Impact of the NCC on NSTX-U edge ballooning stability, and the implications for edge transport

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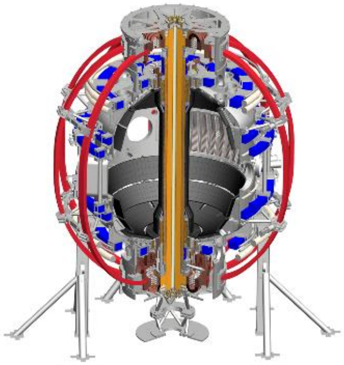
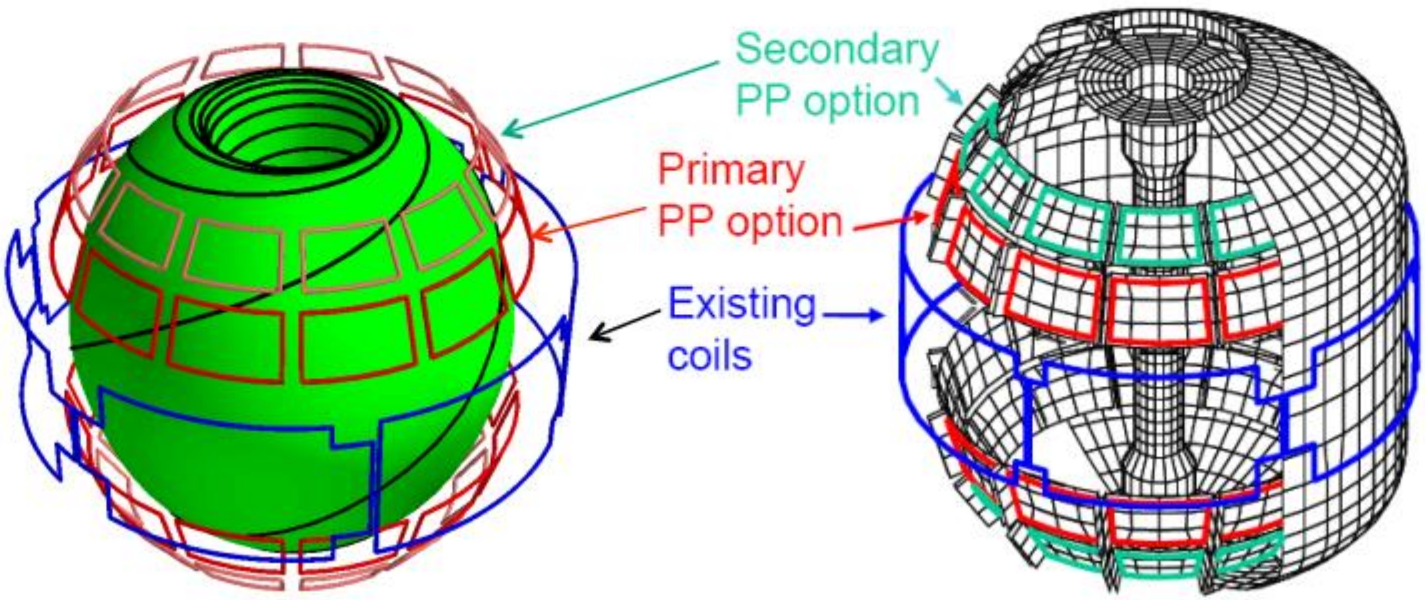
11/17/15



NCC: Non-axisymmetric Control Coil

- NCC is a set of internal, off-midplane coils under consideration for NSTX-U
  - Attached to passive plates (max 48 locations)
  - Intended to increase spectral flexibility for, e.g., ELM control studies

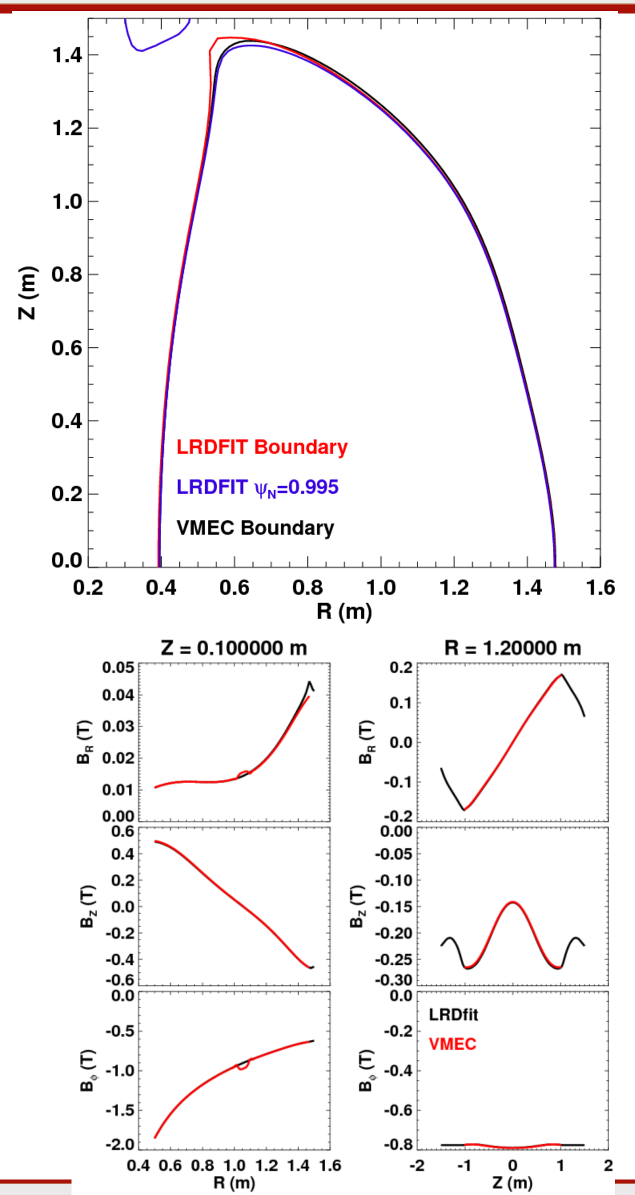


Effect of NCC on ballooning stability studied with VMEC and COBRA

- Analysis of experimental cases has shown that ballooning stability can be degraded by 3D fields
  - Canik NF '12, Chapman PoP '13; VMEC/COBRA
  - Bird & Hegna NF '13; Analytic theory based on local 3D equilibrium (Miller+RMP)
- 3D MHD equilibrium calculated with VMEC
  - Minimizes total (magnetic+thermal) plasma energy
  - 3D geometries with no restriction on symmetry
  - Mainly used for stellarators, increasingly for tokamaks
  - Hirshman, CPC '86
- Ballooning stability calculated with COBRA
  - Infinite-n ideal stability of VMEC 3D equilibria
  - Sanchez, CPC '01

