# Gyrokinetic Microtearing Studies

C M Roach

summarising work involving many collaborators:

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# Outline of the Talk

*Summary of mostly old gyrokinetic simulations of microtearing modes in STs, using GS2.*

(1) Tearing Parity Modes and Simulation Literature

(2) Microtearing Mode in MAST

(3) Contact with Analytic Theory

(4) Nonlinear Simulations

(5) Key Questions

# Eigen-Mode Parity along Equilibrium Magnetic Field is Even or Odd

Local ballooning space represents physical quantities as twisting slices:

$$F(x,y,\theta) = e^{ik_y(y+s(\theta-\theta_0)x)} \sum_{p=-\infty}^{\infty} \hat{F}(\theta-\theta_0-2\pi p)\, e^{inq(x)2\pi p}$$

*fast ⊥ variation* *slow ll variation*

x is equ’m flux surface label, x=0 at q(x)=m/n
y equ’m field line label, ⊥ to **b,** lying in the flux surface
θ is ll to **b**

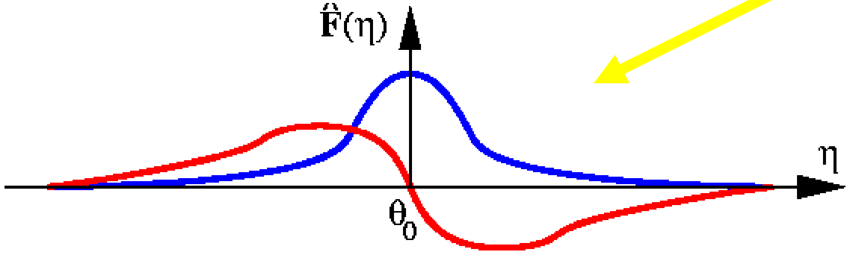
$\hat{F}$ is defined on infinite domain in the ballooning angle η,
$\theta_0$ is the ballooning parameter.

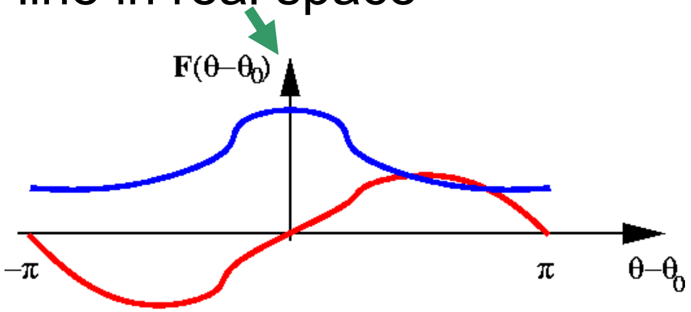
$$\hat{F}(\eta) \to 0 \quad \text{as}\; \eta \to \pm\infty$$

$\hat{F}$ eigenfunctions are either even or odd in η, about η= $\theta_0$

# Tearing Parity Modes

At x=0, the parity of $\hat{F}(\eta)$ about $\eta = \theta_0$ in ballooning space determines the symmetry of F along the field line in real space





Perturbed magnetic field comes from $\delta\mathbf{B} = \nabla\times\delta\mathbf{A}$

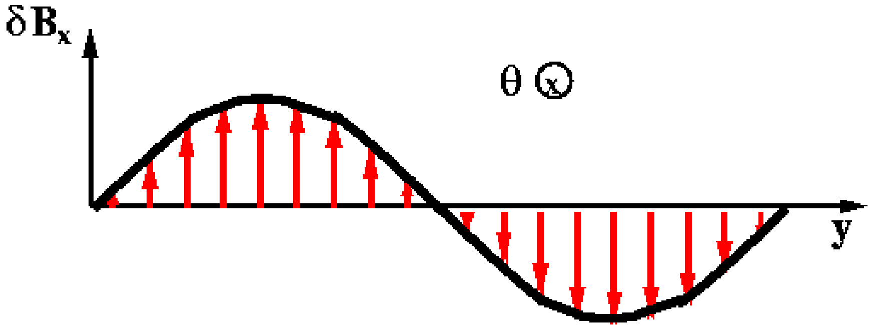
⇒ radial component: $\delta B_x = \partial A_{||}/\partial y = ik_y A_{||}$

**$A_{||}$ even, conclude for x=0 that**

⇒ $\delta B_x$ same sign along equ'm field line

⇒ $\delta B_x$ sinusoidal in y at fixed $\theta$

⇒ equilibrium field lines are torn!



**Even $A_{||}$** implies **tearing** of magnetic flux surface x=0

# Some Gyrokinetic Microtearing Mode Simulations in the Literature

Microtearing found in study high $\beta$ and high performance plasmas:

- M Kotschenreuther *et al*, Nuclear Fusion **40**, 677 (2000)

GS2

Often dominant instabilities for $k_y\rho_i < 1$ at mid-radius in MAST plasmas:

- D J Applegate *et al*, Phys Plasmas **11**, 5085 (2004)
- C M Roach *et al*, PPCF **47**, B323 (2005)

GS2

Microtearing found to dominate ST Power Plant equilibrium:

- H R Wilson *et al*, Nuclear Fusion **44**, 917 (2004)

GS2

Detailed numerical study of microtearing, ST reference, includes scan in R/a:

- D J Applegate *et al*, PPCF **49**, 1113 (2007)

GS2

Nonlinear analytic theory of $\mu$-tearing may explain electron transport in NSTX

- K L Wong *et al*, Phys. Rev. Lett. **99**, 135003 (2007)

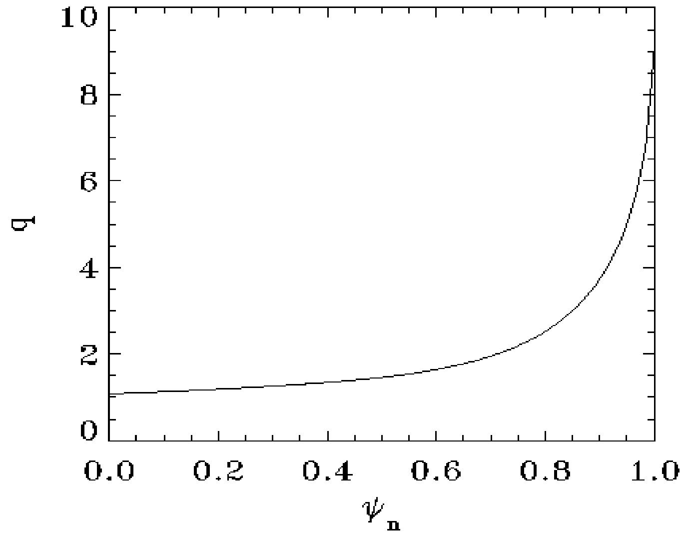
Edge plasmas in ASDEX-Upgrade have $\mu$-tearing modes

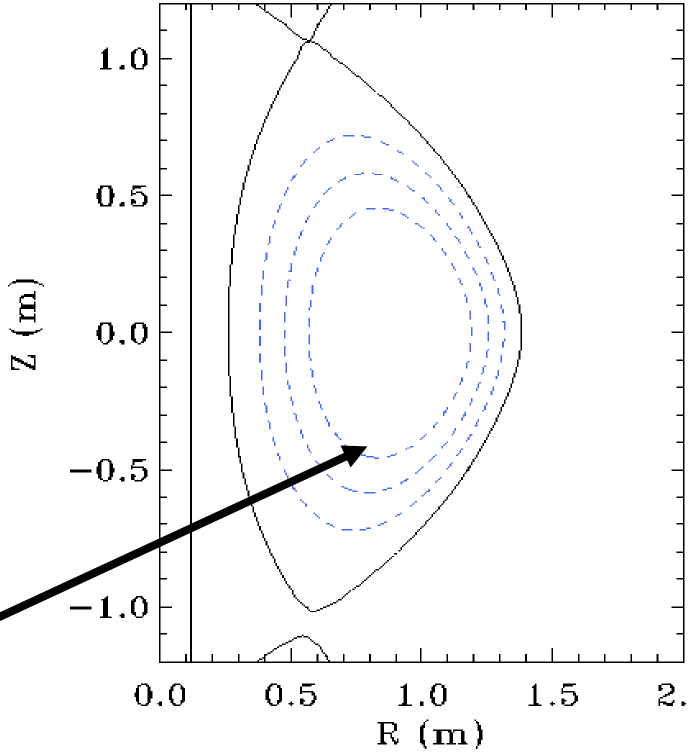
- D Told *et al*, Phys. Plasmas **15**, 102306 (2008)

GENE!

