Gyrokinetic Microtearing Studies

C M Roach

summarising work involving many collaborators:

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This work was funded by the United Kingdom Engineering and Physical Sciences Research Council and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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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:

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

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,

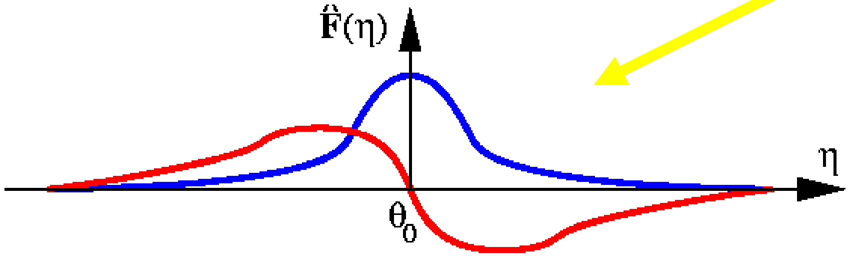
θ_0 is the ballooning parameter.

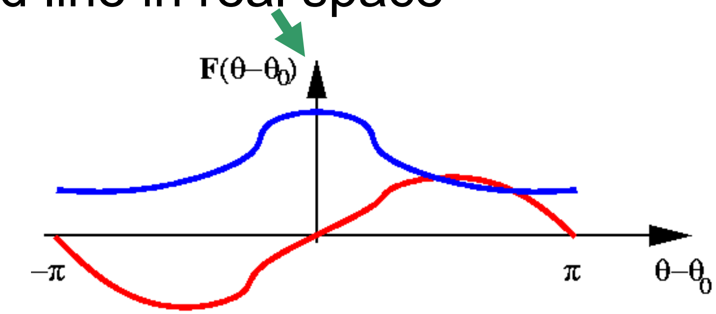
$$\hat{F}(\eta) \to 0 \quad \text{as } \eta \to \pm\infty$$

$\hat{F}$ eigenfunctions are either even or odd in η, about η= θ_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 $\delta\mathbf{B} = \nabla\times\delta\mathbf{A}$

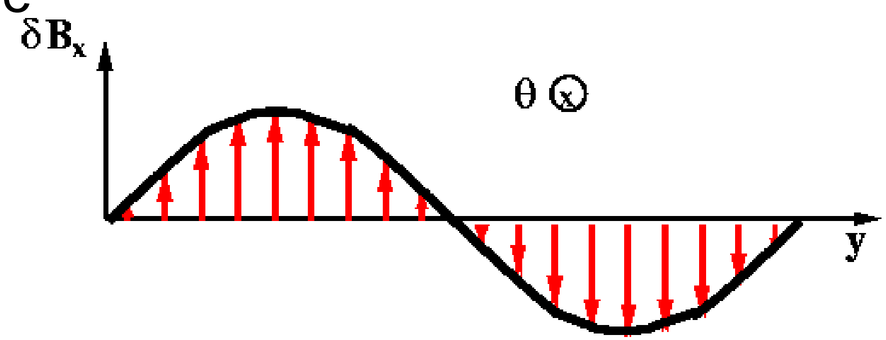
$\Rightarrow$ radial component: $\delta B_x = \partial A_{||}/\partial y = ik_y A_{||}$

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

$\Rightarrow$ δB_x same sign along equ'm field line

$\Rightarrow$ δB_x sinusoidal in y at fixed θ

$\Rightarrow$ 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 β 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 μ-tearing may explain electron transport in NSTX

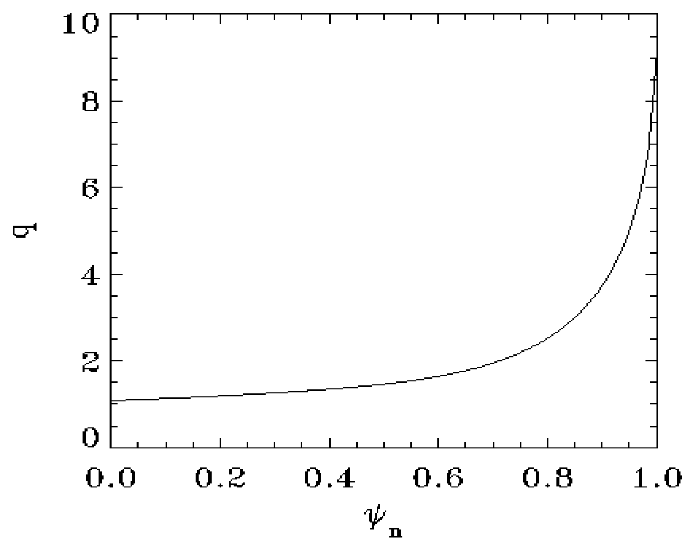
- K L Wong *et al*, Phys. Rev. Lett. **99**, 135003 (2007)

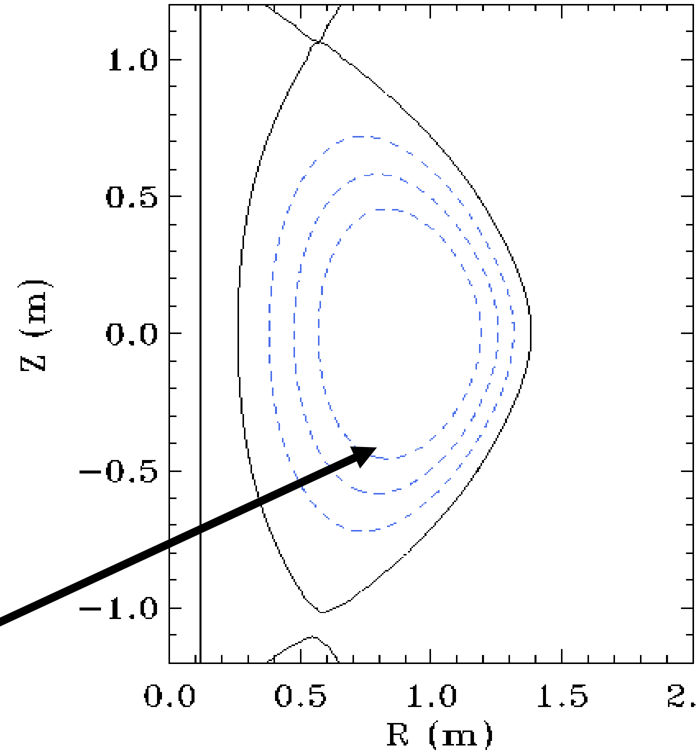
Edge plasmas in ASDEX-Upgrade have μ-tearing modes

- 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 Ψ_n=0.4,
β_e=0.05, q~1.35 $T_i \sim T_e$, a~0.3m, R~0.9m $\Rightarrow$ R/a~3