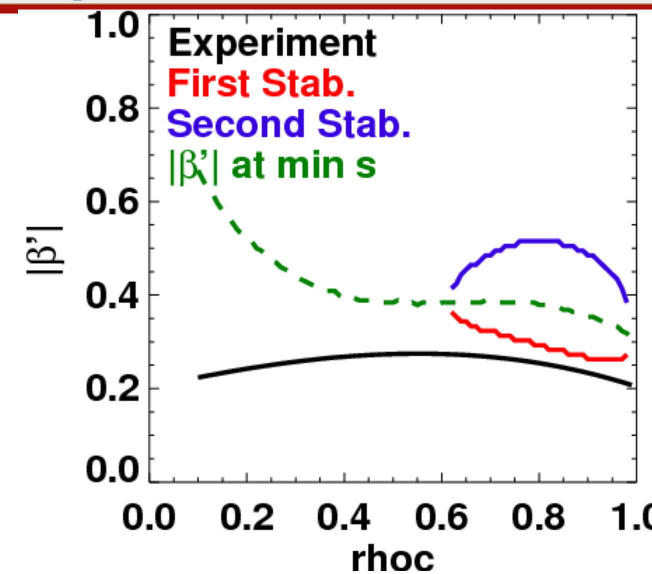
Projected 2D equilibrium transferred to VMEC

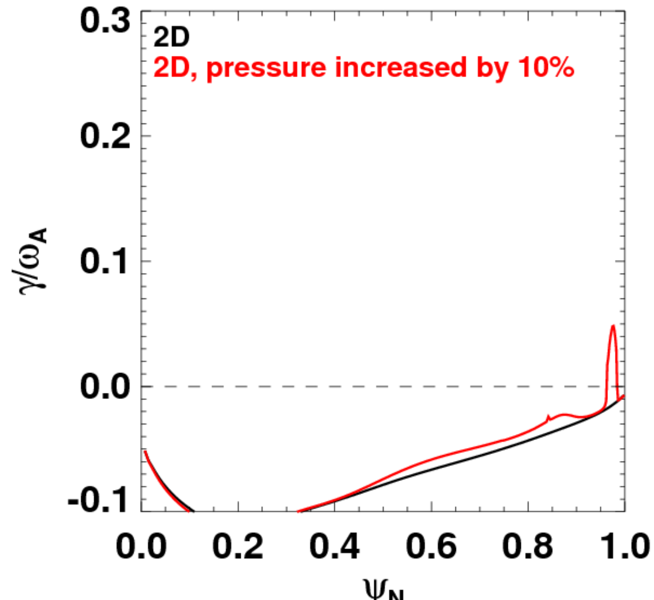
- Tables built of B-fields from coils, including NSTXU PF, NSTX TF, and NCC coils
  - Current in each coil type is input to VMEC
  - Need to do this to run VMEC in free-boundary mode when we turn on 3D fields
- Pressure and safety factor profiles read from Isolver-generated g-file, fitted with polynomials and fed into VMEC input
  - Truncated at psiN=0.995, since VMEC can't go all the way to the X-pt
- Free-boundary VMEC boundary, B-fields agree with 2D equilibrium



2D equilibrium is ballooning stable, but close to threshold in pressure gradient

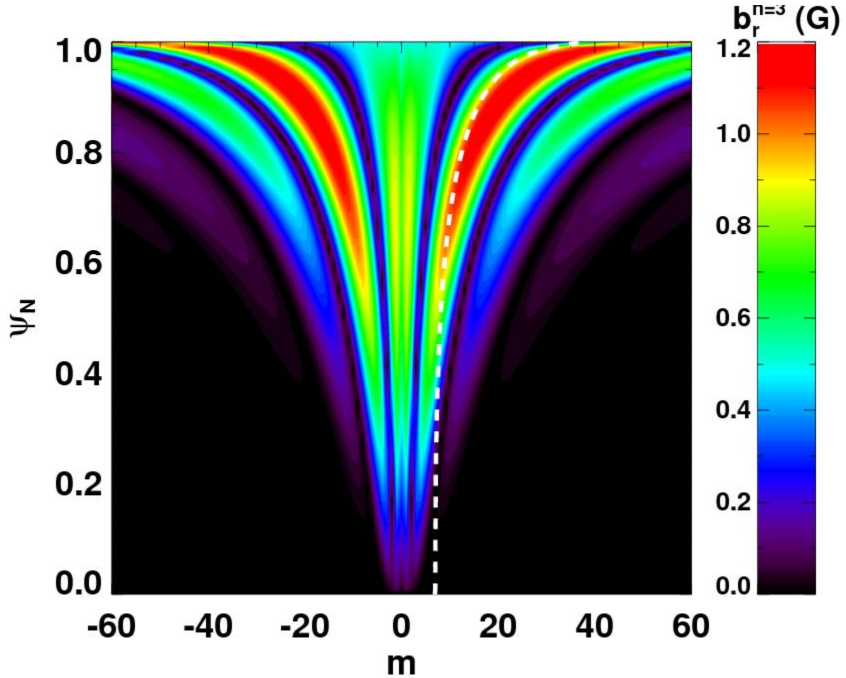
- Ballooning analysis shown in upper plot done with ‘ball’ module of GS2
  - Based on g-file, not VMEC
  - Edge pressure gradient is just below ballooning onset
- Balloon analysis shown in lower plot done with COBRA
  - Based on VMEC (2D only so far)
  - Nominal equilibrium (transferred from Isolver) is stable
- Increasing pressure in VMEC causes small unstable region at edge
  - Note that global equilibrium is changing (e.g., Shafranov shift)

