resolution at the vessel



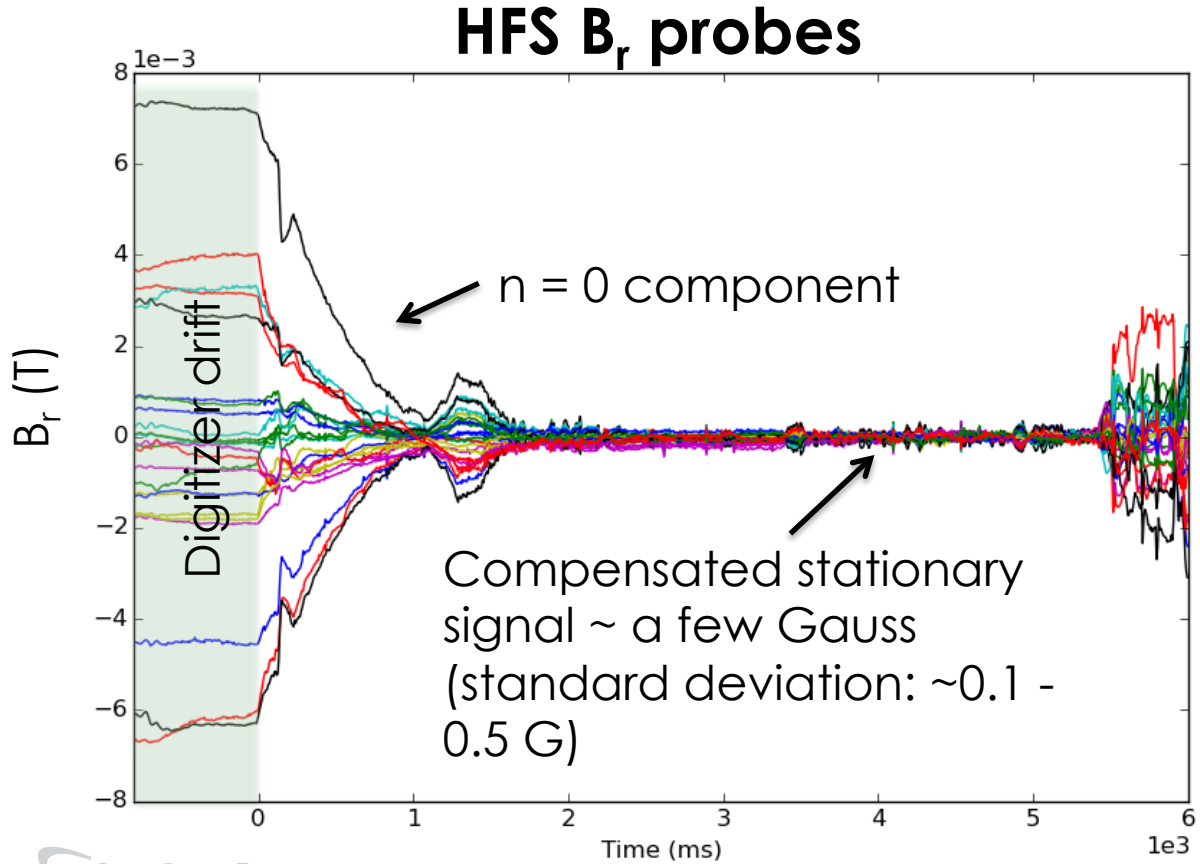


- **Probe locations were chosen carefully to distinguish n=1-3 modes**
  - Condition numbers of fit matrices show probes sensitive to m < ~±14
- **Precision manufacturing and positioning (uncertainty ~0.5 mm)**
  - For HFS B_p → residual n=0 pickup < 2 G

J.D. King et al., Rev. Sci. Instrum. ***85*** *(2014) 083503*

Background subtraction of average over I-coil phase flips removes digitizer drift, n=0 component of fields

- **Low frequency digitizer drift falls off above ~4 Hz**
  - Background subtraction can resolve this for I-coil phase flips with f > 4 Hz
- **Hardware changes are being made to attempt to reduce drift**



Before background subtraction: Vacuum field compensation removes component of signal from each external coil independently based on annual calibration

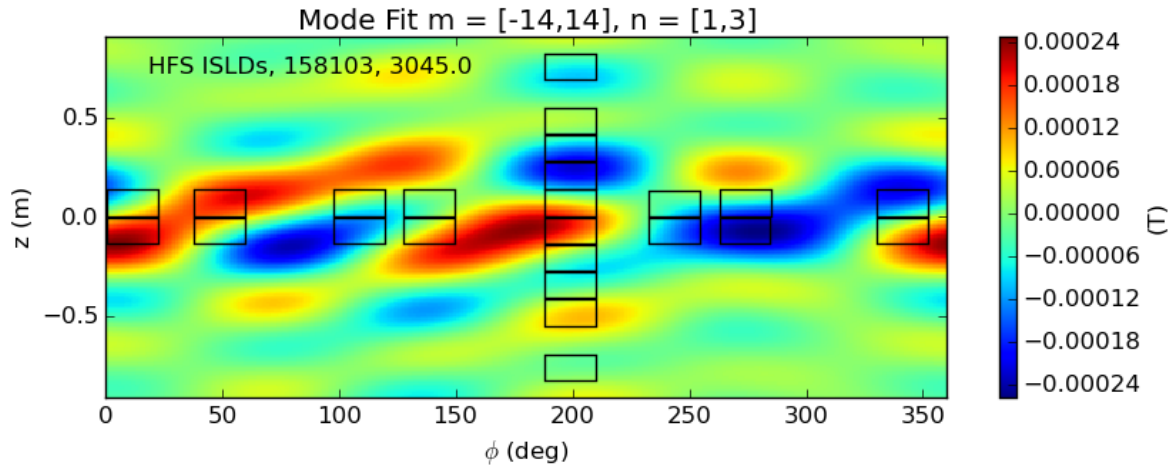
Fitting structures to differenced magnetic sensors allows measured 3D components of fields to be matched with synthetic diagnostics

