The effect of 3D magnetic perturbations on Tokamak turbulence

Tom Bird
Max Planck Institut für Plasmaphysik, Greifswald

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In collaboration with:

C. Hegna
University of Wisconsin, Madison

F. Jenko, D. Told, T. Görler, P. Xanthopoulos
Max Planck Institut für Plasmaphysik, Garching & Greifswald

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Outline

- Overview of experimental ELM mitigation results
- The physics of 3D local shear modulation
- Gyrokinetics in nonaxisymmetric configurations
- The effect of near-resonant Pfirsch-Schlüter currents on turbulence
- A quick look at turbulence in the presence of general, centimeter-sized 3-D deformations

ELM mitigation is essential for ITER

- The type-I ELMy H-mode will be the standard operation regime for ITER

- Our best guess for the energy loss due to ELMs in this scenario is:

  from: ΔW / Wped ~ 5-10% (5-10MJ per ELM)

  up to: ΔW / Wped ~ 20% (~20MJ) [Loarte et al PPCF 2003]

- This could raise the temperature of the divertor materials to >3000˚C in less than a millisecond.

- These heat loads could significantly reduce the lifetime of plasma facing components (or worse).

- The plan is to mitigate these losses with either pellet pacing or by applying 3D magnetic fields with the IVCC.

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
- Enhanced transport: - not observed in ASDEX-U

  - often observed in DIII-D, MAST

  (especially during suppression)

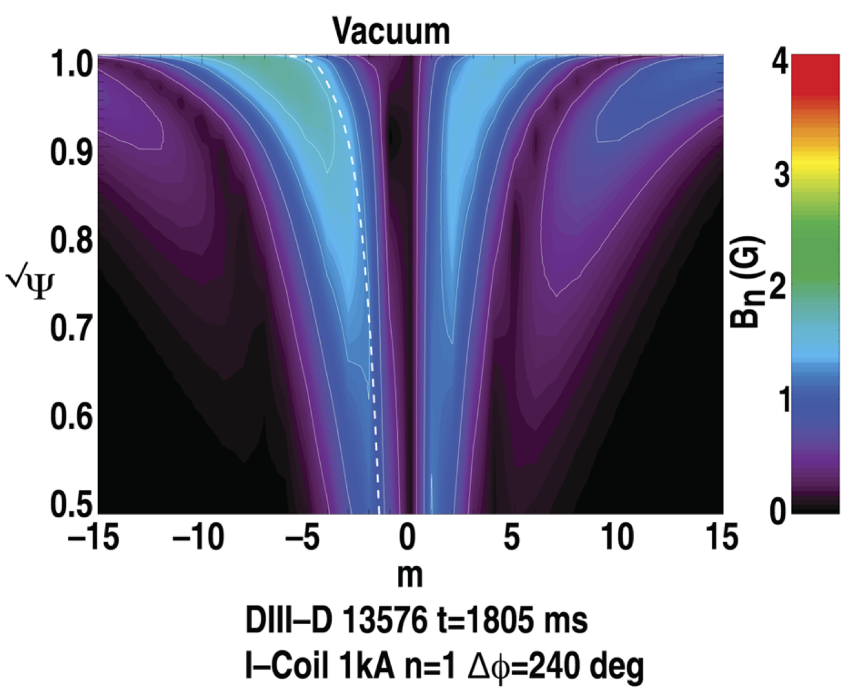
- RMPs can modify:
  - Magnetic topology
  - Plasma rotation
  - Turbulent transport, through:
    - Linear microinstability physics
    - Nonlinear saturation physics
    - Magnetic flutter induced transport
  - MHD stability

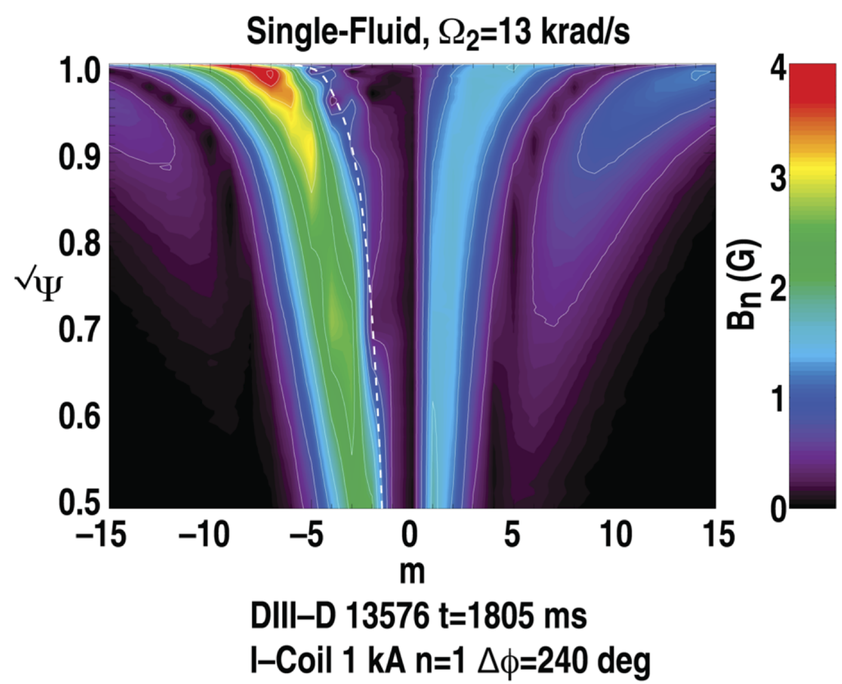
Focus of this talk

Explored in recent papers by Leconte and Diamond.

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]

What halts the pedestal advance during ELM suppression?

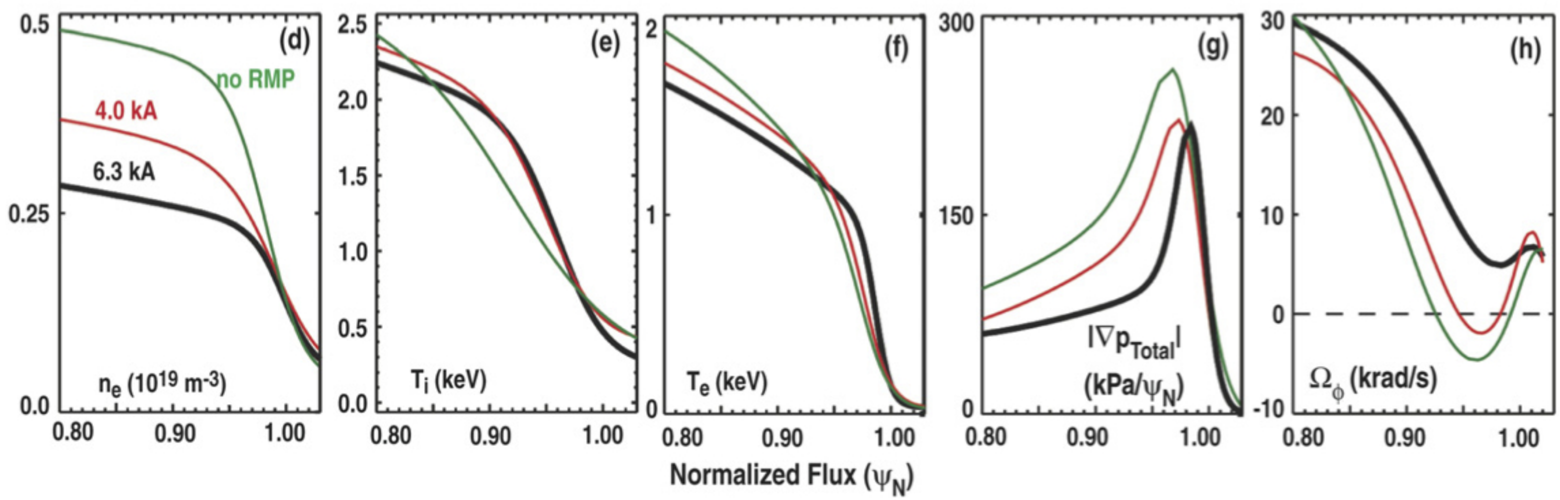


Figure 6. Lower divertor D_α signals showing the ELM characteristics in similar ISS plasmas with $n = 3$ I-coil currents of (*a*) 6.3 kA, (*b*) 4.0 kA and (*c*) 0 kA. Pedestal profiles showing the (*d*) density, (*e*) ion temperature, (*f*) electron temperature, (*g*) absolute value of the total pressure gradient and (*h*) C^{6+} toroidal rotation for the 3 I-coil currents shown in (*a*), (*b*) and (*c*) where black, red and green correspond to 6.3 kA, 4.0 kA and 0 kA, respectively.

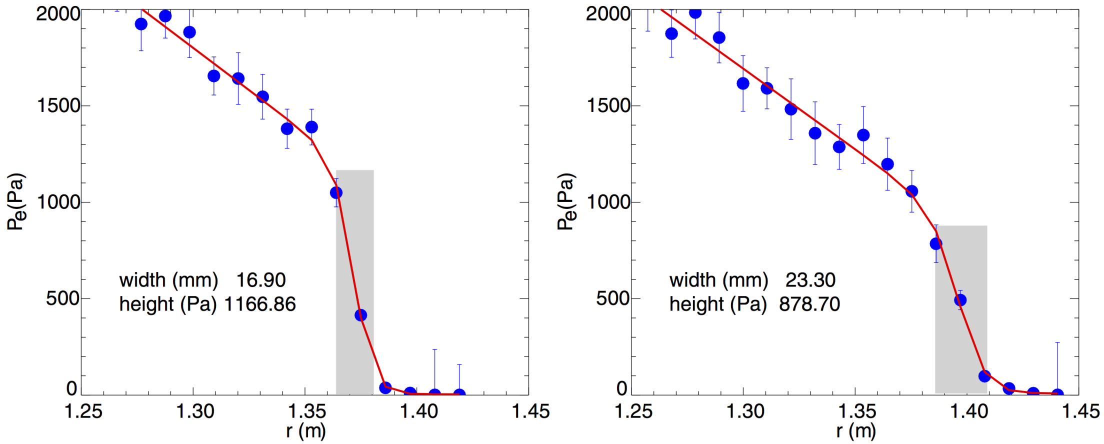
- During ELM suppression, the peak pedestal pressure gradient is lowered
- Something other than ELMs is limiting the inward growth of the pedestal

  (thus precluding the crossing of the P-B stability boundary)
- Hypothesis presented here:

  - 3-D fields can limit the achievable pressure gradient in radially localized regions via microinstability destabilization (e.g. KBMs)

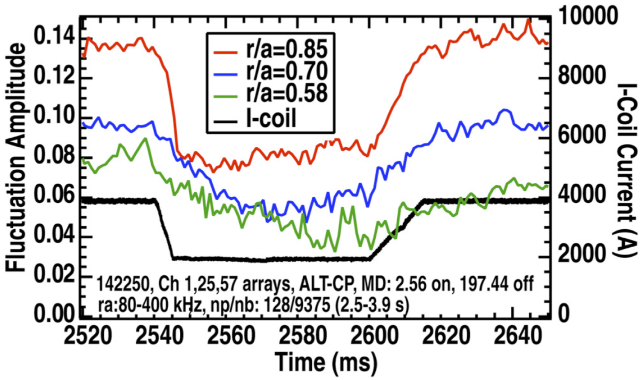
In many cases there is evidence of enhanced anomalous transport.

