Turbulent transport in 3D geometry: from Tokamaks to Stellarators

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Outline

- 3D geometry and equilibrium

  - What role does geometry play in turbulence?

- Part I: Stellarators
  - Ion temperature gradient driven turbulence in W7-X

    - non-stiffness, streamers, zonal flows?
  - Putting it all together: Full surface gyrokinetic simulation

- Part II: ELM Mitigation with 3D fields in Tokamaks

  (turning Tokamaks into Stellarators to make them more interesting)
  - What role does turbulence play in RMP experiments?
  - Resonant Pfirsch-Schlüter currents

    - Equilibrium physics, effect on ITG turbulence
  - Centimeter-scale 3D deformations

    - Effect on equilibrium/geometry, enhancement of ITG turbulence

What does the curvature of magnetic field lines tell us?

Ideal MHD equilibrium:

$$\nabla\left(p+\frac{B^2}{2\mu_0}\right)=\frac{B^2}{\mu_0}\vec{\kappa}$$

Curvature vector:

$$\vec{\kappa}=(\hat{b}\cdot\nabla)\hat{b}$$

Frenet-serret theorem: only need 3 scalars!

$$(\hat{\mathbf{b}}\cdot\nabla)\hat{\mathbf{b}}=\kappa_n\hat{\mathbf{n}}+\kappa_g\hat{\mathbf{b}}\times\hat{\mathbf{n}},$$

$$(\hat{\mathbf{b}}\cdot\nabla)\hat{\mathbf{n}}=-\kappa_n\hat{\mathbf{b}}+\tau_n\hat{\mathbf{b}}\times\hat{\mathbf{n}},$$

$$(\hat{\mathbf{b}}\cdot\nabla)\hat{\mathbf{b}}\times\hat{\mathbf{n}}=-\tau_n\hat{\mathbf{n}}-\kappa_g\hat{\mathbf{b}},$$

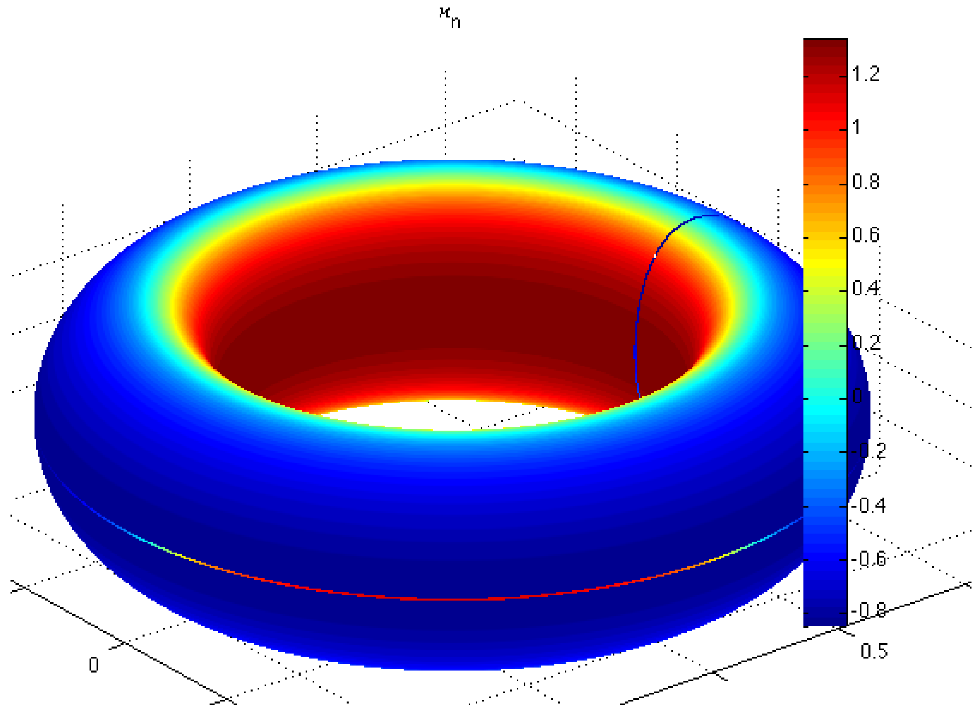
Normal curvature

$$\kappa_n$$

- The normal curvature:

  - Component of curvature vector normal to flux surfaces

  - Instability drive (“toroidal curvature”)



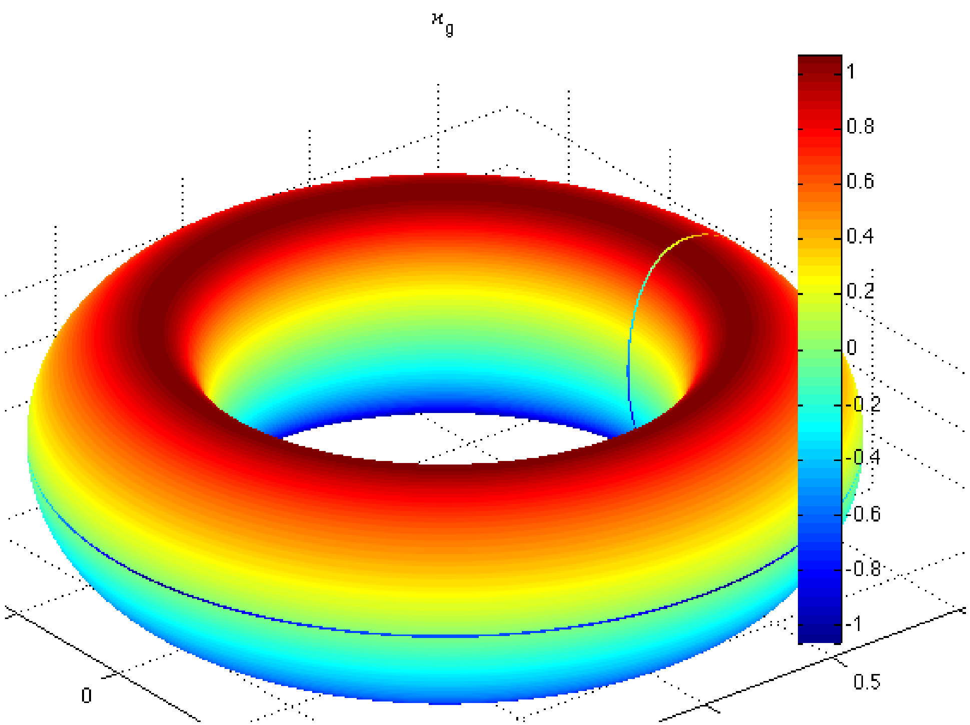
Geodesic curvature

$$\kappa_g$$

- The geodesic curvature:

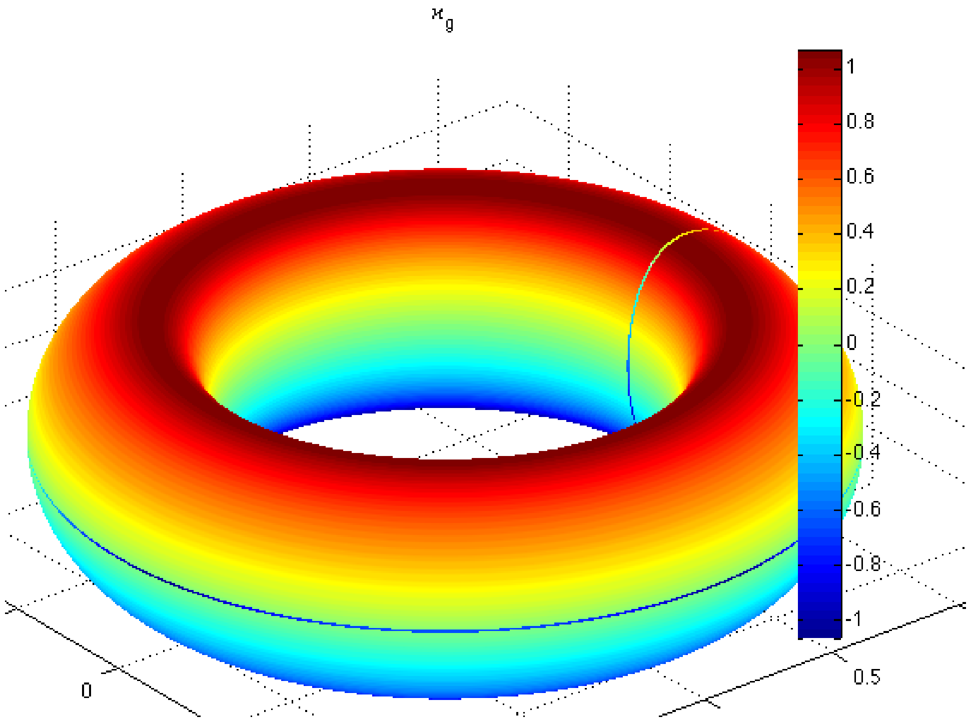
  - Component of curvature vector lying <u>within</u> flux surfaces

  - Measures deviation of field lines from geodesics



What is the role of the geodesic curvature?

- It is ubiquitous in my research:
  - Source term for resonant Pfirsch-Schlüter currents in 3D
  - Couples zonal flows (flux surface averaged flows w/ radial variation) to GAMs (toroidally symmetric flow w/ radial and poloidal variation)
  - Sets the radial grad B drift velocity (and thus step size for neoclass. trans)



The local magnetic shear

- A measure of how field lines on different surfaces shear apart
- Is simply a mathematical property of a magnetic surface:

$$S_{\text{loc}} = \frac{d}{d\chi}\left(\frac{g^{\rho\alpha}}{g^{\rho\rho}}\right) \qquad s = (\hat{\mathbf{b}} \times \hat{\mathbf{n}}) \cdot \nabla \times (\hat{\mathbf{b}} \times \hat{\mathbf{n}})$$

- What physics mechanisms produce this magnetic shear?