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

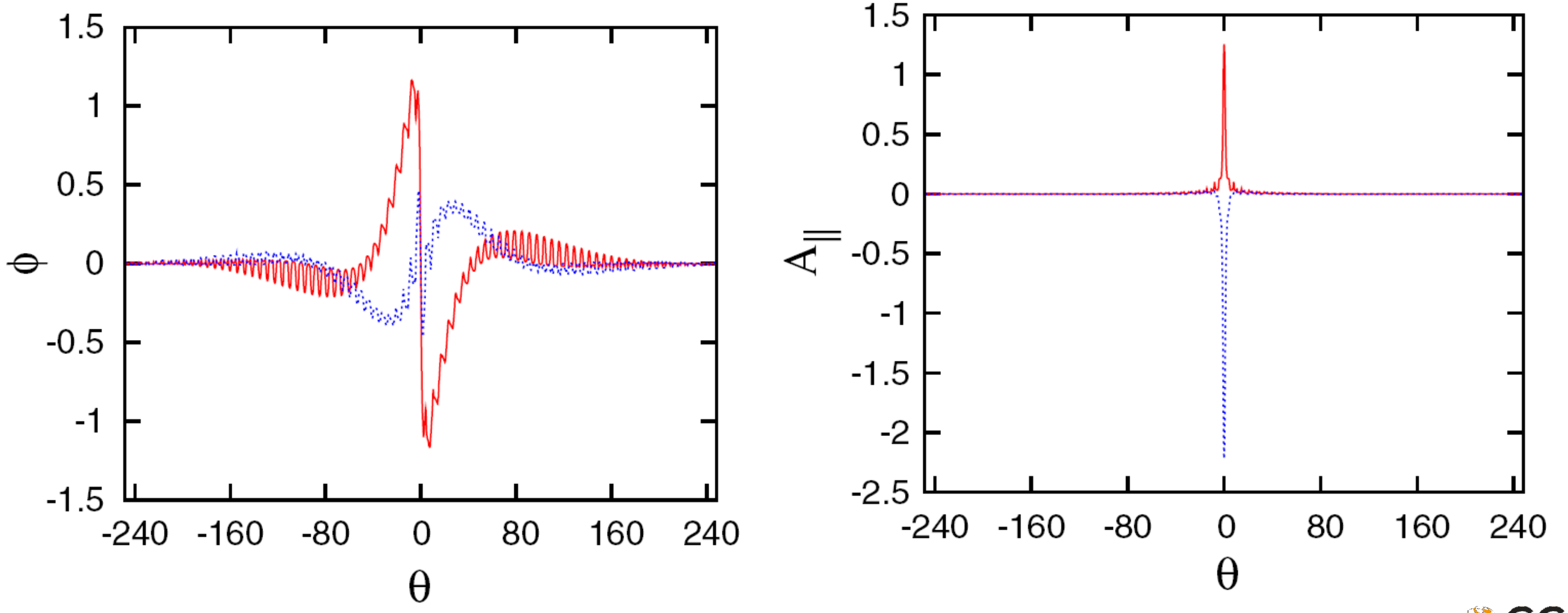
Tearing Parity Modes at ρ_i scale

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

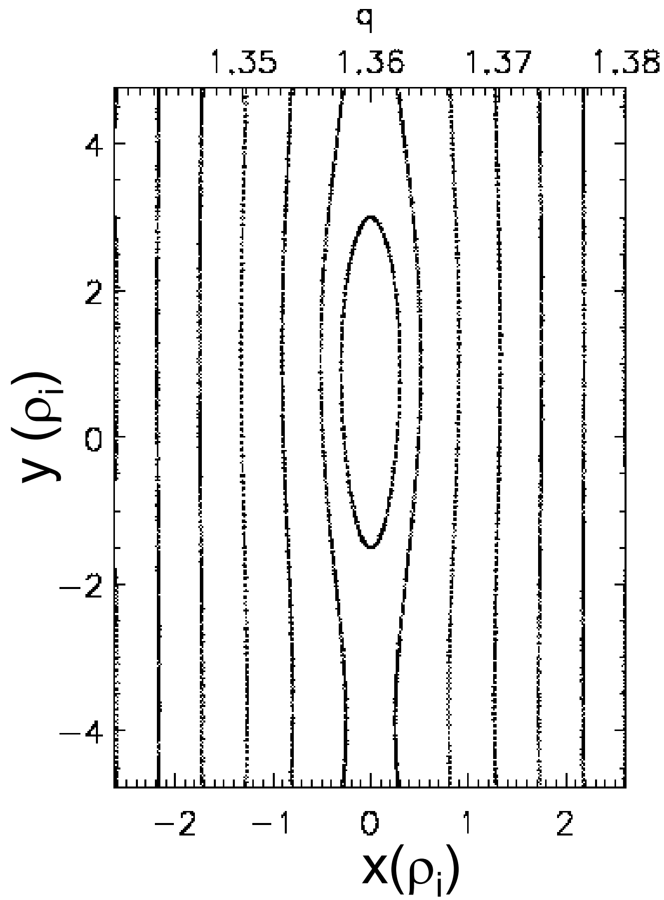


Visualising Micro-tearing Mode in Real Space

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

∇T_e microtearing drive discovered in cylinder

- *Hazeltine Dobrott and Wang (1975):* kinetic, collisions key, any ν_e/ω

Further slab calculations confirm ∇T_e drive at high ν_e/ω

- *Drake and Lee (1977), Gladd et al (1980):* kinetic, *Hassam (1980):* fluid

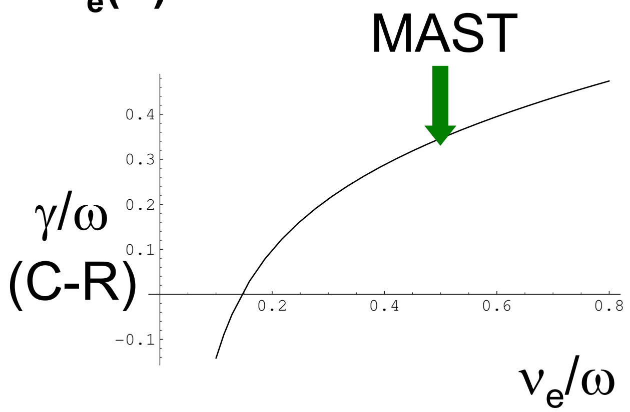
=> collisional slab drive requires energy dependent $\nu_e(E)$

Kinetic calculations in toroidal geometry (large R/a), for low ν_e/ω

- *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 ν_e/ω ~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 ν_e, ∇T_e and ∇n_e
- **sensitive** to β, ∇p, s
- **insensitive** to ion parameters ν_i and ∇T_i and $\delta \mathbf{B}_{||}$
- current layer width ~$O(\rho_i)$