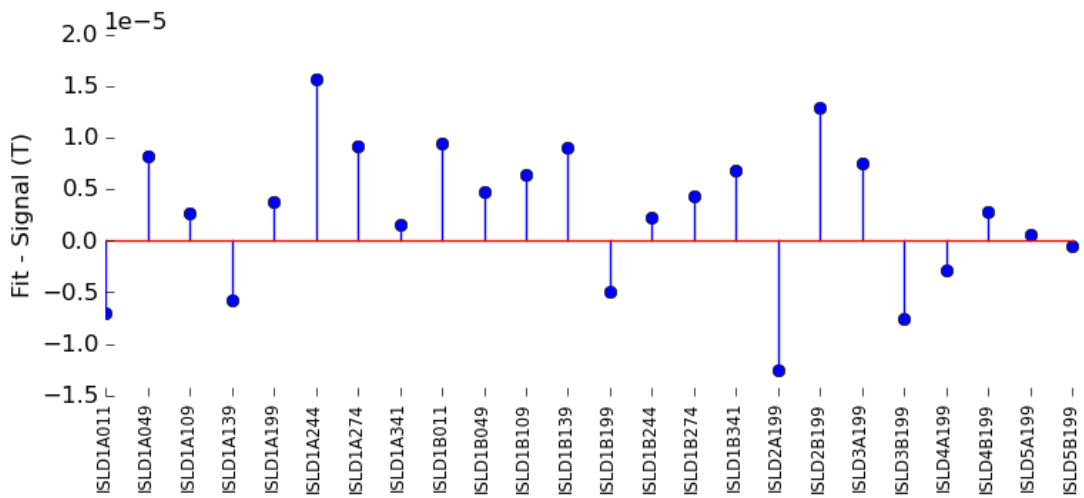
- **Solve for C assuming sinusoidal basis functions (*B*) and signals (*S*)**

$$B \cdot C = S$$

- **Basis functions with bad condition numbers are removed**
  - Only fit modes that diagnostics are sensitive to

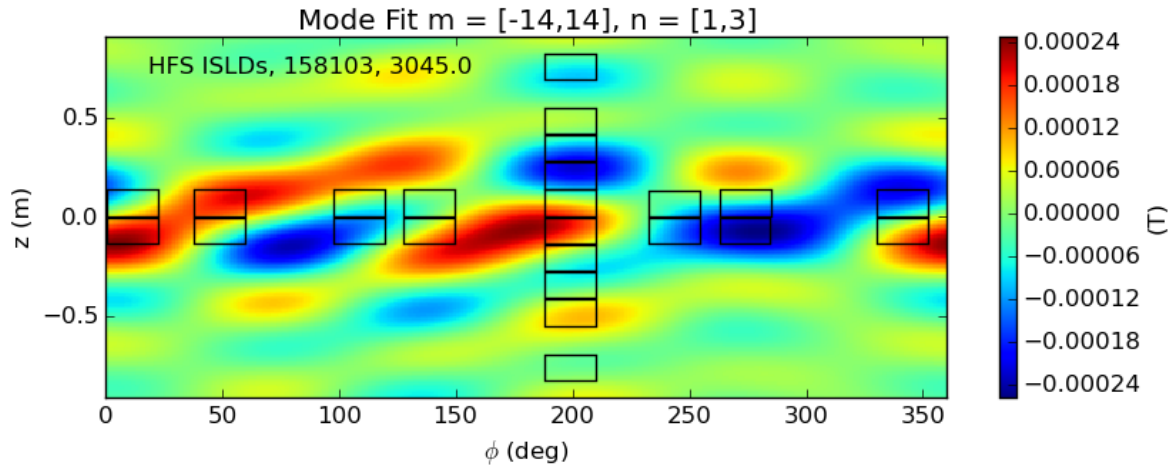
- **Independent fits for HFS and LFS, B_r and B_θ arrays**

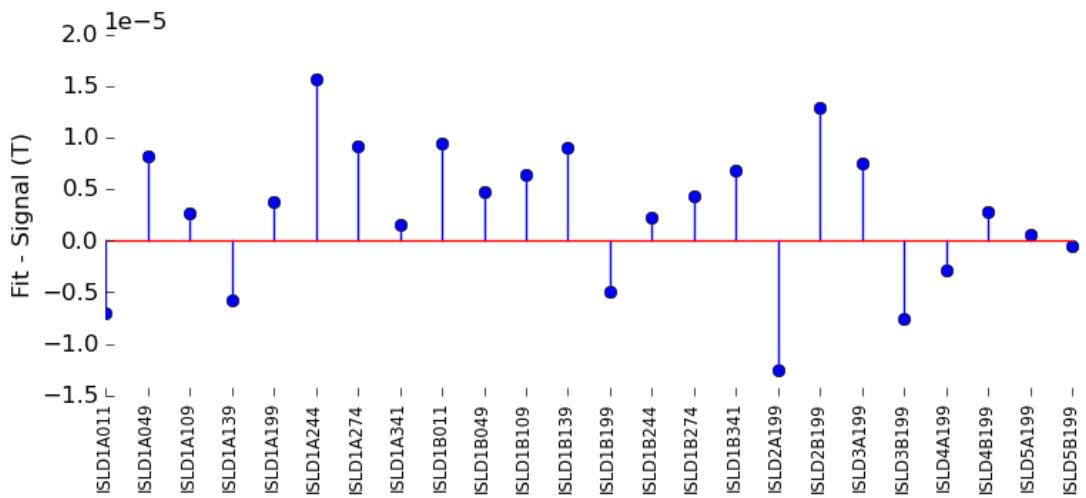




Fitting structures to differenced magnetic sensors allows measured 3D components of fields to be matched with synthetic diagnostics

- **Use fitted field at probe locations as the input measurements in V3FIT**
  - Uncertainty is combination of fit residual, signal fluctuations and systematic uncertainty
- **Use pseudo-diagnostic in V3FIT to compare with modeled field normal to sensors**





Based on shaping of reconstructed equilibrium, proxy functions can be used to model predicted transport

- **A pressure-curvature coupling term in the gyrokinetic equations is similar for most modes:**

$$\frac{\kappa_n + \Lambda \kappa_g}{|\nabla \psi|}$$

Where Λ is integrated local magnetic shear: $\Lambda = \frac{|\nabla\psi|^2}{B} \int \frac{B^2}{|\nabla\psi|^2} \sqrt{g} s d\zeta$