- In both MAST and DIII-D there is clear evidence of enhanced transport in many cases, as can be seen in the profiles:



[I. Chapman et al, NF 2012]

- BES measurements of density fluctuations also show a sensitivity to the RMP strength:



[Z. Yan et al, IAEA 2010]

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

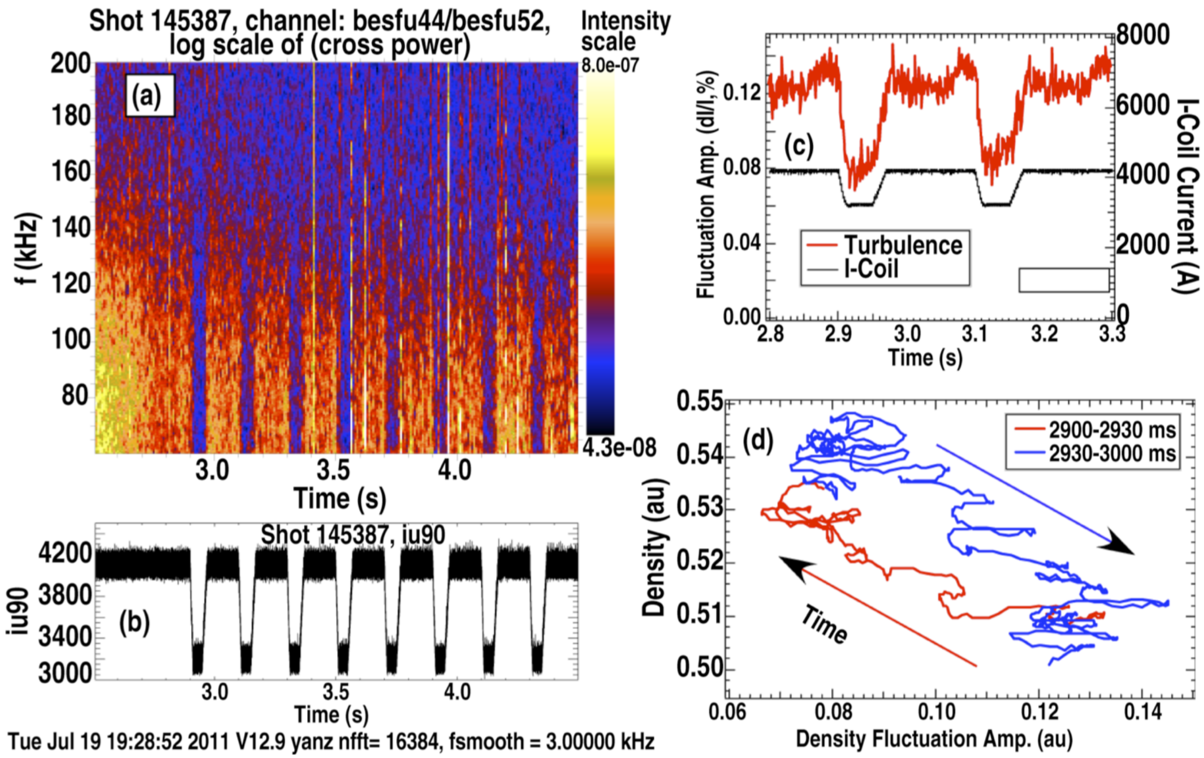


Fig. 5. (a) Spectrogram of density fluctuations from BES during a modulated RMP ELM-suppressed discharge, (b) internal coil current (suppressed zero), (c) integrated low-k fluctuation evolution at ρ=0.88, (d) relation of density fluctautions to local density.

[G. McKee et al, IAEA 2012]

In this work we examine how 3-D fields can affect microinstabilities in the pedestal.

- KBMs are primary candidates to explain transport in the pedestal:

  - Success of EPED

  - Gyrokinetic stability calculations of MAST equilibria by D.Dickinson

    (PPCF 2011, PRL 2012)

  - Global gyrokinetic stability calculations by W. Wan et al

    (PRL 2012)

  - BES fluctuation measurements during QH-mode at DIII-D

    (Z. Yan et al, PRL 2011)

  - Somewhat different results found in recent paper by E. Wang et al

    (NF 2012)

- The bulk of this talk will examine how resonant Pfirsch-Schlüter currents driven by 3-D components of |B| can affect microinstabilities.

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

Near-resonant Pfirsch-Schlüter currents substantially modulate the local magnetic shear.

- The Pfirsch-Schlüter current spectrum is given by:

$$(\vec{B}\cdot\nabla)\lambda = 2\mu_0\kappa_g\frac{|\nabla\psi|}{B} \qquad\qquad \lambda_{mn}\sim\frac{(RHS)_{mn}}{q-m/n}$$

- The local magnetic shear can be decomposed into:

$$s=\frac{|\nabla\psi|^2}{B^2}(\vec{B}\cdot\nabla)[\iota'\zeta+D]$$

- The Pfirsch-Schlüter current enters via:

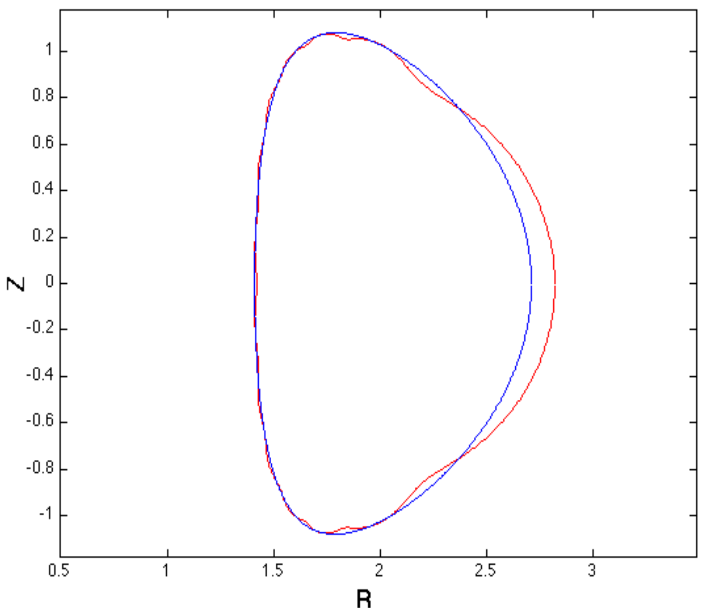
$$(\vec{B}\cdot\nabla)D=\iota'\left(\frac{B^2}{|\nabla\psi|^2}\frac{1}{\left\langle\frac{B^2}{|\nabla\psi|^2}\right\rangle}-\frac{1}{\sqrt{g}}\right)+p'\left(\frac{B^2}{|\nabla\psi|^2}\lambda-\frac{B^2}{|\nabla\psi|^2}\frac{\left\langle\frac{B^2}{|\nabla\psi|^2}\lambda\right\rangle}{\left\langle\frac{B^2}{|\nabla\psi|^2}\right\rangle}\right)$$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

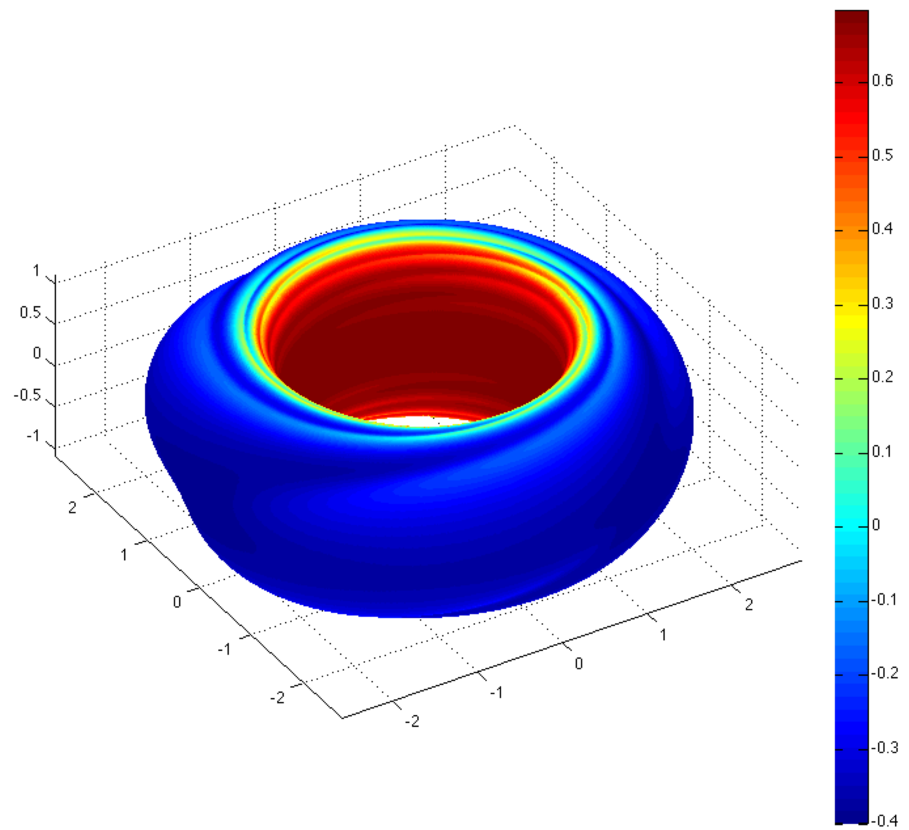
Shearing due to parallel currents

Shearing due to variation in |B|

Geometric shearing

Throughout this work we use 3-D local equilibria





- Described in: [C.C. Hegna, PoP 2000]
- A 3D generalization of the Miller model [Miller et al PoP 1998]

3D perturbations with a broad poloidal mode spectrum are used.

$$R = R(\Theta) + \sum_i \gamma_i cos(M\Theta - N\zeta)$$

$$Z = Z(\Theta) + \sum_i \gamma_i sin(M\Theta - N\zeta)$$

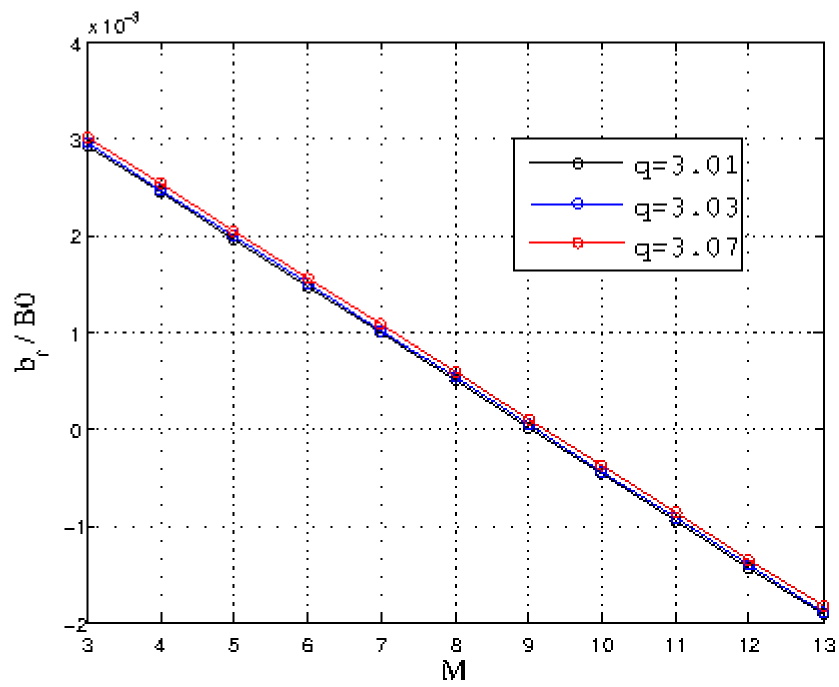
- Axisymmetric shaping:

$$A = R_0/\rho = 3.17$$
$$\delta = 0.416$$
$$\kappa = 1.66$$
$$s_\kappa = 0.70$$
$$s_\delta = 1.37$$
$$\delta_r R_0 = -0.354$$

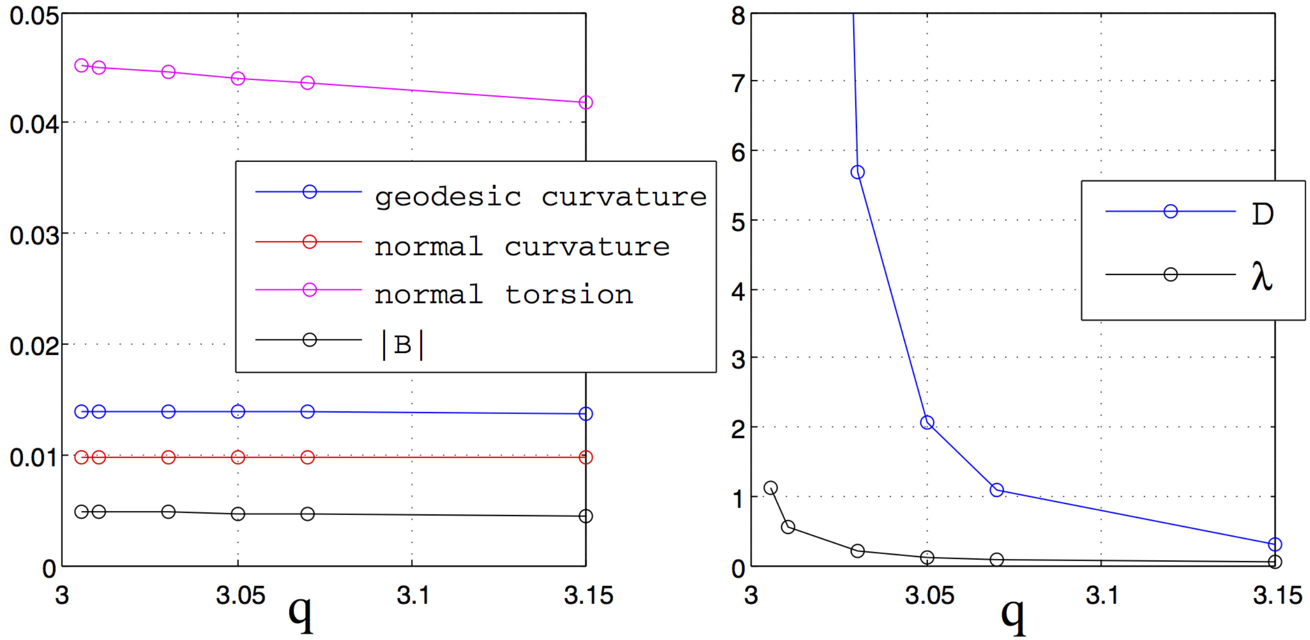
- (same parameters as used in Miller PoP 98)