# Linear Microstability Analysis at Mid-Radius in MAST

MAST equilibrium from ELMy H-Mode #6252





At mid-radius surface $\Psi_n$=0.4,
$\beta_e$=0.05, q~1.35 $T_i \sim T_e$, a~0.3m, R~0.9m ⇒ R/a~3

See Applegate *et al*, Physics of Plasmas (2004)

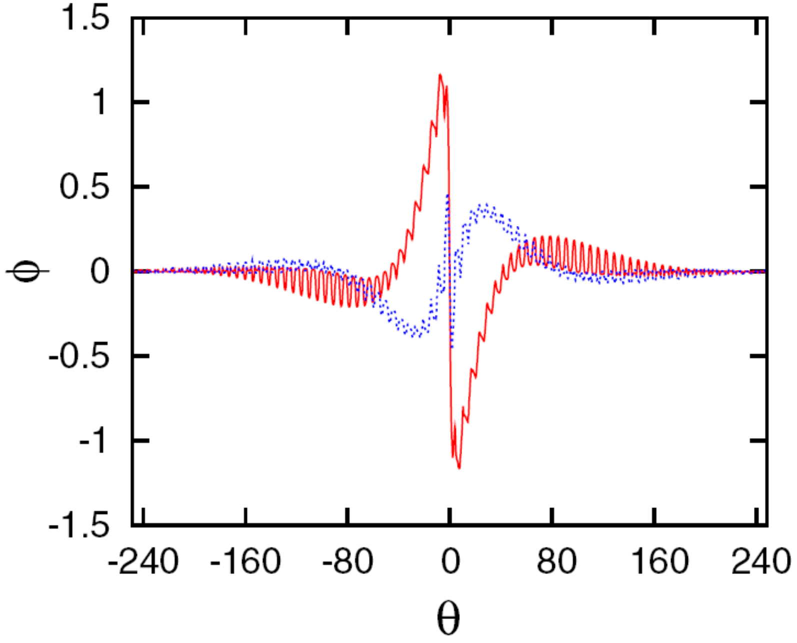
# Tearing Parity Modes at $\rho_i$ scale

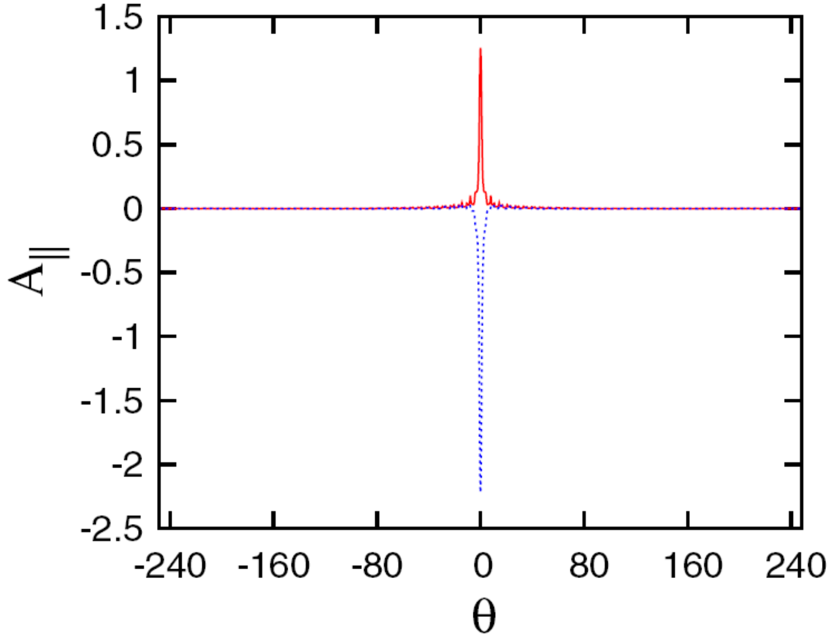
Fastest growing modes in STs often found to have tearing parity:

- MAST [1], and NSTX [2]
- conceptual burning STs [3,4]

[1] Applegate *et al*, Phys Plasmas **11**, 5085, (2004).
[2] Redi et al, EPS, St Petersburg (2003)
[3] Kotschenreuther *et al*, Nuc Fus **40**, 677 (2000),
[4] H R Wilson et al, Nuclear Fusion, 44, 917 (2004)

MAST tearing parity modes rotate in **electron** diamagnetic drift direction



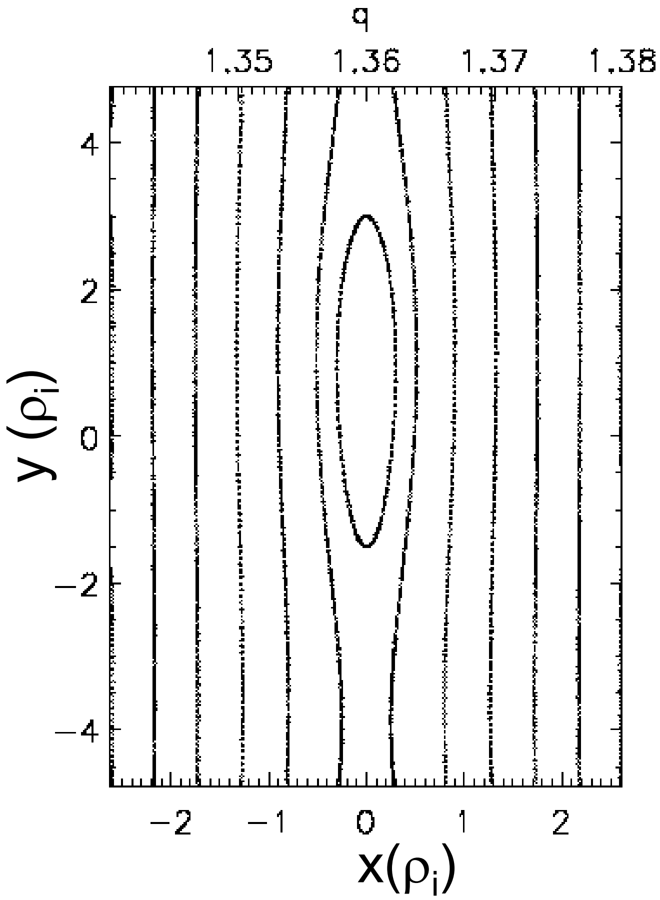


# Visualising Micro-tearing Mode in Real Space

Poincaré plot shows perturbed magnetic field at intersection of GS2 flux-tube with the outboard mid-plane.

Magnetic island on rational surface at x=0.

Microtearing mode is candidate to explain electron transport



**Two Major Questions:**

What is the linear physics mechanism underlying these modes?

How much anomalous transport is generated at nonlinear saturation?

# Analytic Theories of Microtearing Instabilities

$\nabla T_e$ microtearing drive discovered in cylinder
- *Hazeltine Dobrott and Wang (1975):* kinetic, collisions key, any $\nu_e/\omega$

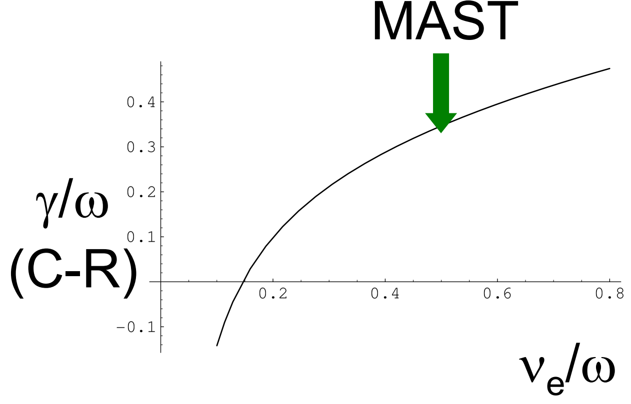
Further slab calculations confirm $\nabla T_e$ drive at high $\nu_e/\omega$
- *Drake and Lee (1977), Gladd et al (1980):* kinetic, *Hassam (1980):* fluid

**=> collisional slab drive requires energy dependent $\nu_e(E)$**

Kinetic calculations in toroidal geometry (large R/a), for low $\nu_e/\omega$
- *Catto and Rosenbluth (1981), Connor, Cowley and Hastie (1990)*

$\Rightarrow$ **low collisionality drive from trapped particle collisions on passing particles also requires energy dependent $\nu_e(E)$**

MAST has small R/a and $\nu_e/\omega$ ~0.5
so analytic theories should be poor.
Catto-Rosenbluth trapped particle
drive mechanism, nevertheless,
predicts growth with MAST parameters!
....Connor, Cowley, Hastie does not!



CM Roach *et al*, PPCF **47**, B323 (2005)

# Analytic Theories of Microtearing Drives and Properties of the GS2 Modes

Two classes of linear drive in analytic theory literature:
- time dependent thermal force (high collisionality, $\upsilon_{ei} > \omega$)
- collisions close to the trapped-passing boundary ($\upsilon_{ei} < \omega$)

Both drives require
- finite $dT_e/dr$
- energy dependent collision frequency $\nu_{ei}(v)$

Some properties of the GS2 mode:
- **sensitive** to electron physics $\nu_e$, $\nabla T_e$ and $\nabla n_e$
- **sensitive** to $\beta$, $\nabla p$, s
- **insensitive** to ion parameters $\nu_i$ and $\nabla T_i$ and $\delta \mathbf{B}_{||}$
- current layer width ~$O(\rho_i)$

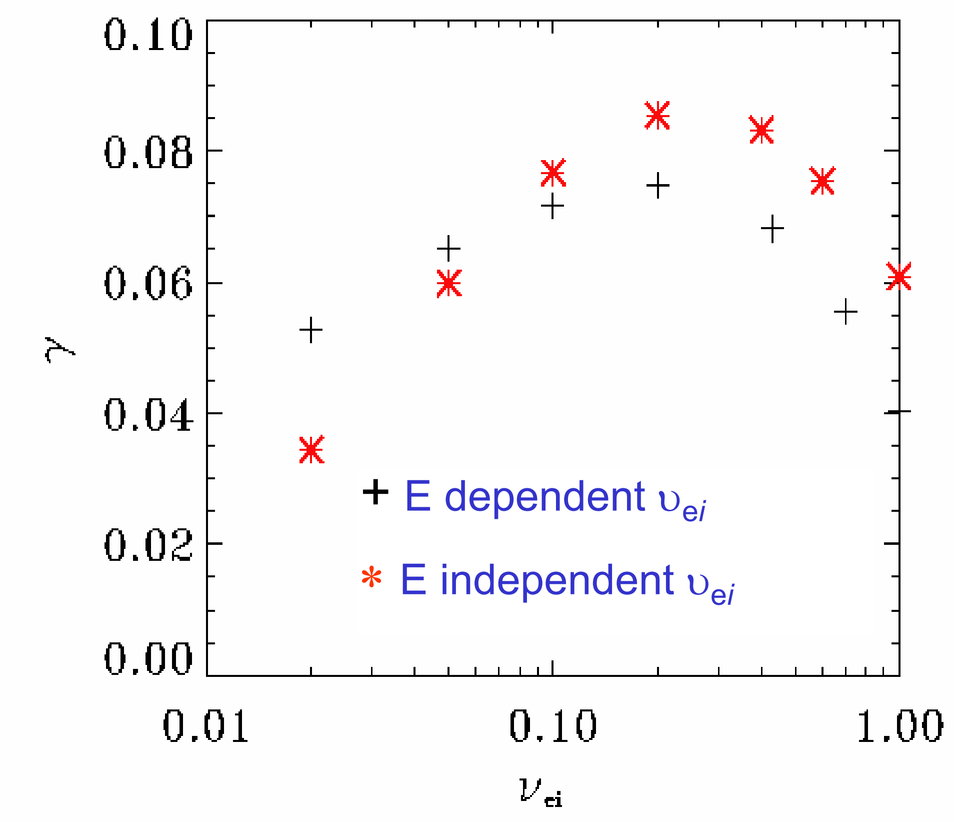
[1] DJ Applegate *et al*, PPCF **49**, 1113 (2007) and PhD Imperial College (2006)

# Experiment with Collision Operator

DJ Applegate *et al*, PPCF **49**, 1113 (2007) and PhD Imperial College (2006)

GS2 Lorentz collision operator can capture boundary layers.