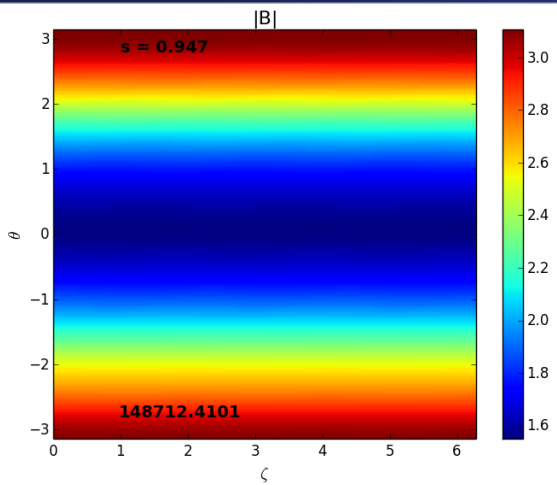
- **Modeling done by H. Mynick to optimize stellarator ITG transport**

$$D \propto \frac{\gamma}{k_\perp^2} \propto \sqrt{\kappa_n} \left(\rho_i^2 + \frac{\rho_i L_p}{1 + \left\langle \left(\tau_s s_{loc} \right)^2 \right\rangle} \right)$$

H. Mynick, Plasma Phys. Control. Fusion ***56*** *(2014) 094001*

- **May need different proxy functions depending on which mode is expected to be most unstable**
  - ITG in core / at top of pedestal
  - KBM in pedestal → Pressure-curvature coupling term / COBRA?

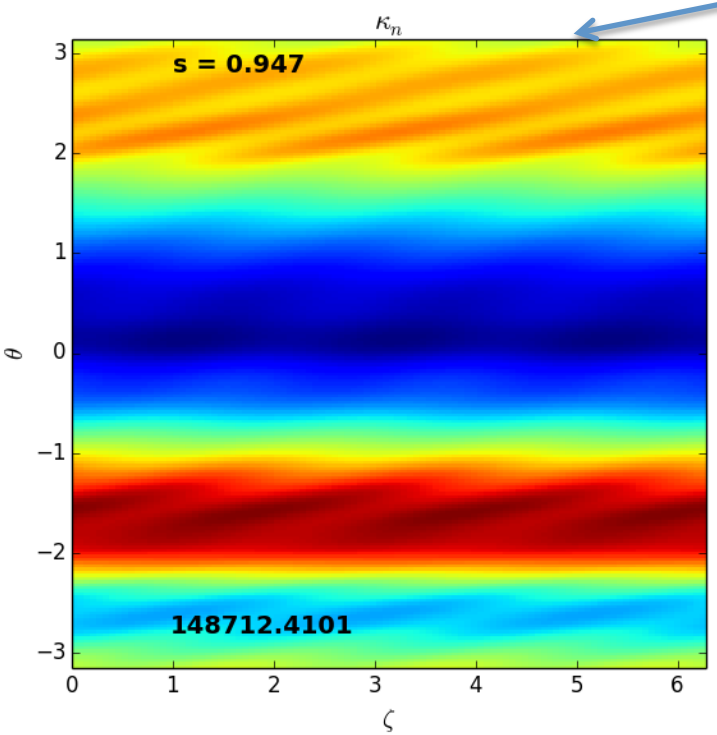
Curvature and local shear are modified significantly more than |B| with applied 3D fields

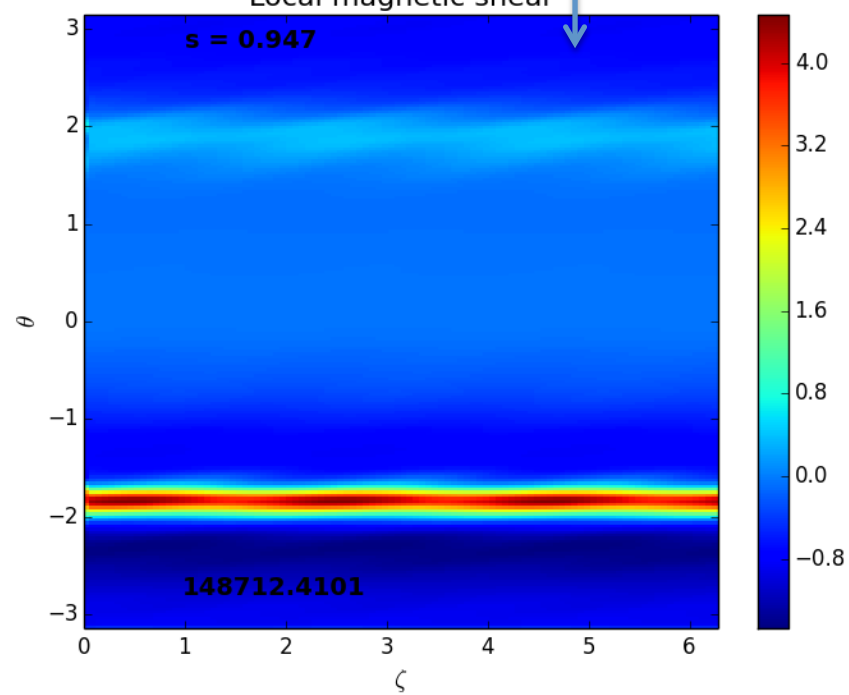


- Curvature and local magnetic shear are modulated toroidally much more than |B|
- Local shear damps instability growth, but simple numerical dependence is not clear

$$D \propto \frac{\gamma}{k_\perp^2} \propto \sqrt{\kappa_n}\left(\rho_i^2 + \frac{\rho_i L_p}{1+\left\langle\left(\tau_s s_{loc}\right)^2\right\rangle}\right)$$