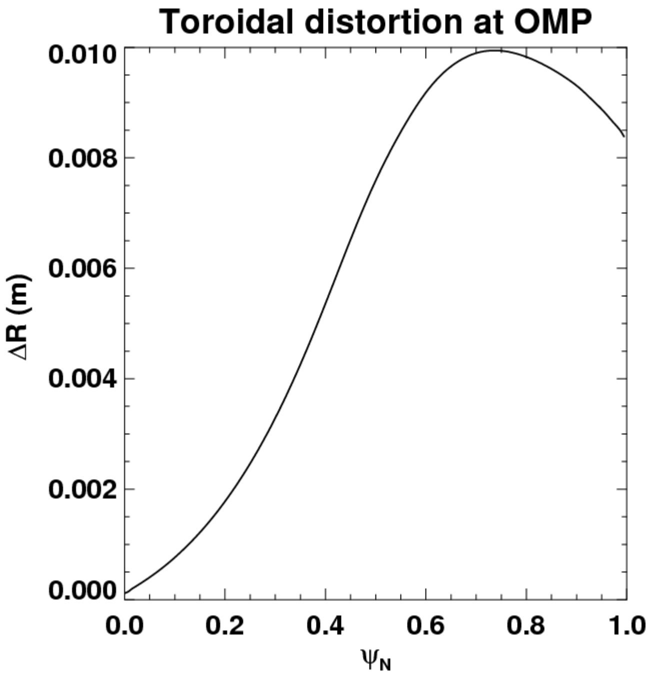




Fields from NCC added to generate 3D VMEC equilibrium

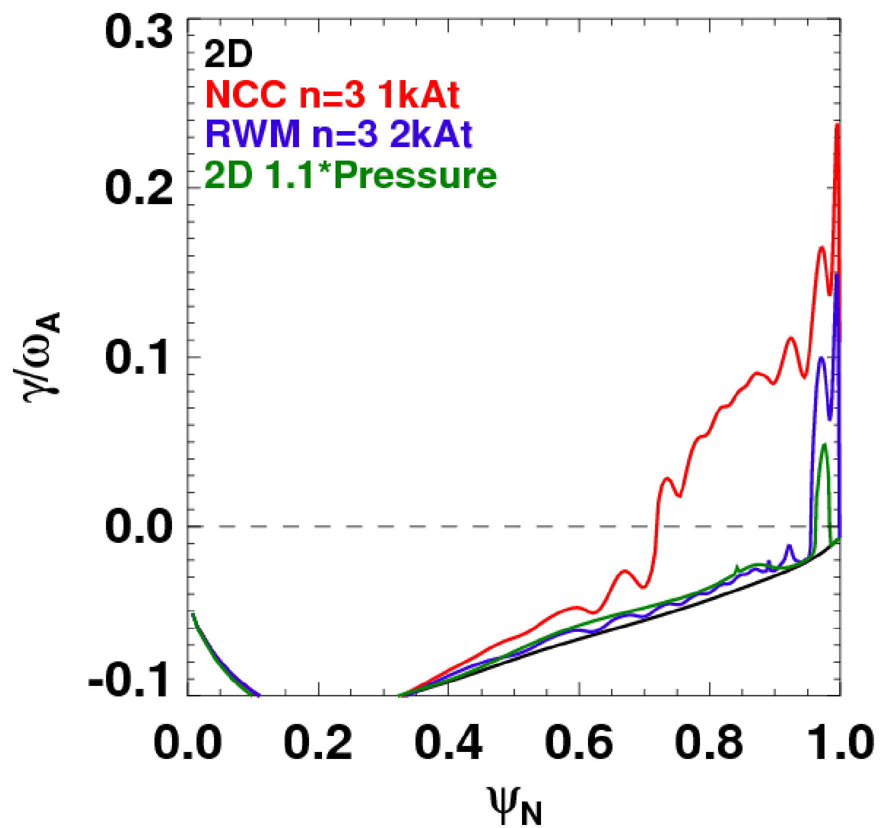
- Full NCC considered so far: 12 U+L
  - The VMEC runs shown here are for n=3 applied, even parity
- VMEC rerun with NCC turned on (1kAt), p/q profiles unchanged
  - Yields nonaxisymmetric surface displacements of order ~1 cm





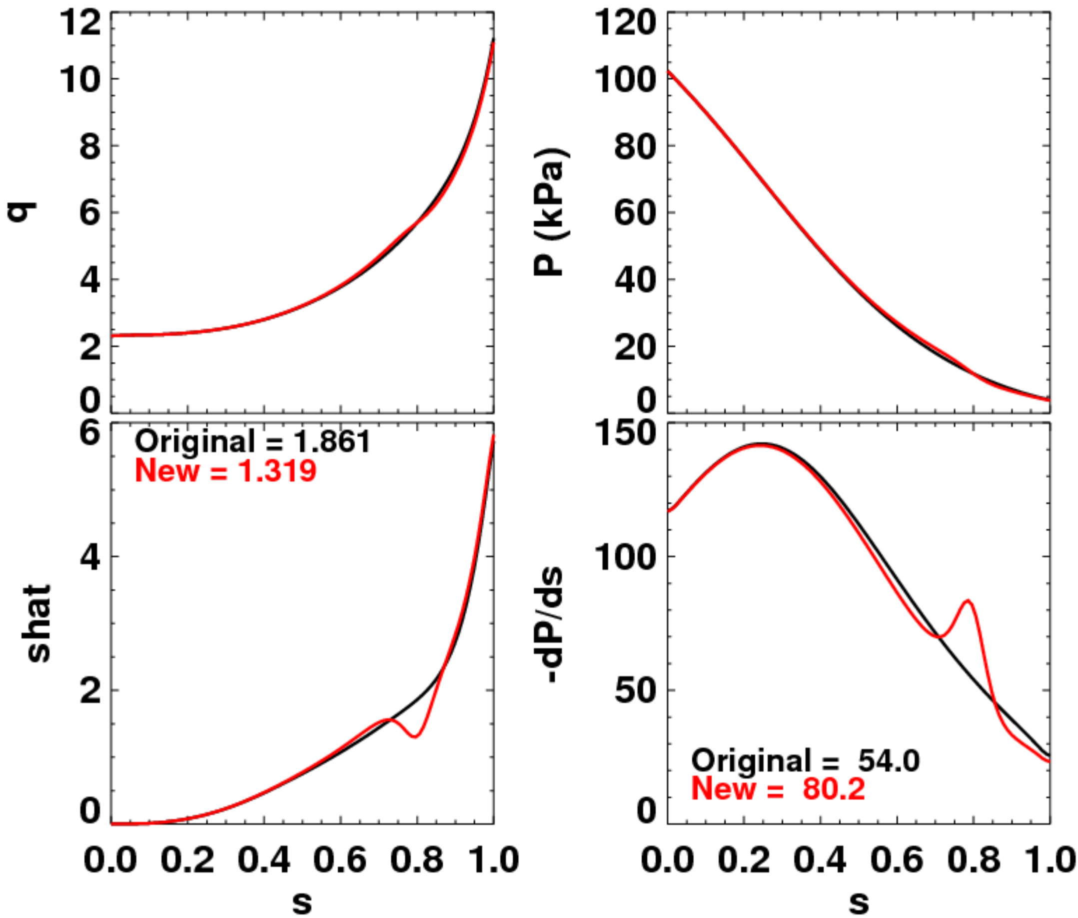
COBRA indicates that NCC can strongly affect ballooning stability

- Large edge region is unstable with NCC turned on
- Much larger effect than increasing pressure in 2D equilibrium
- Much larger than effects of RWM coils
  - Even with lower coil current