Parallel currents + normal torsion

The simple version:

$$s = \mu_0 \frac{\mathbf{J} \cdot \hat{\mathbf{b}}}{B} - 2\tau_n$$

Profile effects — Pfirsch-Schlüter currents — Normal torsion

The messy version:

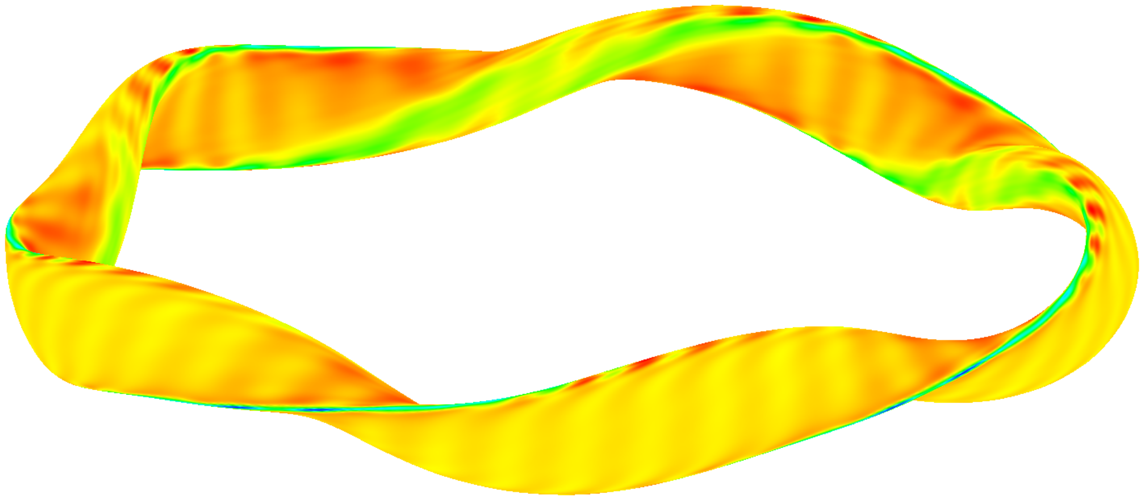
$$(\vec{B} \cdot \nabla) D = \iota' \left(\frac{B^2}{|\nabla\psi|^2} \frac{1}{\left\langle \frac{B^2}{|\nabla\psi|^2} \right\rangle} - \frac{1}{\sqrt{g}} \right) + p' \left(\frac{B^2}{|\nabla\psi|^2}\lambda - \frac{B^2}{|\nabla\psi|^2} \frac{\left\langle \frac{B^2}{|\nabla\psi|^2}\lambda \right\rangle}{\left\langle \frac{B^2}{|\nabla\psi|^2} \right\rangle} \right) + 2 \left(\frac{B^2}{|\nabla\psi|^2} \frac{\left\langle \frac{B^2}{|\nabla\psi|^2}\tau_n \right\rangle}{\left\langle \frac{B^2}{|\nabla\psi|^2} \right\rangle} - \frac{B^2}{|\nabla\psi|^2}\tau_n \right)$$

What are the ingredients for turbulence?

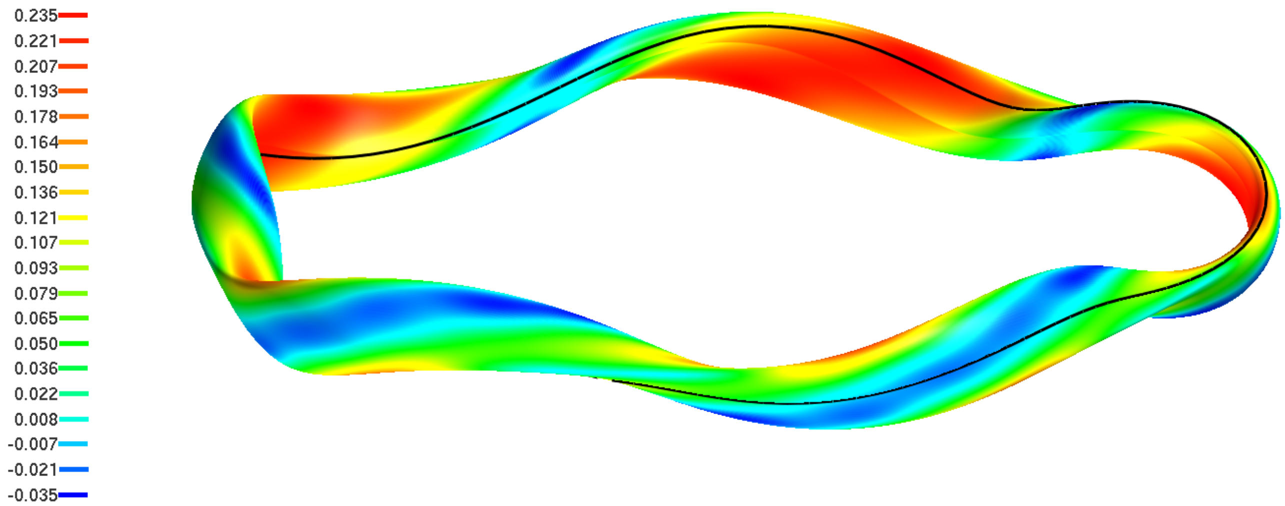
- (Negative) normal curvature
  - Magnitude sets the strength of the curvature drive
  - Spatial structure determines parallel connection length
- Local magnetic shear
  - Where it is large, unfavorable conditions for instability
  - Field line bending (electromagnetic instabilities: KBM, MHD ballooning)
  - FLR effects: large shear “decorrelates” fluctuations
- Geodesic curvature and |B|
  - Geodesic curvature plays a central role in ZF/GAM dynamics
  - Structure of |B| as well
  - [Sugama/Watanabe , Mischenko, Helander]

The geometry of W7-X
(the ingredients for turbulence)

The local magnetic shear:



The normal curvature:



Temperature profiles in W7-AS were "non-stiff".

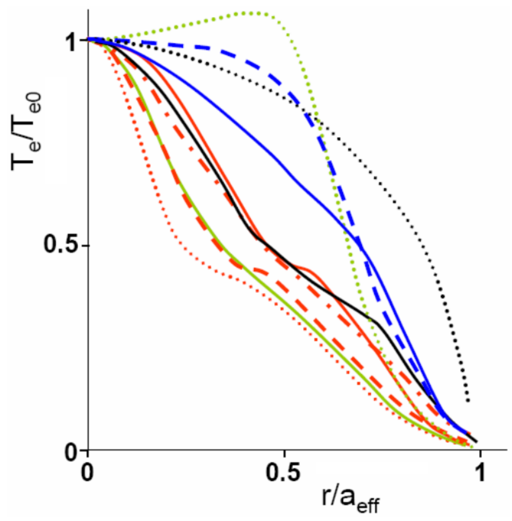
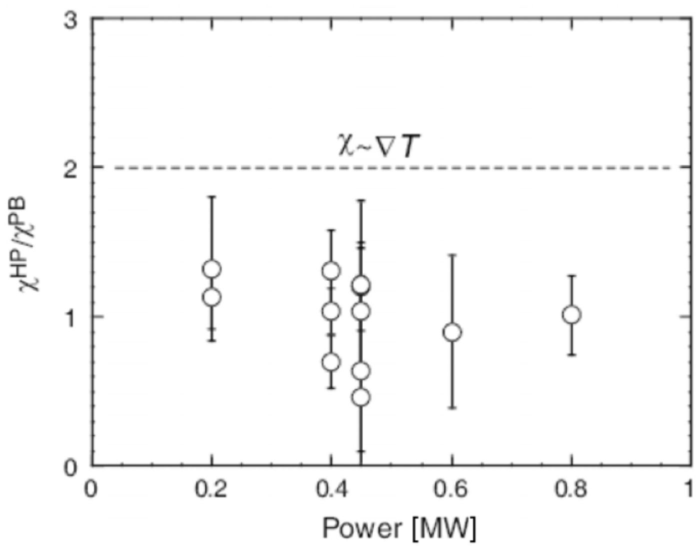


Figure 1. Normalized electron temperature of W7-AS for various conditions. Blue: variation of heating method; - - - -: 0.45 MW NBI; ——: 1.35 MW NBI + 0.75 MW ECRH. Green: variation of ECRH power deposition; ——: central; · · · · · ·: off-axis. Black: variation of confinement; ——: quiescent H-mode; · · · · · ·: low confinement as established between major rationals [55]. Red: power scan with ECRH: ——: 0.23 MW; — · —: 0.46 MW; - - - -: 0.77 MW; · · · · · ·: 1.23 MW.



- [F. Wagner et al, PPCF 2006]

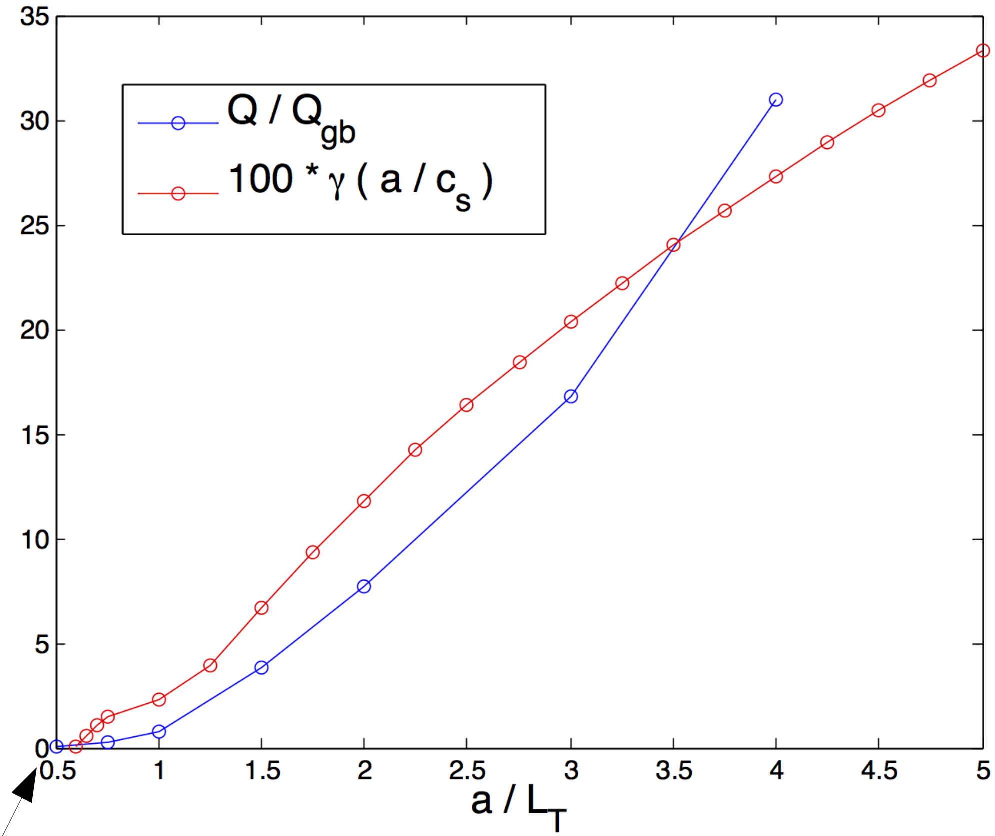
- No observed profile resilience

- Heat pulse experiments [Hirsch et al, PPCF 2008]