Removed energy dependent collisions by setting $\nu_e(E)$=constant



Modest affect on tearing $\gamma$

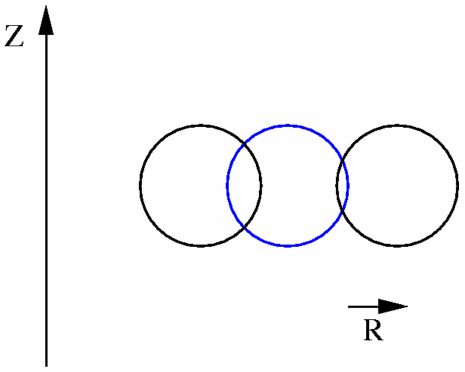
- ➢ not consistent with analytic drive models!

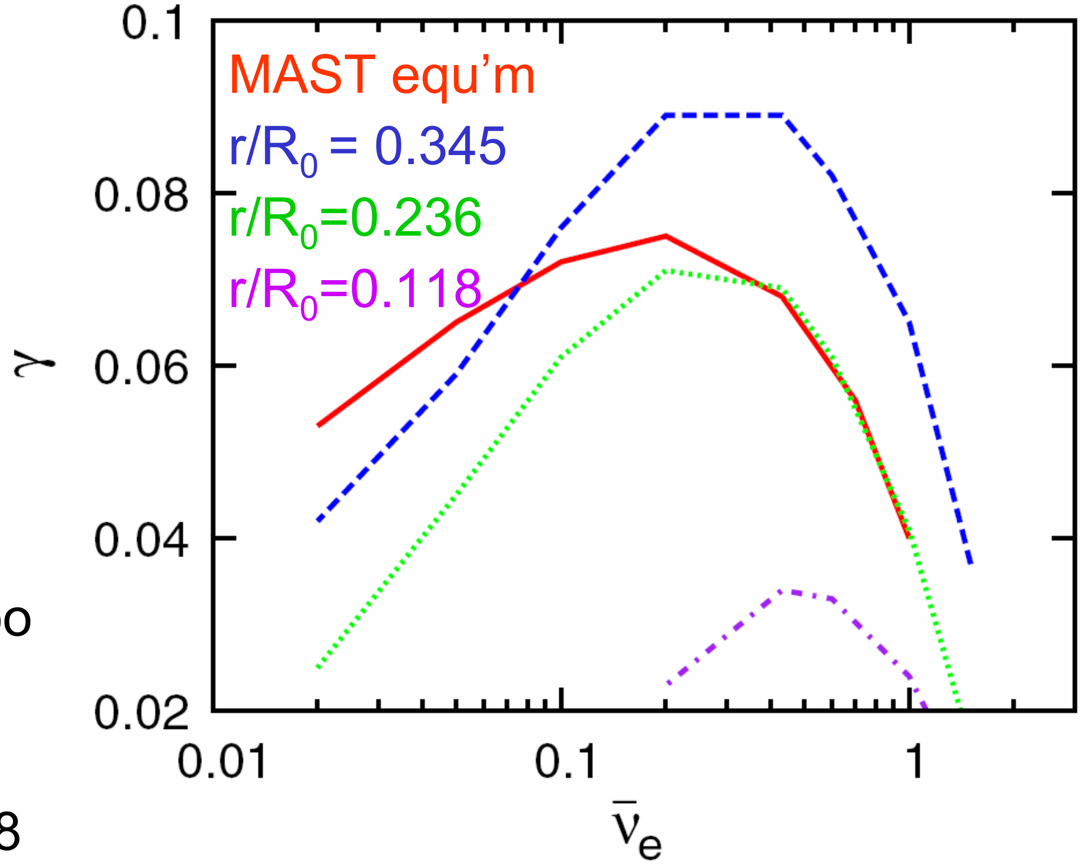
# Experiments Using s-α Model Equilibrium: Scan Aspect Ratio by varying $R_0$ at Fixed r

DJ Applegate *et al*, PPCF **49**, 1113 (2007)

Fit MAST mid-radius surface with s-α model for fixed β, $a/L_T$, $a/L_n$, q, s

Scan $r/R_0$ by varying $R_0$ and fixing r and other parameters, varies drifts + $f_t$





- MAST instability in s- α too

⇒ shaping not essential

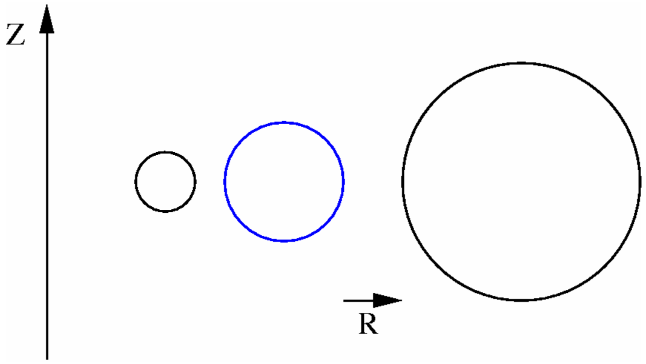
- γ ↓ as $r/R_0$ ↓
- still unstable at $r/R_0=0.118$

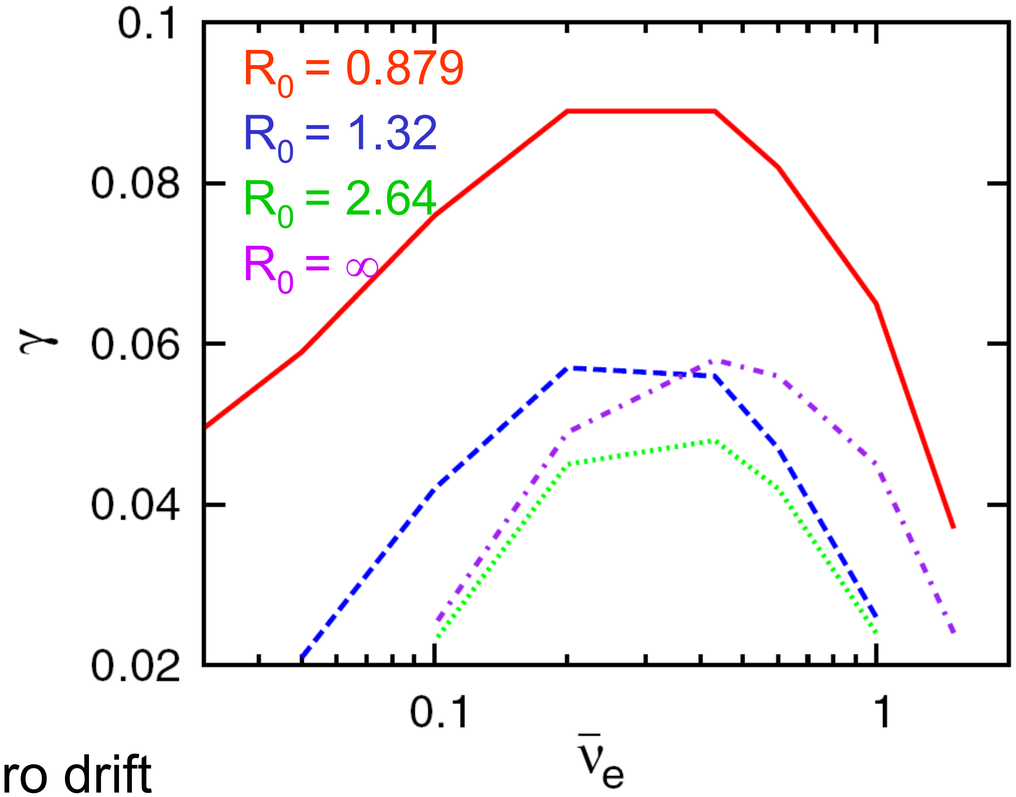
⇒ µtearing may appear at conventional aspect ratio

# Experiments Using s-α Model Equilibrium: Scan $R_0$ at fixed $r/R_0$ to Vary Drifts

DJ Applegate *et al*, PPCF **49**, 1113 (2007)

Now scan in $R_0$ at fixed $r/R_0$ with other parameters constant





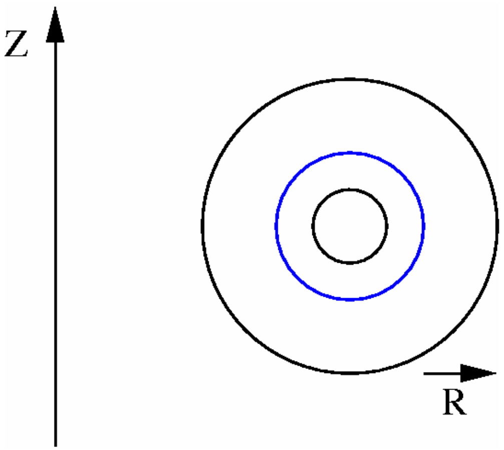
Mode survives at $R_0 = \infty$ i.e. zero drift