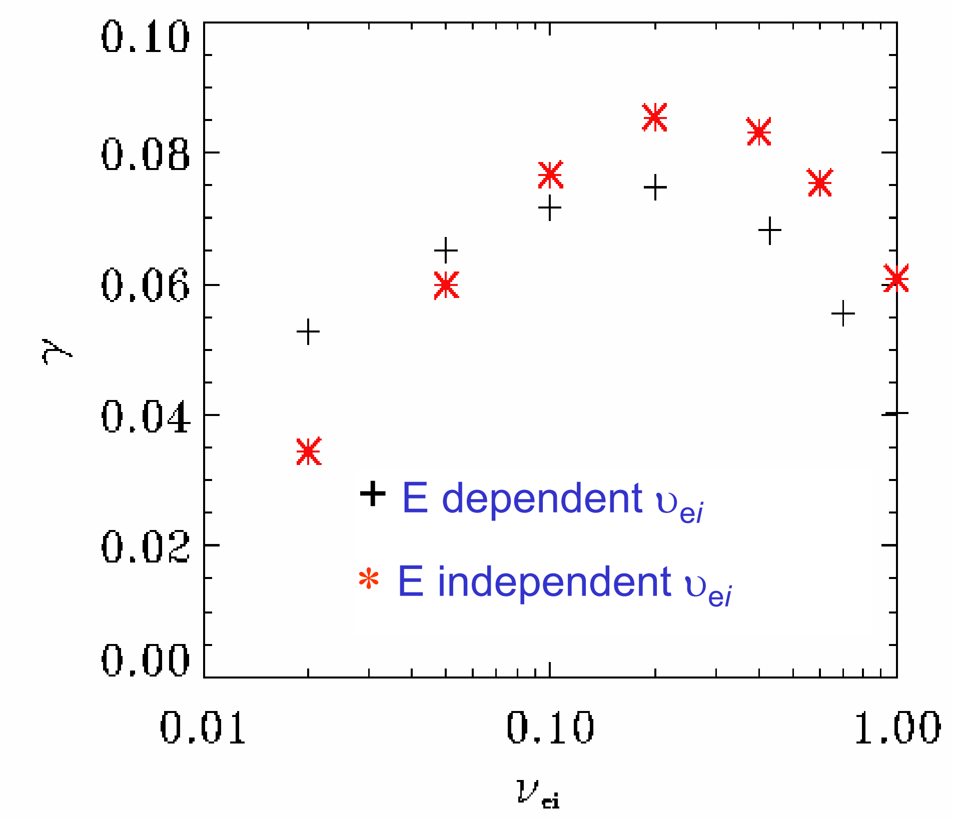
[1] DJ Applegate *et al*, PPCF **49**, 1113 (2007) and PhD Imperial College (2006)

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



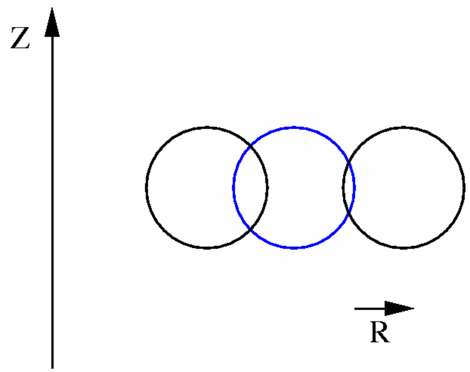
Modest affect on tearing γ

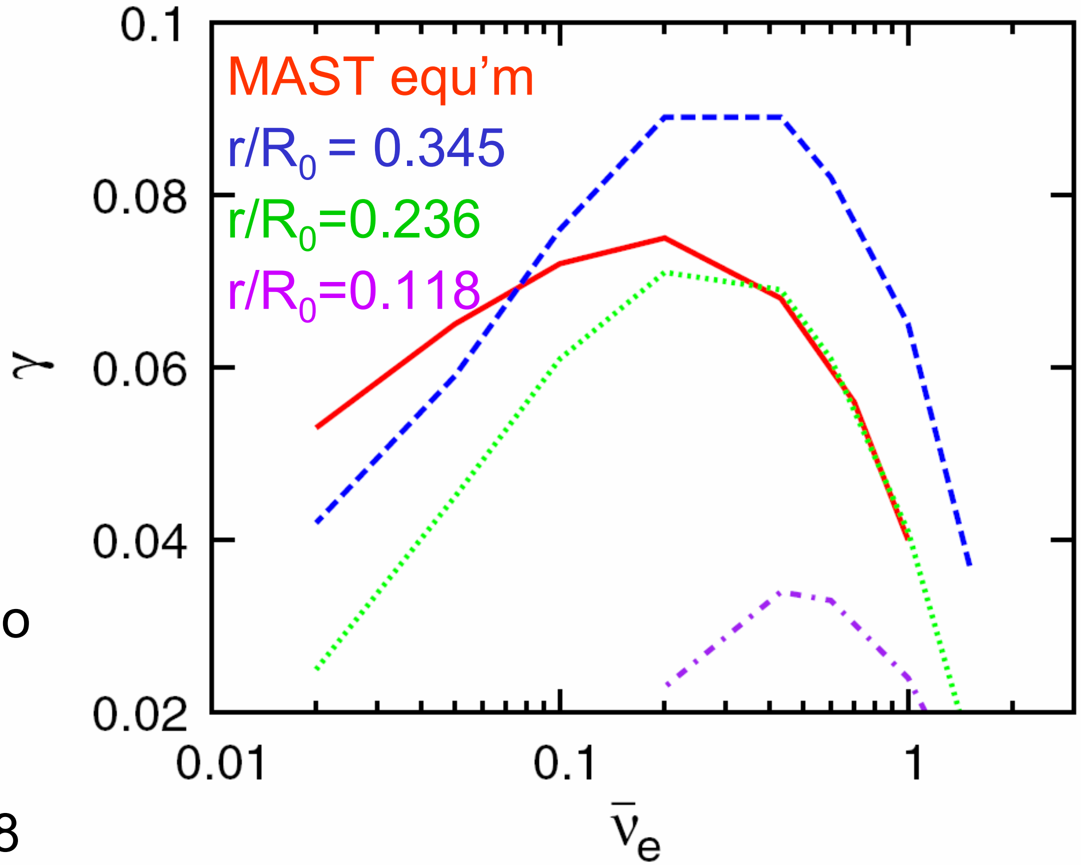
➢ not consistent with analytic drive models!

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

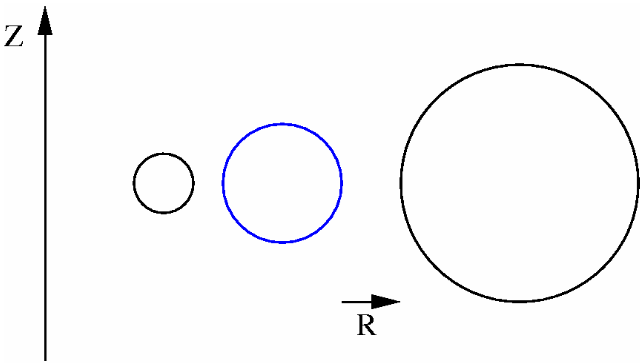
- $\gamma \downarrow$ as $r/R_0 \downarrow$
- still unstable at r/R_0=0.118