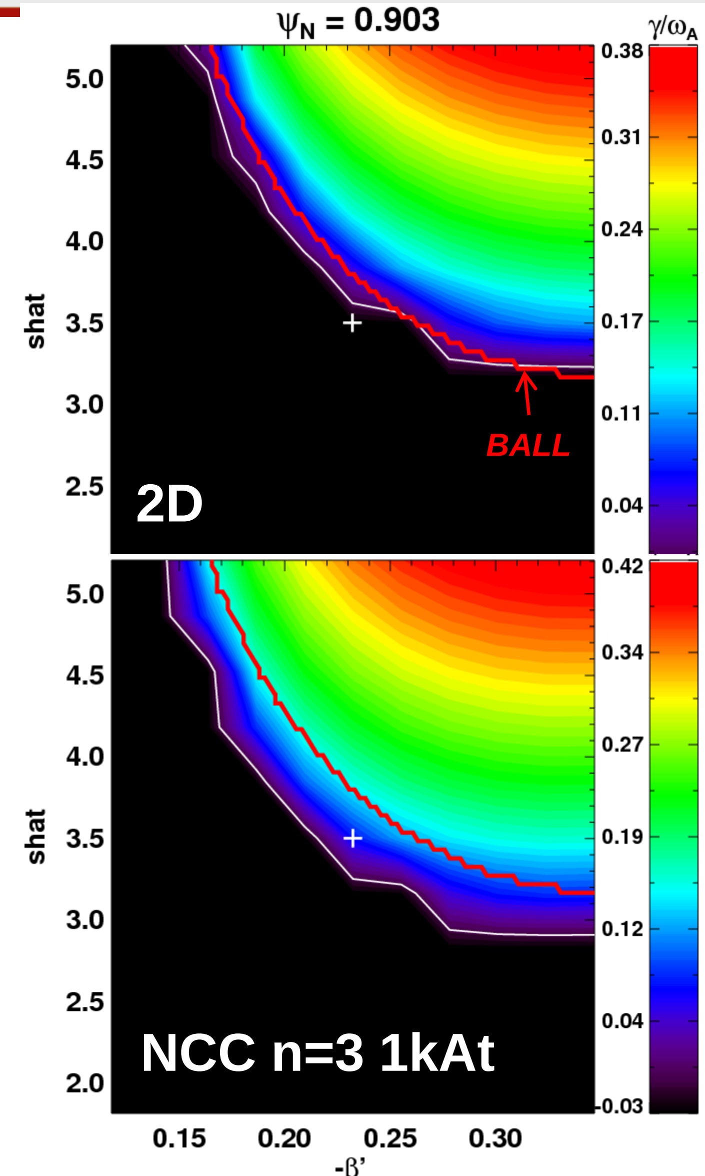
Shear, pressure gradient varied in large set of VMEC equilibria

- Profiles near chosen radius modified to change the shear and pressure gradient locally, without large changing to the global equilibrium
  - Added two tanh functions with opposite sign and different widths to q/p profs
  - Pressure and q far from and exactly at that surface are unchanged
- New profiles put into VMEC input for VMEC/COBRA calcs
  - Fixed boundary VMECs this time, using boundary from original free boundary run without altered profiles
  - ~100 new cases run to scan shat/p’



NCC moves the stability boundary at s=0.8 (ψ_N=0.903)

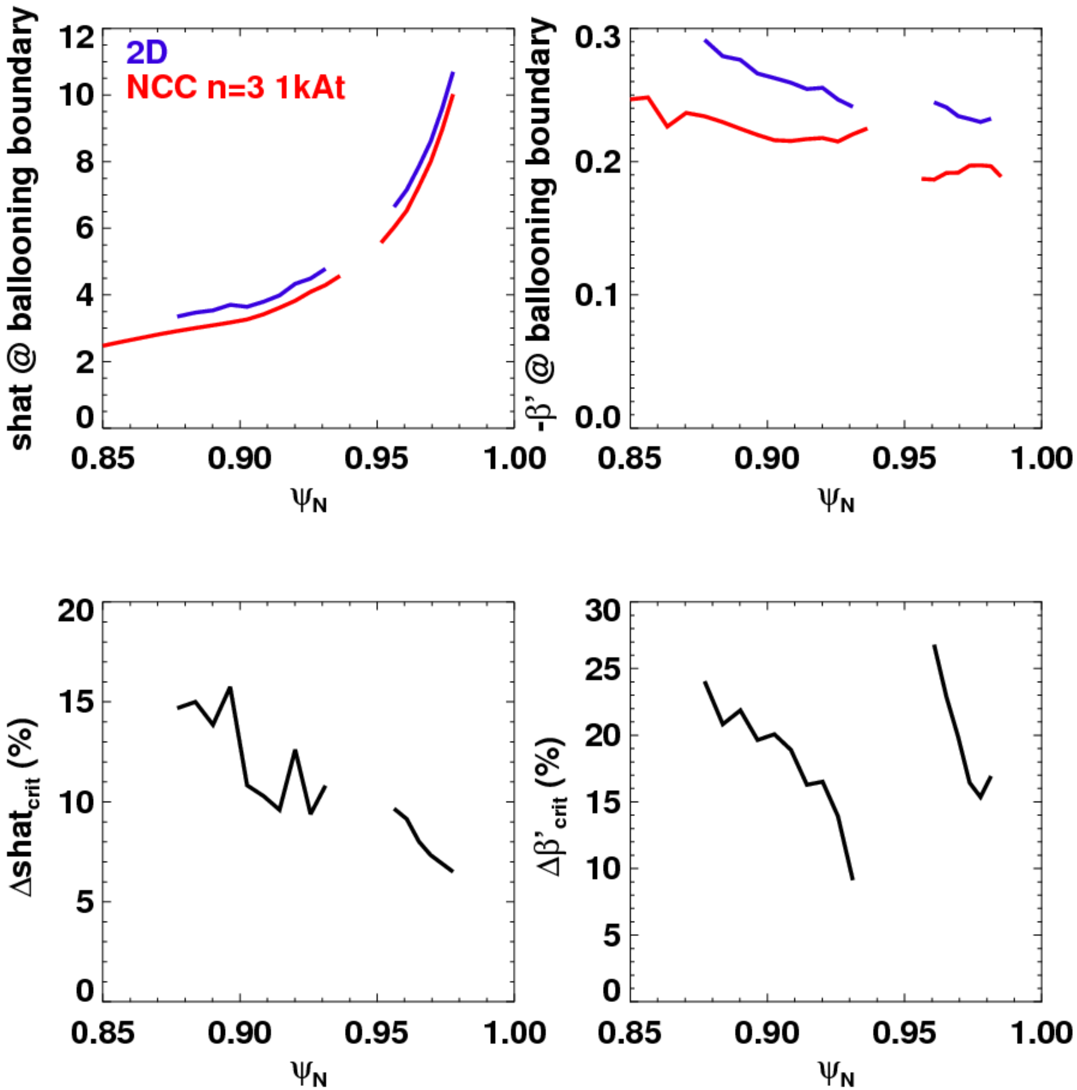
- COBRA/VMEC agree well with BALL code in axisymmetric case
  - Red contour is stability boundary from ball, based on g-file
  - Color contours are from shear/P’ scans using VMEC/COBRA
- Shift in stability boundary when NCC fields are applied is clear
  - BALL boundary is unchanged-shown for reference
  - Boundary moves both in shear and pressure gradient
  - In this case, nominal profiles (white plus sign) goes from stable to unstable (consistent with previous slides)