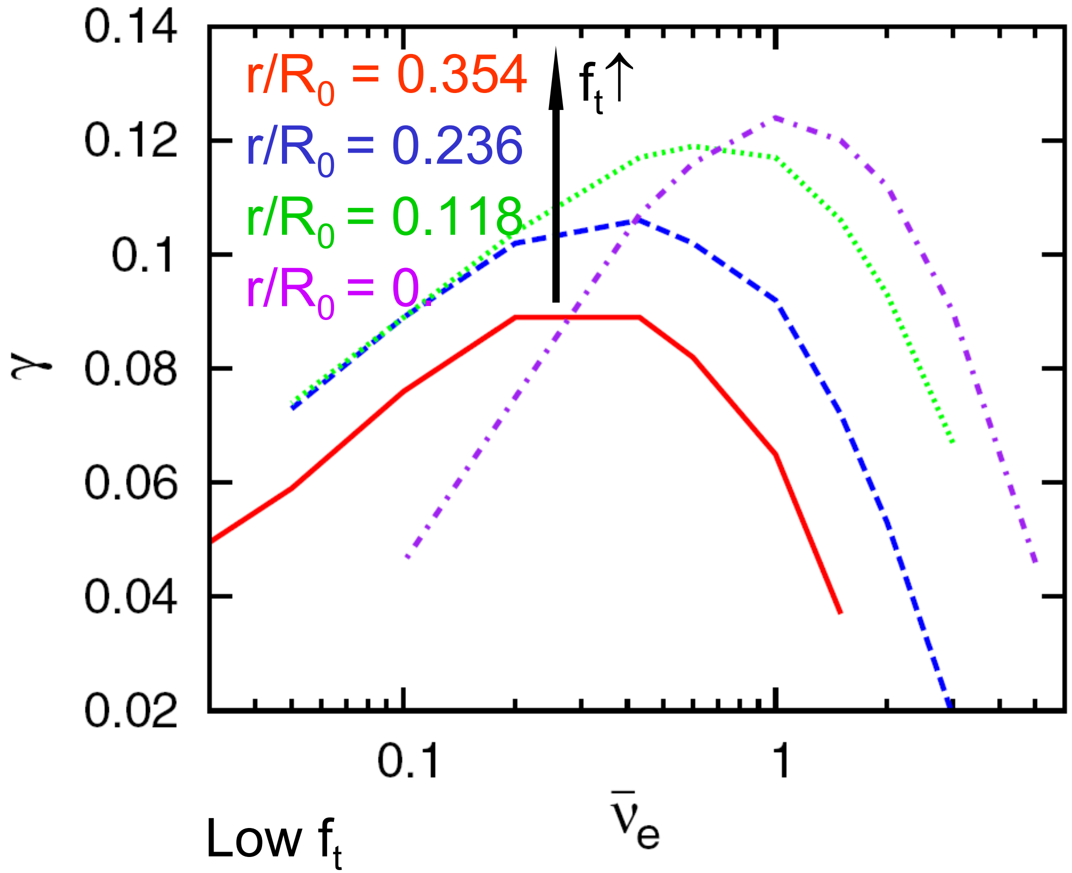
- mode has slab drive

# Experiments Using s-α Model Equilibrium: Scan in Trapped Particle Fraction, $f_t$

DJ Applegate *et al*, PPCF **49**, 1113 (2007)

Now scan $r/R_0$ to vary $f_t$ at fixed $R_0$ and other parameters





High $f_t$

- $\gamma\uparrow$ at low $\nu_e$
- $\gamma\downarrow$ at high $\nu_e$ (fewer passing e)

Low $f_t$

- $\gamma$ more sensitive to energy dependent collision rate $\nu_e(E)$

# Overview of Most Interesting Findings

DJ Applegate *et al*, PPCF **49**, 1113 (2007)

Microtearing mode is driven by $dT_e/dr$ as expected.

Mode is complicated and in awkward regime for analytic theory:

- unstable over broad range of collisionality $0.05<\upsilon_{ei}/\omega<1.2$
- current layer width ~ $O(\rho_i)$, so need ion FLR effects

Regimes where mode robust to energy independent collisions $\Rightarrow$ puzzle

Mode not only unstable in ST

- unstable in large aspect ratio s-$\alpha$ model equilibria

Gyrokinetic microtearing also at r/R ~ 0.3 (~ MAST mid-radius) in conventional aspect ratio: D Told *et al*, Phys. Plasmas **15**, 102306 (2008)

# * Very High β:   Microstability in STPP

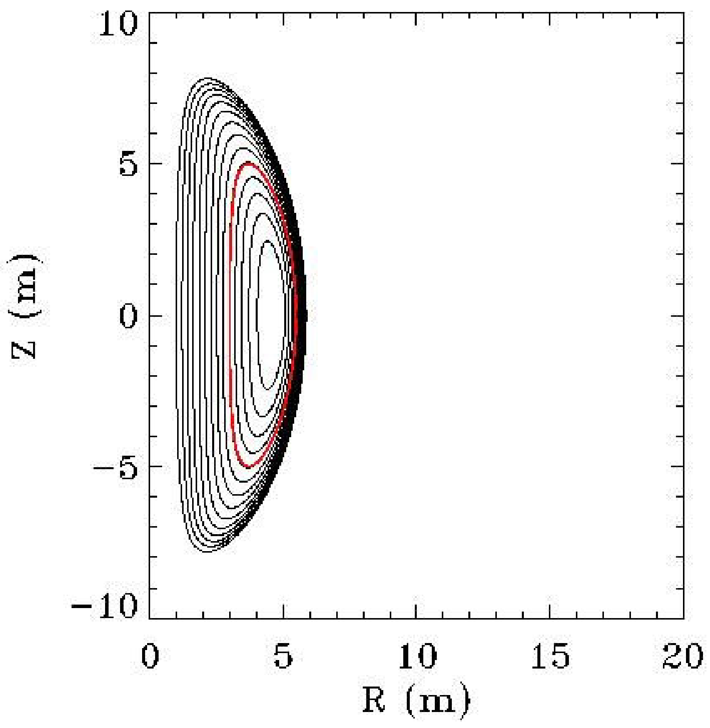
see H R Wilson *et al*, Nuc Fus 44, 917 (2004)

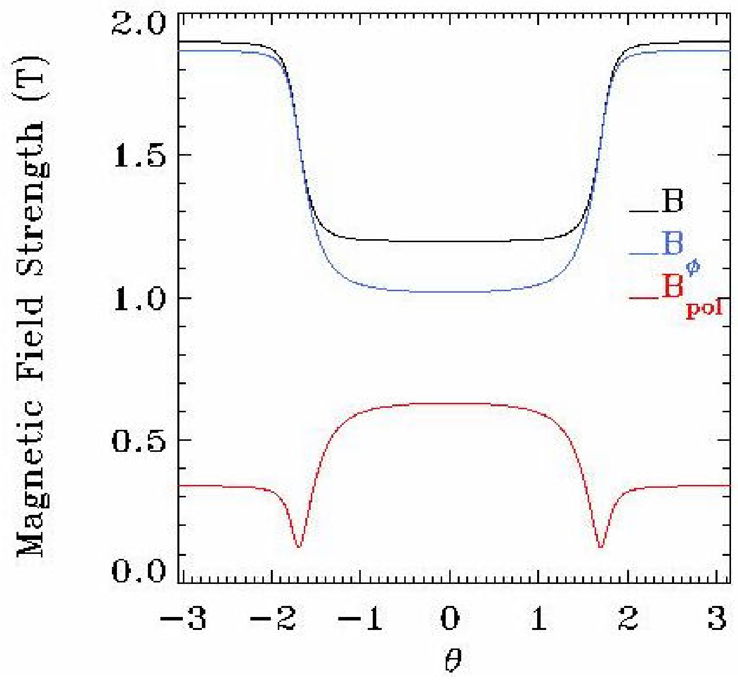
Conceptual Culham ST Power Plant (STPP), 1GW electrical, β=0.59

GS2 used for microstability analysis of mid-radius flux-surface, $\Psi_n$=0.35.

Equilibrium features:

- striking variation in |B| around the magnetic flux surface
- magnetic drift reversal owing to high pressure gradient
- diamagnetic $\omega_{se}$ strongly peaked on outboard midplane