- Critical temp. gradient model would yield > 2

W7-X: “Gradual onset” of turbulence

W7-X, 4% beta equilibrium, no density gradient, adiabatic electrons, collisionless
Flux tube simulation



Still nonzero heat flux

-Note: W7-X A=11
(huge scan in R/L_T)

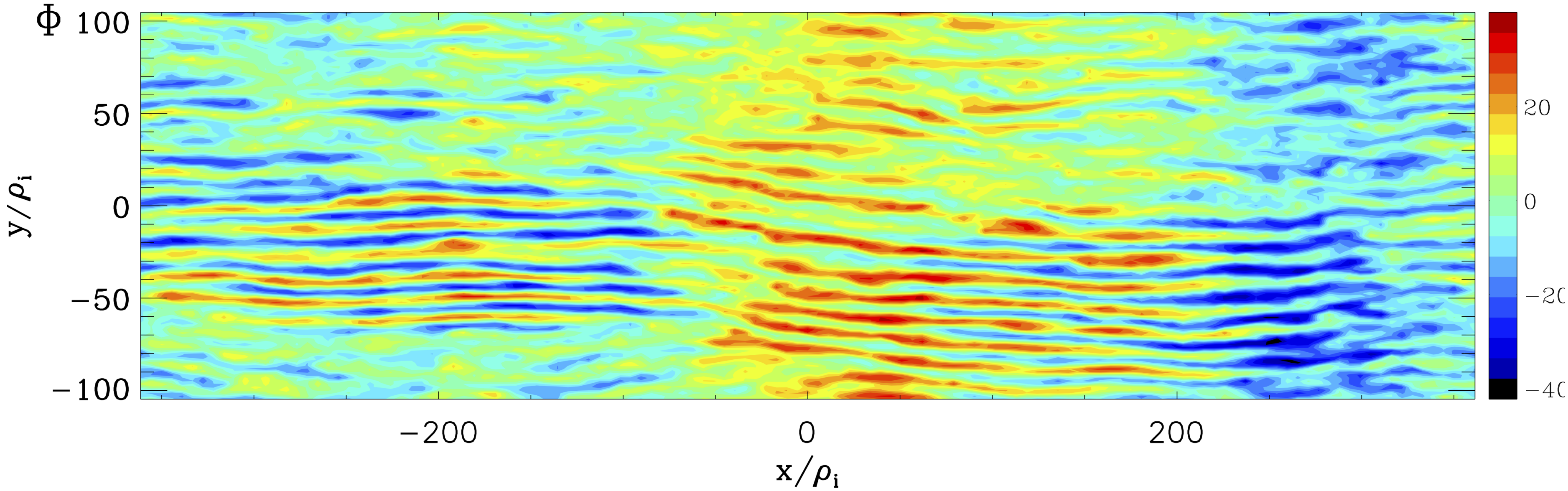
- No “Dimits shift” regime

- No clearly identifiable NL critical gradient

- Turbulence below the linear critical gradient!

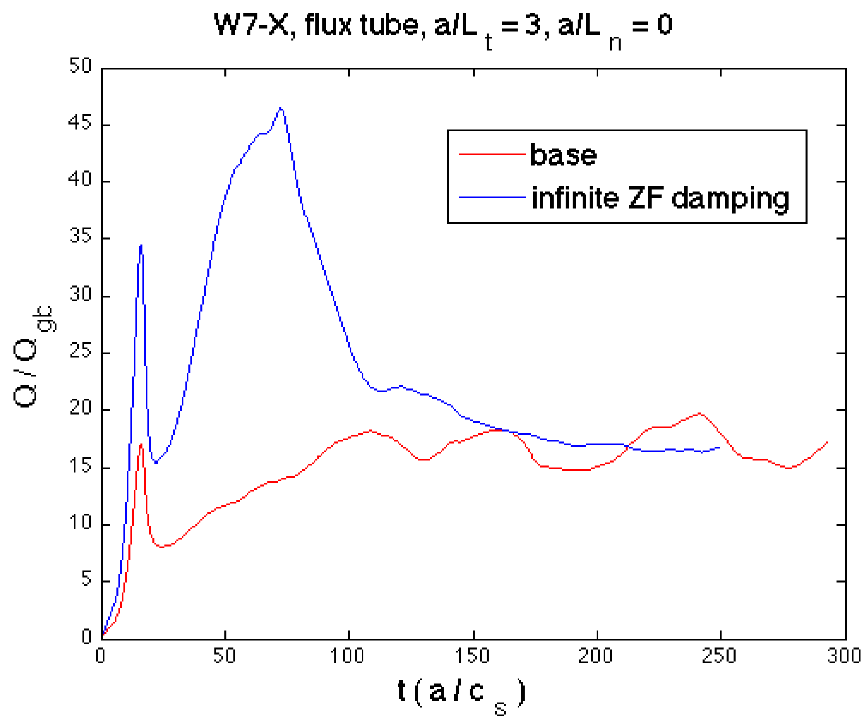
W7-X flux tube turbulence is dominated by elongated streamers

Y = q*theta - zeta

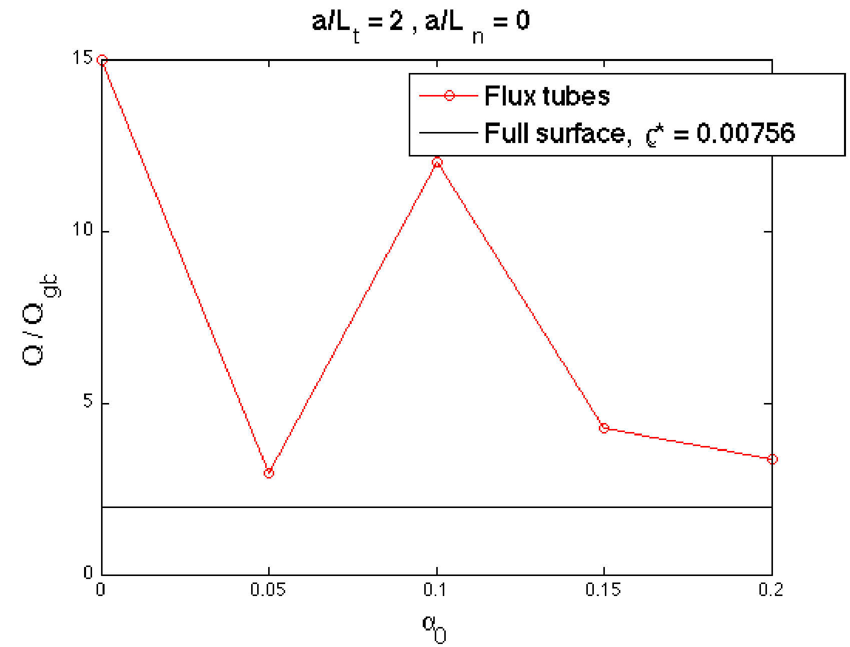


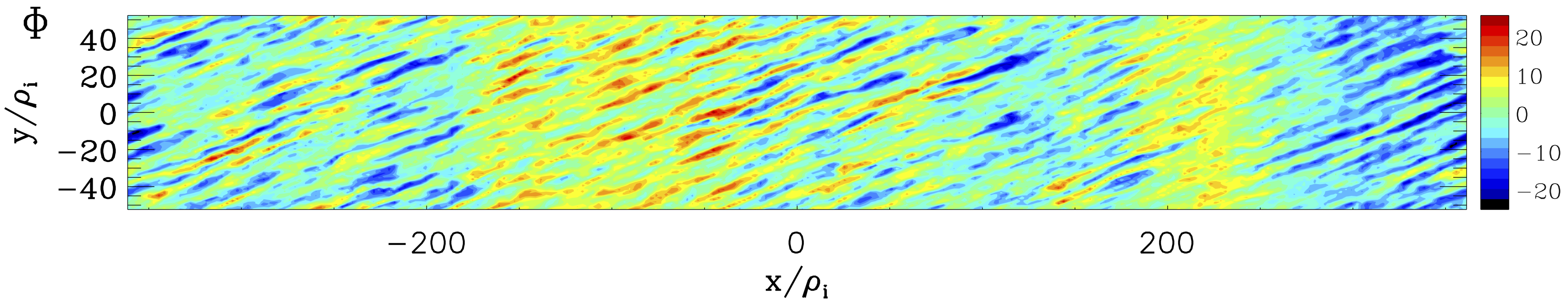
- Actual radial correlation length ~ 15 ion gyroradii

W7-X with “infinite ZF damping”



What about different flux tubes?