- N = 3

  M = 4 $\rightarrow$ 14

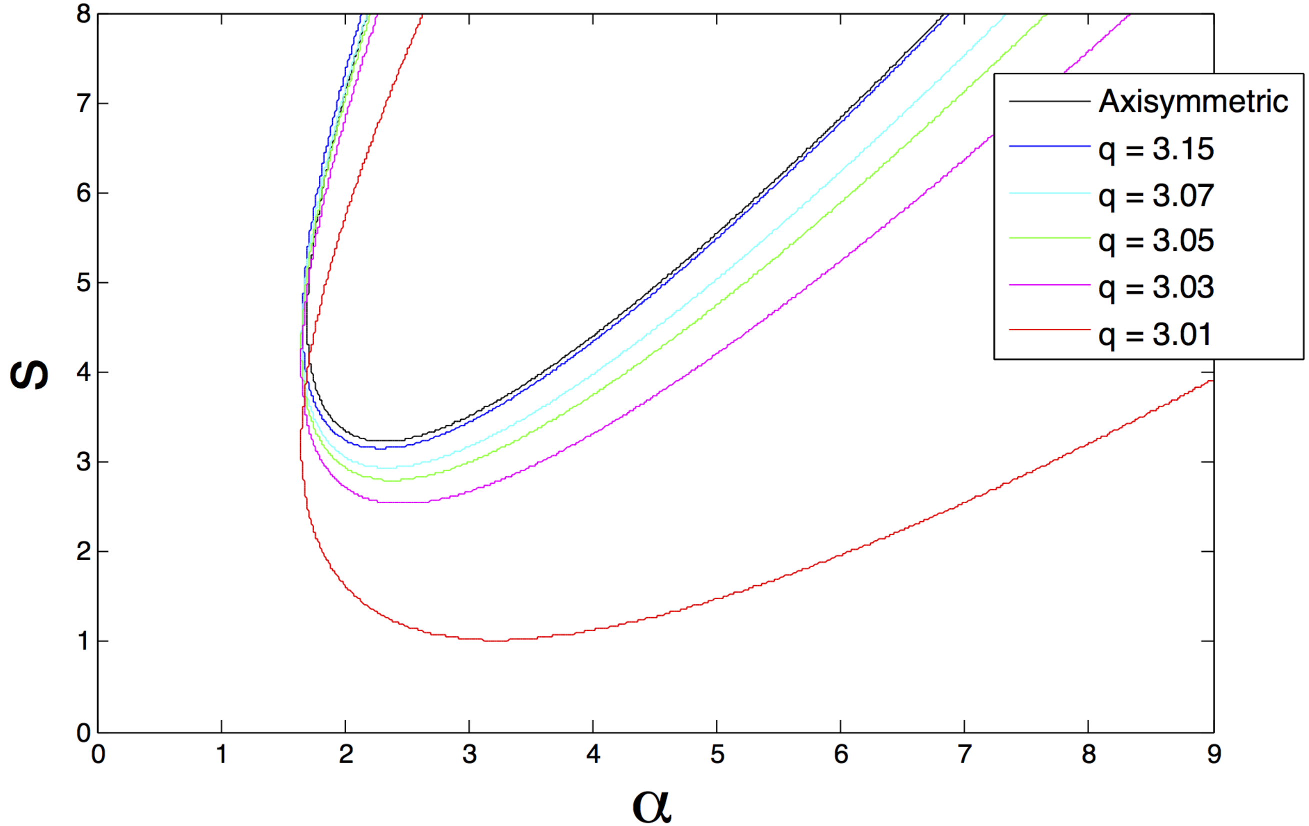


Only the local magnetic shear is appreciably modified.



A value of 0.01 corresponds to a 1% perturbation

Linear, infinite-n ideal MHD ballooning stability is substantially modified.



Details can be found in: T.M. Bird, C.C. Hegna, “A model for microinstability destabilization and enhanced transport in the presence of shielded 3-D magnetic perturbations”, NF 2013.

Local shear modulation is the culprit.

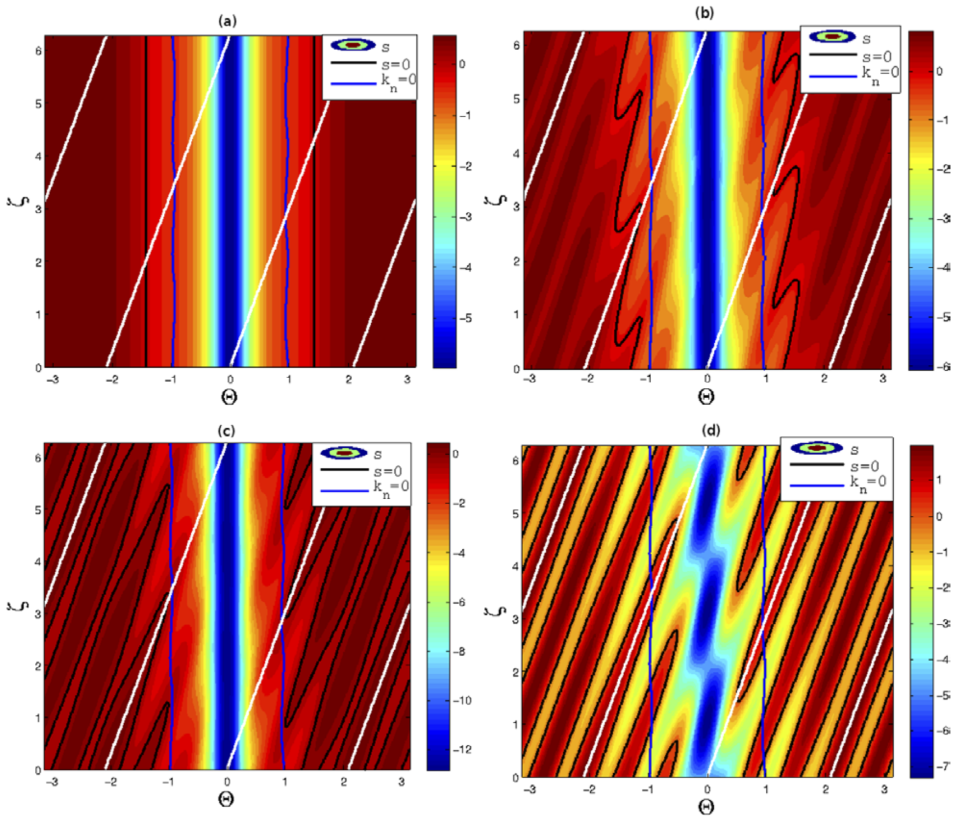
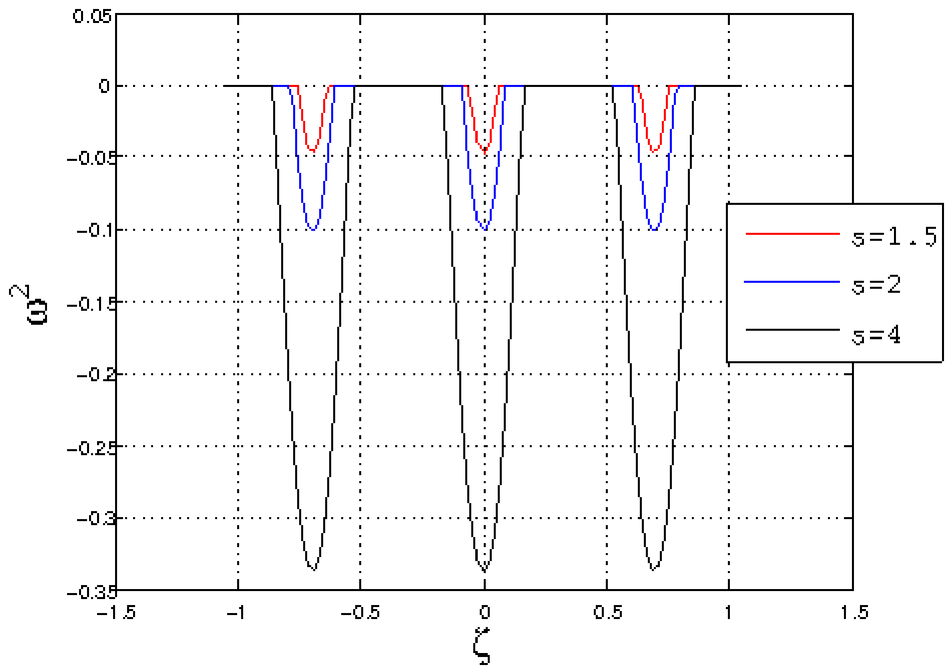


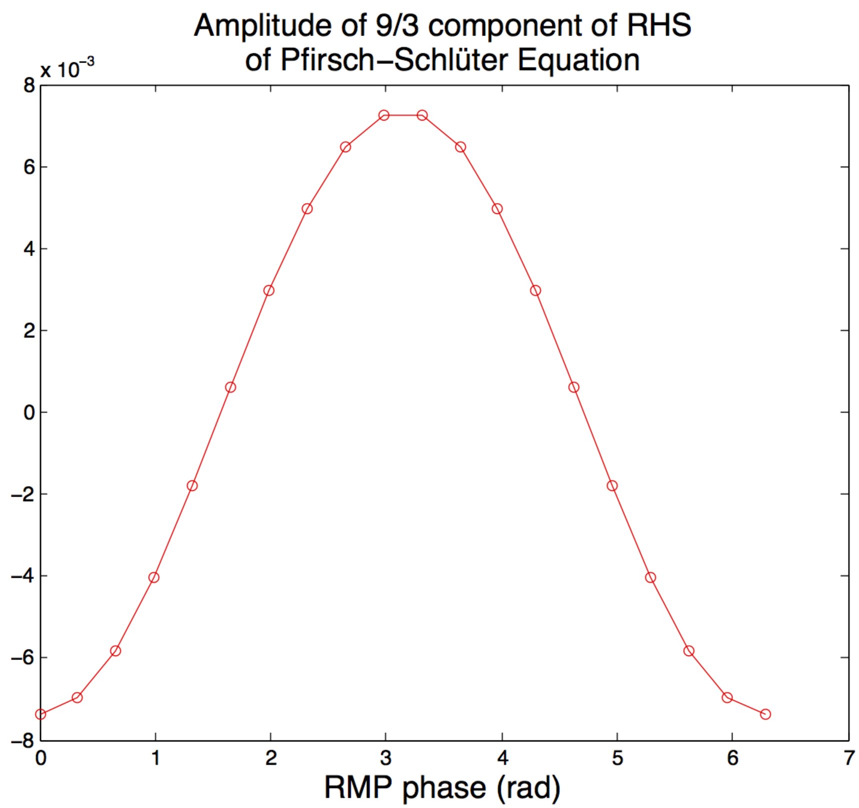
Figure 5. Contours of the local magnetic shear for (*a*) the axisymmetric base case, and 3D equilibrium with (*b*) $q = 3.07$, (*c*) $q = 3.03$ and (*d*) $q = 3.01$. The thick black line marks the zero contour of the local magnetic shear, the thick blue line (which runs nearly parallel to $\Theta = \pm 1$) marks the zero contour of the normal curvature (which is negative near $\Theta = 0$), and the thick white line shows the path of a magnetic field line which passes through ($\Theta = 0, \zeta = 0$).

There is a strong dependence on field line label.



- Some field lines are stabilized, others are destabilized.
- Why? Consider the ballooning equation:
- Growth rate ~ (stabilizing field line bending) vs (destabilizing pressure/curvature drive)
- The stabilizing effect of field line bending is intimately related to the local magnetic shear.