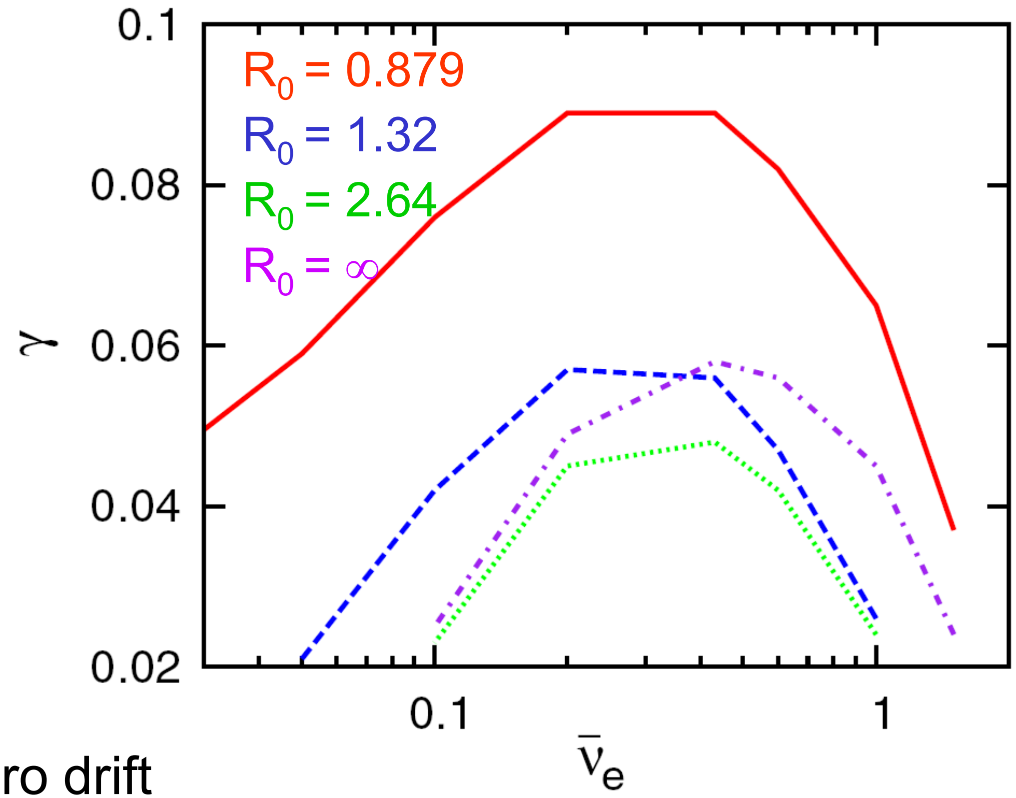
⇒ μtearing may appear at conventional aspect ratio

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





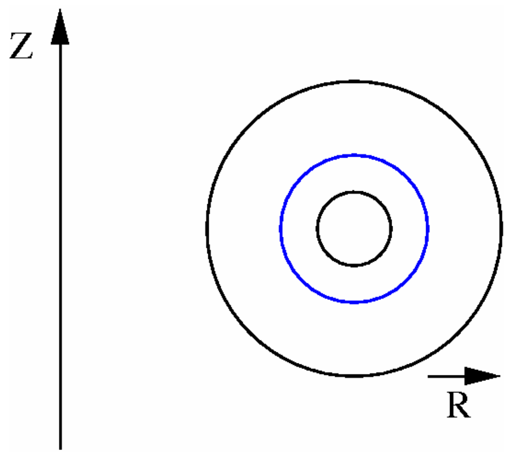
Mode survives at $R_0 = \infty$ i.e. zero drift

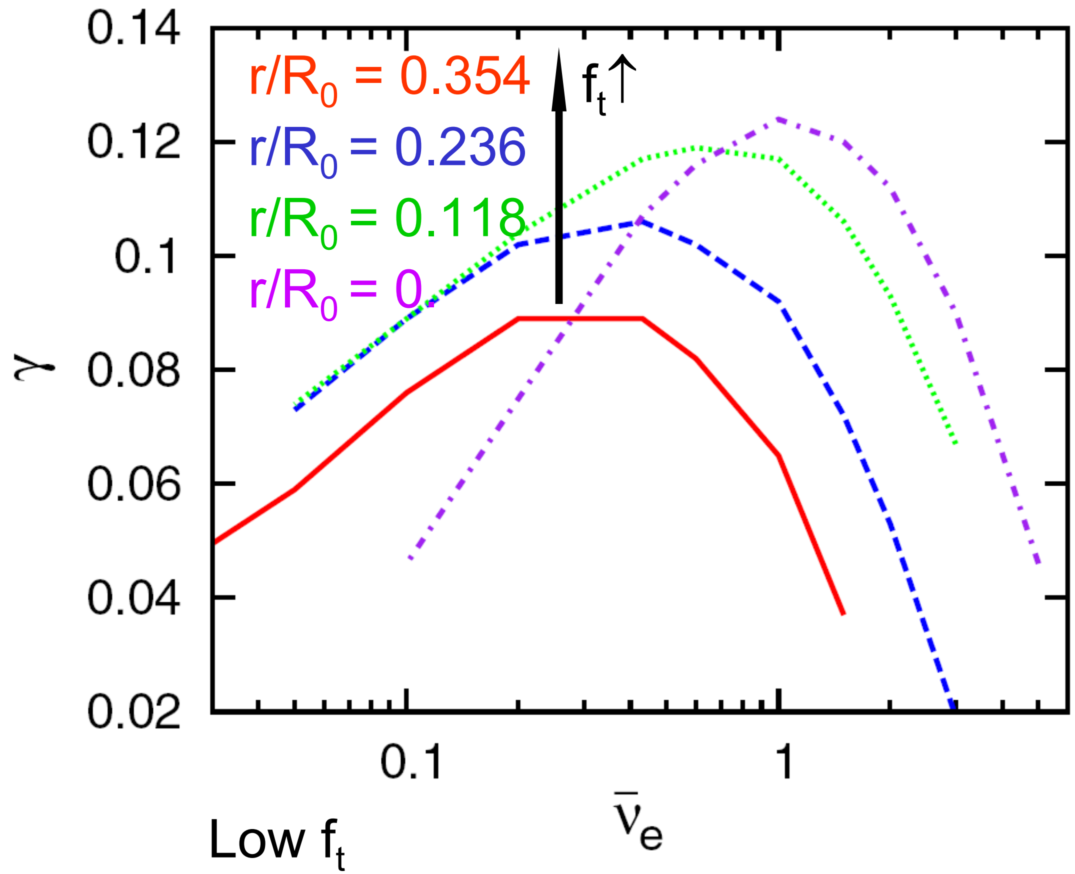
- mode has slab drive

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 ν_e
- $\gamma \downarrow$ at high ν_e (fewer passing e)

Low f_t

- γ 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-α 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