The full-surface GENE code

- Numerically, nearly identical to the radially global GENE version

  (i.e. Görler et al, JCP 2011)

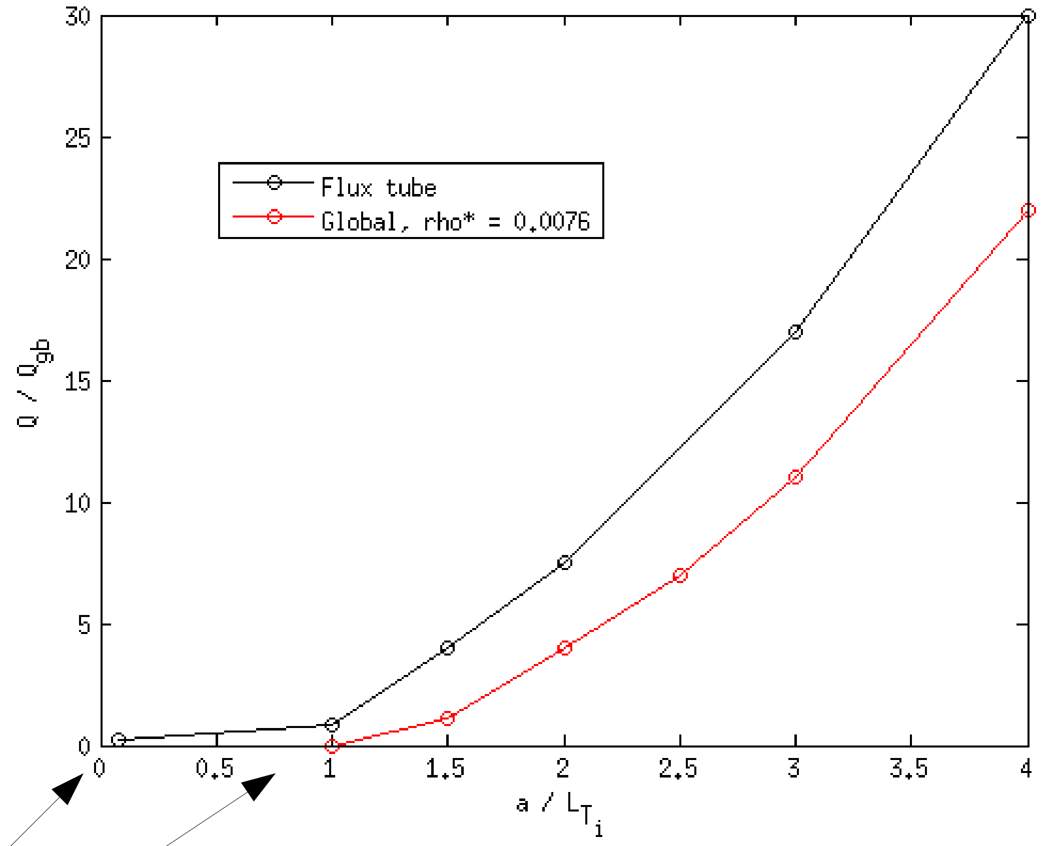
- Doubly periodic finite difference grid covering the entire poloidal plane.

- Gyroaveraging via Lagrange interpolation of the fields.

- Exhaustively tested for single species, adiabatic electron runs – good scaling (70-80% efficiency) up to 32,768 cores on IFERC.

- Functioning with kinetic electrons, electromagnetic effects, finite beta.

Flux tube simulations tend to over-predict full surface heat flux.



Still nonzero
heat flux

Stellarator summary

- W7-X flux tube results:
    - Different flux-gradient relationships
    - No clearly identifiable NL crit gradient, no Dimits shift
    - Sub-critical turbulence
    - Radially elongated streamers
- Full surface GENE
    - At finite rho*, lower transport than flux tubes
    - Self-consistently “puts together” all the flux tubes
    - Generally, a close connection between full surface and flux tube

RMP experiments have produced widely varying results.

- One key distinction: Mitigation vs Suppression
- Density pumpout: commonly seen in DIII-D, MAST but not ASDEX-U
  - Can be compensated w/ fueling: maybe not essential?
- Enhanced transport: - often observed in DIII-D, MAST
  - lower pedestal pressure, less instability drive
- Sensitivities:
  - q95
  - RMP phasing
  - Parity of RMP coils
  - Threshold 3D field strength typically

I-coil modulation experiments at DIII-D demonstrate a clear effect on turbulence.

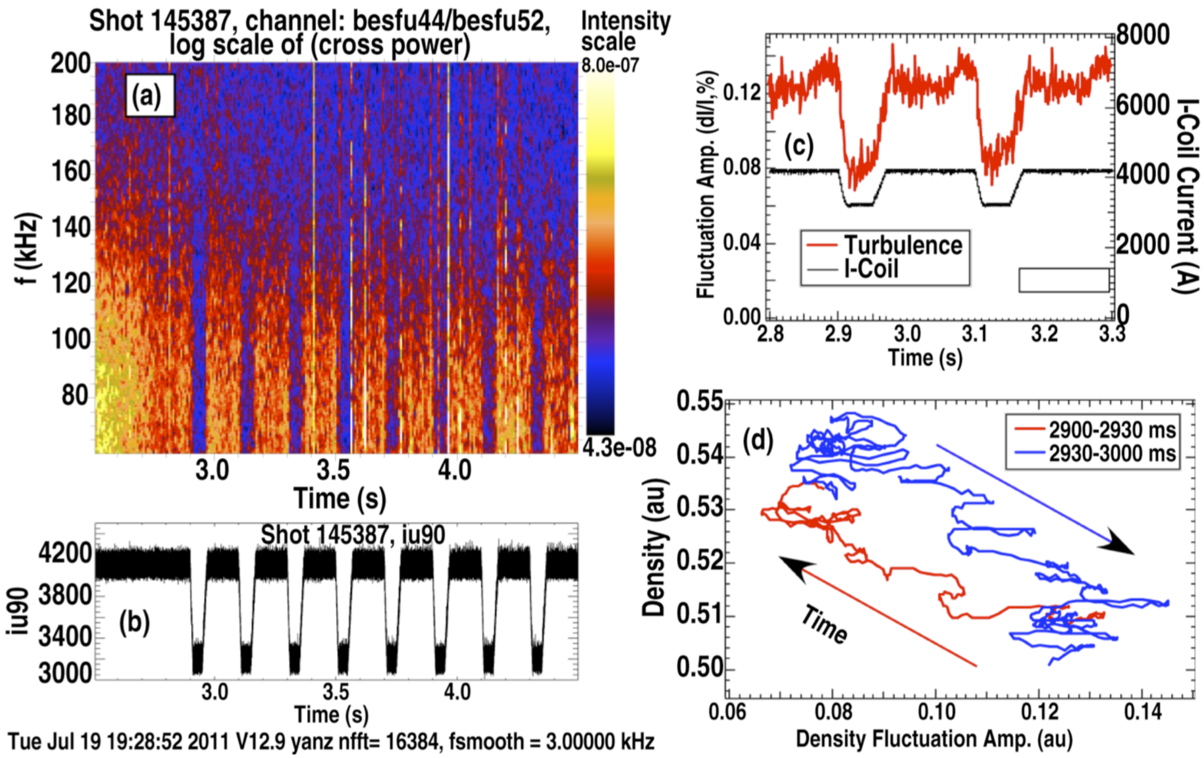
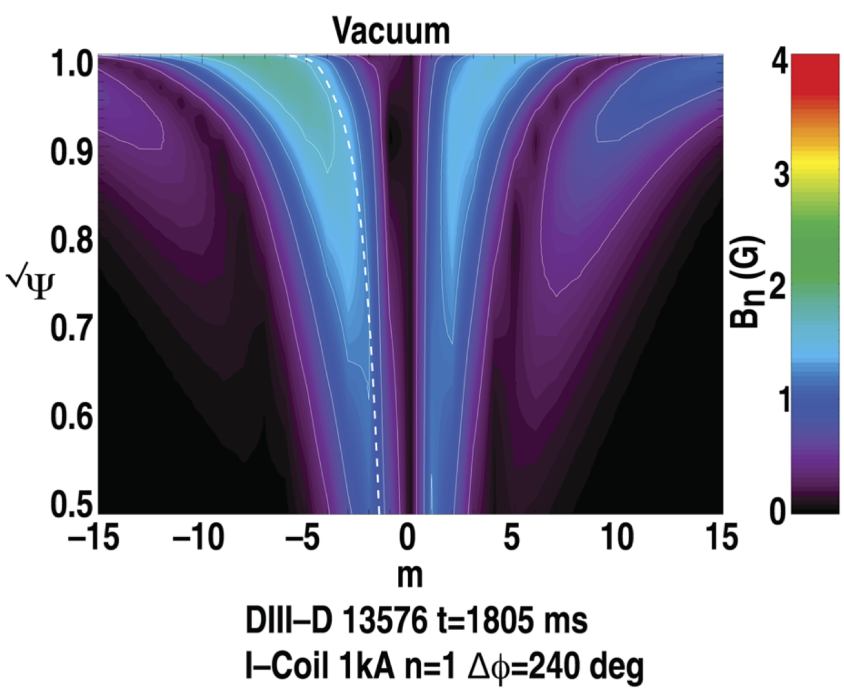


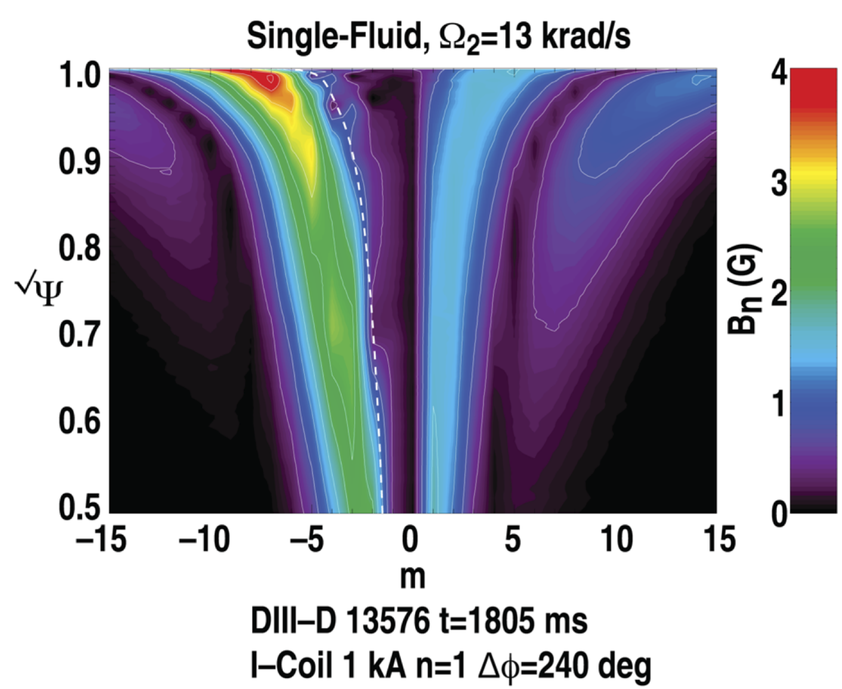
Fig. 5. (a) Spectrogram of density fluctuations from BES during a modulated RMP ELM-suppressed discharge, (b) internal coil current (suppressed zero), (c) integrated low-k fluctuation evolution at ρ=0.88, (d) relation of density fluctautions to local density.