This effect is sensitive to the phase of the perturbations



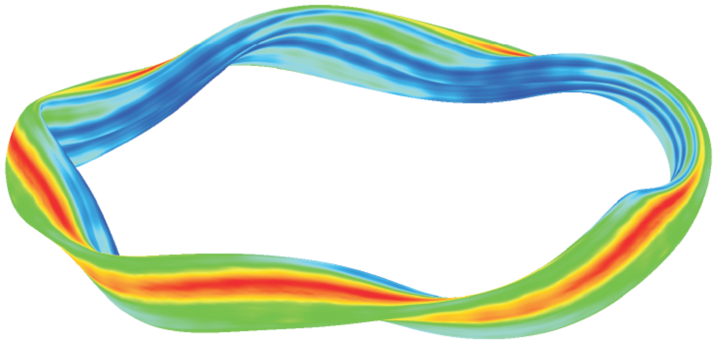
$$R = R(\Theta) + \sum_i \gamma_i cos(M\Theta - N\zeta)$$

$$Z = Z(\Theta) + \sum_i \gamma_i sin(M\Theta - N\zeta)$$

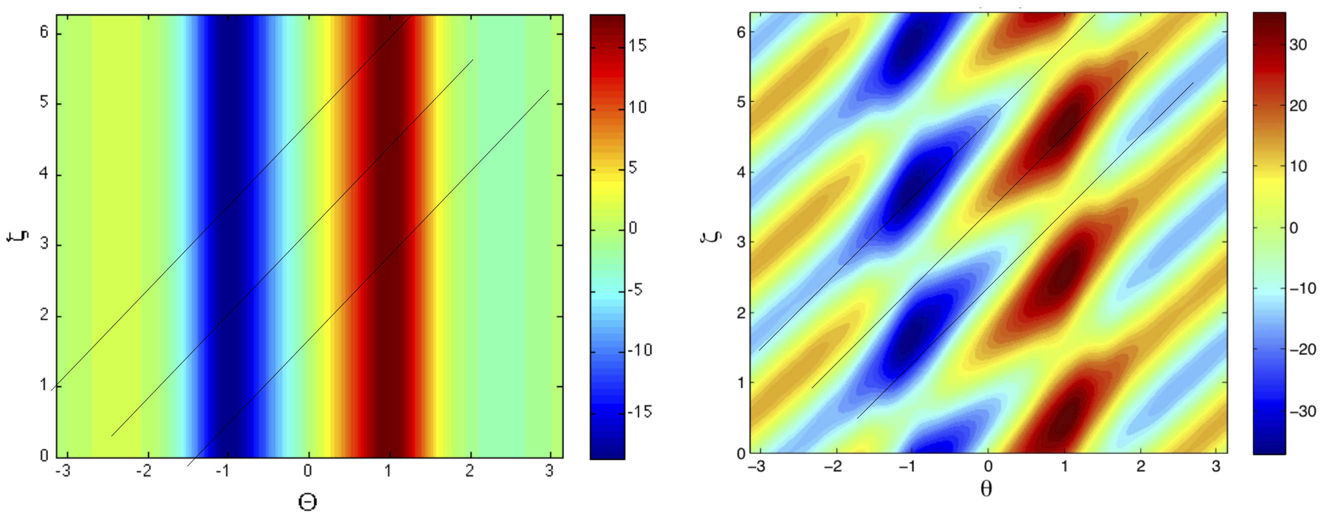
The full surface version of GENE

- 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.
- Caveat: still local in the radial direction!
- 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.

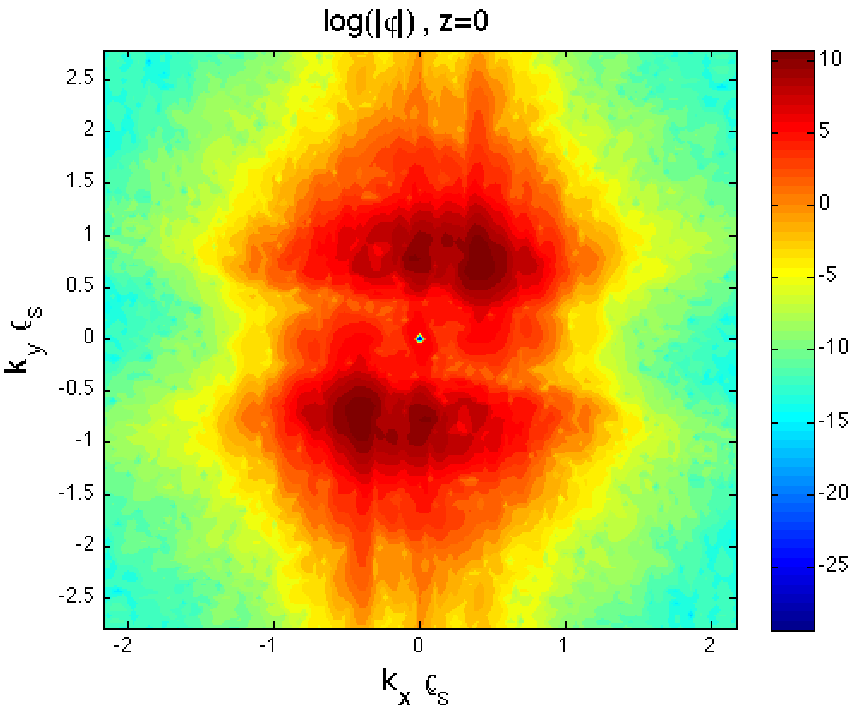


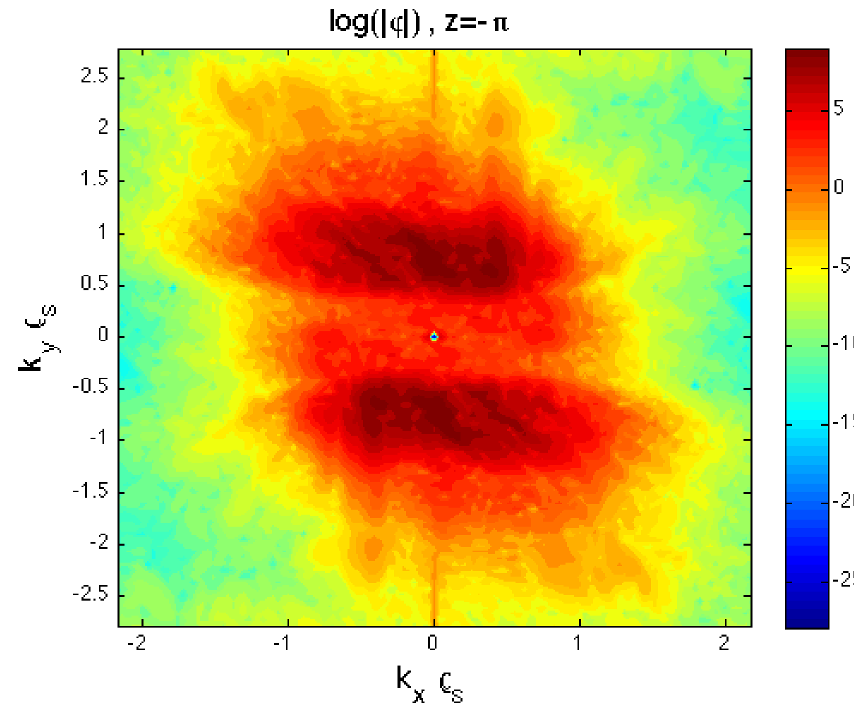
The effect of nonaxisymmetry on gyrokinetics.

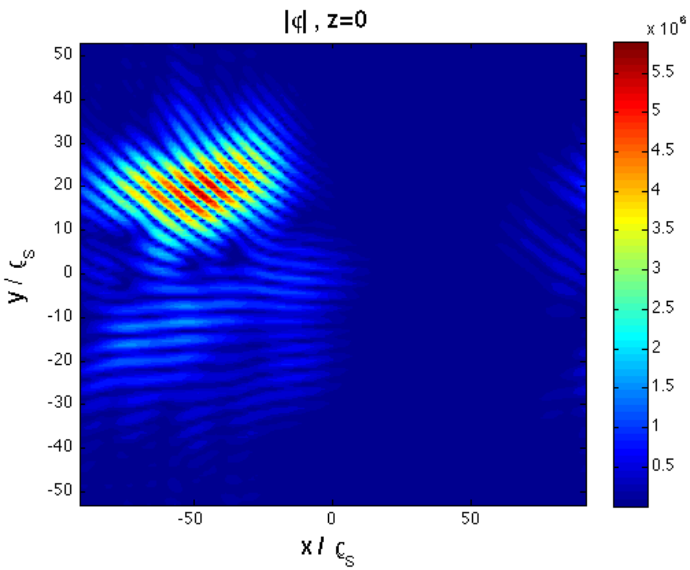


- In 3D: different field lines can have very different stability properties
- The binormal wavevector is no longer a meaningful quantum number – even linear instabilities have a complicated spectrum in ky-space.
- Gyroaveraging requires interpolation of the fields along the actual particle orbits.

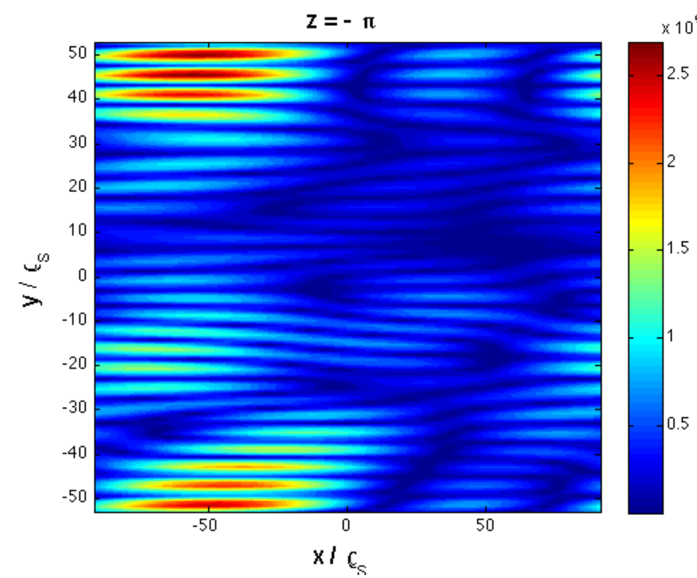
The linear mode structure can be significantly more complicated than in axisymmetry.



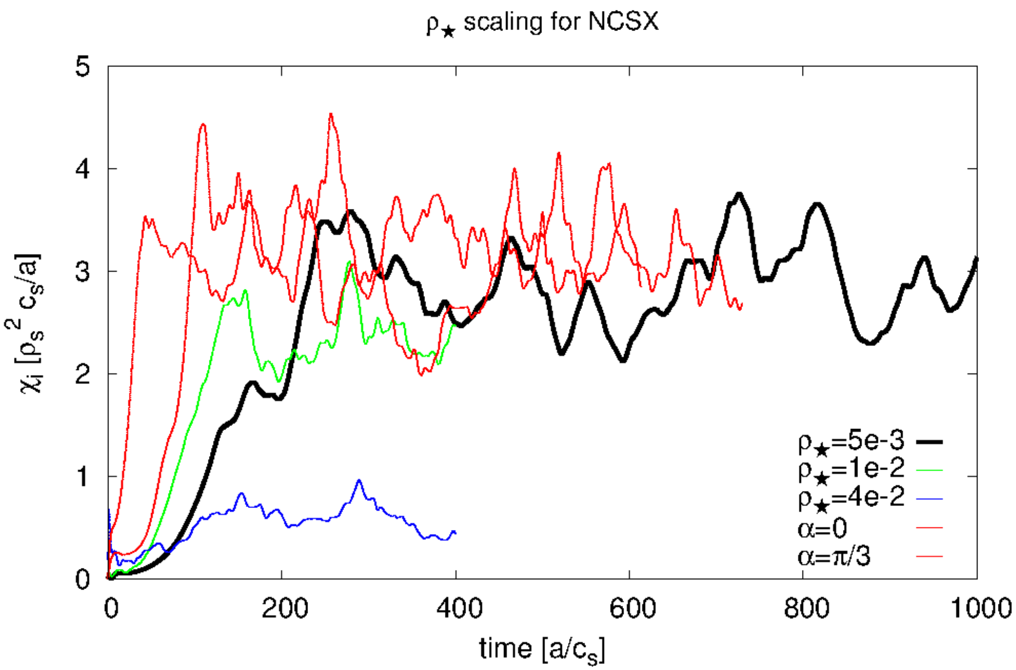




W7-X



The rho*->0 limit



- For NCSX, different field lines have similar properties

- Basic code check: as rho*->0, full surface result converges to flux tube results

- Still an open question: what should happen as rho*->0 when different field lines have different properties?