Local magnetic shear





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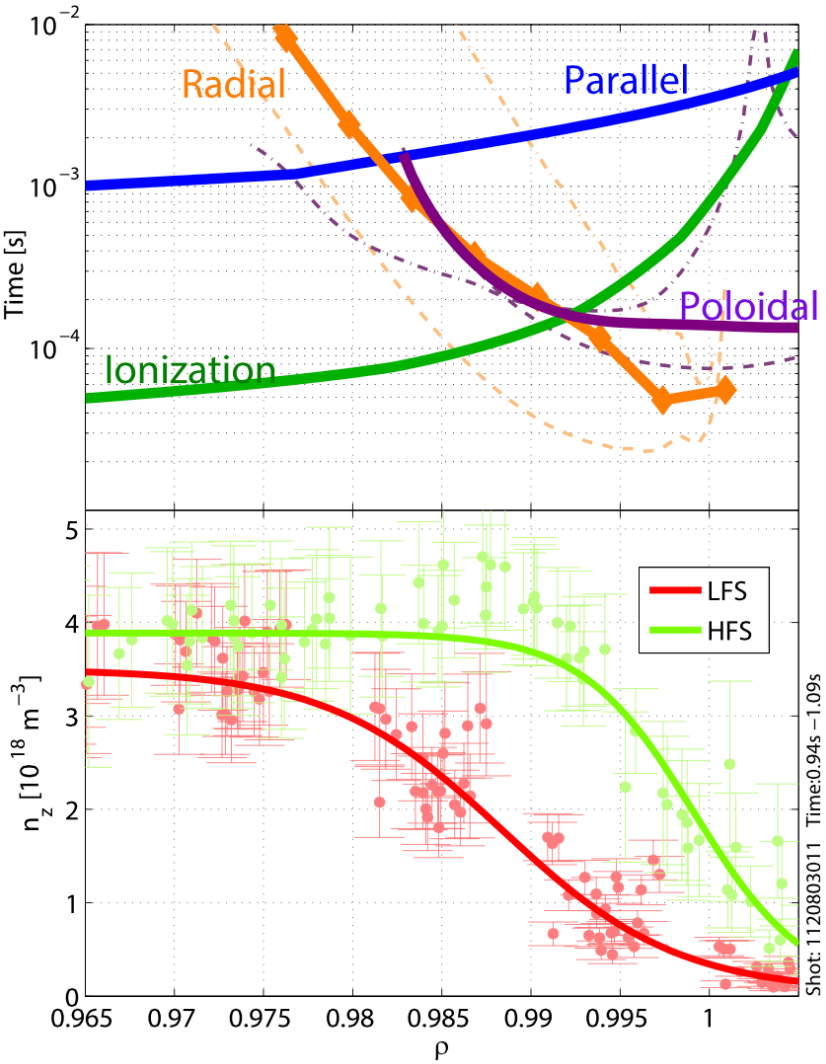
Local impurity asymmetries may be useful in detection of toroidally / poloidally localized transport



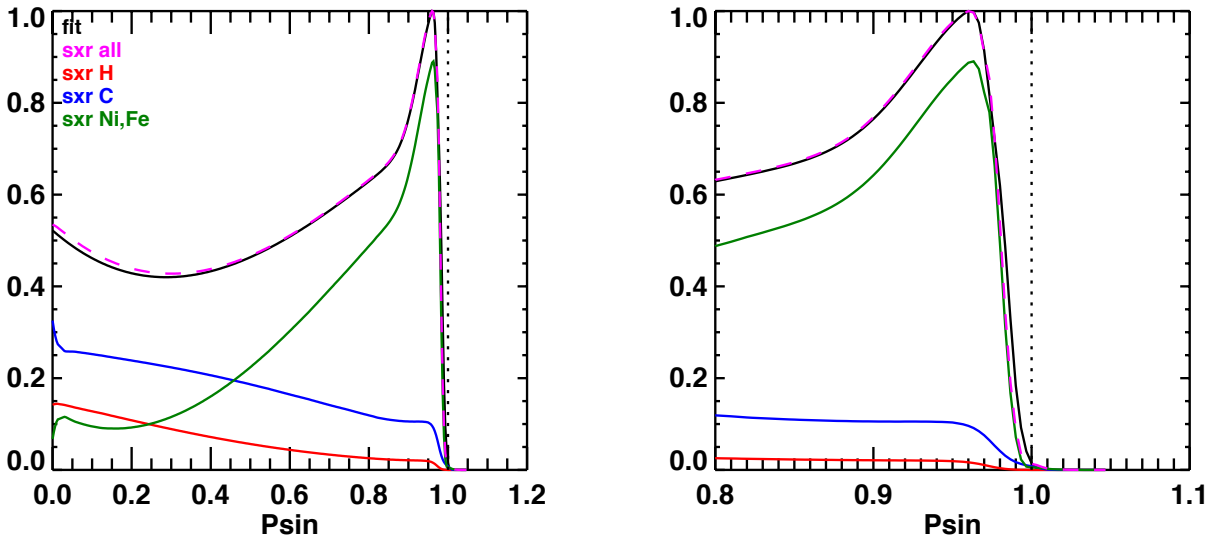
- **Fluctuations drive particle flux in toroidally / poloidally localized regions**
  - Assume $\Gamma_{imp} \approx \Gamma_{main}$
- **Parallel transport leads to T_e, n_e, T_i, n_i rapidly equilibrating on a surface**
  - Impurities diffuse more slowly
  - Local impurity densities may indicate localized transport
- **Differenced SXR images with I-coil phase flips mostly measure impurity line radiation**
  - Might be able to use this to diagnose localized transport

R. M. Churchill et al., Phys. Plasmas ***22*** *(2015) 056104*

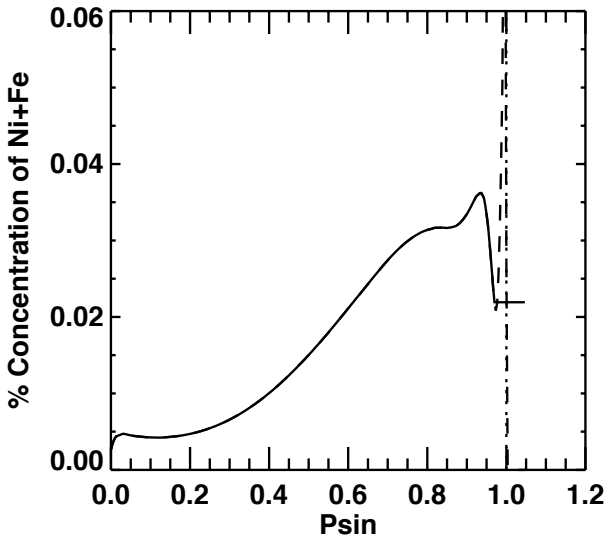
Based on modeling, line emission from metallic impurities could be a dominant part of the edge SXR emission