[G. McKee et al, IAEA 2012]

The plasma response to 3-D perturbations is quite complicated.

- In toroidally rotating plasmas, radial magnetic perturbations are shielded at their rational surfaces
  - Screening due to the perpendicular electron velocity
  - Resonant b_r reduced by 1-2 orders of magnitude typically
- The plasma response often amplifies non-resonant radial perturbations





[N. Ferraro, PoP 2012, see also: Y. Liu et al, NF 2011, M. Becoulet et al, NF 2012]

Ideal MHD exhibits singular currents at every rational surface in 3-D

- This is why solving ideal MHD equilibrium eqns in 3D is so challenging:

$$\nabla \cdot \mathbf{J} = 0 = \nabla \cdot (\frac{J_{\|}\mathbf{B}}{B} + \mathbf{J}_{\perp}),$$

$$\sum_{mn} \left(\frac{J_{\|}}{B}\right)_{mn} [m - nq(\psi)]\ sin(m\Theta - n\Phi) \sim \frac{\partial p(\psi)}{\partial \psi} \sum_{mn} \left(\frac{1}{B^2_{mn}}\right)_{mn} sin(m\Theta - n\Phi).$$

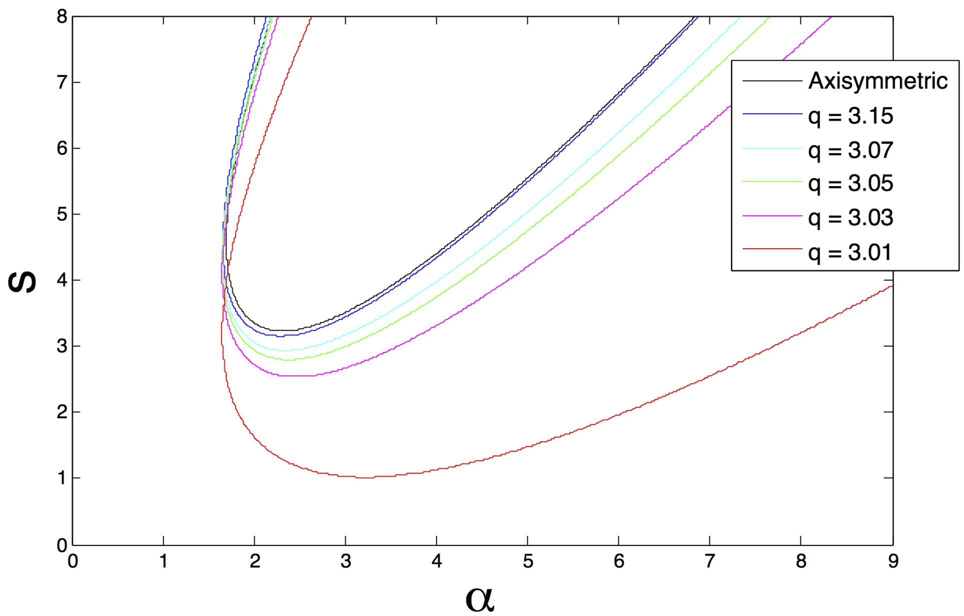
- At rational surfaces, more physics is needed:

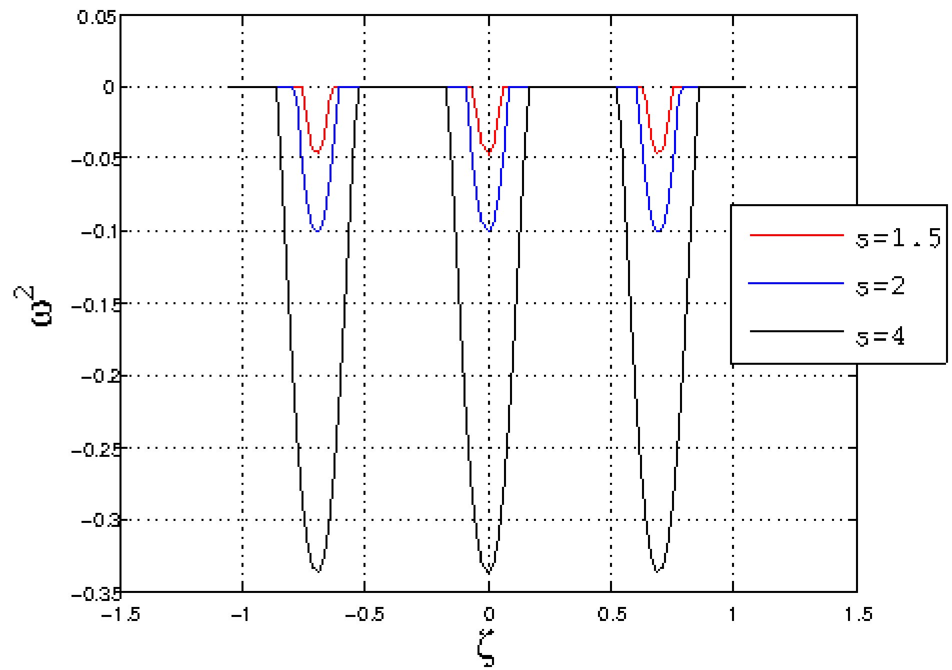
  - In resistive MHD the singularities are resolved by island formation.

  - In reality, there is a competition between MHD forces trying to create islands and a kinetic response which screens the island-producing currents.

  - See details in: C. C. Hegna, "Kinetic shielding of magnetic islands in 3D equilibria", PPCF 2011

These currents can strongly affect ballooning stability.





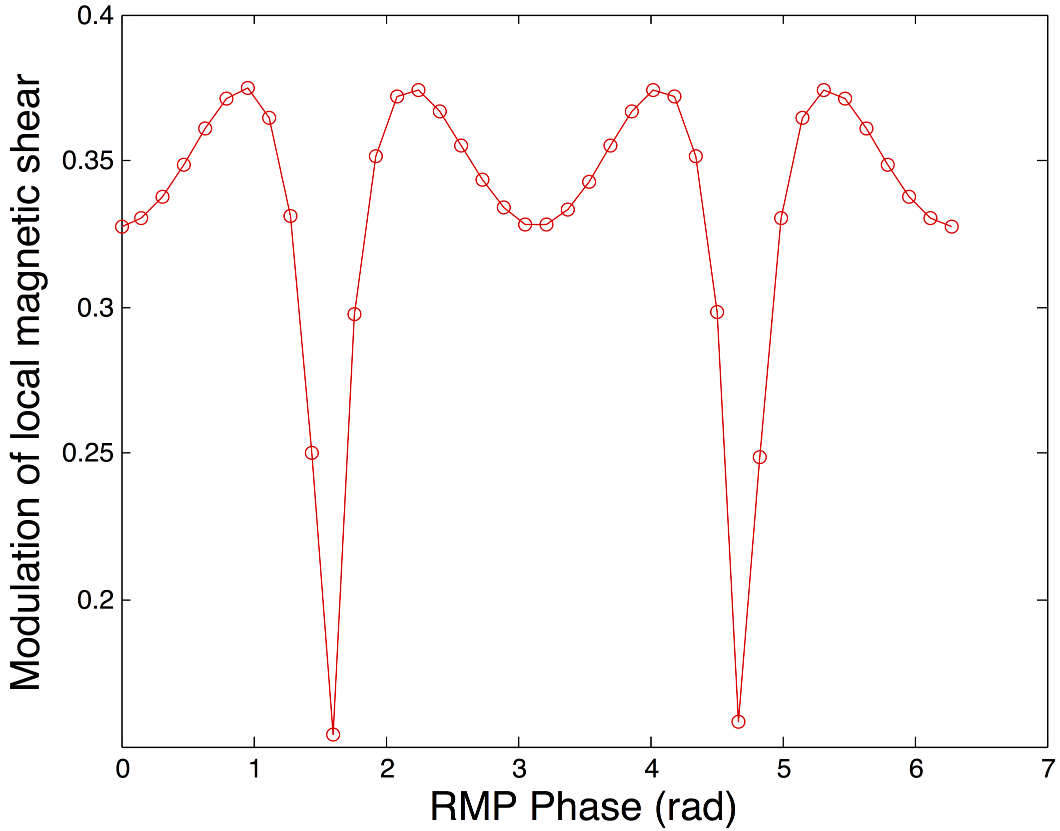
- T.M. Bird, C. C. Hegna, Nuclear Fusion 2013

- Pfirsch-Schlüter currents modulate the <u>local magnetic shear</u>

- This effect is highly sensitive to q95, pressure gradient, and the <u>RMP phase</u>

- Near rational surfaces, provides a mechanism for small 3D perturbations to have a big effect!