A few comments

- These runs are at low shear ($s < 0.1$) and high pressure gradient (alpha_mhd > 1) due to a historical accident

- The large pressure gradient amplifies the effect of the 3D perturbations

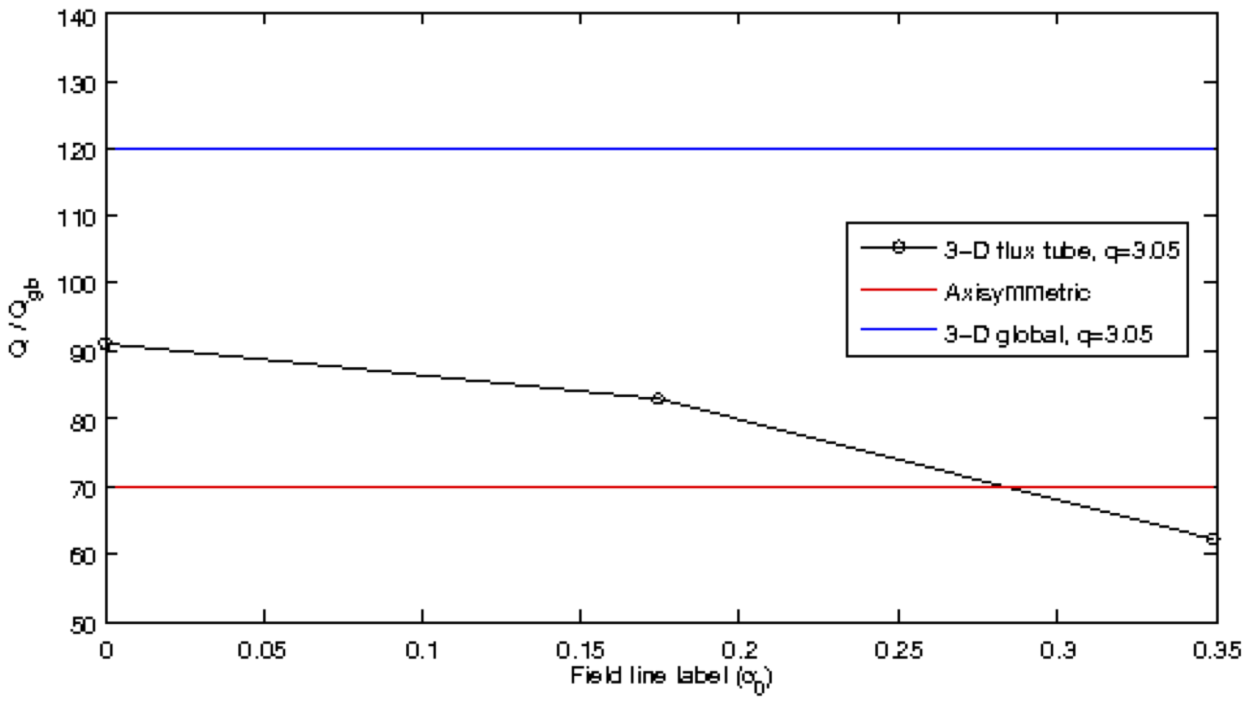
- The pedestal pressure gradient is generally even larger than what I've used here

- However, the focus of this work at the moment is just to start taking a look at the basic microinstability physics

- Everything here will be electrostatic with adiabatic electrons. Modeling the pedestal more accurately in the future will require a lot more physics (sheared ExB flow, kinetic electrons, electromagnetic effects, etc...)

- There is a decent agreement between some things seen in these simulations and some experimental results already, but I wouldn't put too much weight behind it.

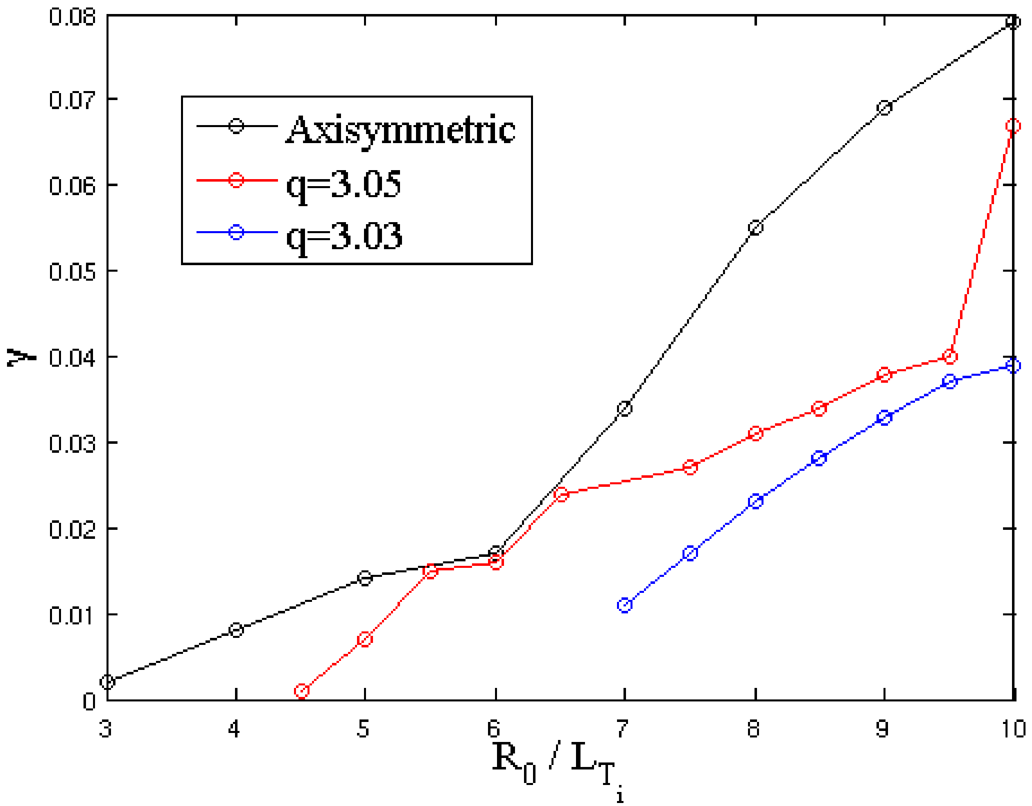
Flux tube ITG simulations match the MHD results



- R/L_Ti = 15
- R/L_n = 0
- Adiabatic electrons

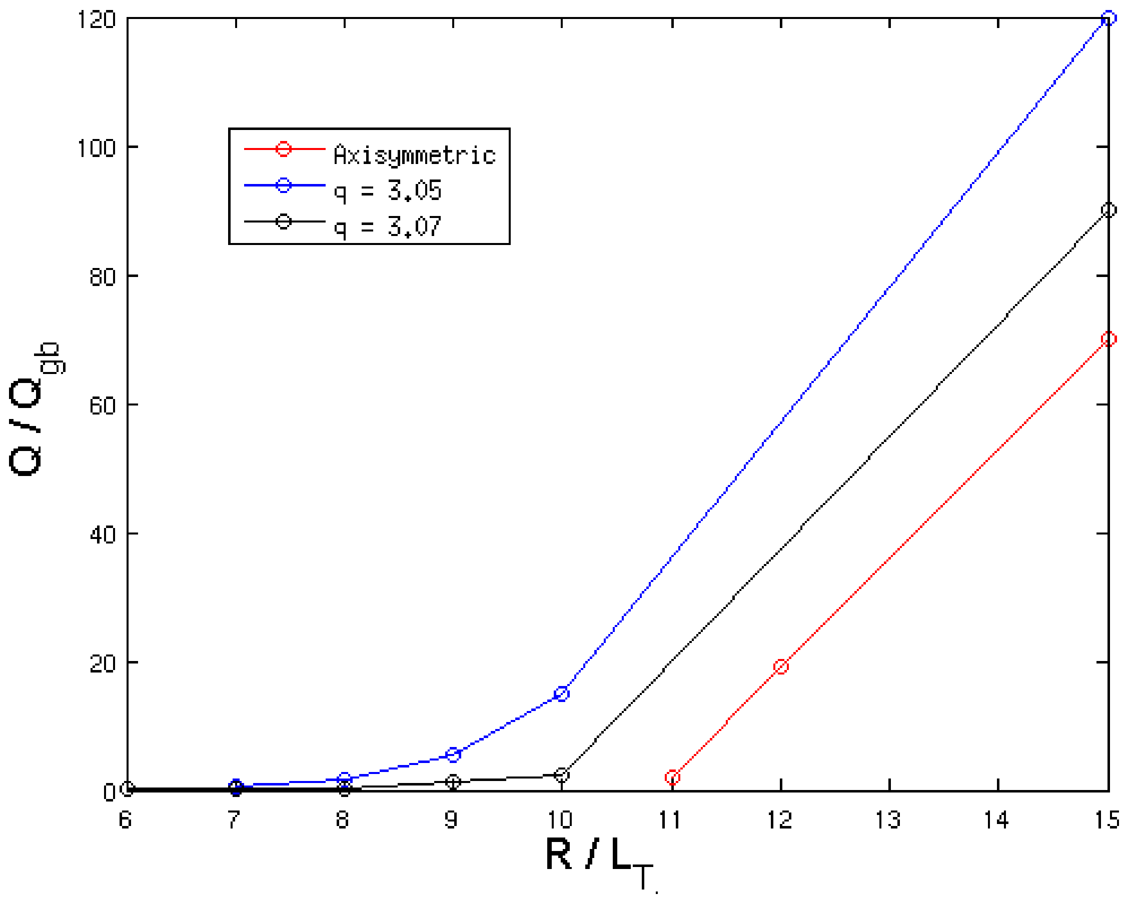
- 3-D flux tube simulations (analogous to infinite-n ballooning)
- Again, some field lines are destabilized and others stabilized
- However, local calculations underestimate the heat flux through the full-flux-surface

For linear ITGs, the full surface is actually stabilized.

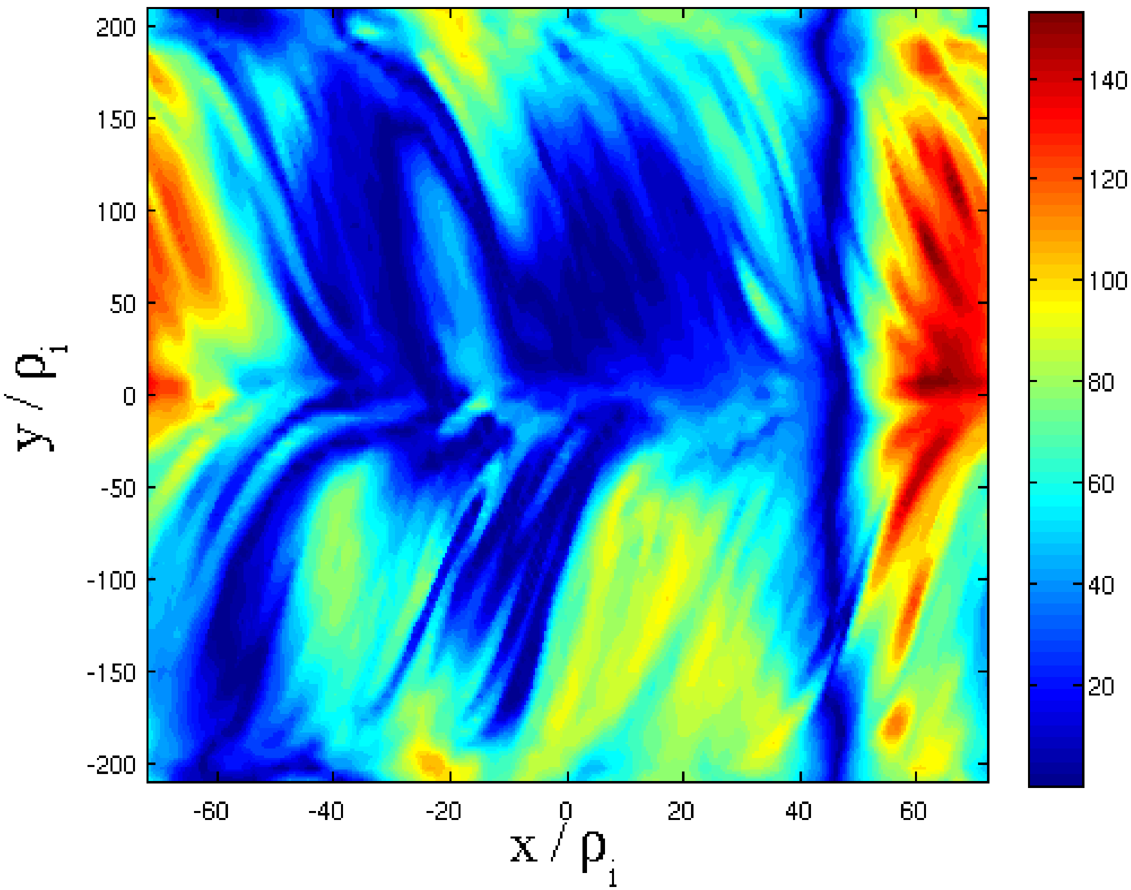


- Adiabatic electrons
- No density gradient
- rho* = 0.005 = 1/200

However, the full surface is nonlinearly destabilized.