- **How much Ni / Fe is necessary to match emission from 1D CHIANTI modeling with measured emission?**
  - Only a small modeled nickel concentration is necessary to account for observed emission

Simulated SXR Radiant Power Densities + Fit

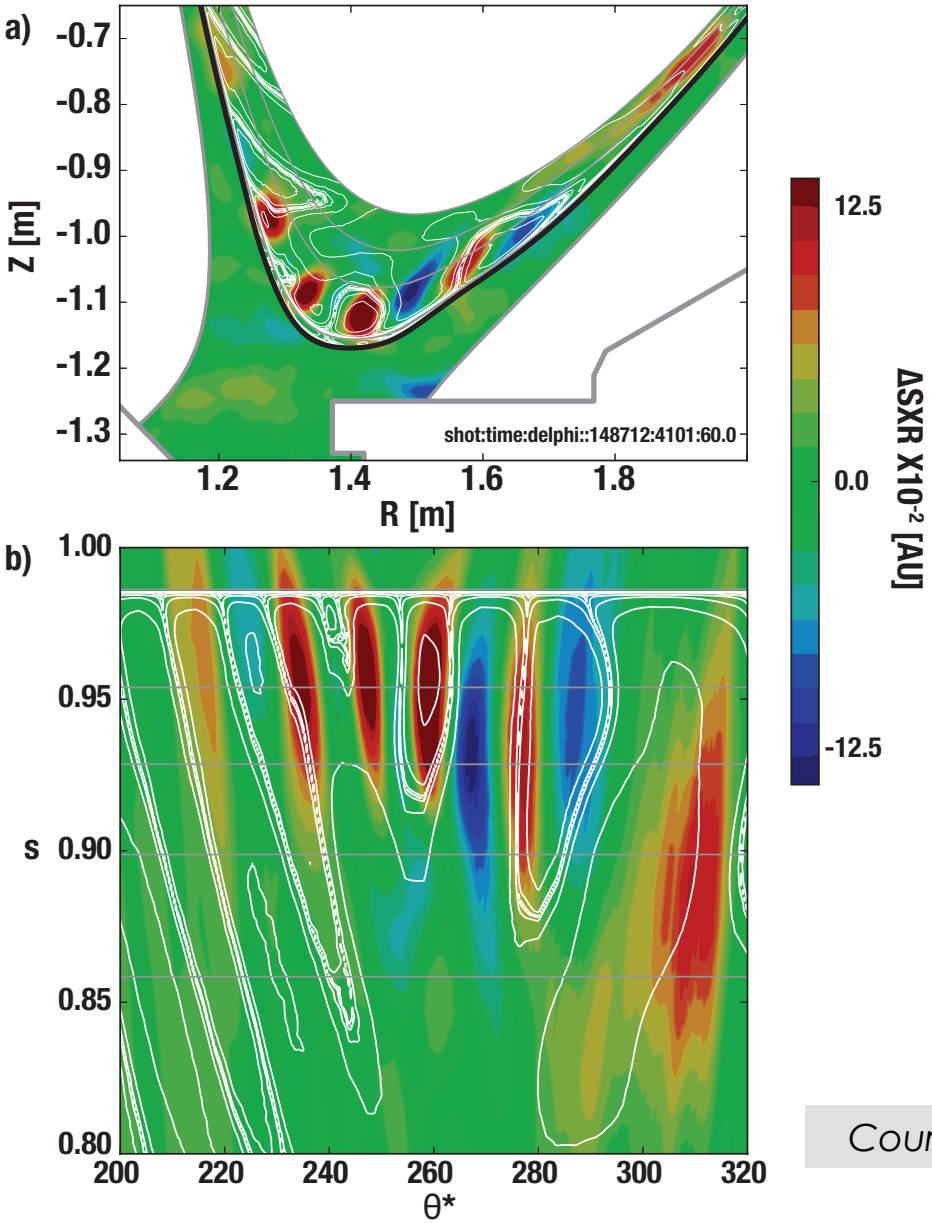


Metal Concentration



Courtesy M.W. Shafer

Differenced SXR images may be useful in identifying regions of localized transport via impurity densities in the pedestal



- **I-coil phase-flipping allows background subtraction of n=0 emission**
- **White contours indicate change in local values of $\kappa_n + \Lambda\kappa_g$ with phase flip**
  - Should be mapped along a field line from most unstable region in a flux tube
- **Reconstructed equilibrium would help quantify how much of emission change is due to surface deformation vs localized impurity density changes**