Stability boundary moves by ~10-20% in shear and pressure gradient with NCC on

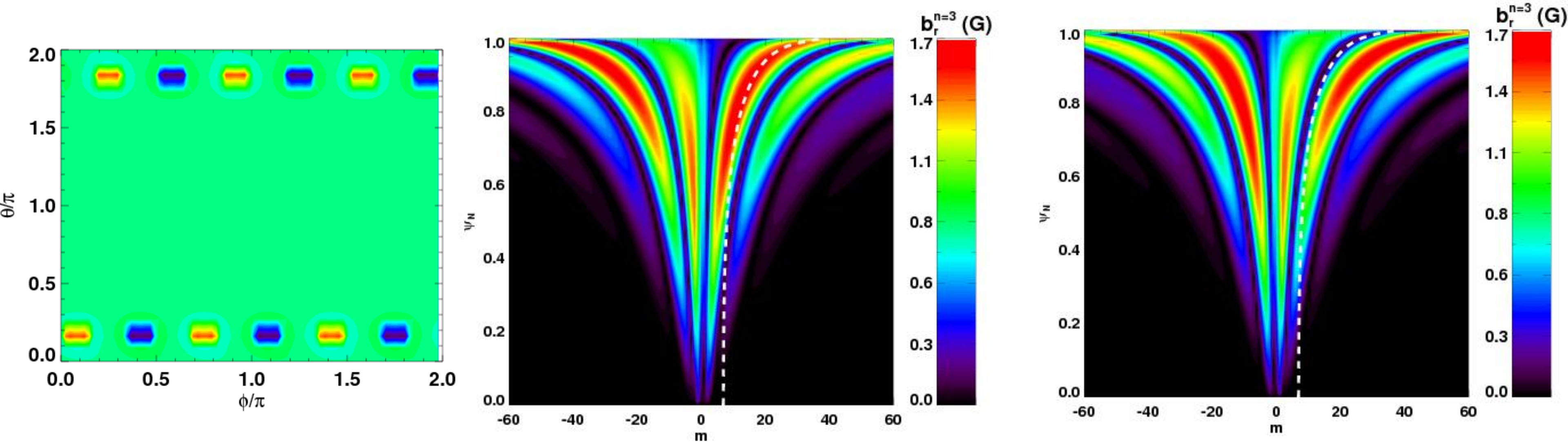
- Shear/pressure gradient at the stability boundary
  - Each is a 1D scan around operating point

- Change in the critical values due to NCC



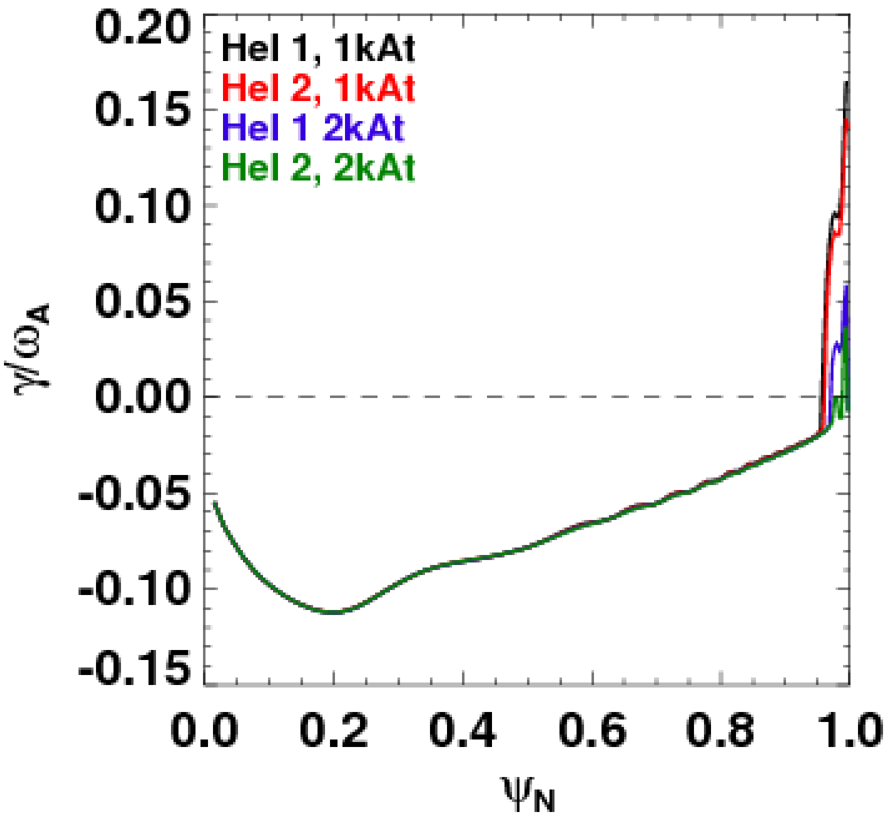
Partial NCC implemented in new VMEC runs

- 6 coils each in U and L rows, but staggered
  - n=3 always considered here
  - Two helicities considered, depending on up-down phasing
  - One is dominantly resonant (more-so than full NCC), the other non



Impact on ballooning stability is more modest than full NCC

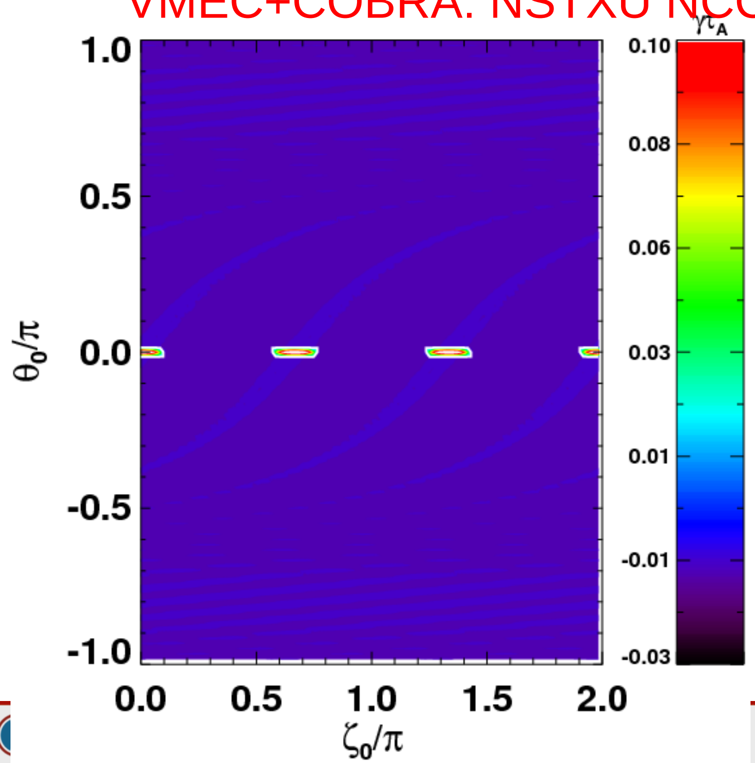
- With 1kAt, partial NCC has small impact on ballooning
  - Small, positive growth rates very near edge
- Increasing to 2kAt gives larger change in gamma
  - Instability still restricted to ψ_N>~0.95
  - More like RWM coils than full NCC
  - Not much difference between two helicities
- Related to kink-resonant perturbation?
  - Full NCC appears strongest