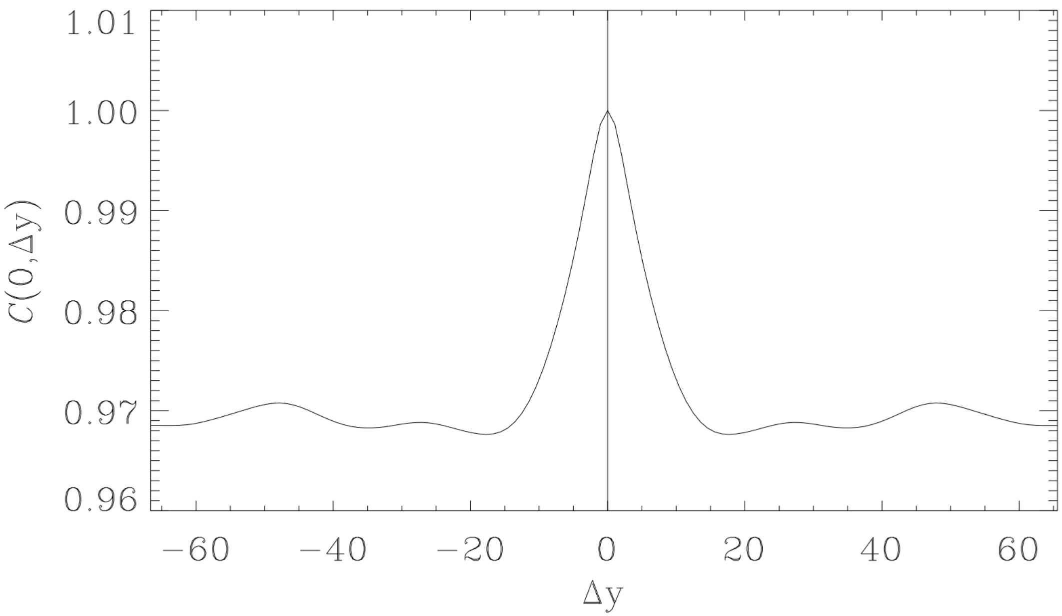
New modes exist in the system (compared to axisymmetry)



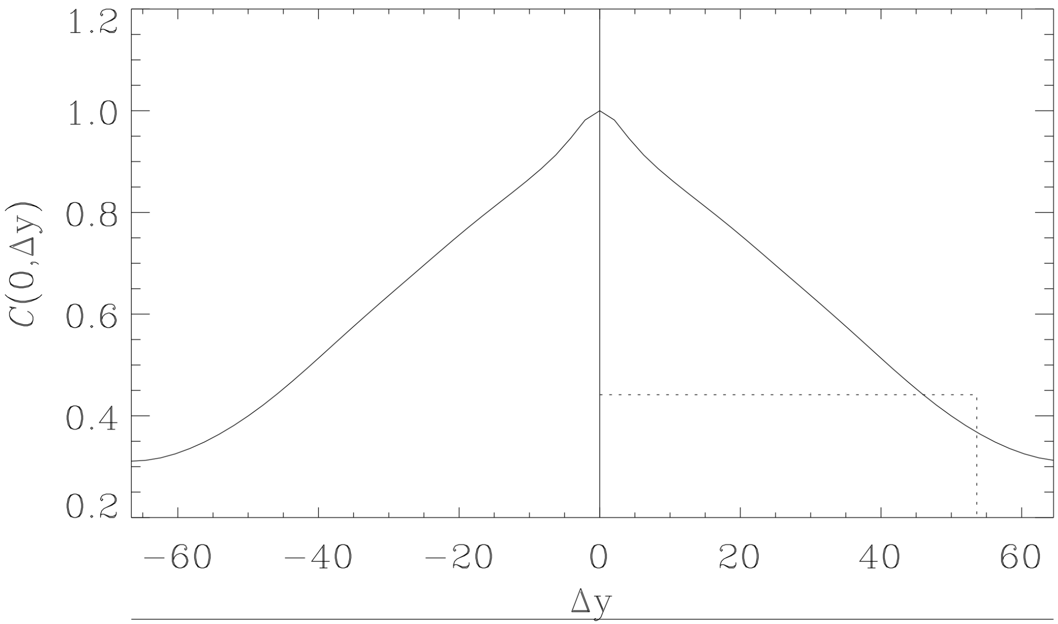
- Zonal flows still active, though less effective (nonlinear upshift in the critical gradient still present here).

Long range poloidal correlations change significantly.

Axisymmetric:

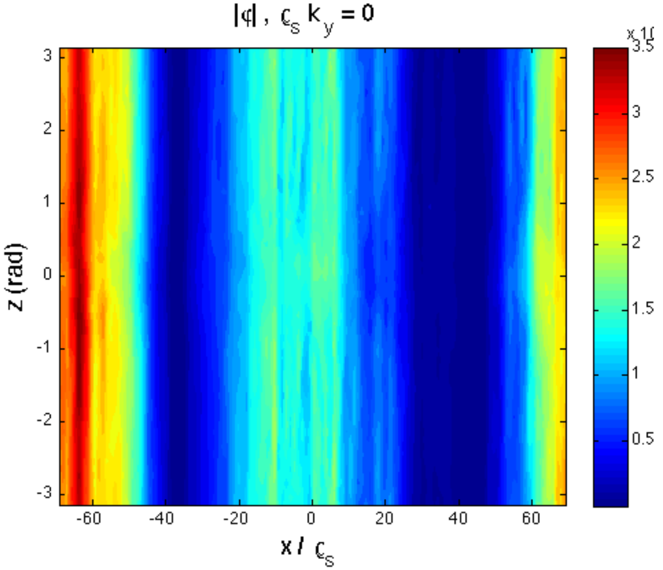


3D:

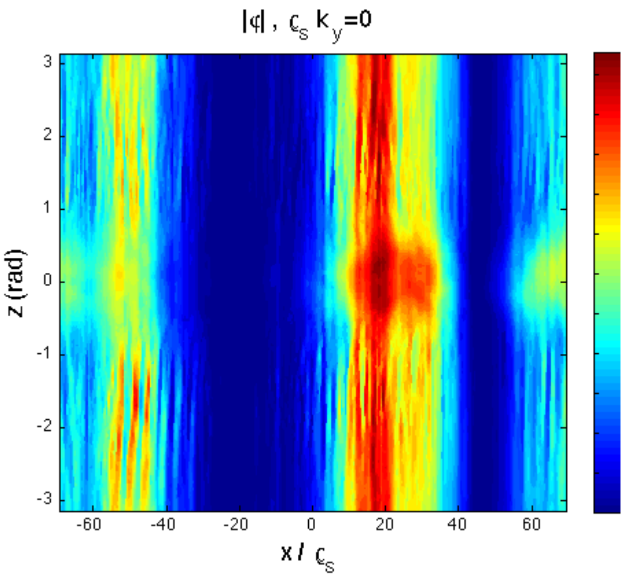


In nonaxisymmetry, the ky=0 modes tend to have finite k_parallel.

2D Tokamak



3D Tokamak



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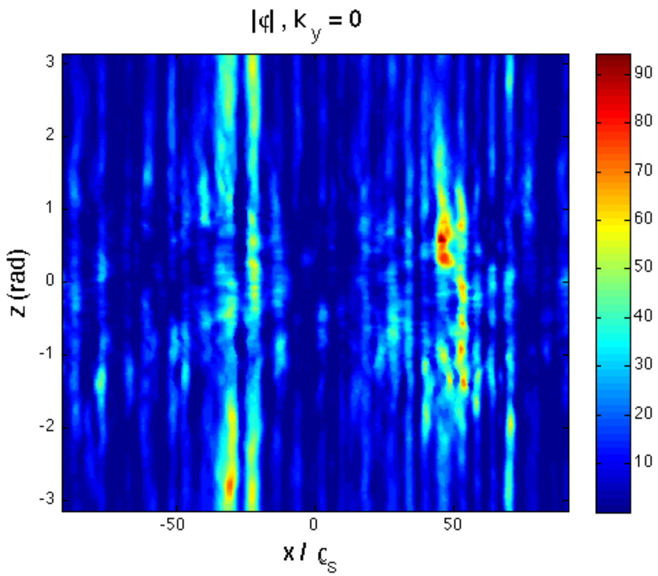
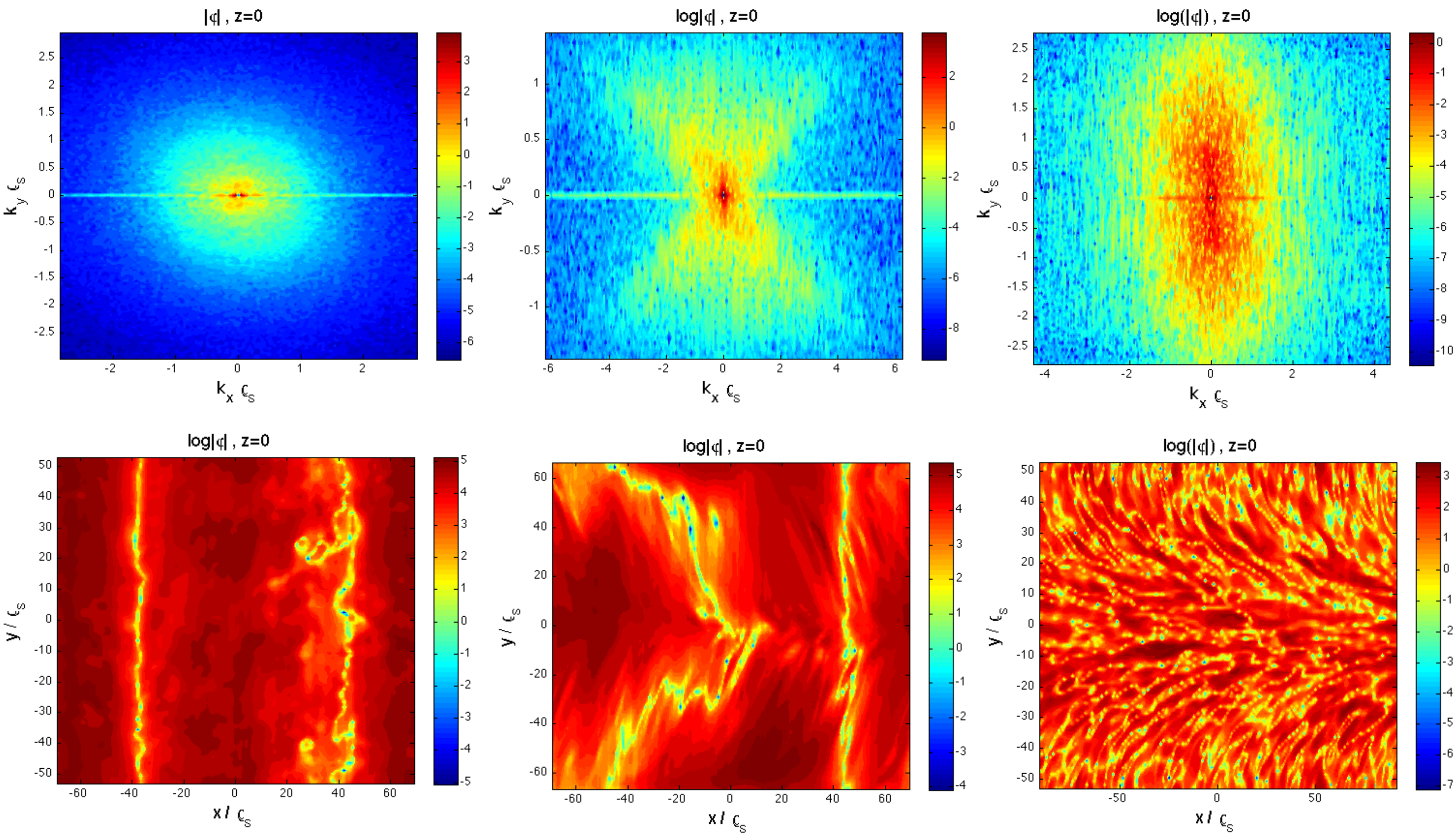