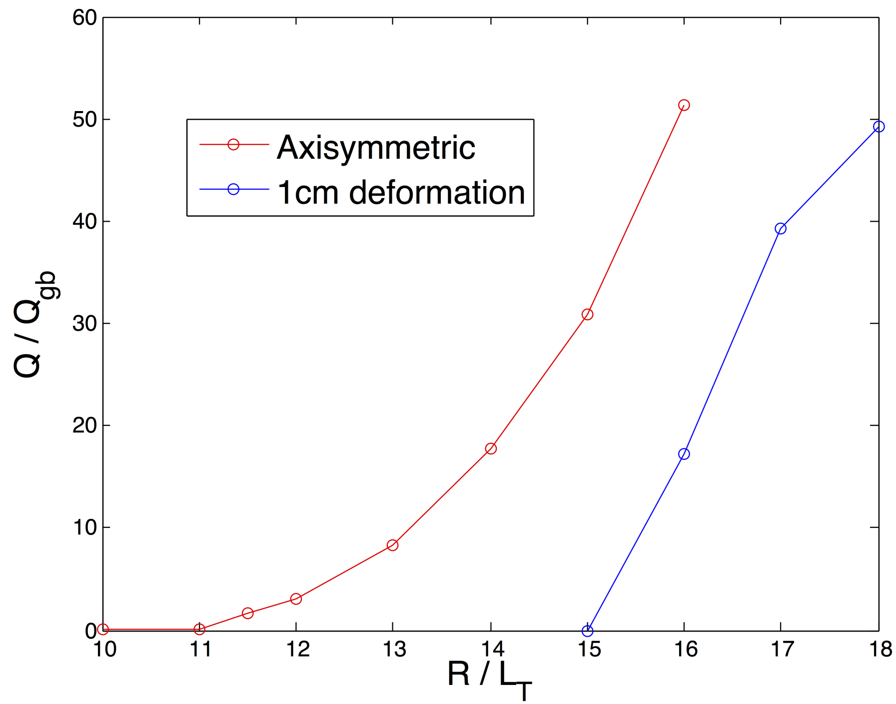
There is a strong sensitivity to the RMP phase



$$s^{3D} \sim \frac{dp}{d\psi} \frac{\kappa_g^{res}}{q - m/n}$$

No conclusions yet on the effect on ITG turbulence.

- Sometimes stabilizing, sometimes destabilizing, depending on parameters

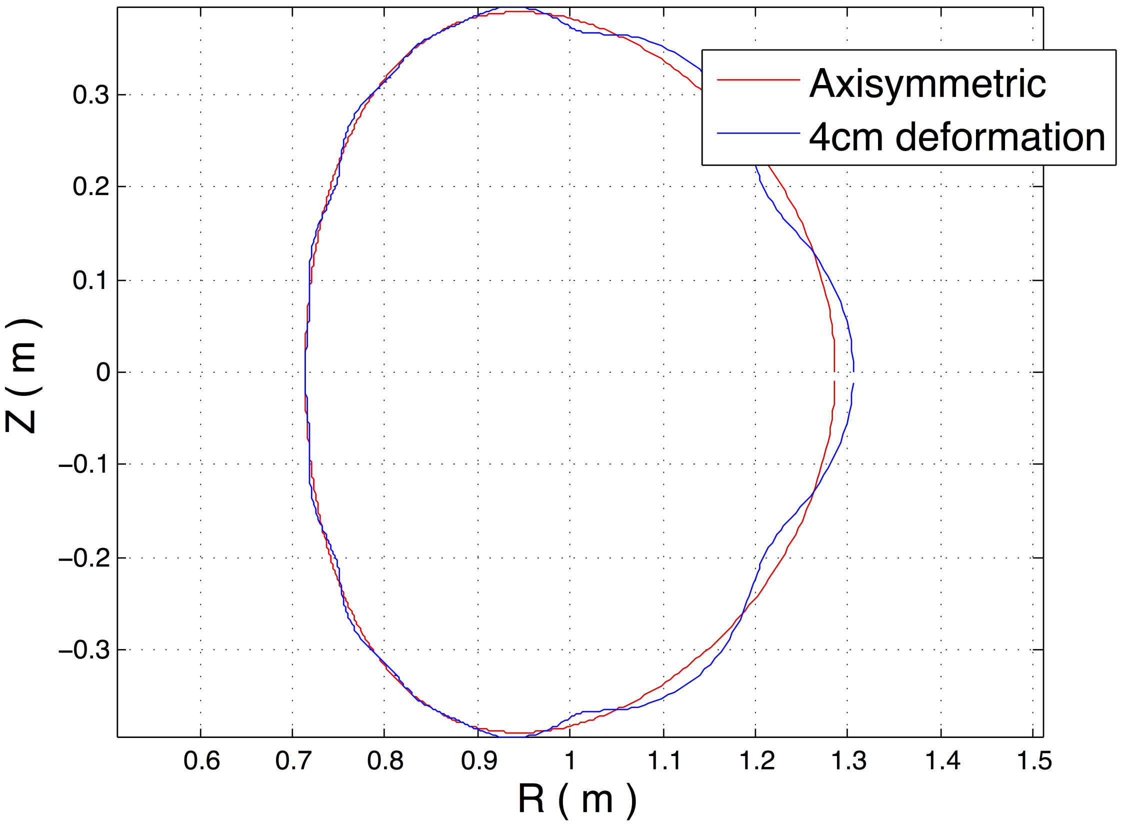


- Pfirsch-Schlüter effect scales up with MHD pressure gradient (alpha)

- Moves the nl critical gradient up, but increases stiffness

$$s^{3D} \sim \frac{dp}{d\psi} \frac{\kappa_g^{res}}{q - m/n}$$

What about bigger 3D perturbations?



- Shaping characteristic of DIII-D 'outer core':

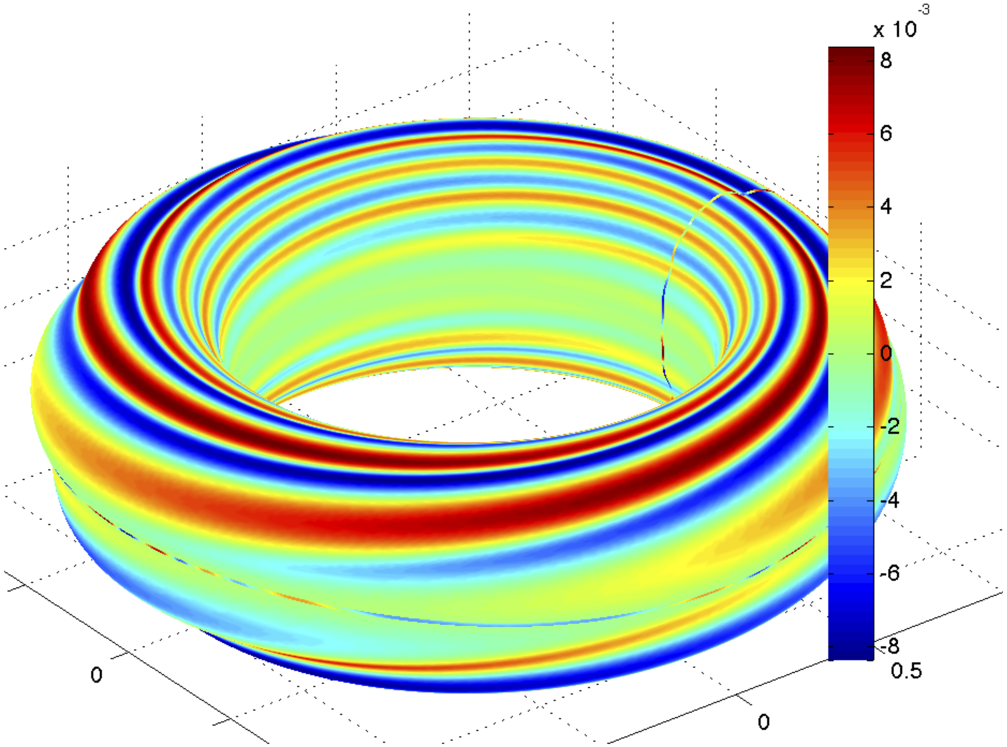
  - Elongation=1.36, Triangularity=0.19

- ~4cm radial displacement near q=8/3 rational surface

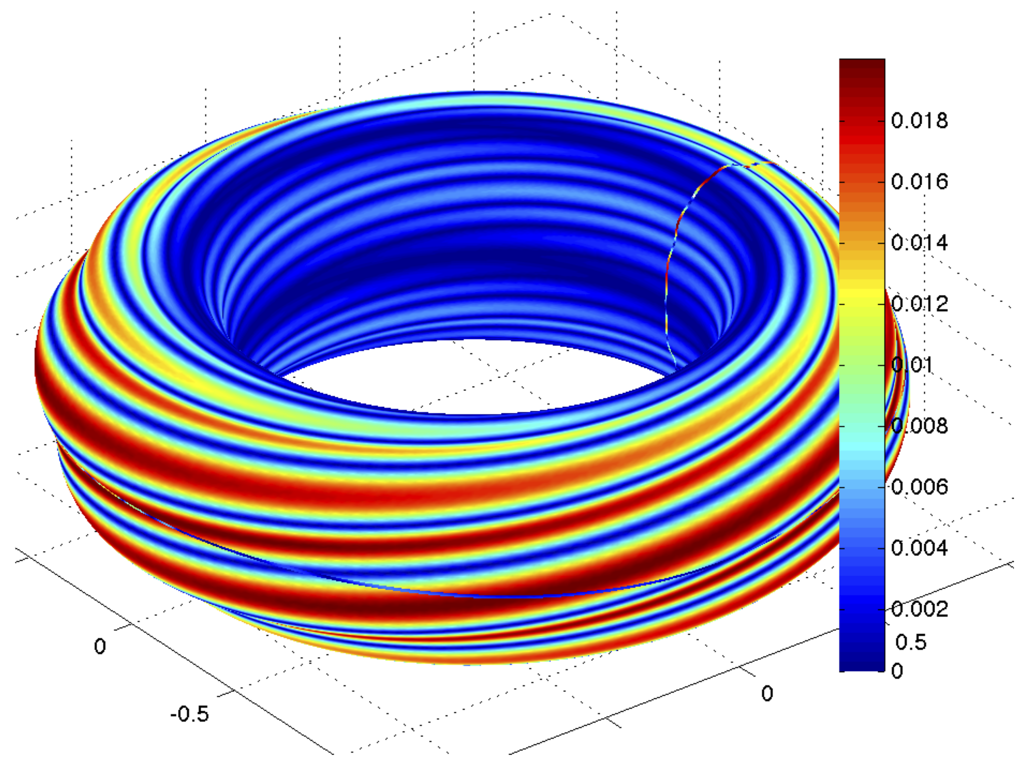
  (for a DIII-D sized device)

What about bigger 3D perturbations?