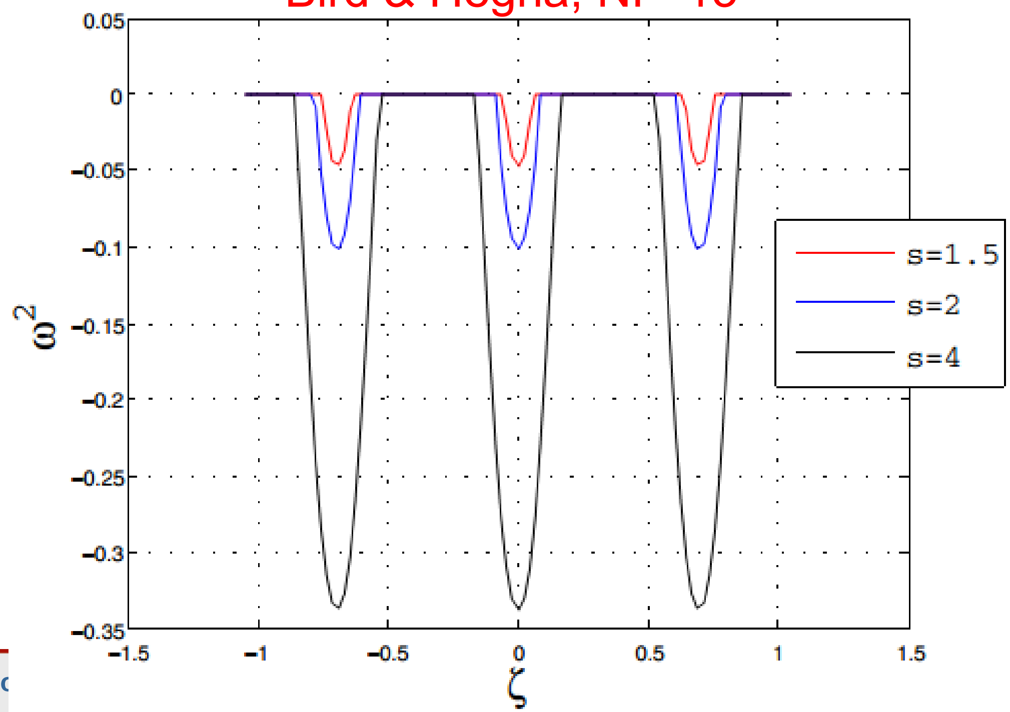
Impact on edge transport: growth rate depends on toroidal angle when field is 3D

- Local ideal ballooning stability shows toroidal localization
  - Will n=3 structure carry over to global modes?
- State-of-the-art physics picture: edge transport dominated by KBM
  - At least in pedestal, some evidence in near SOL too
  - Will cross-field heat fluxes show n=3 dependence?

VMEC+COBRA: NSTXU NCC

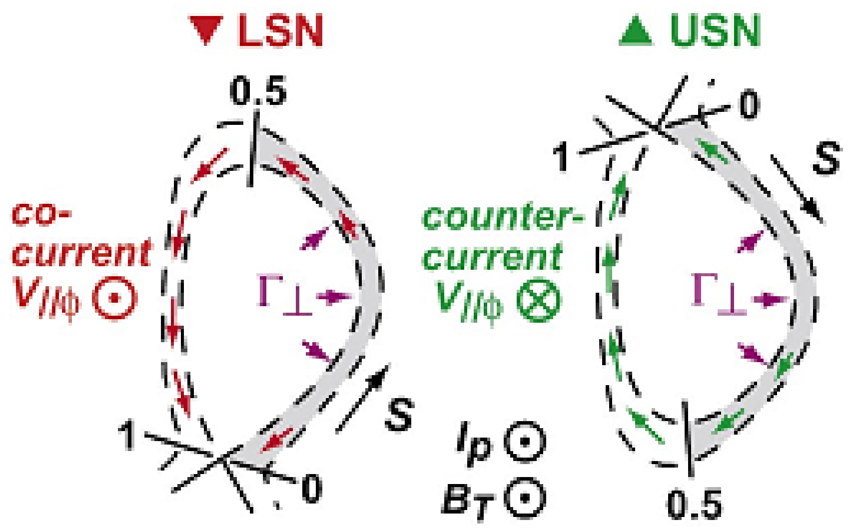


Analytic: Miller+RMP near q=3
Bird & Hegna, NF '13



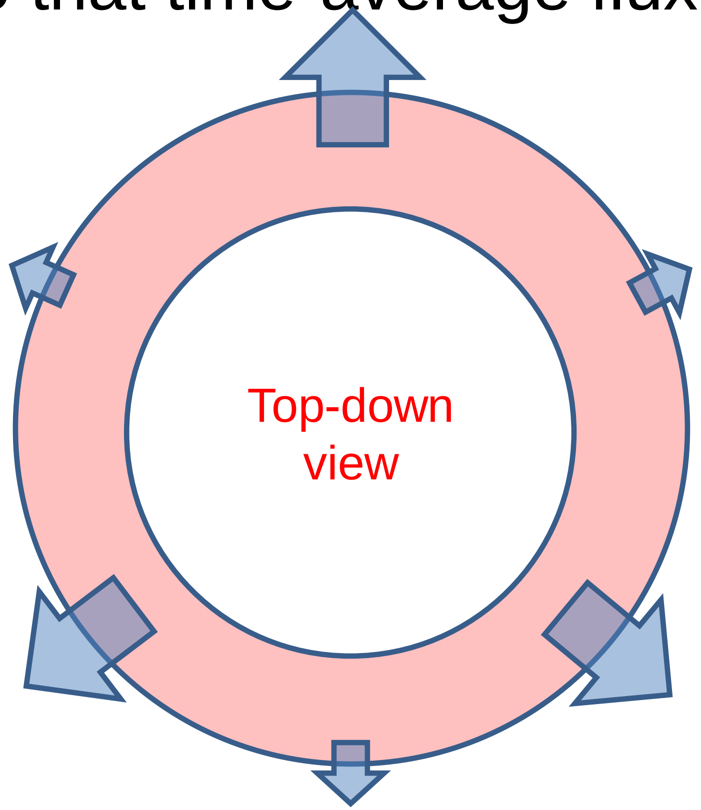
How would toroidal modulation of radial heat flux affect SOL/divertor?

- Imagine resonant fields are perfectly shielded everywhere
- But 3D fields affect turbulence so that time-average fluxes are 3D



Implied transport-driven flow pattern

We already think transport is ballooning-like: Stronger on LFS



What if it’s also toroidally asymmetric?