Courtesy E. Unterberg

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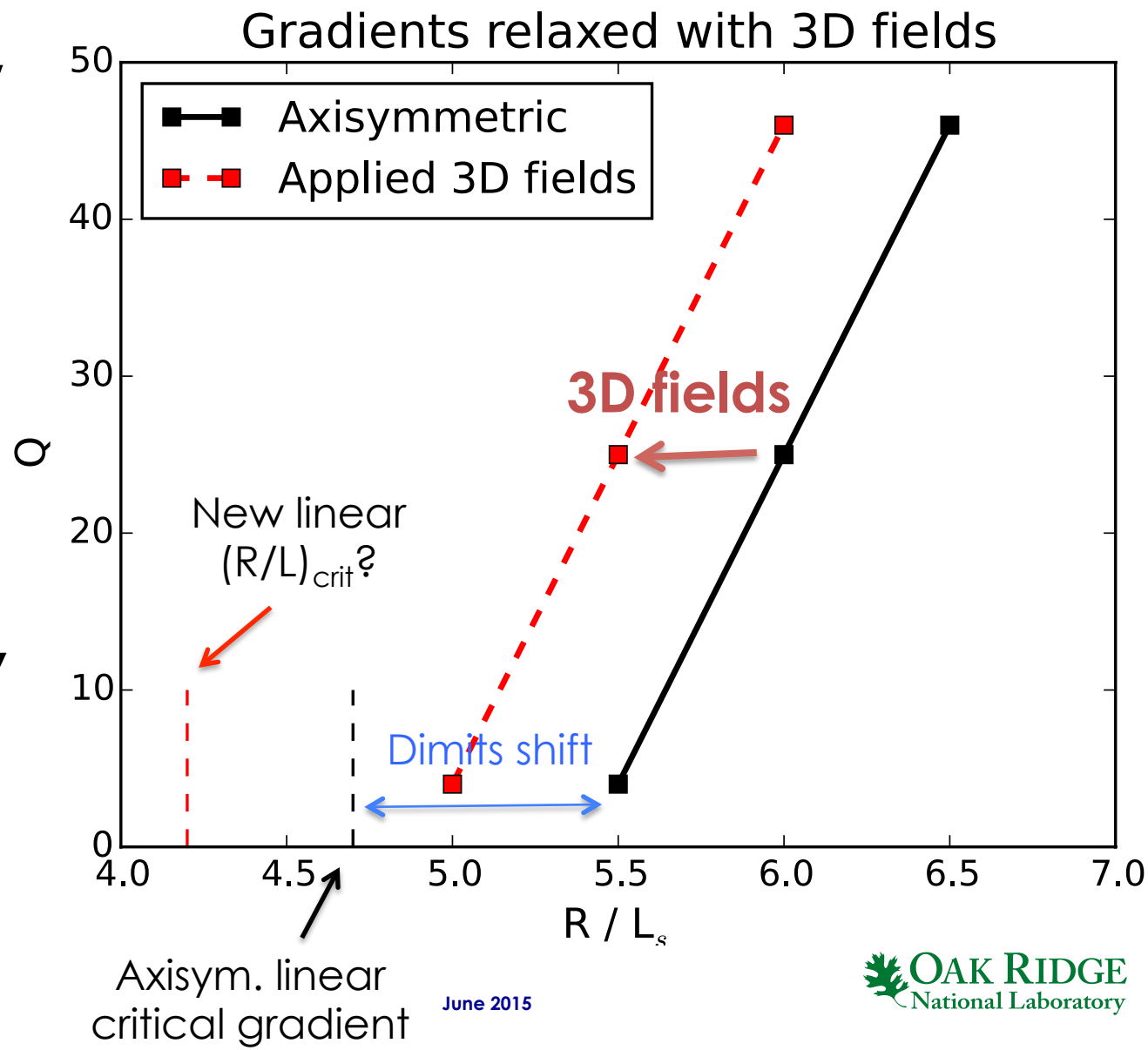
Gradients would relax similarly from changes to either linear stability or reduction of non-linear zonal flow

- **For constant heat/ particle flux, gradient scale length is reduced**
- **Could try to find independent experimental shaping "knobs" to turn for linear, non-linear stability**
  - We're only looking at linear stability first



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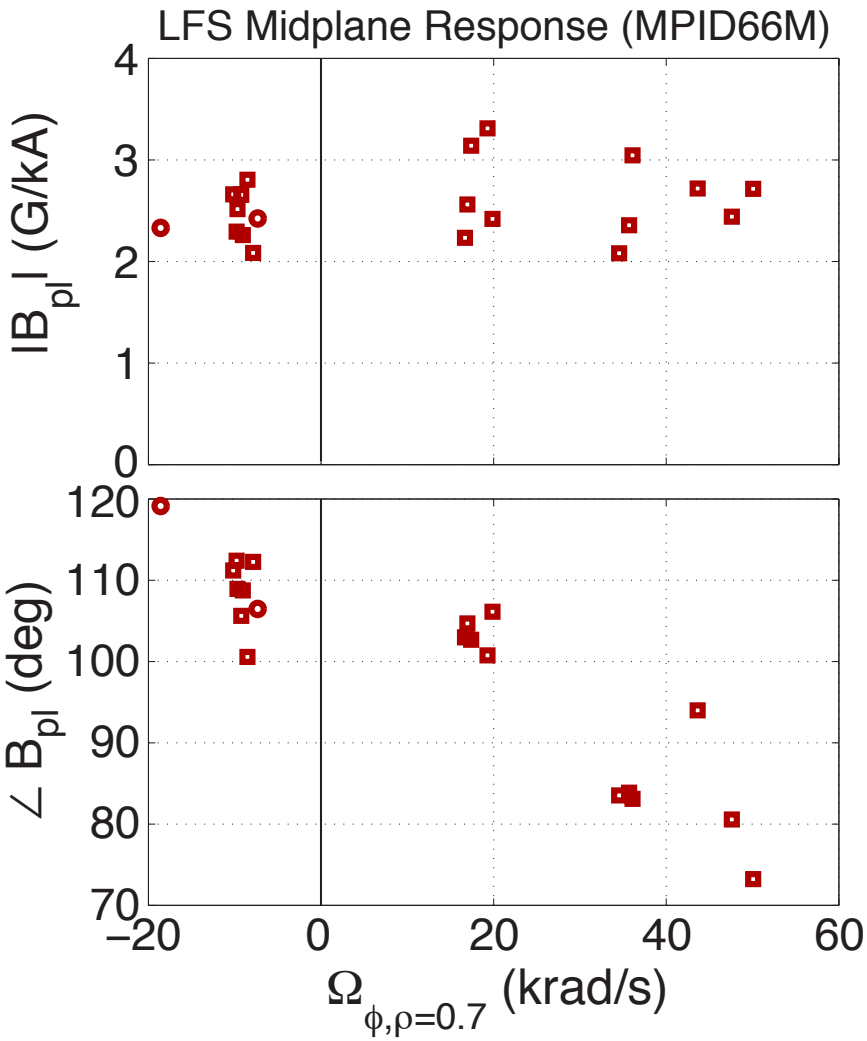
Rotation scan with rotating phase n=2 fields showed magnetic sensor response was phase shifted wrt applied field at high rotation



- **Phase between plasma response at a single magnetic sensor (LFS B_p) and the rotating applied n=2 field shifts significantly above ~20 krad/s**
- **Including rotation in VMEC may be necessary to properly reconstruct a rapidly rotating tokamak equilibrium**