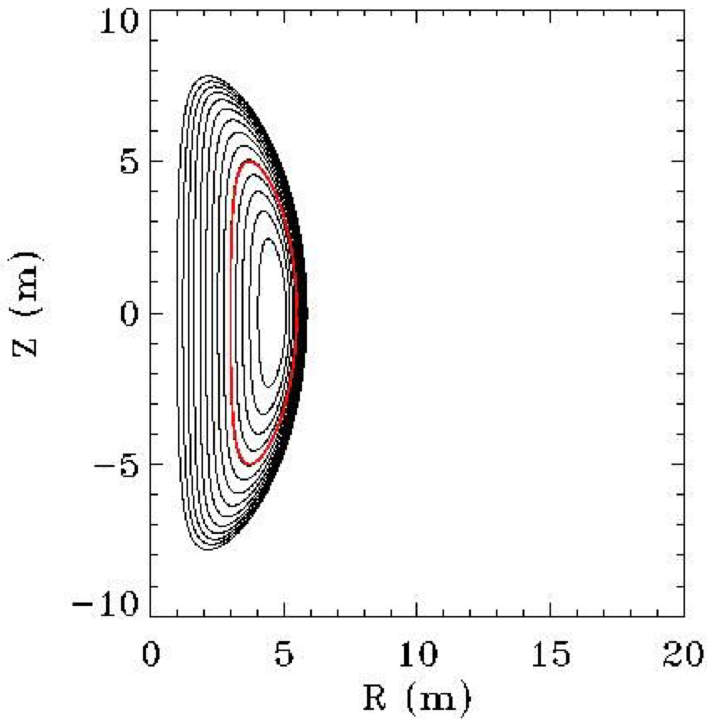
see H R Wilson *et al*, Nuc Fus 44, 917 (2004)

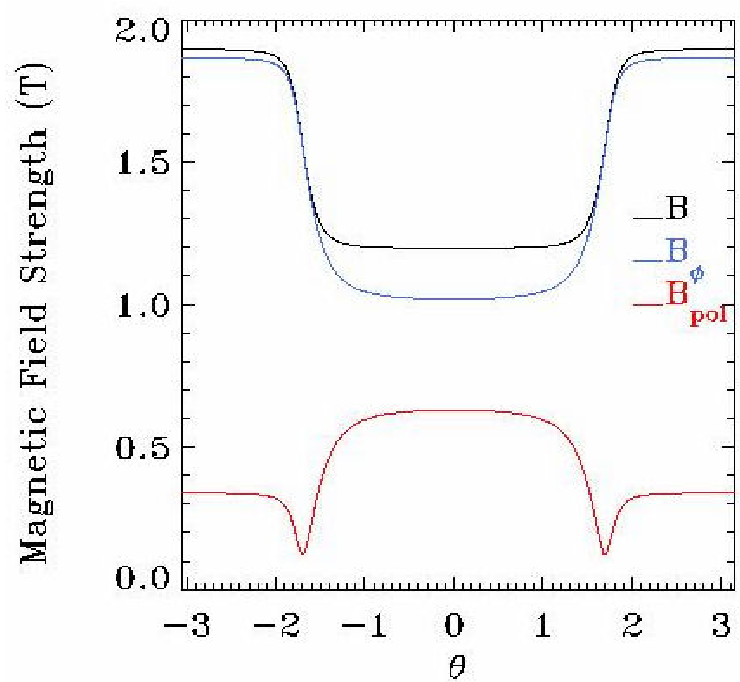
Conceptual Culham ST Power Plant (STPP), 1GW electrical, β=0.59

GS2 used for microstability analysis of mid-radius flux-surface, Ψ_n=0.35.

Equilibrium features:

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





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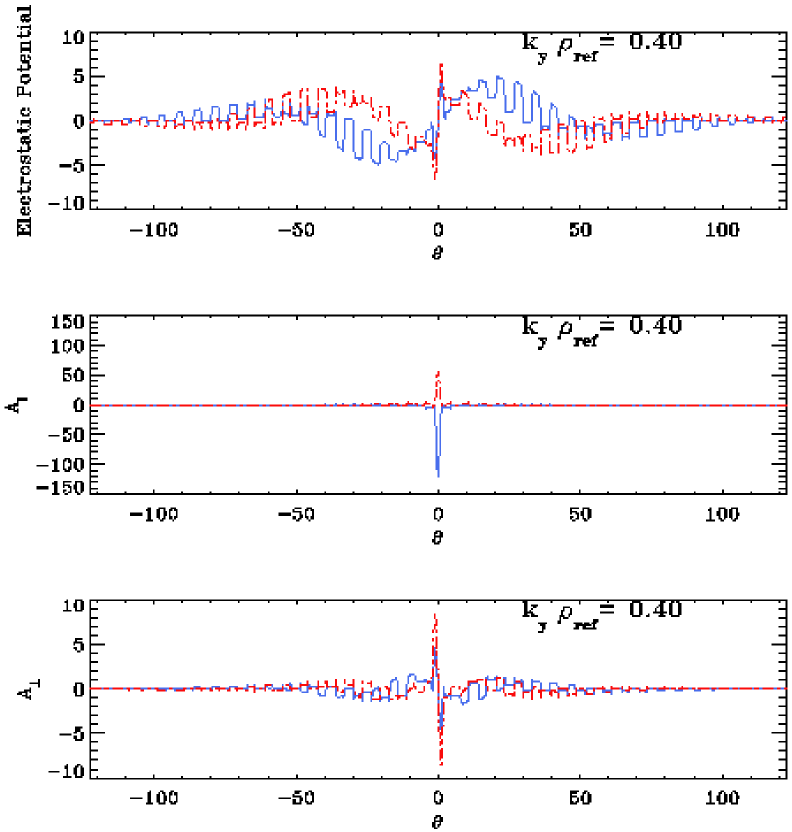
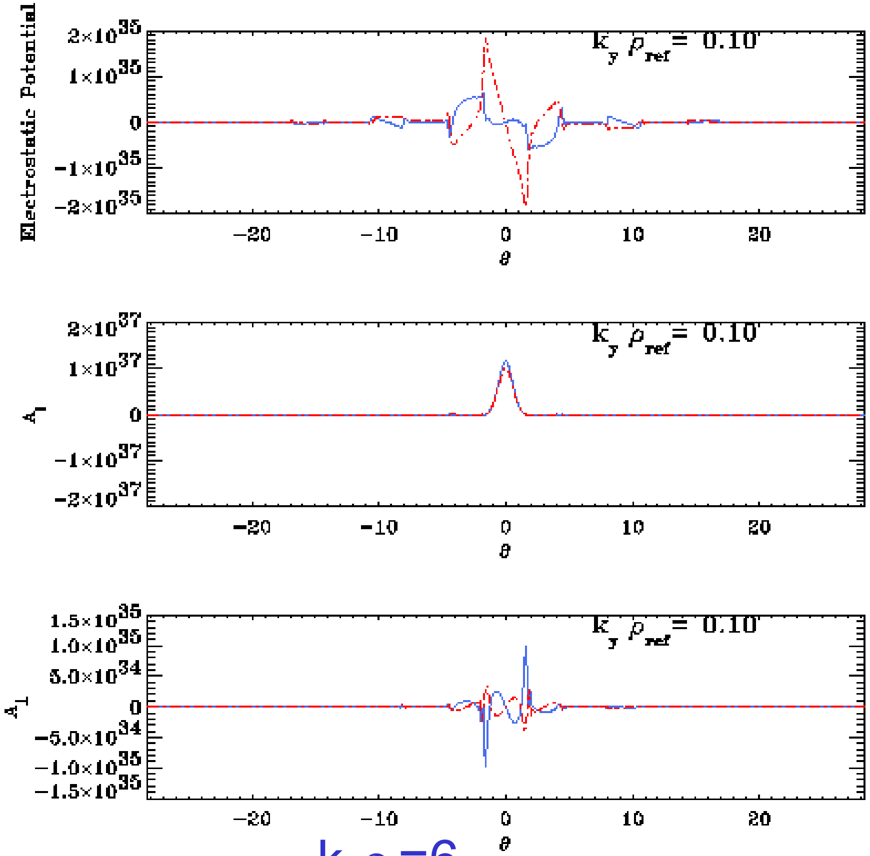
* Microstability Results for Mid-radius Surface in STPP