Br / B0



Displacement



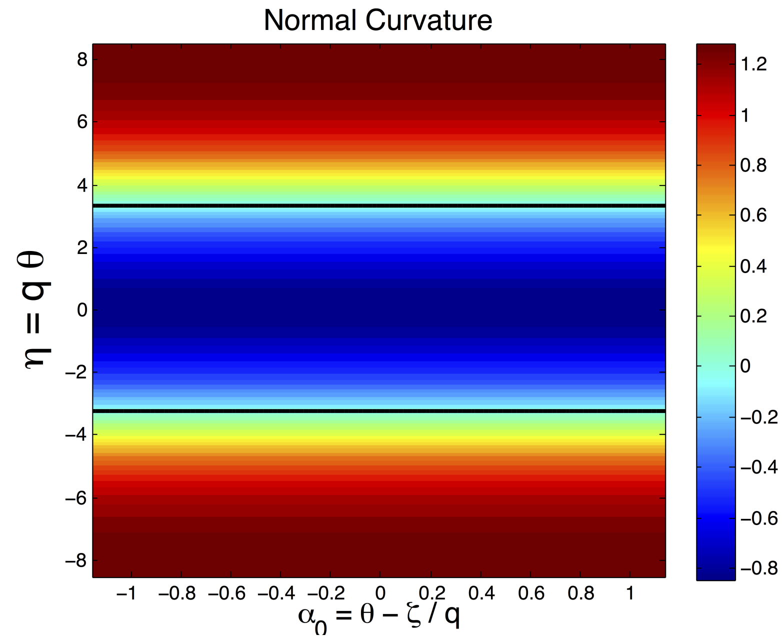
- ~4cm radial displacement near q=8/3 rational surface

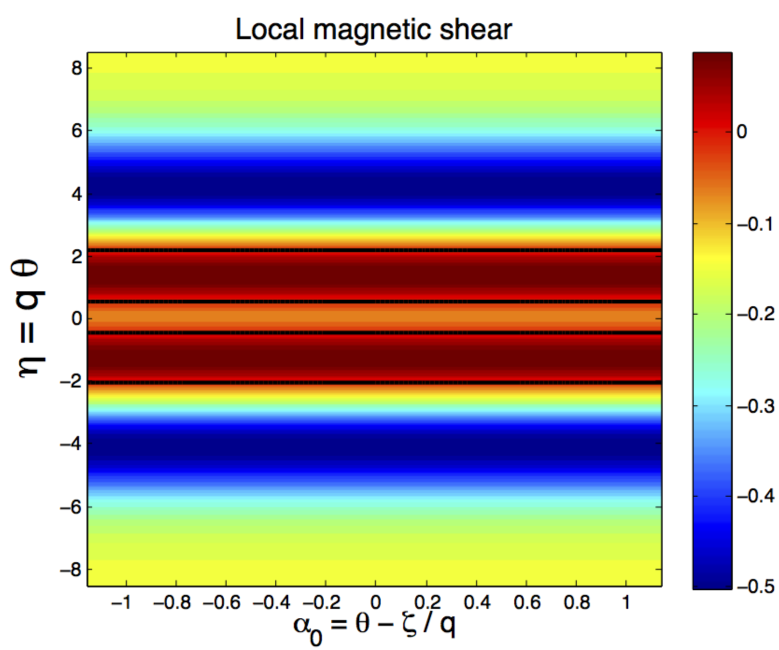
  (for a DIII-D sized device)

[I. Chapman et al PPCF 2012, L. Lao et al APS 2005, I. Chapman et al NF 2007]

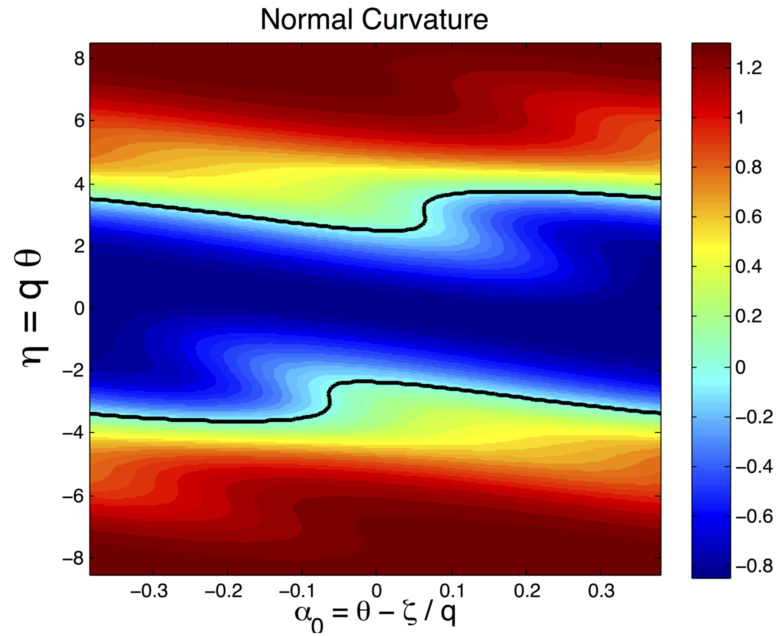
All the relevant quantities see significant 3D modulation.

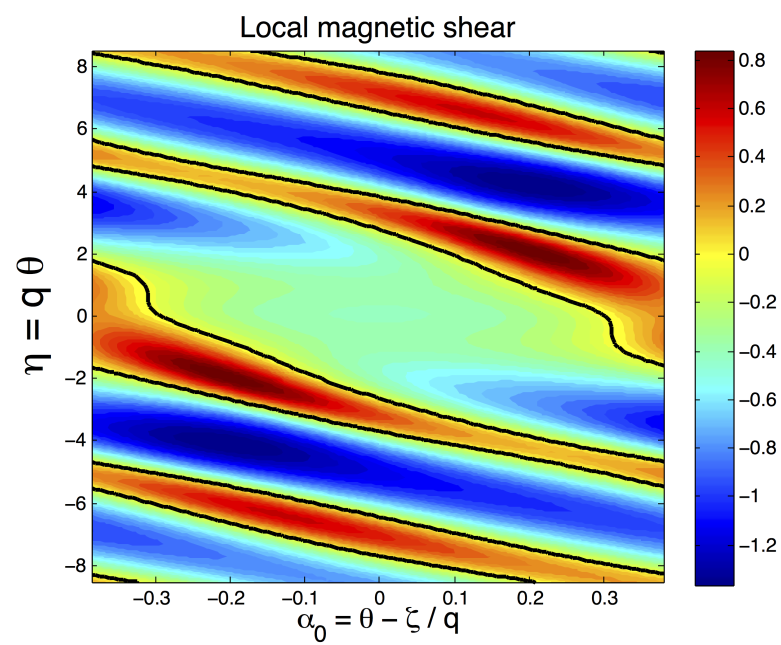
Axisymmetry



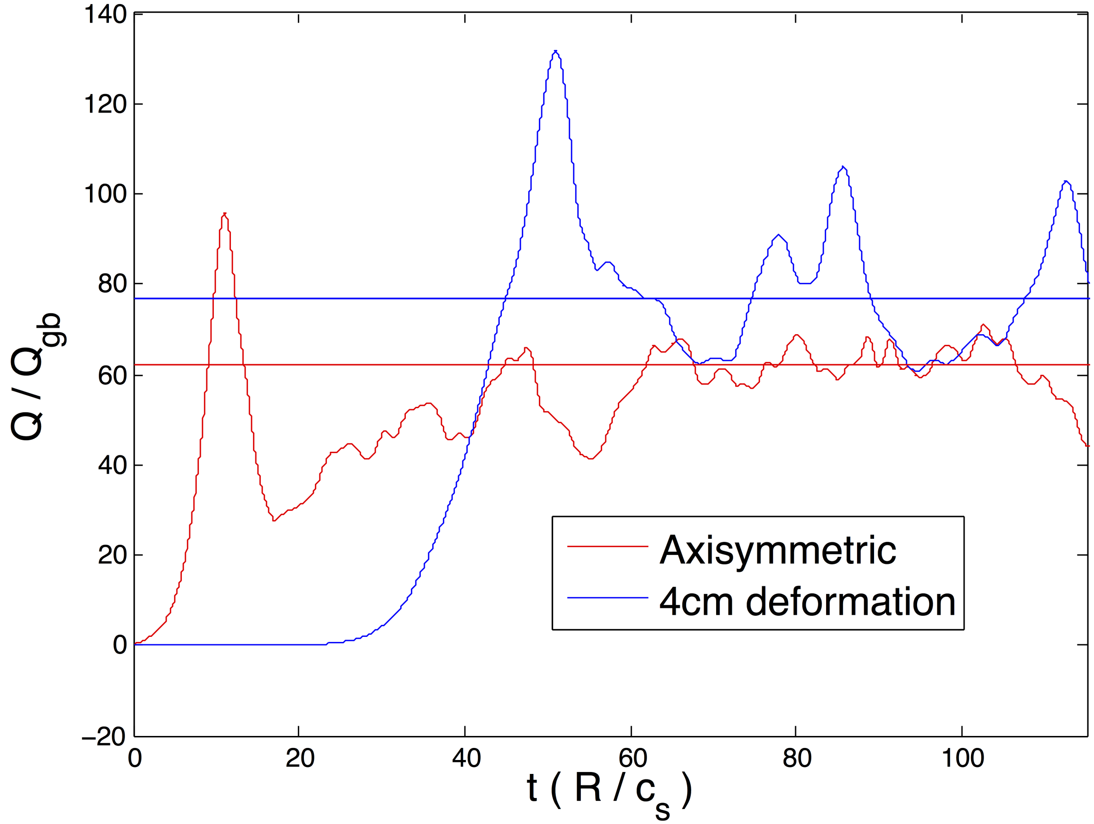


4cm def.