Courtesy C. Paz-Soldan

Future / ongoing work

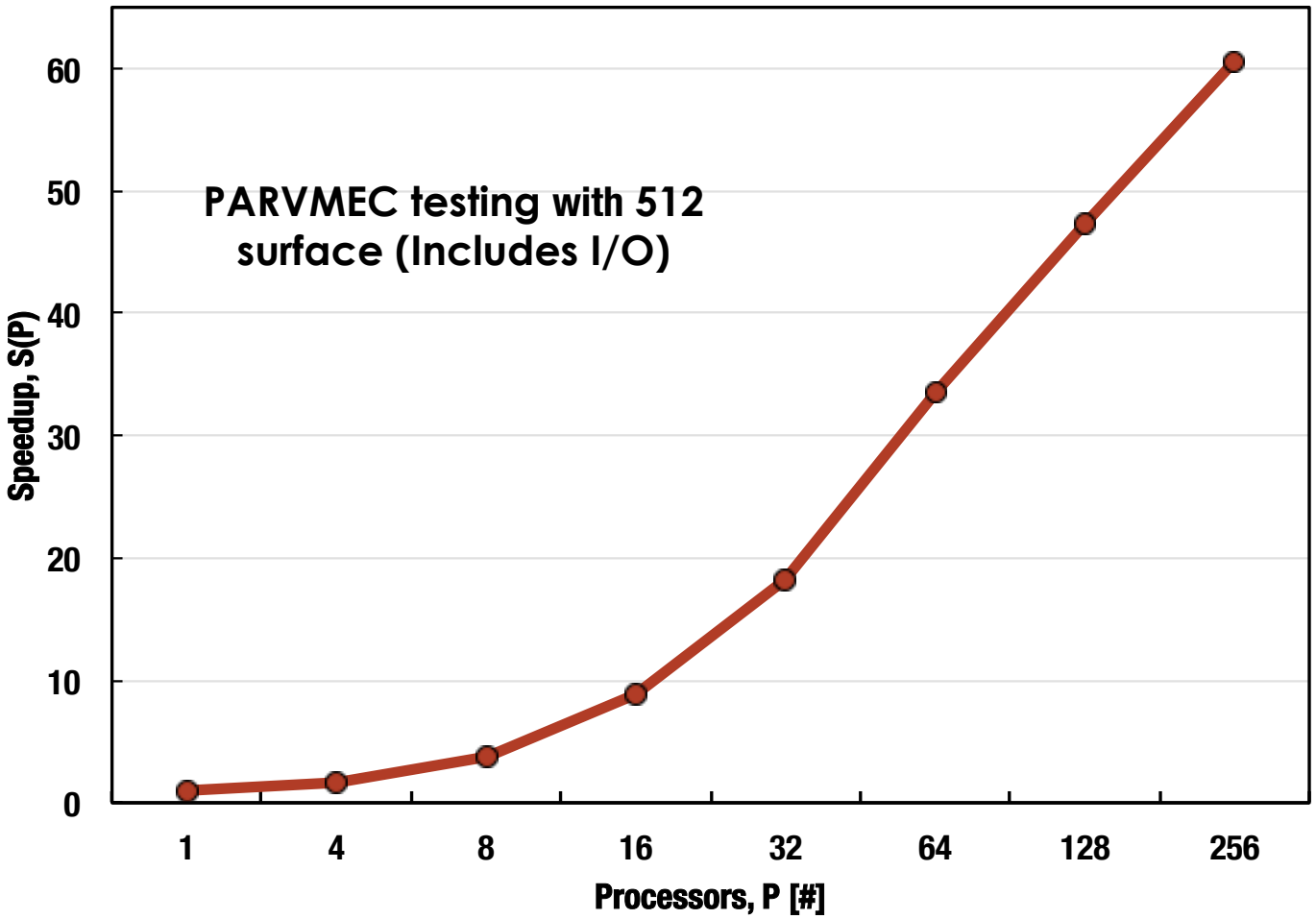
- **3D equilibrium reconstructions**
  - Integrating diagnostics and improving reconstruction
- **Determine importance of rotation in VMEC**
- **Modeled equilibrium scan, mapping proxy functions**
- **GENE, GTC enforce stellarator symmetry (requires up-down symmetry in a tokamak)**
  - New version of non-SS GTC in development

Summary

- **Application of small 3D fields in tokamaks can lead to rapid change in turbulence, relaxation of edge gradients**
- **V3FIT has been developed and is being implemented on DIII-D for 3D reconstructions**
- **Reconstructed equilibria can be used to model transport**
  - Compare to fluctuation diagnostic measurements and possibly inverted SXR images
- **In lieu of expensive (and presently unavailable) gyrokinetic calculations, use proxy functions as first comparison of geometry to transport**