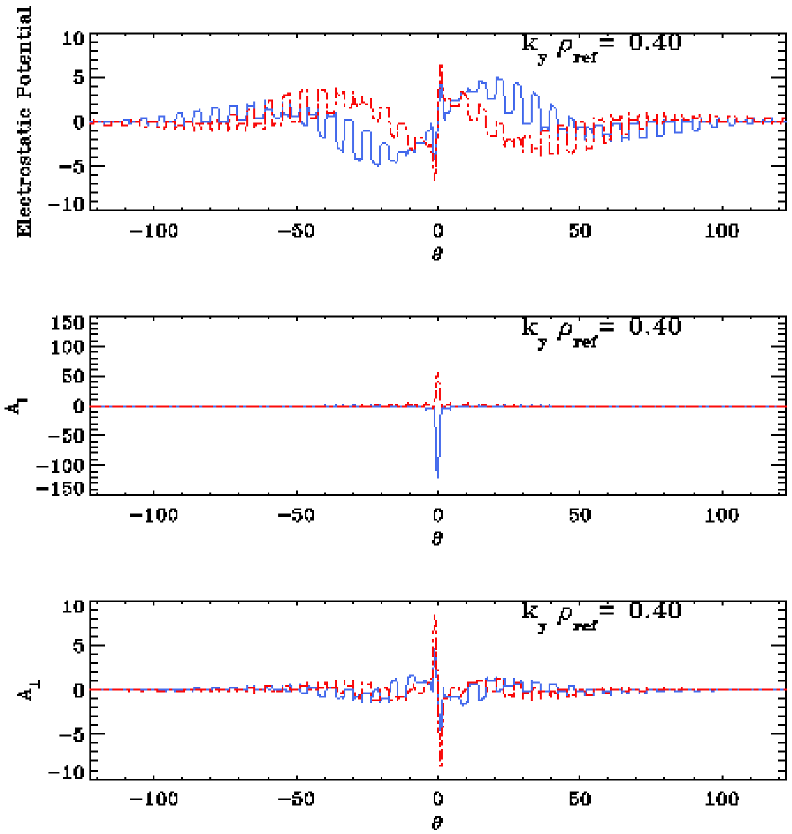




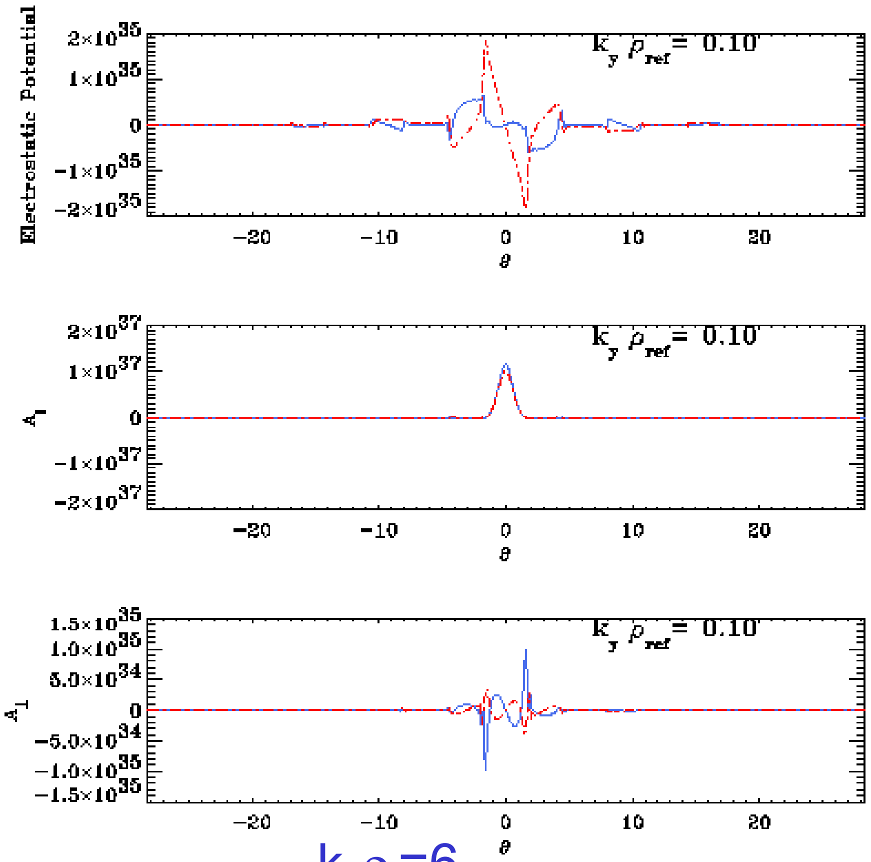
# * Microstability Results for Mid-radius Surface in STPP

STPP surface $\Psi_n$=0.35

- **no electrostatic instabilities**, $\alpha$ stabilisation giving drift reversal
- including EM gives **tearing parity modes at ion and electron scales**



$k_y\rho_i$=0.4

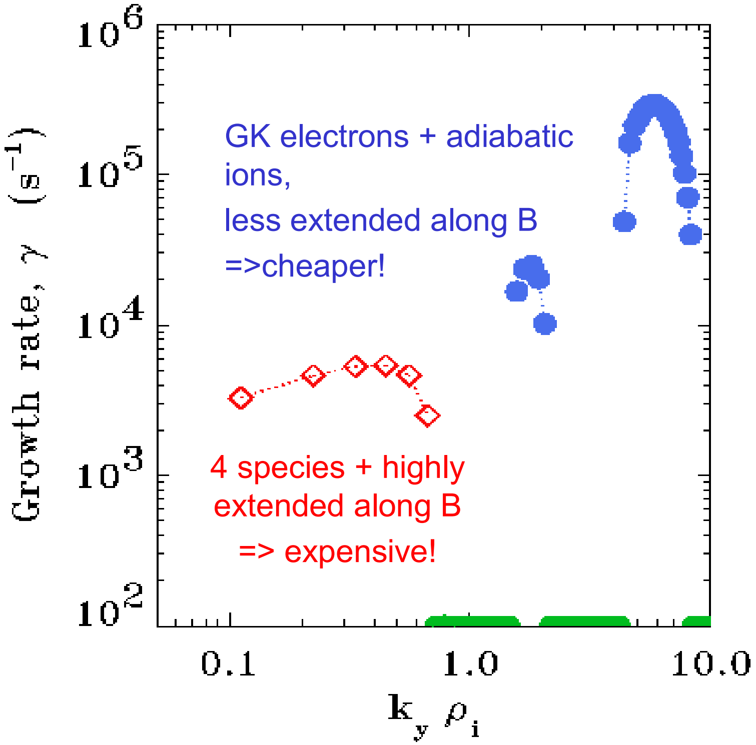


$k_y\rho_i$=6

# * Microstability Results for Mid-radius Surface in STPP

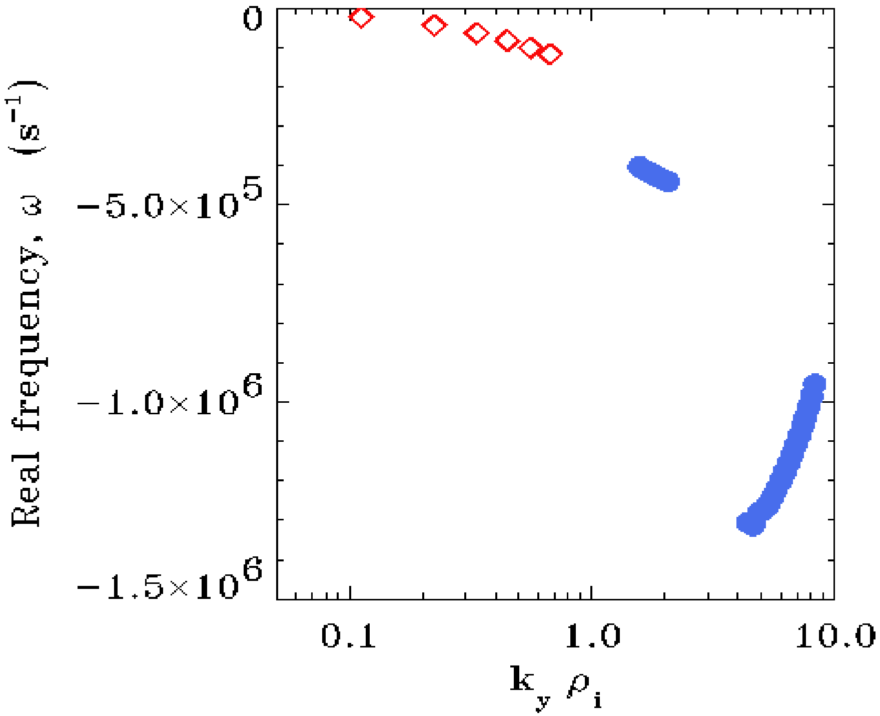
STPP surface $\Psi_n$=0.35

- **no electrostatic instabilities** ($\alpha$ stabilisation from drift reversal)
- EM effects gives **tearing parity modes at ion and electron scales**, all propagating in electron drift direction
- Mixing length $\chi$~4m$^2$s$^{-1}$ (no $\omega_{se}$)



GK electrons + adiabatic ions,
less extended along B
=>cheaper!

4 species + highly
extended along B
=> expensive!



# Nonlinear Microtearing Simulations with GS2

D J Applegate

First nonlinear GK simulations with GS2 [1,2] :

- modified mid-radius MAST equilibrium for increased tractability

| | MAST Equilibrium | Nonlinear Model |
|---|---|---|
| $q$ | 1.3463 | 1.3463 |
| $\hat{s}$ | 0.286 | 1.4 |
| $\beta$ | 0.0495 | 0.12 |
| $a/L_{n_e}$ | -0.1766 | 2.4 |
| $a/L_{T_e}$ | 2.0433 | 2.0433 |
| $a/L_{P_e}$ | 1.8667 | 4.4433 |
| $a/L_{n_i}$ | -0.1766 | 2.4 |
| $a/L_{T_i}$ | 2.0433 | 2.0433 |
| $a/L_{P_i}$ | 1.8667 | 4.4433 |

reduces radial box size by factor 5

Few $k_y$ modes: $n_{ky}$=4, $n_{kx}$=47, $n_\theta$=32  $n_E$=8, $n_\lambda$~20

- “pseudo-saturation” with low transport, blows up later at high $k_x$
- small timesteps imposed by the CFL condition

[1] D J Applegate PhD Thesis, Imperial College (2007).