The cascade of electrostatic energy in 3D

2D Tokamak | 3D Tokamak | W7-X

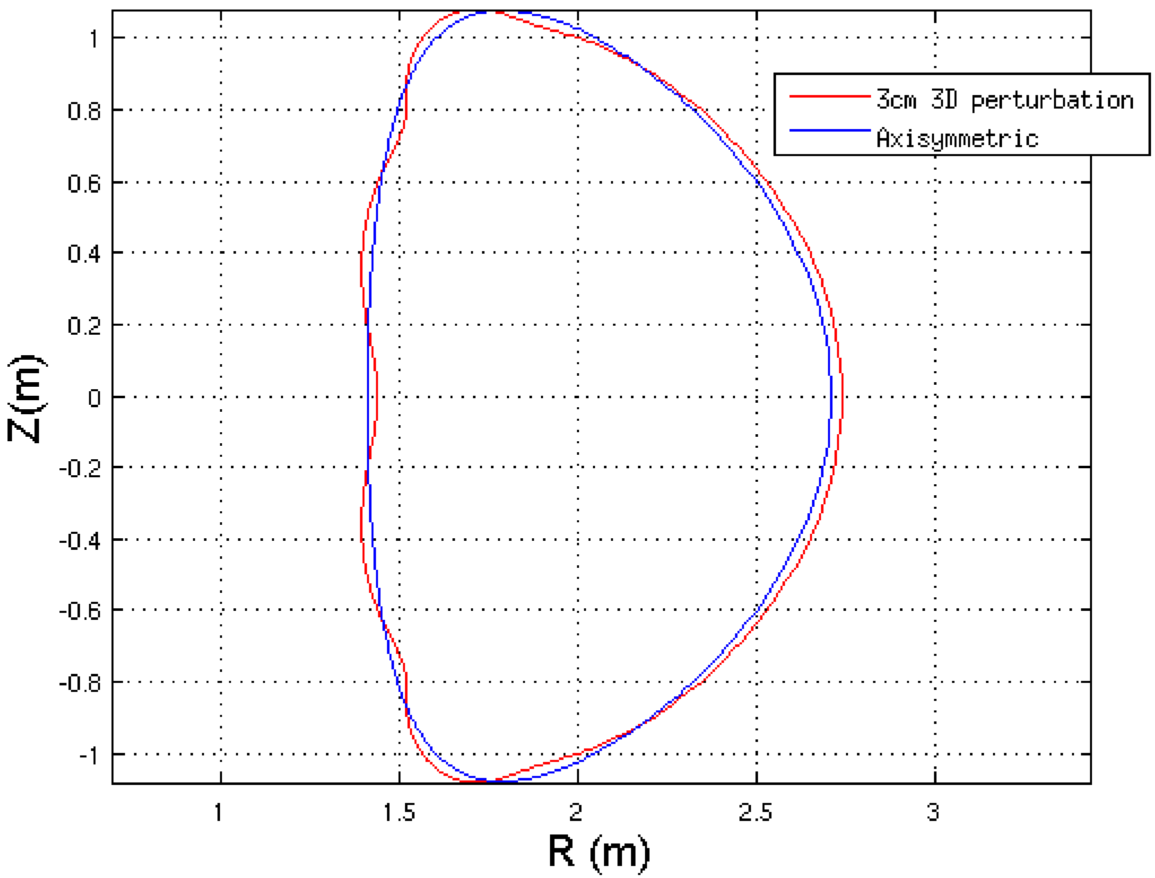


MAST, JET, and DIII-D see ~cm displacements during RMP

- Previous calculations used a 1mm perturbation and focused on resonant effects – essentially only the local magnetic shear was perturbed.
- With ~cm level 3-D displacements, most MHD equilibrium quantities see a non-trivial perturbation.
- How big of a displacement is necessary for the transition to “3D turbulence”?
- What is the effect of more general (i.e. non-resonant) 3-D deformations on turbulence?

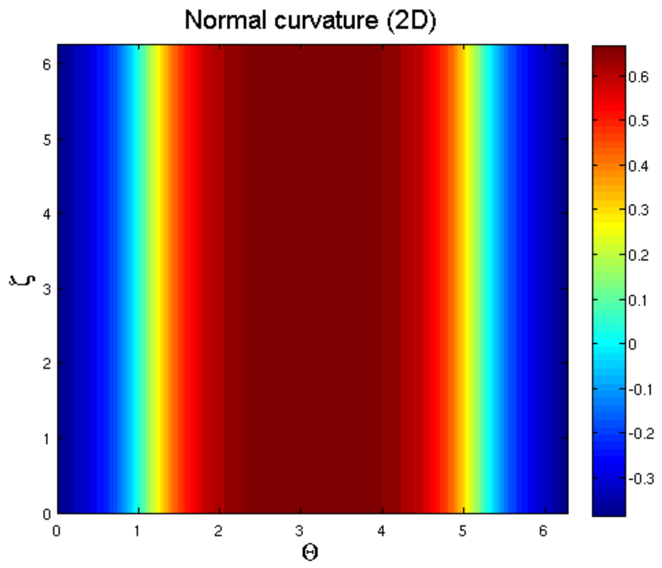
[I. Chapman et al PPCF 2012, L. Lao et al APS 2005, I. Chapman et al NF 2007]

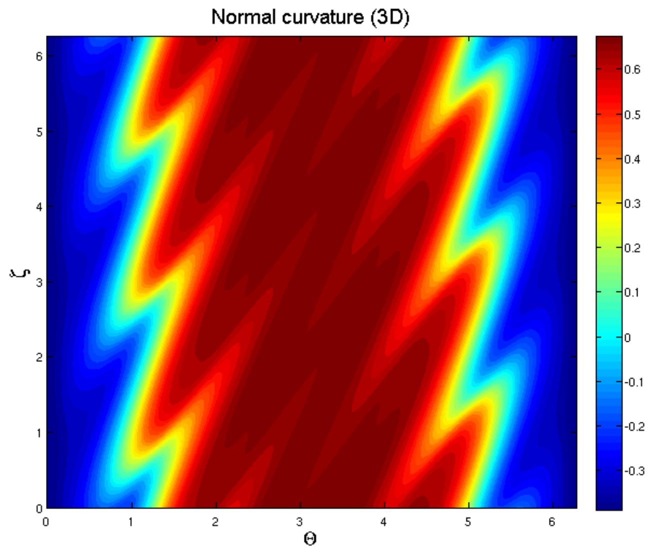
Let's consider a 3cm, non-resonant perturbation.

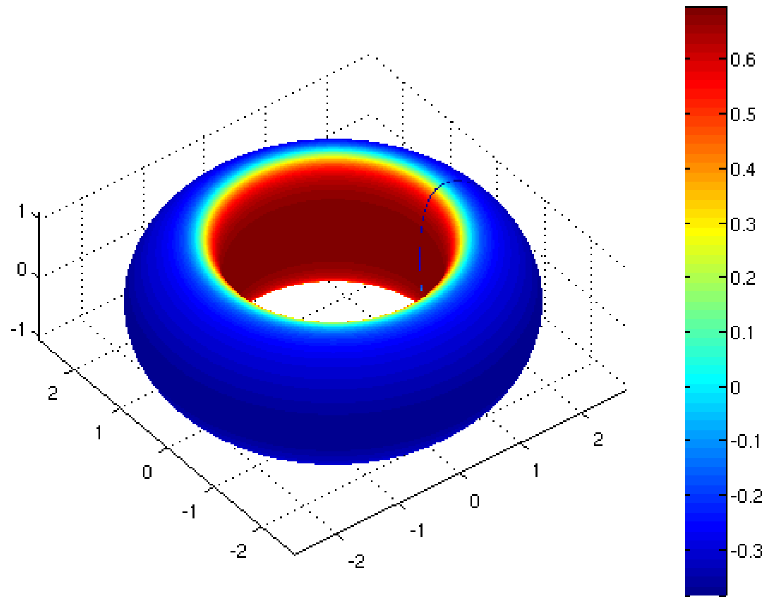


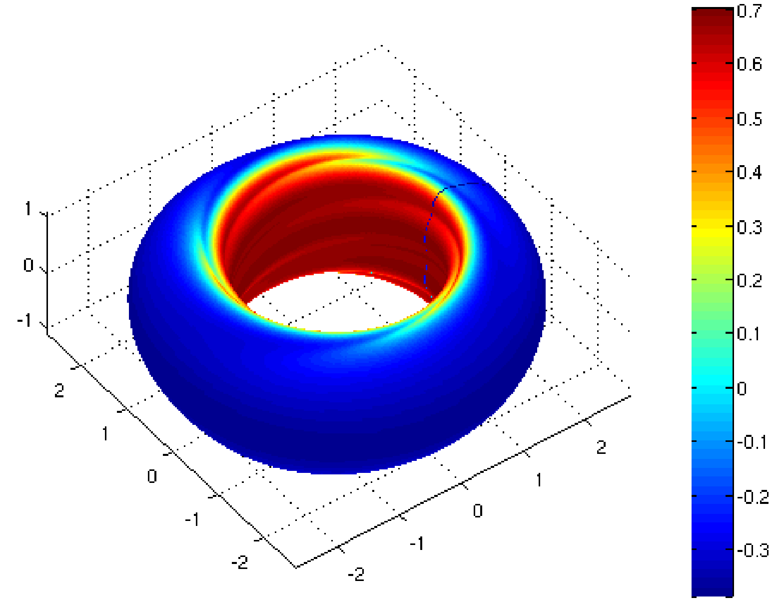
- 3cm single helicity displacement (M=6, N=3) at q=3.15 surface
- Corresponds to br / B0 ~ 5e-2