Extra Slides

PARVMEC parallelizes calculations for many surfaces



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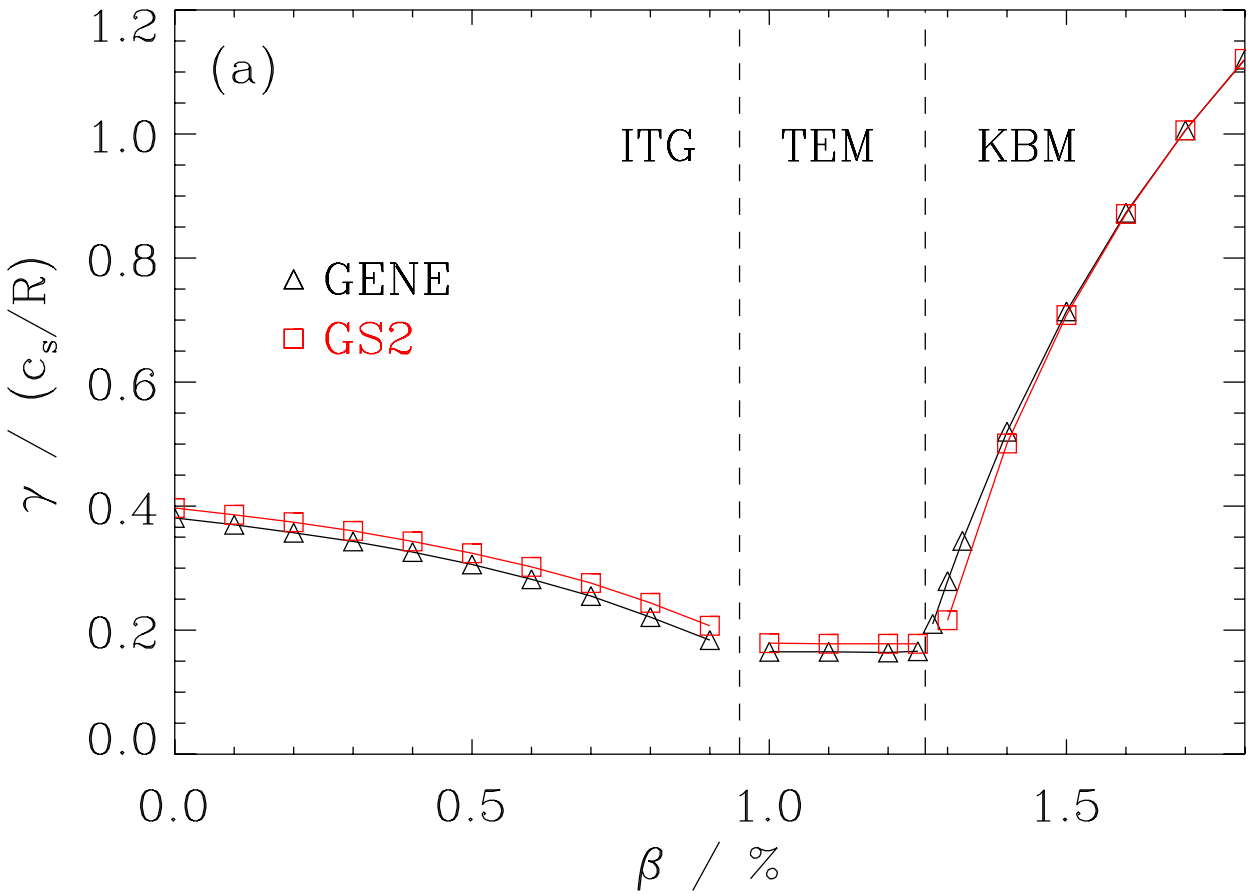
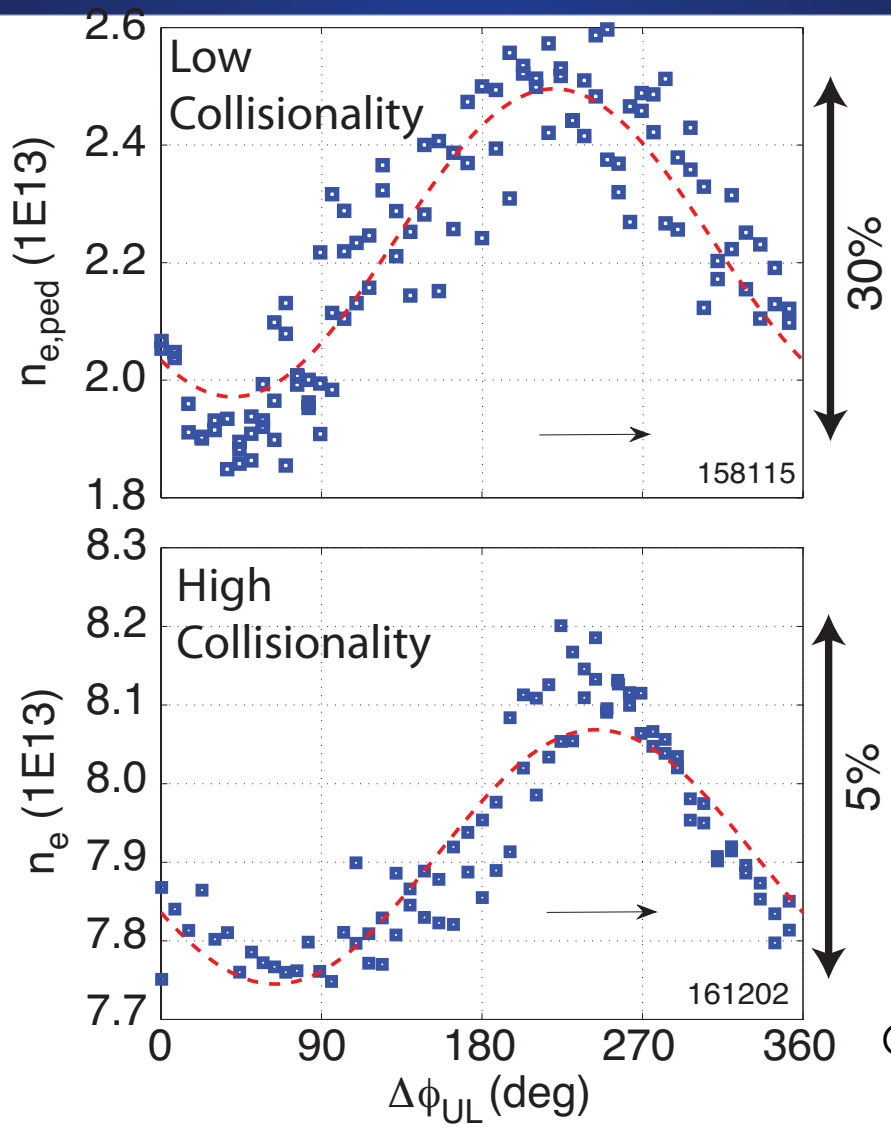
KBM expected to be dominant in steep gradient region

- **ITG / TEM quenched by sheared flows**



*M. J. Pueschel et al., Phys. Plasmas **15** (2008) 102310*

Larger density pumpout for lower collisionality



Courtesy C. Paz-Soldan

Free/fixed boundary reconstructions each have advantages

	Free	Fixed
Pros	• Fewer parameters to reconstruct	• Direct control over plasma shaping
Cons	• Only allows reshaping of surfaces via changing the current in external coils (or J and P profiles)	• Requires measurements to constrain each reconstructed parameter • Reconstruction convergence with many parameters may be difficult • Not implemented yet

Other goals of magnetic reconstruction

- **Can error fields be resolved?**
  - Compare n=1 phase to applied field for EF compensation
  - Can we resolve discrepancy between Thomson scattering and EFIT separatrix locations (TS separated toroidally from location of many magnetic sensors)

  - But: Baseline subtraction methodology would have to change (subtraction over phase flips removes stationary error fields)
    - Can error fields be resolved beneath minor sensor misalignments picking up B_T?