[2] D J Applegate et al, 32nd EPS, Tarragona, ECA volume 29C, P5-101, 2005

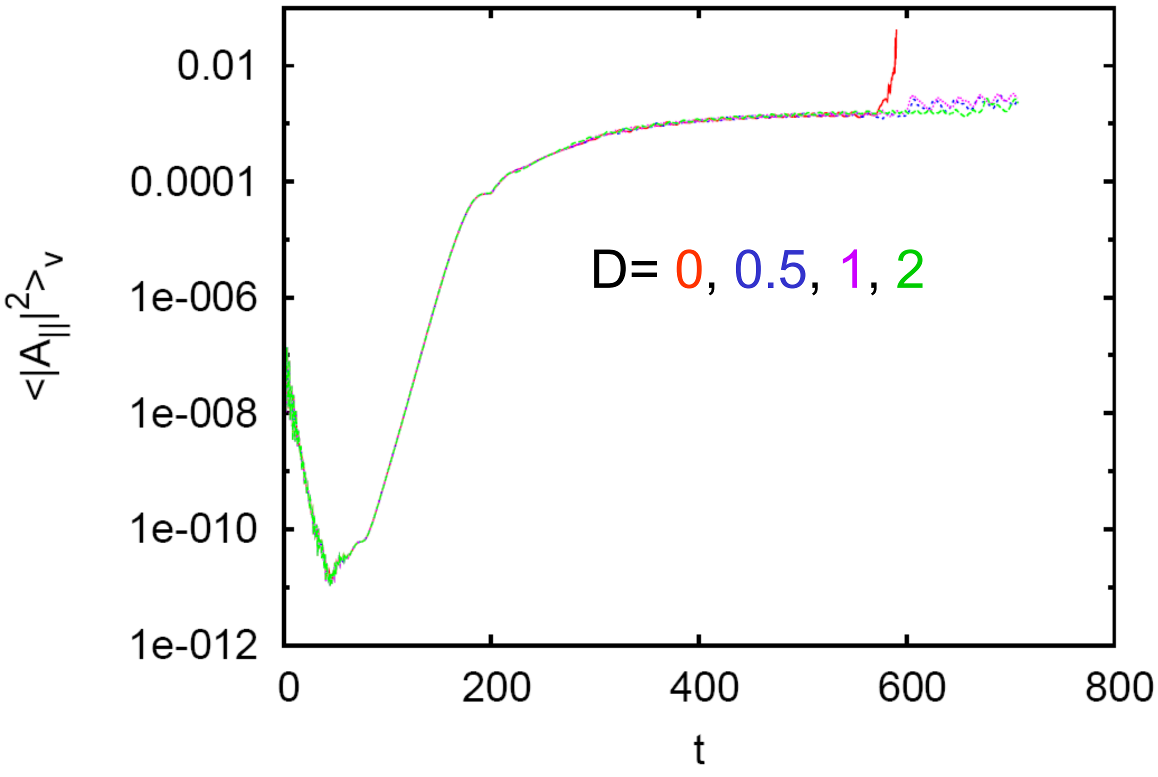
# Impact of Adding Dissipation at High k

R J Akers et al, IAEA FEC, Geneva, October 2008 EX/2-2

Use hyperviscosity for high k dissipation, parameterised by D

- no impact on linear physics
- improves convergence
- “saturation” insensitive to D

but what are we throwing away?

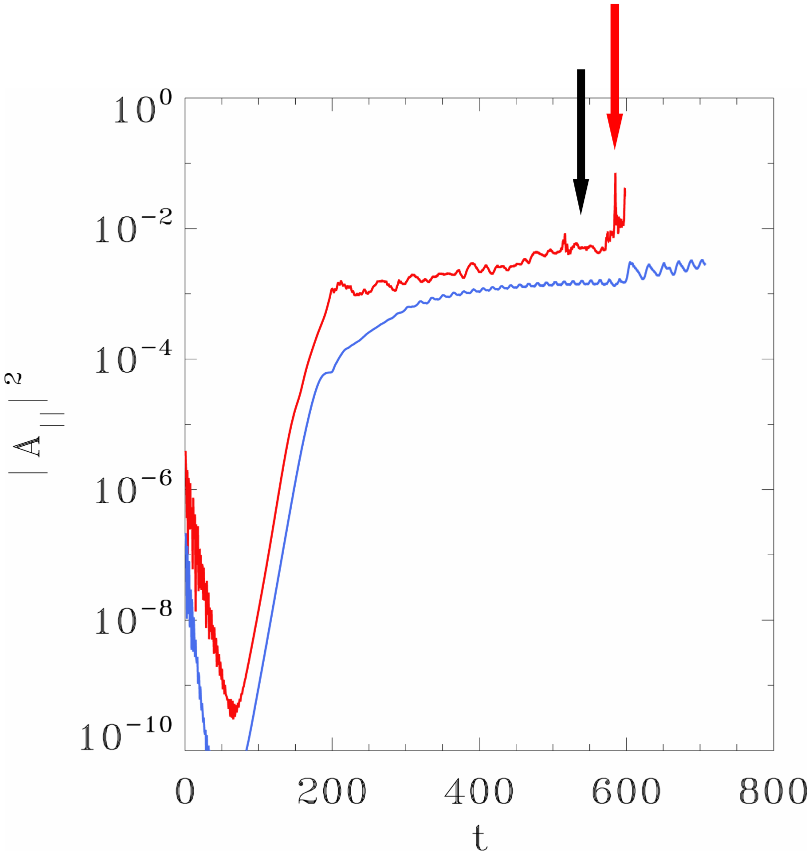


# Nonlinear Electron Heat Flux

D J Applegate

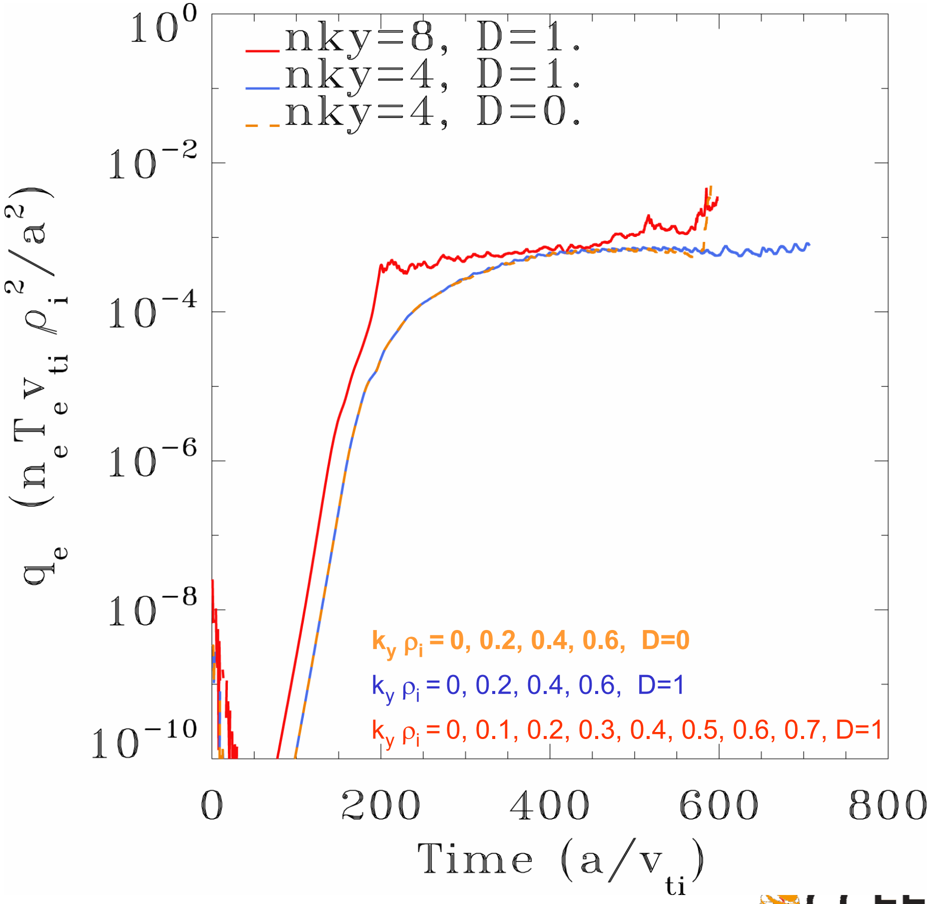
Hyperviscosity smoothes high $k_x$

- spike events reappear at nky=8



$A_{||}$ contribution dominates $q_e$

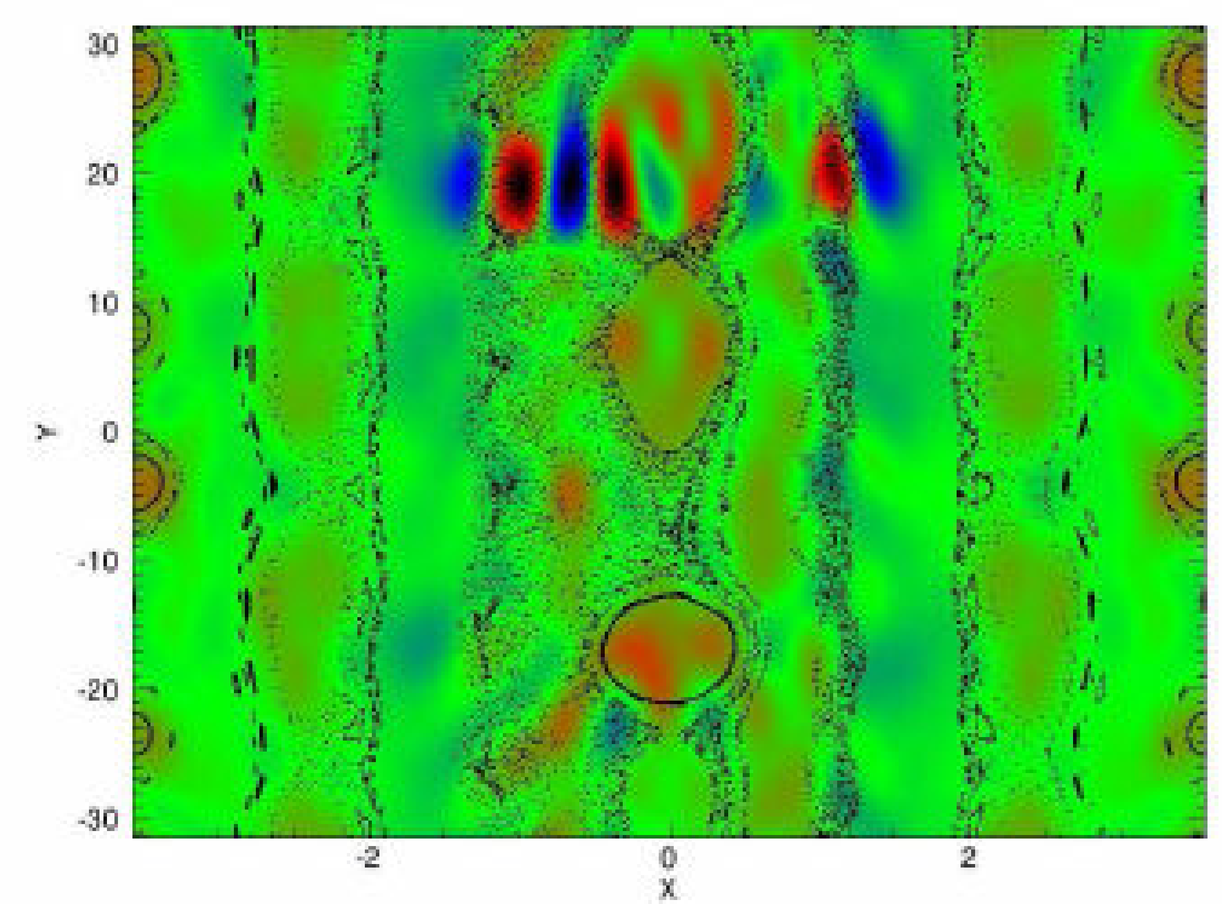
- low heat fluxes at “saturation”