STPP surface Ψ_n=0.35

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



$k_y\rho_i$=0.4

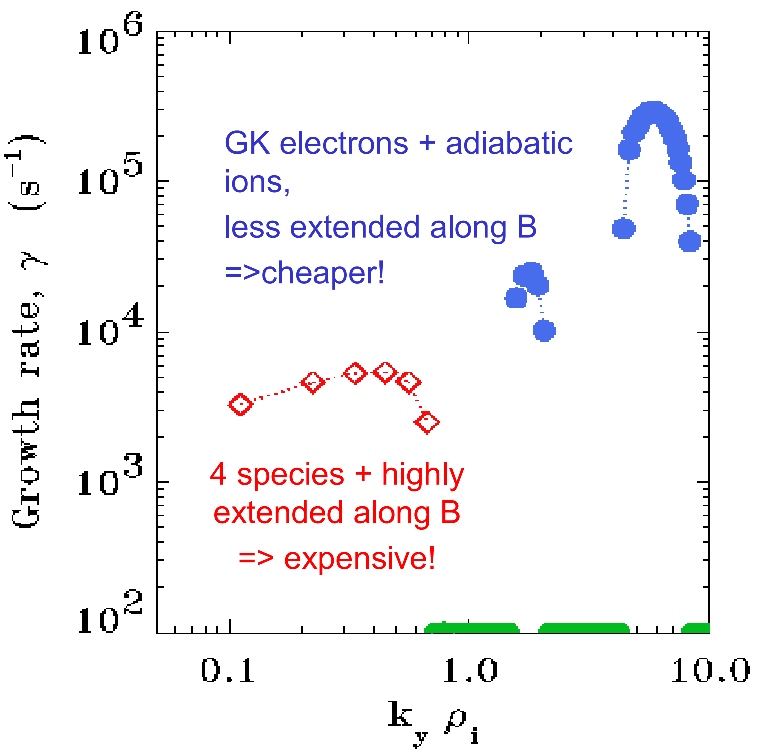


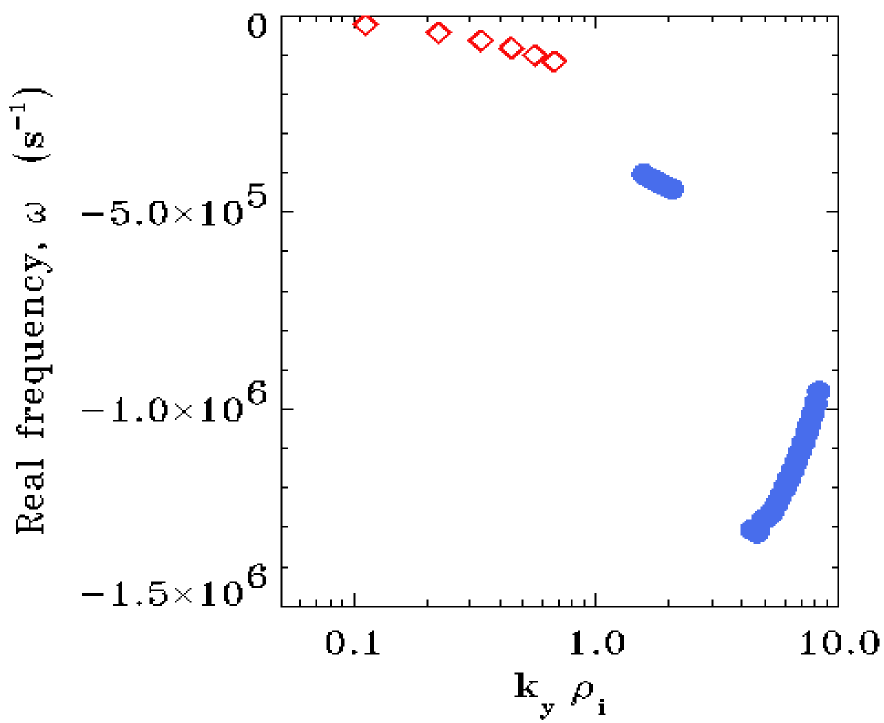
$k_y\rho_i$=6

* Microstability Results for Mid-radius Surface in STPP

STPP surface Ψ_n=0.35

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





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
β	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_θ=32 n_E=8, n_λ~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

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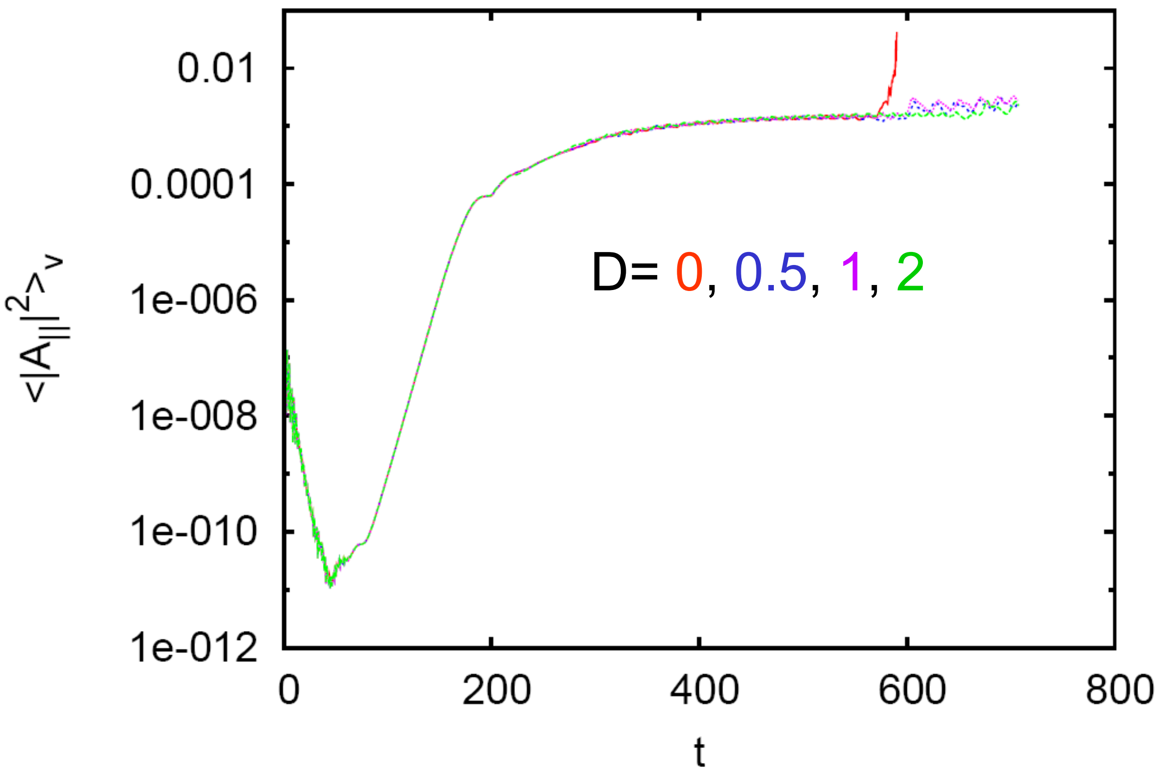
Impact of Adding Dissipation at High k