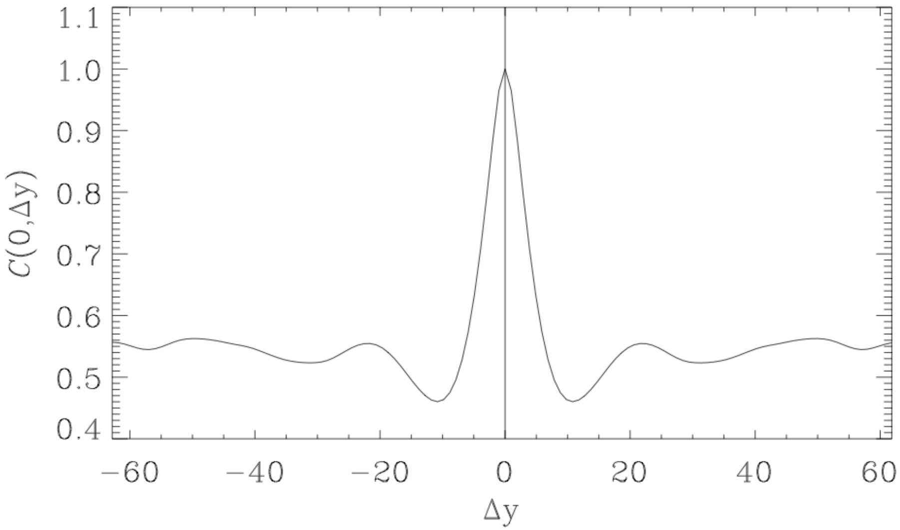
This deformation enhances the ITG driven heat flux



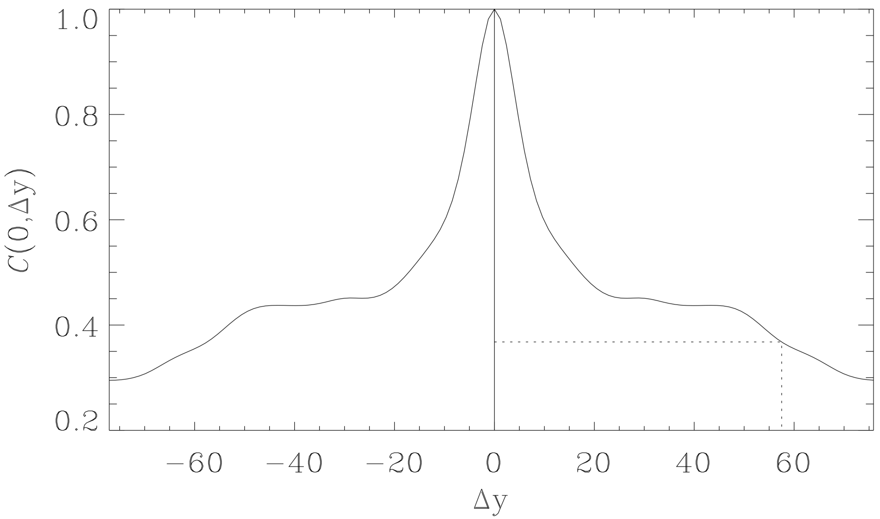
- Full surface ITG simulation, no density gradient, no pressure gradient, collisionless, adiabatic electrons, s_hat = 0.89, rho* = 0.005
- When br/B0 ~ 10^-3, dR ~ cm, ITG turbulence becomes stronger
- Ongoing work: identify threshold/scaling with dR

Long range correlations within the flux surface are lower.

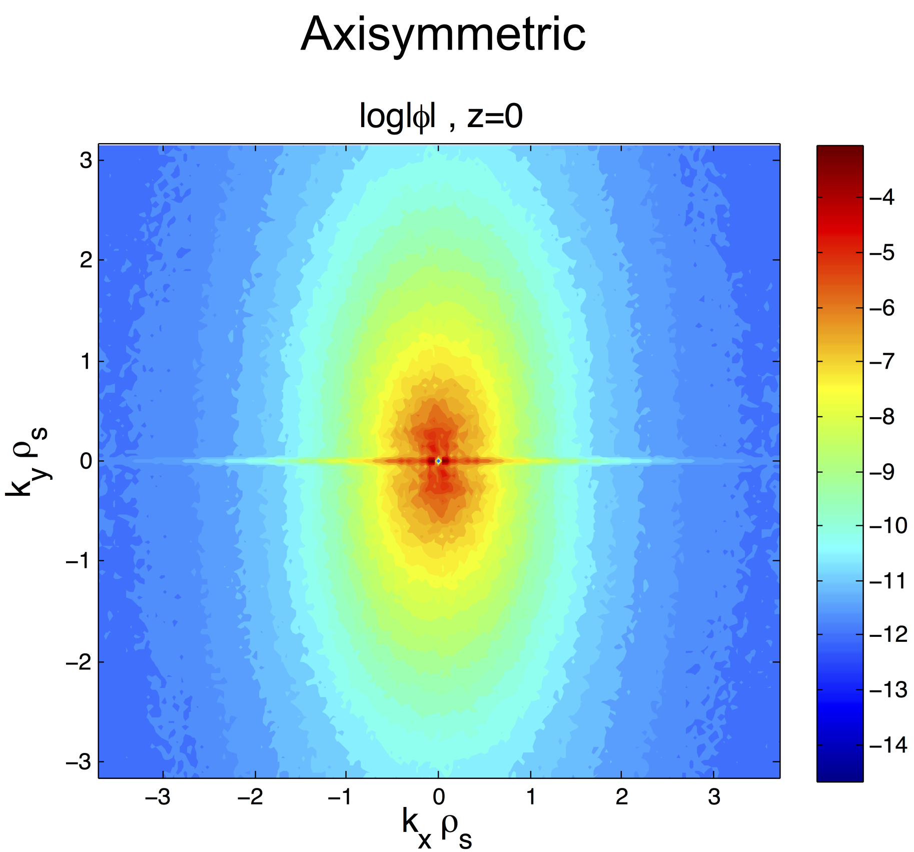
Axisymmetric

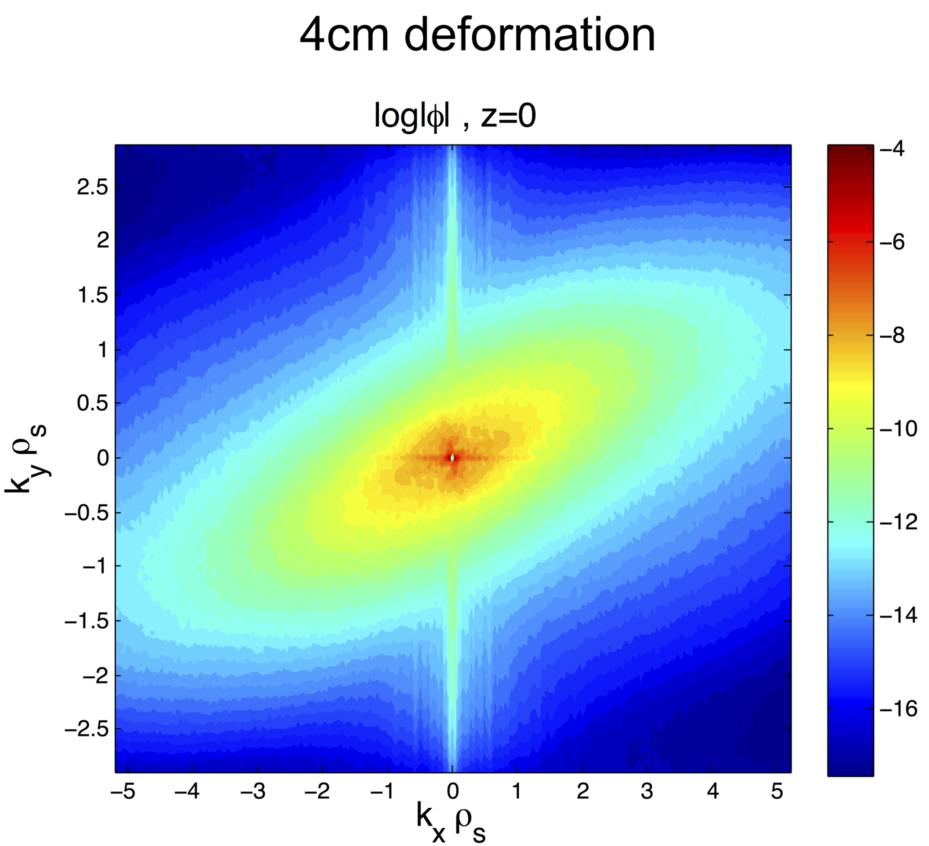


4cm deformation



The turbulent cascade of energy is strongly affected.





- Spectrum of the electrostatic potential at <u>outboard midplane</u>
- “Tilting” due to mode peaking at finite ballooning angle (further along field line)
- Damping of GAM/ZF activity (ky=0 band)

RMP Conclusions

- Resonant Pfirsch-Schlüter currents

  - Modulate the local magnetic shear near rational surfaces

  - Effect sensitive to q95, RMP phase, pressure gradient

  - MHD ballooning: stabilizes some field lines, destabilizes others

  - No conclusions yet for ITG turbulence: sometimes stabilizing, sometimes destabilizing.

- Big 3D deformations, as observed in experiment (cm-sized)

  - Modulate significantly most of the relevant quantities for turbulence

  - Enhances ITG turbulence when br/B0~10^-3

  - Decrease in long range poloidal correlation – primarily a NL effect

  - Evidence of enhanced GAM damping

- Future work

  - Closer modeling of experiments

  - Modeling the pedestal: KBMs