# Poincaré Plot and $\delta j_{||}$ contours at $\theta=0$

D J Applegate

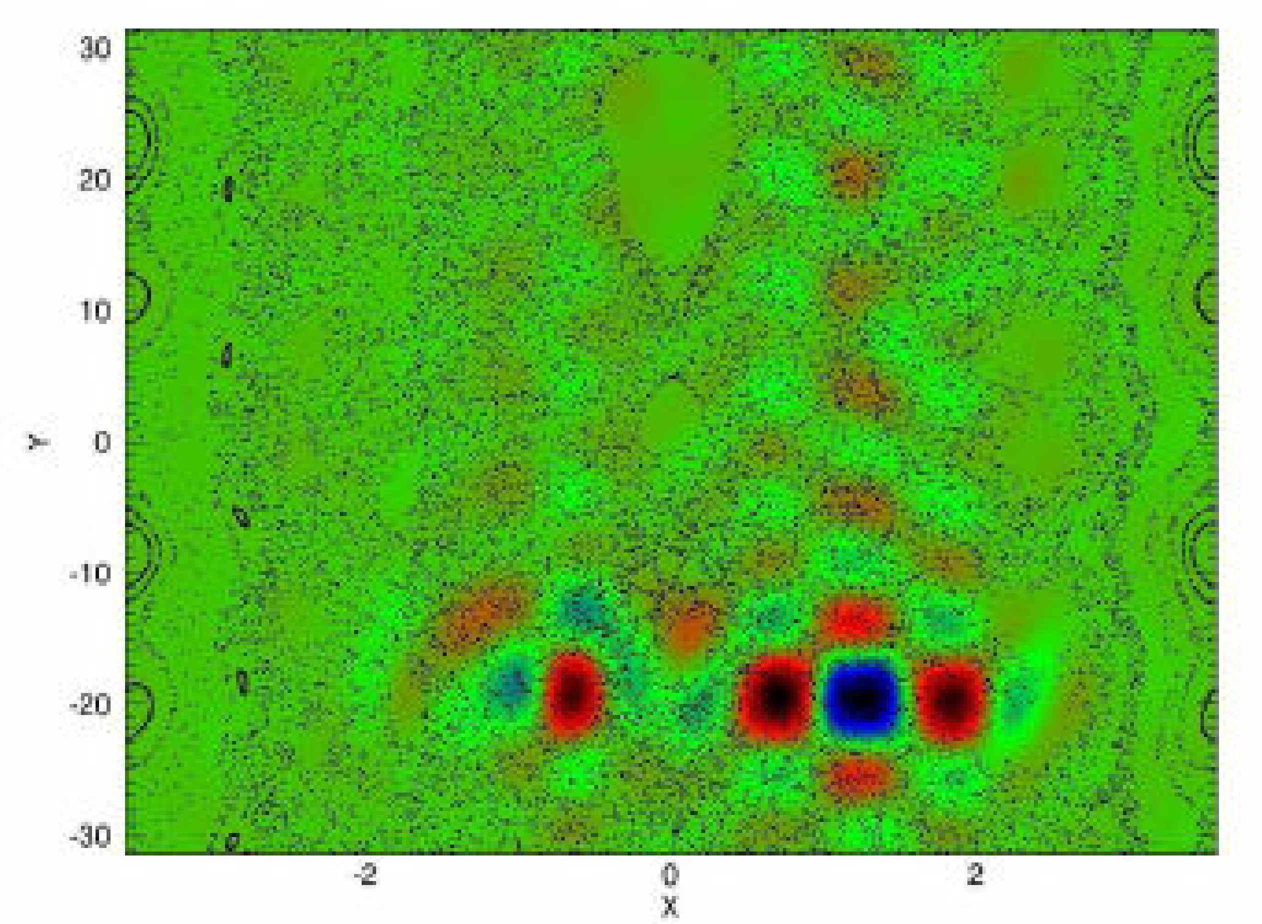
before spike event, t=532



# Poincaré Plot and $\delta j_{||}$ contours at $\theta=0$, $t=598$.

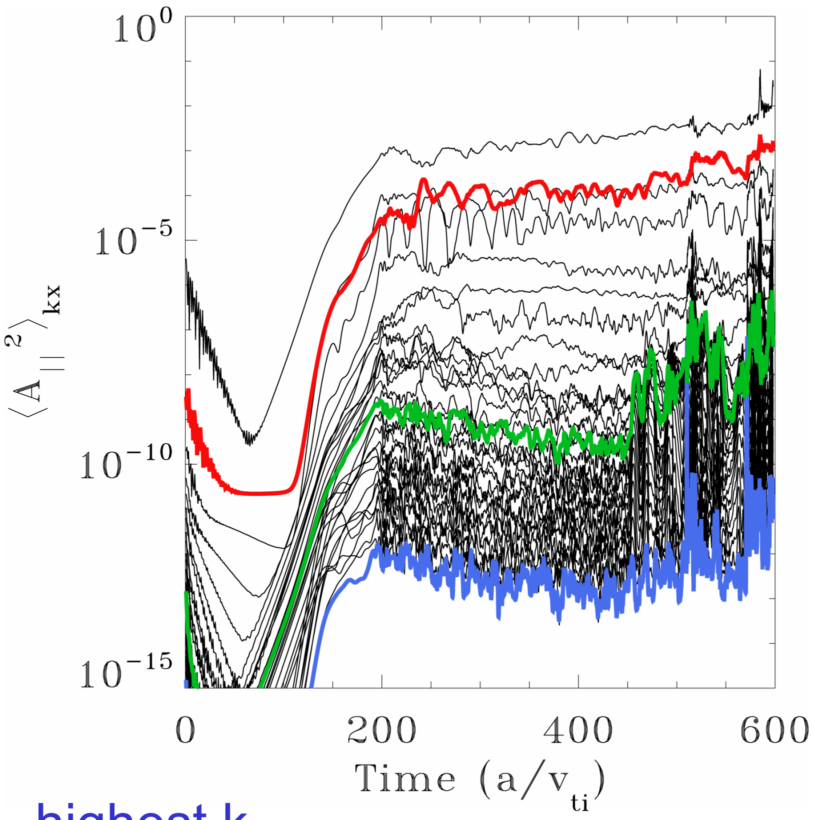
D J Applegate

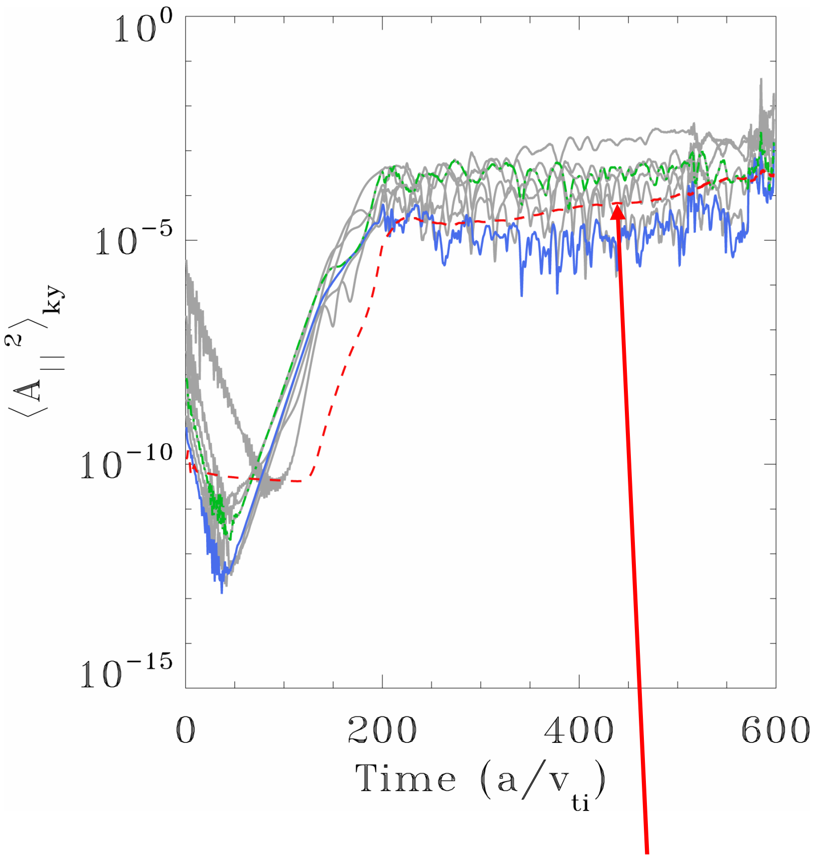
after spike event perturbed field wanders further, transport ↑