Field line tracing used to model effect non-axisymmetric radial heat flux

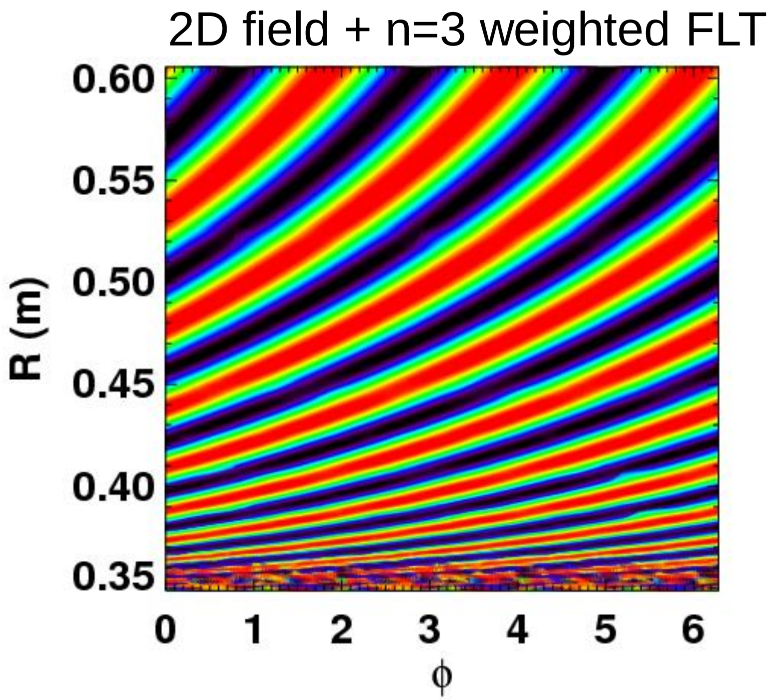
- Imagine radial transport puts heat into SOL at the OMP with an n=3 dependence
- Parallel transport then carries heat to divertor
- Can model with field line tracing
  - In our picture, field is really 3D, but resonances are shielded so effects are relatively small (no topology changes)
  - As a start, use 2D field from EFIT only
- Launch field lines from outer midplane, over range of radius and toroidal angle
- Assign each field line a weight that depends on initial toroidal angle (represents heat flux)
- Follow field lines to wall to get spatial distribution of weights

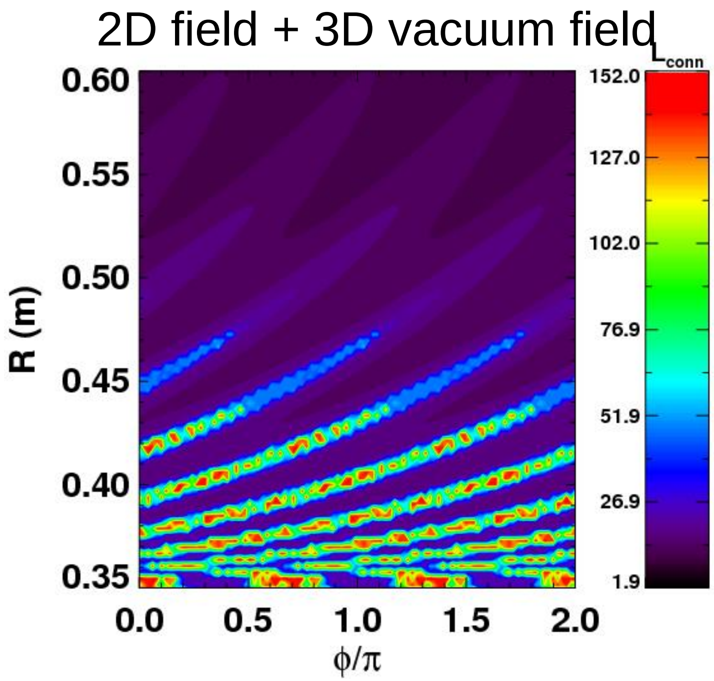
ψ_0=1..1.5
θ_0 = 0
ϕ_0 = 0..2π
$w=1+\varepsilon_t\cos(n\phi_0)$

Field line tracing$\Rightarrow$
$w(\psi,\theta,\phi)$

Toroidally weighted field lines make spiraling patterns on divertor

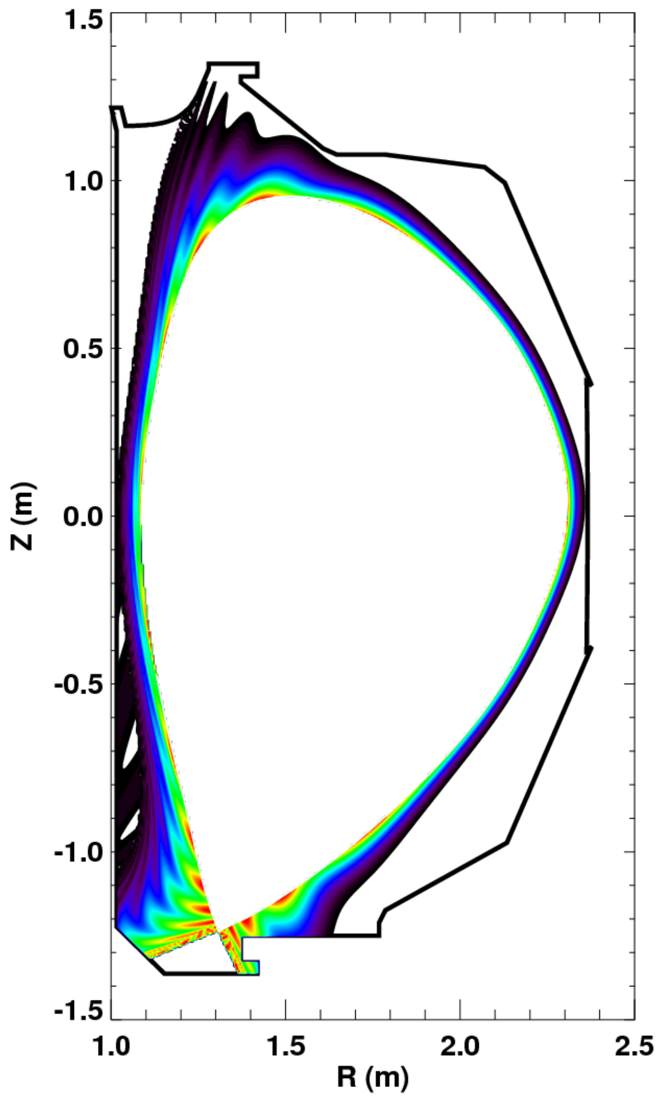
- Following field lines in 2D field with n=3 weight gives patterns on divertor that are the same as 2D+3D field line tracing
  - Spirals due to sheared field
  - 2D+3D field line tracing often show to give patterns in agreement with experiment
    - Ahn NF ‘10, Shafer NF ‘12, Kirk PRL ‘12