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?



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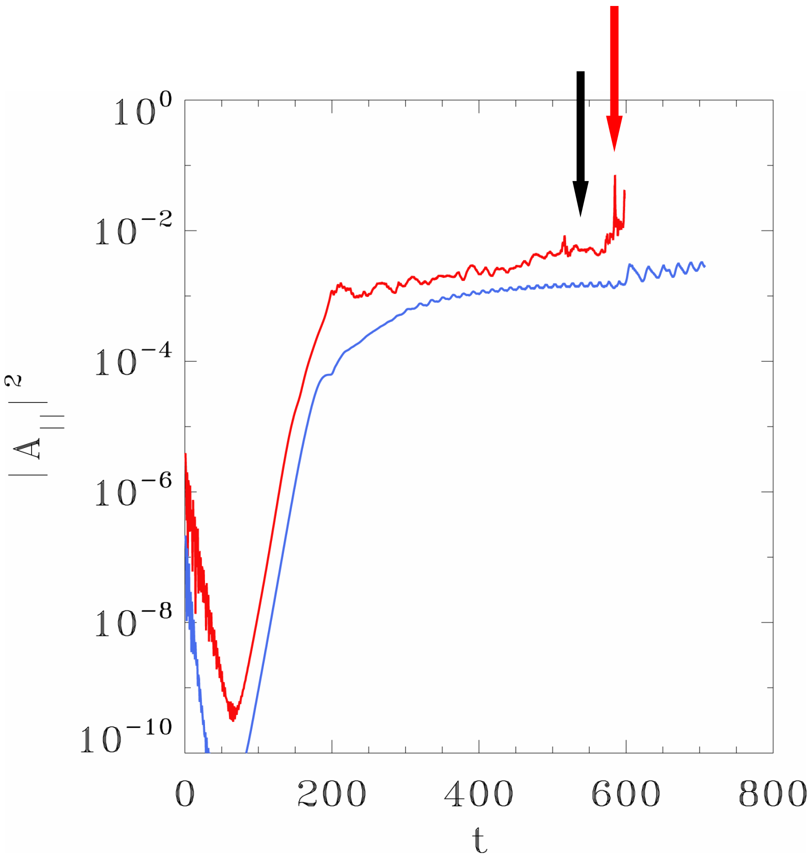
Nonlinear Electron Heat Flux