# $A_{||}$ Spectra for nky=8 Simulation

Spikes most evident at high k, but are controlled by D





highest k

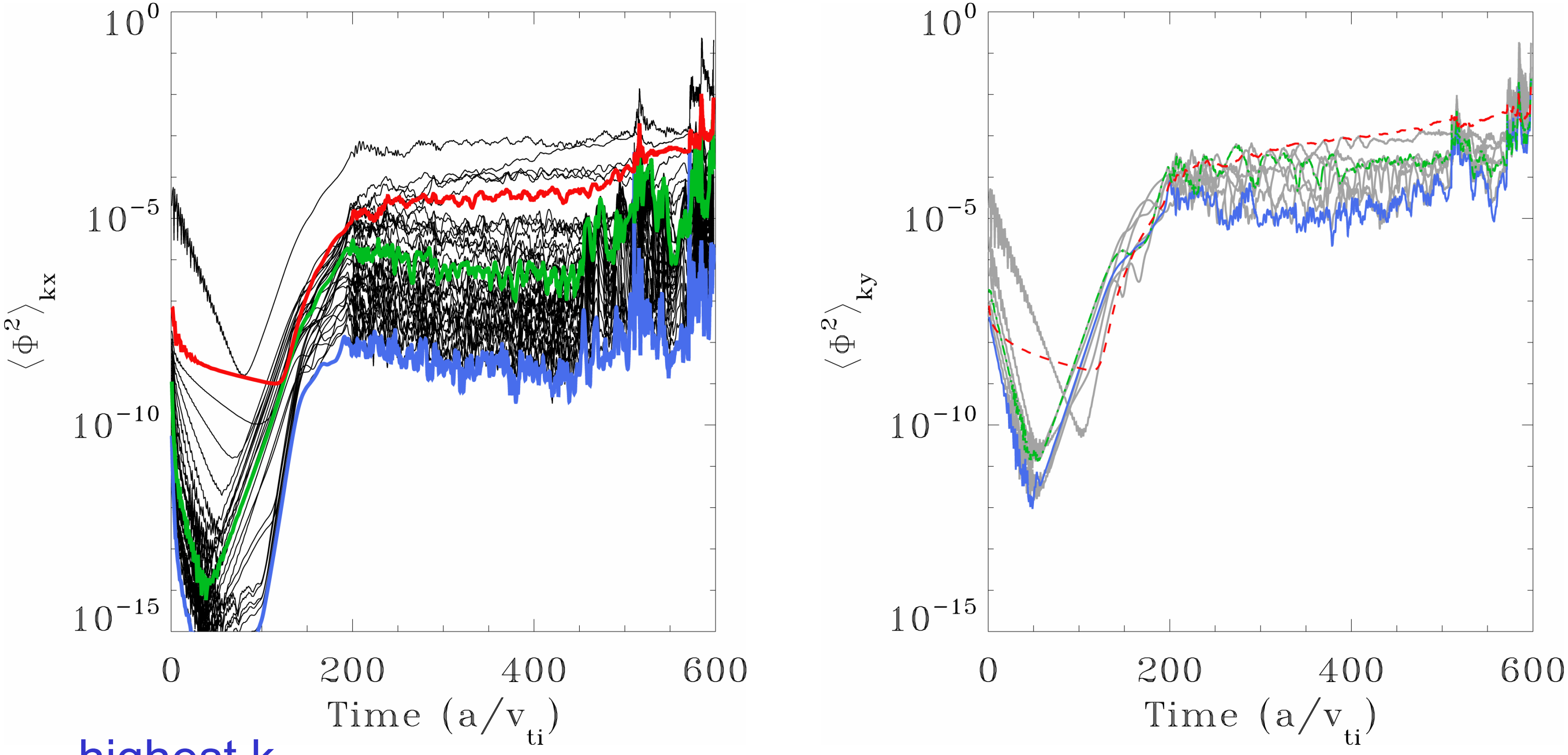
middle k

lowest finite $k_x$, or $k_y$=0

steady growth in zonal modes

# * Φ Spectra for nky=8 Simulation

Spikes most evident at high k, but suppressed by D



highest k

middle k

lowest finite $k_x$, or $k_y$=0

# Fidelity Issues

D J Applegate

Convergence?

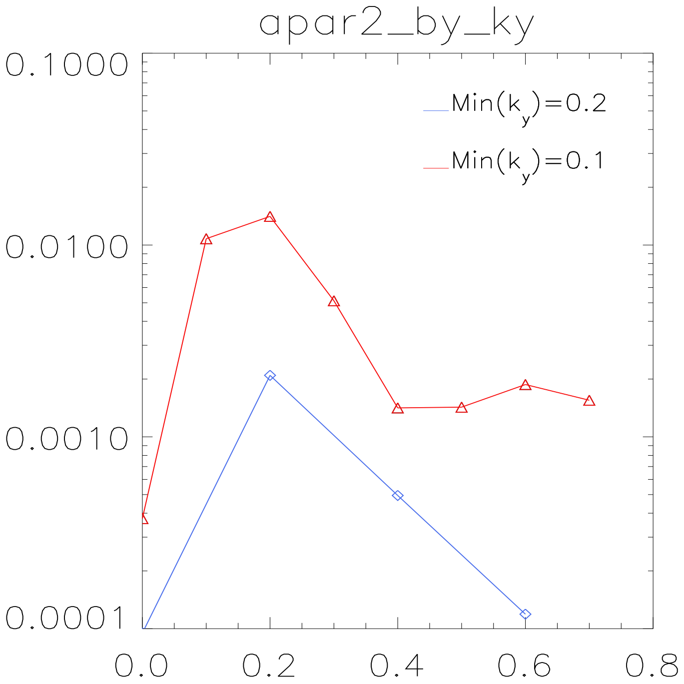
- saturation sensitive to Min($k_y$), and we need to go lower in $k_y$!
- what causes the high k spikes?

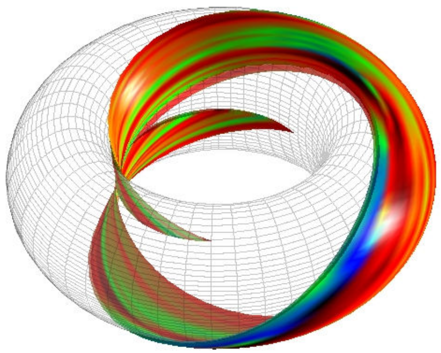
are we dissipating important physics?

Flux-Tube equilibrium?

- as reduce Min($k_y$ $\rho_i$ ), we go to low n
- $s^{SIM} = 5\ s^{MAST}$ so $L_x$ artificially small
- at lower $k_y$ and s, flux-tube gets fatter, to challenge local approximations

More work needed!



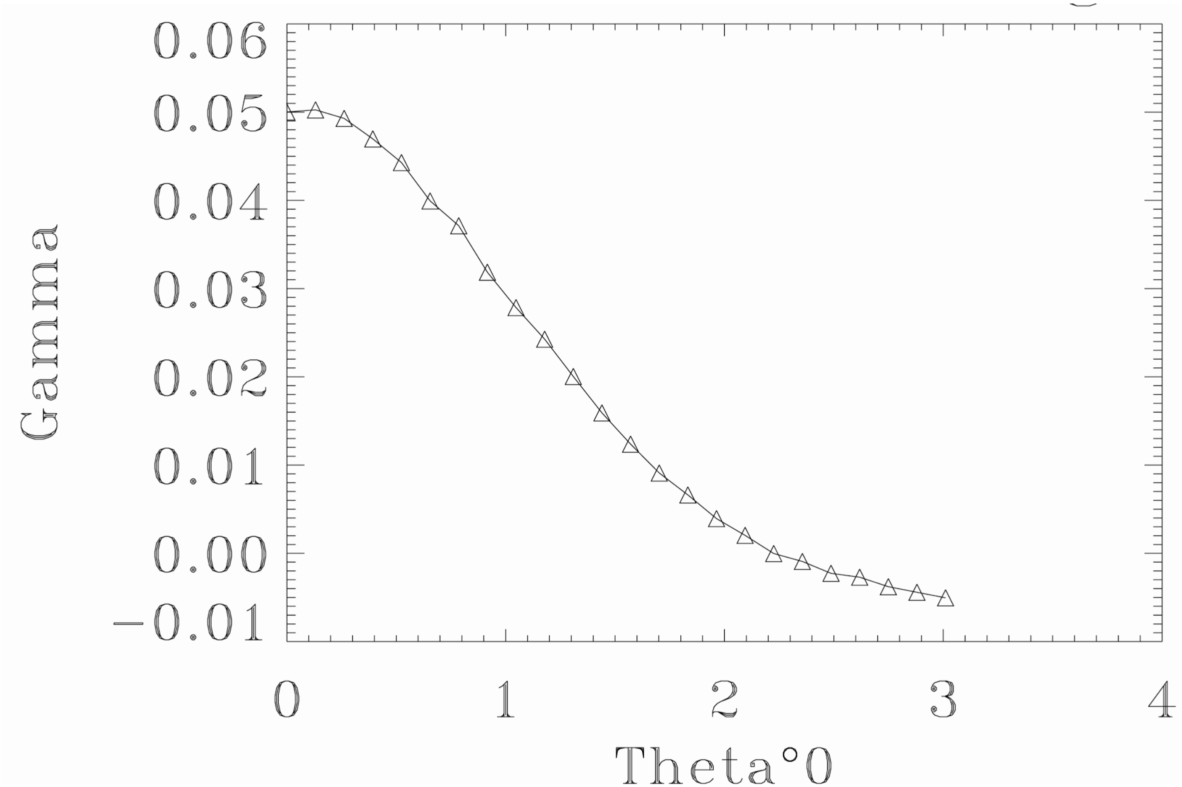


# Do Microtearing Modes Matter in MAST Anyway?

D Dickinson, York

Impact of FLOW SHEAR on microtearing modes?

- $\gamma_E > \gamma_{lin}$ so will they be suppressed?
- slab drive may make suppression more difficult
- almost done



# Conclusions

Microtearing modes from GS2 simulations of MAST are complicated!

- trapped and passing particles contribute drive with $dT_e/dr$
- insensitivity of $\gamma$ to energy dependent collision frequency is puzzling
- µtearing specific neither to ST geometry nor to GS2!
    - linear benchmark?
    - map out where µtearing important

Limited comparisons with analytic theory so far.

- do better in easier limits?

Preliminary nonlinear simulations for MAST mid-radius are interesting, but:

- more work needed to test convergence
- what is happening at high k?
- local flux-tube equilibrium is challenged if n gets too small!
    - easier equilibria?
    - impact of FLOW SHEAR?