The normal curvature is significantly modulated

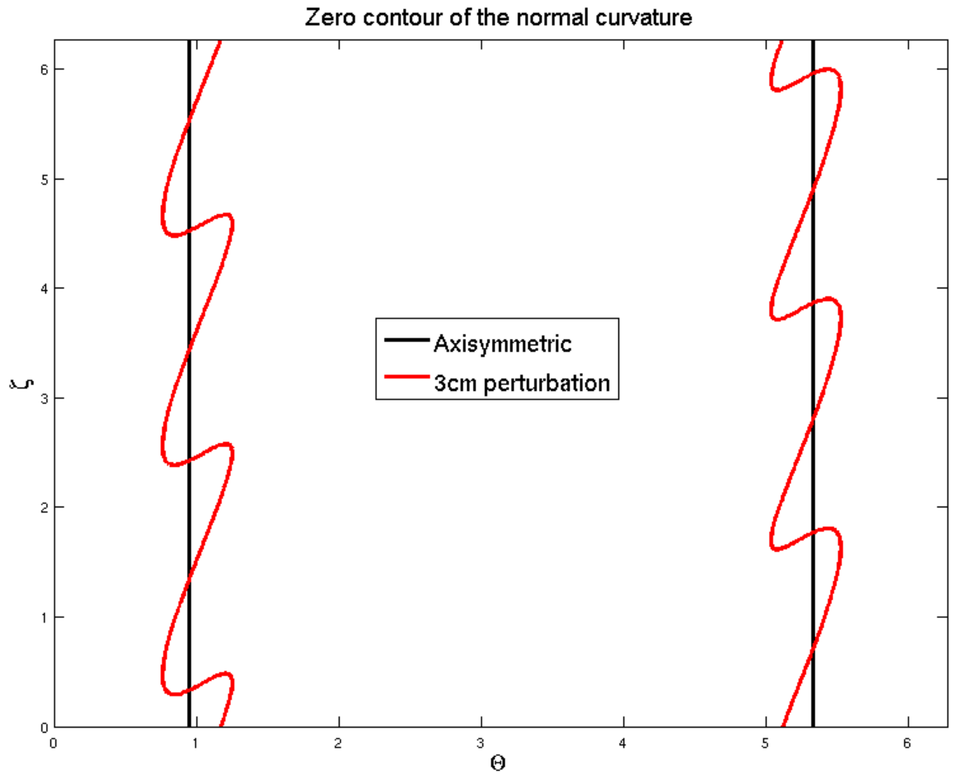




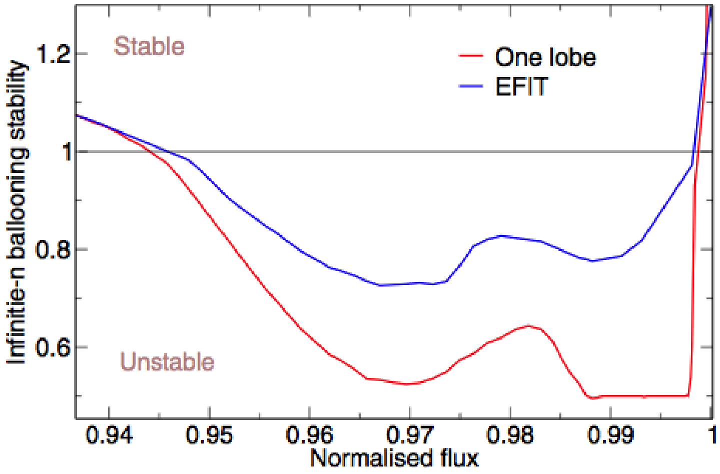




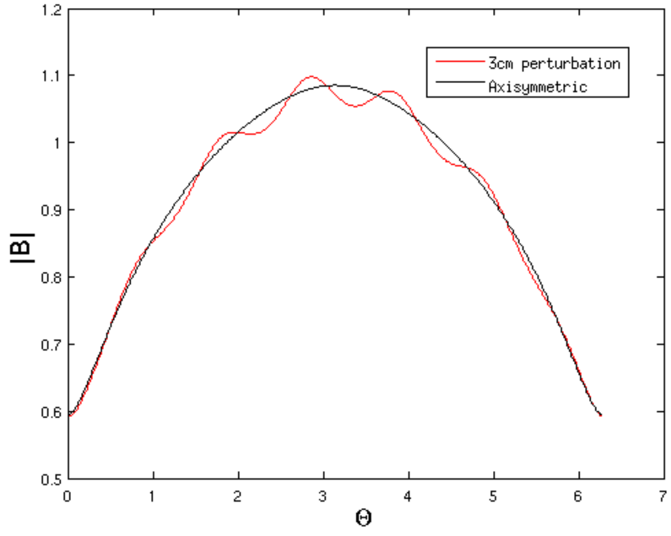
The normal curvature is significantly modulated

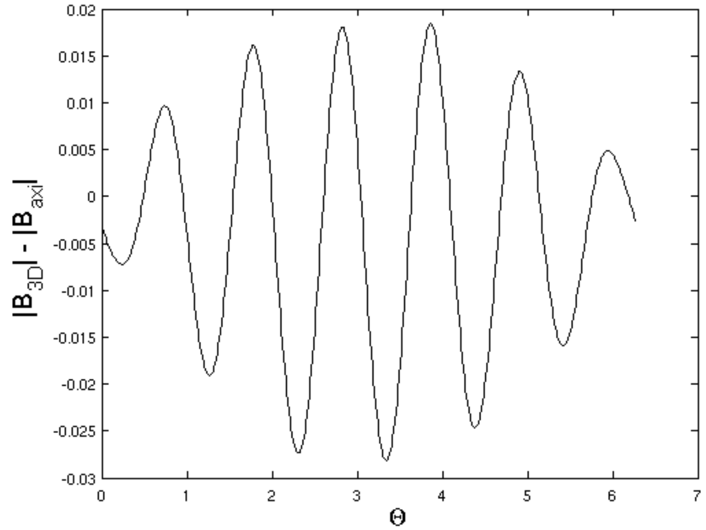


This effect was studied in the recent paper by I. Chapman et al (NF 2012):



Modulation of |B| is still to small to affect neoclassical transport





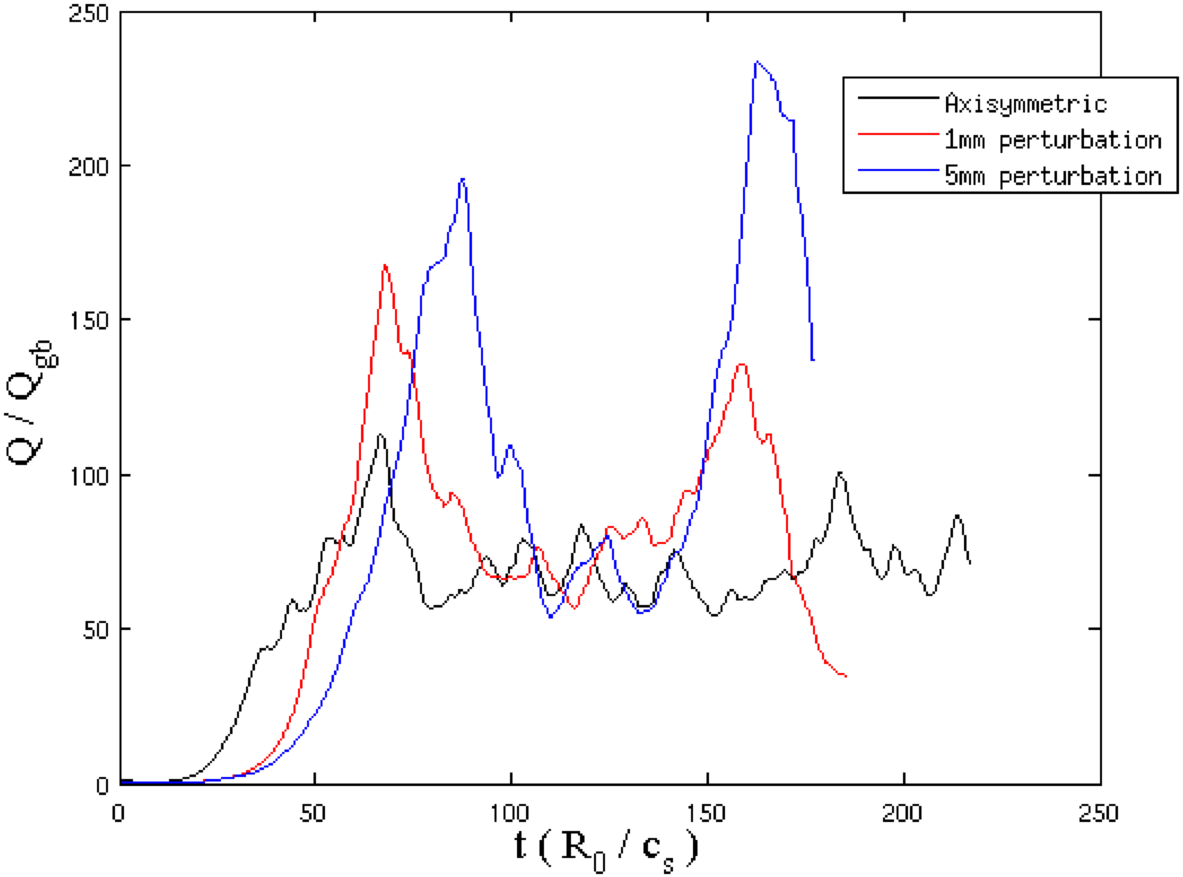
- 1/nu transport scales like:

$$\frac{D_{1/\nu}}{D_{gB}} \sim \epsilon_h^{3/2} \frac{qA^{3/2}a}{\nu_* R} \sim \epsilon_h^{3/2} \frac{A^{1/2}q}{\nu_*}$$

- And becomes important when: $\epsilon_h \sim \left(\frac{\nu_*}{qA^{1/2}}\right)^{2/3}$

- With $\nu_* \sim 0.2, q \sim 3, A \sim 3$ we would need: $\epsilon_h \sim 0.11$

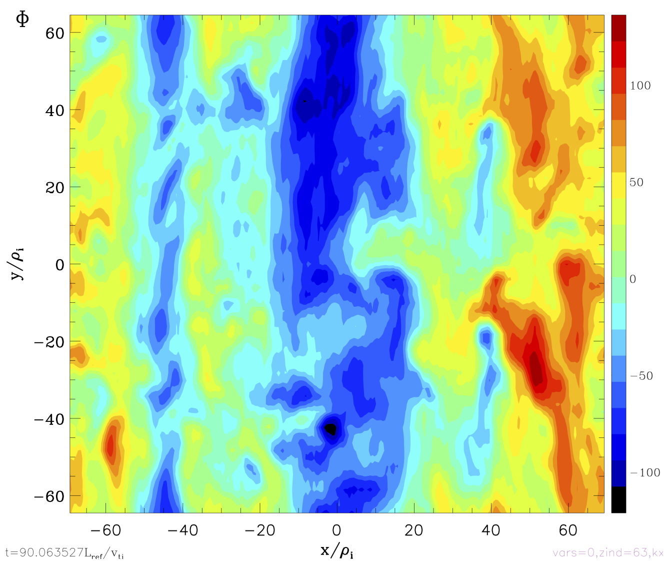
How big of a 3D deformation is required to see 3-D features?



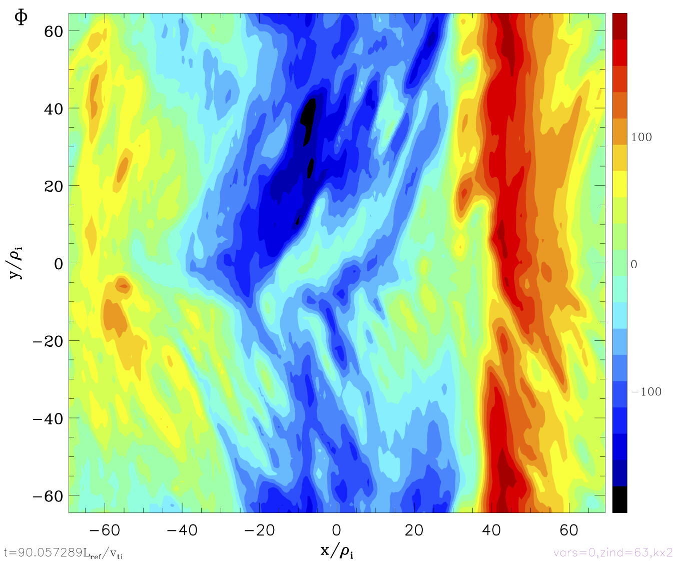
- Increased intermittency and enhanced transport can be seen even with a 1mm non-resonant perturbation.
- In MAST, increased intermittency has been observed with application of 3-D fields [P. Tamain et al, PPCF 2010].

How big of a 3D deformation is required to see 3-D features?

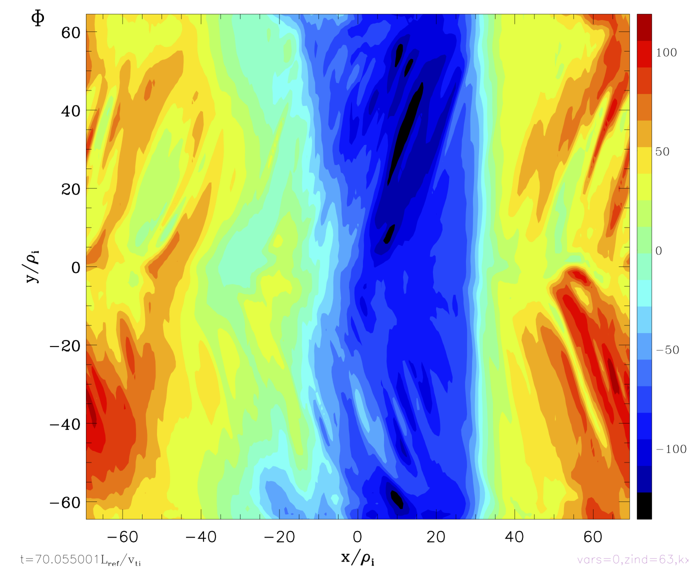
Br ~ 1.7e-3



8e-3



1.e-2



- Radially elongated coherent structures do not appear until the 3-D displacement reaches 5mm

Conclusions

- Pfirsch-Schlüter currents near rational surfaces can modulate the local magnetic shear and destabilize microinstabilities even for tiny perturbations.
- This mechanism could play a role in ELM suppression experiments, though this explanation is still speculative.
- The direct effect on linear micro instability seems to be fairly weak but there is lots of new nonlinear physics in 3-D.
- Centimeter-sized 3-D deformations can introduce non-trivial 3-D variation into most MHD equilibrium quantities – starts to make a Tokamak look like a Stellarator.
- There is still a lot of basic physics to study here, but a closer comparison with experiments will also be useful:

    - Collaboration with N. Ferraro at GA

    - Possible collaboration with MAST?

- The moral of the story:

    - ELM mitigation is extremely messy, it would be surprising if any one effect can explain everything. Turbulence does seem to play a role in some DIII-D and MAST discharges, though.