Viewed in R-Z plane, lobe structures near X-point are clear

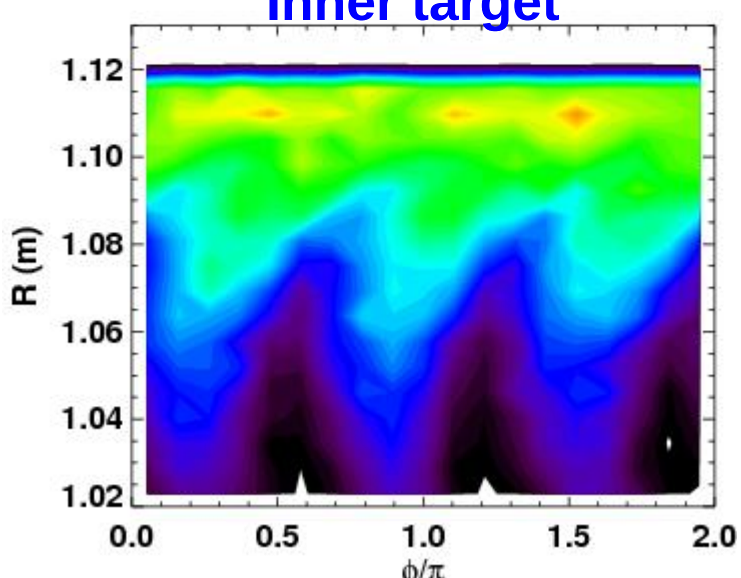
- Radial decay added to weight to reflect SOL λ_q
- Lobes evident, qualitatively very similar to FLT using vacuum RMP field
- But in this picture, there's no topology change
  - Lobes don't indicate magnetic field structure, they're due to n=3 dependence of radial transport



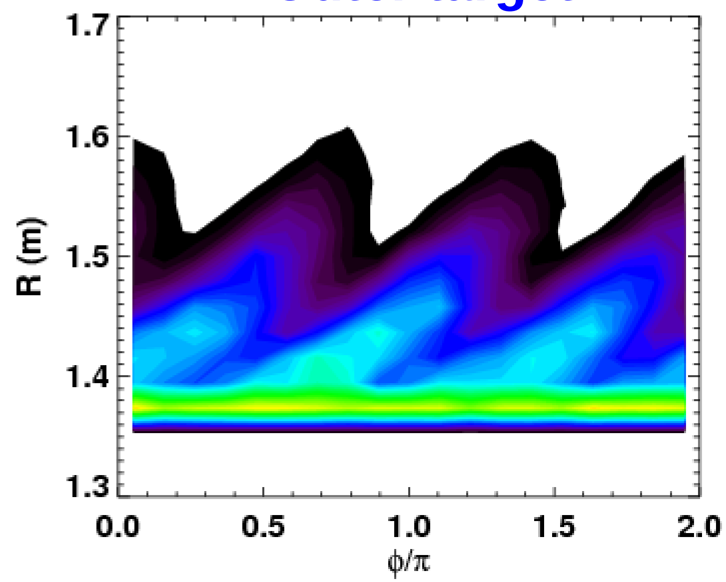
Transport simulations based on diffusing field lines also show divertor striations

- Method: field lines traced, with spatial diffusion added to model transport
  - In this case magnetic field used in tracing is 2D EFIT
  - Technique used to estimate heat flux patterns in stellarators (Lore IEEE TPS ‘14)
- Field line diffusion is given toroidal and poloidal dependence
  - Localized to 20º poloidally at the outer midplane
  - n=3 sinusoidal toroidal modulation added
- Could also implement in EMC3-EIRENE to calculate n, T, fluxes

Field line strike density
Inner target



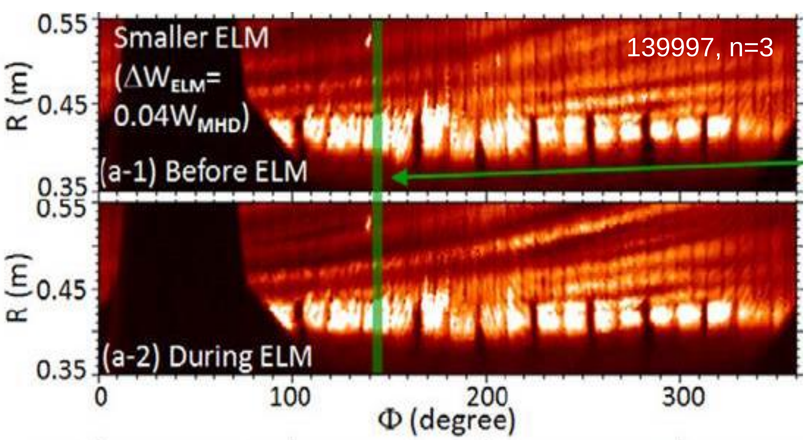
Field line strike density
Outer target



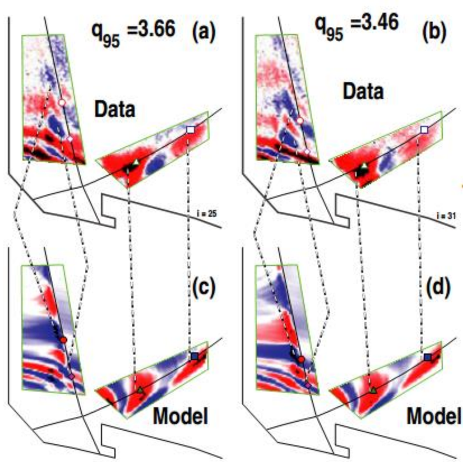
Vacuum / Partial Screening / Some Plasma Response Typically Used to Describe Measured Lobes/Striations

- Generally attributed to ‘separatrix splitting’
  - Under vacuum approximation, 3D fields generate tangles that can connect hot core plasma to wall
  - Fact that lobes are measured often taken of evidence that RMP has penetrated at least somewhat
- The further out in radius fields are screened, the more the radial extent of lobes is reduced (Cahyna, JNM ‘11)
  - Ideal response all the way to separatrix should nearly eliminate them (Cahyna, IAEA ‘12)
  - Could transport picture be more consistent with lack of edge T_e flattening?

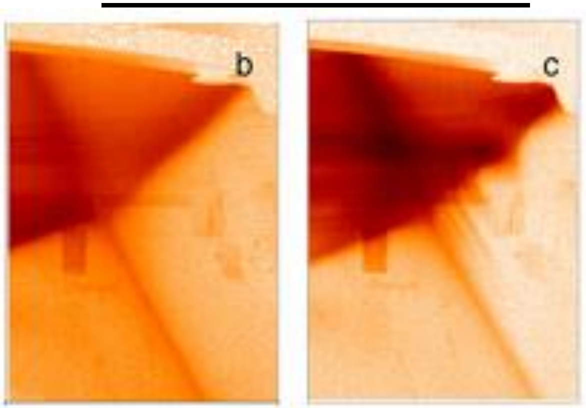
NSTX: Ahn PPCF 2014



DIII-D : Shafer NF 2012



MAST: Kirk PRL 2012



Conclusions: NCC can have a large impact on edge stability and transport

- VMEC and COBRA calculations show strong degradation of ballooning stability possible
  - Strong increase of growth rates near marginal stabilty
  - ~10-20% change in stability boundary
- Toroidal localization of instabilities could result in striations in divertor fluxes
  - Asymmetric loading of fieldlines results in lobes/strike point splitting even with perfeclty axisymmetric B-field
  - Lack of stochasticity more consistent with pedestal measurements?