D J Applegate

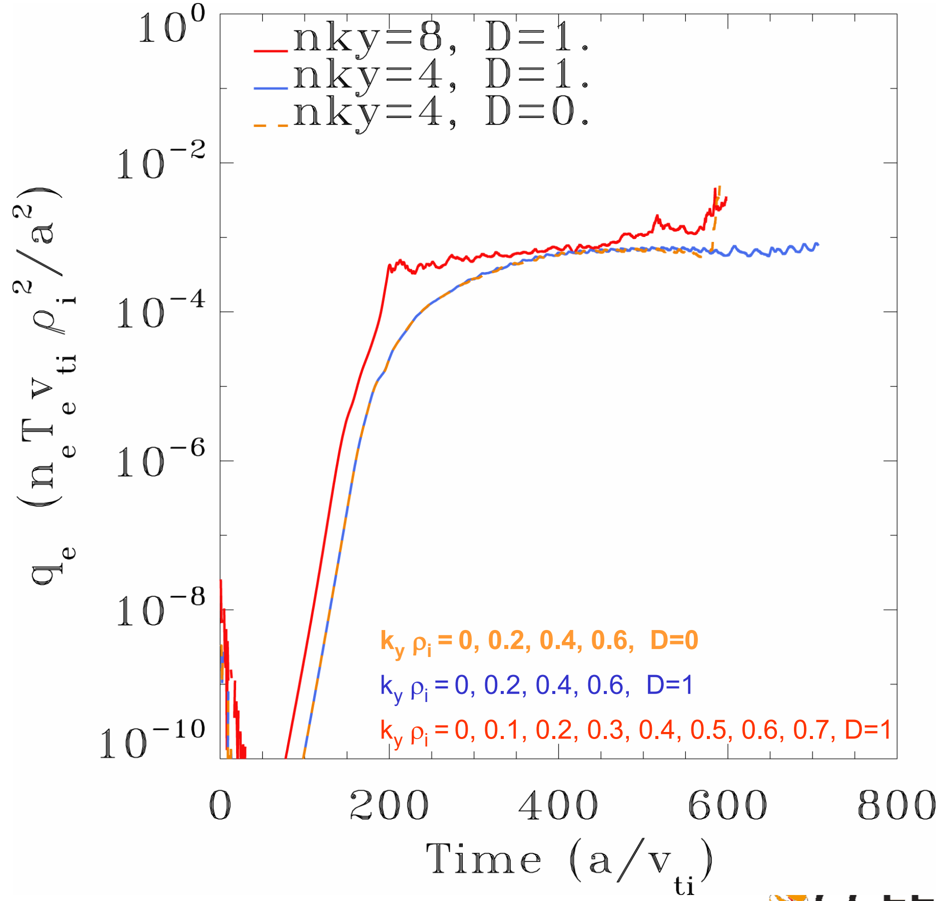
Hyperviscosity smoothes high k_x

- spike events reappear at nky=8



$A_{||}$ contribution dominates q_e

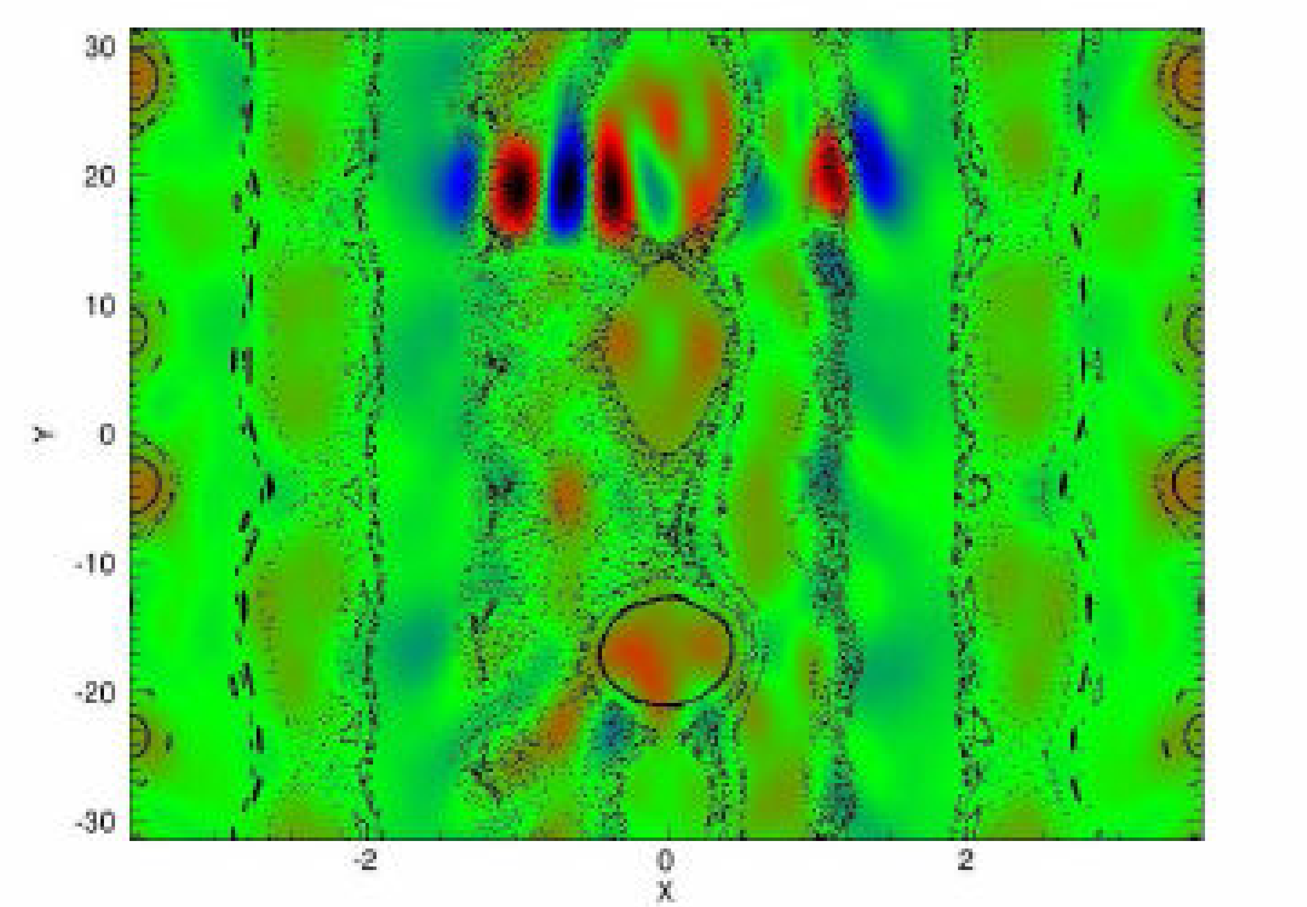
- low heat fluxes at “saturation”



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

D J Applegate

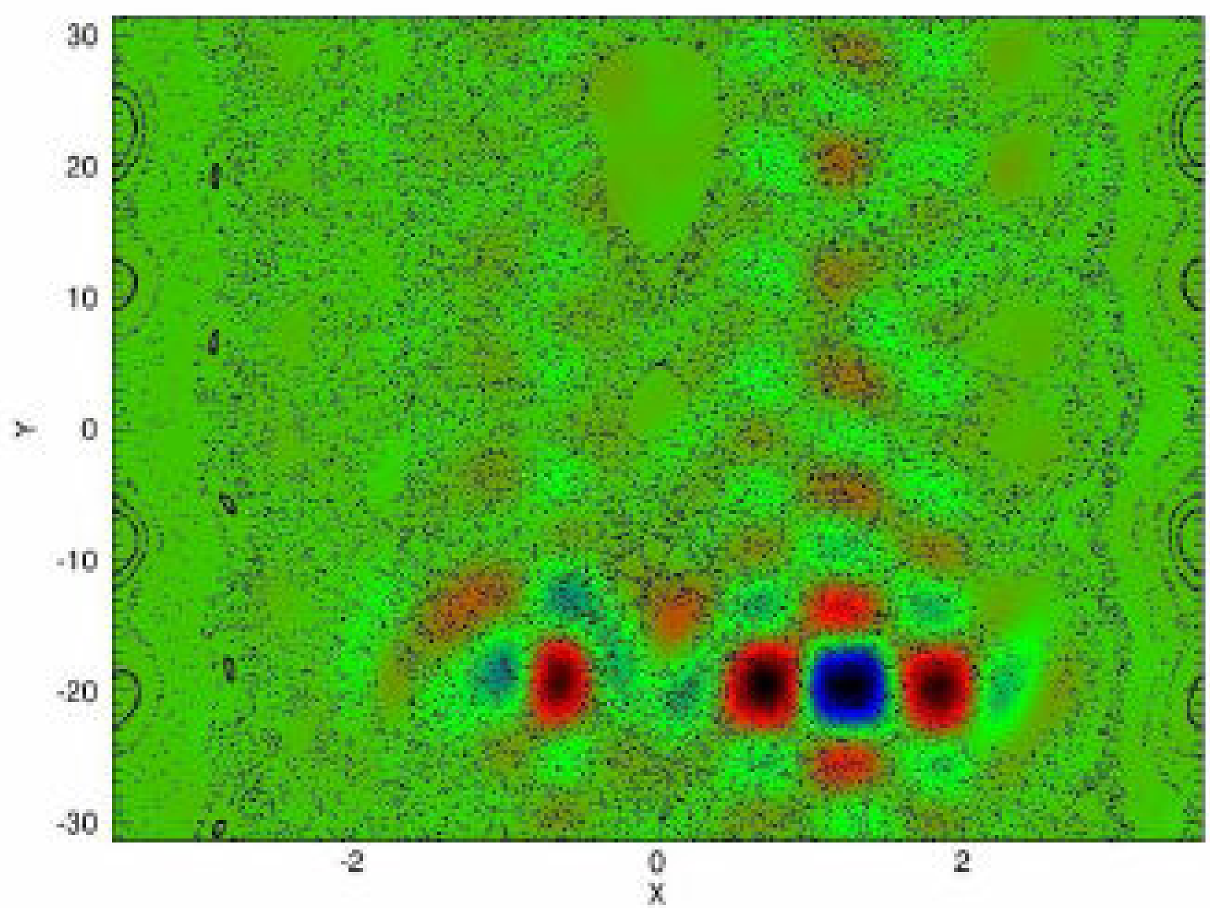
before spike event, t=532



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

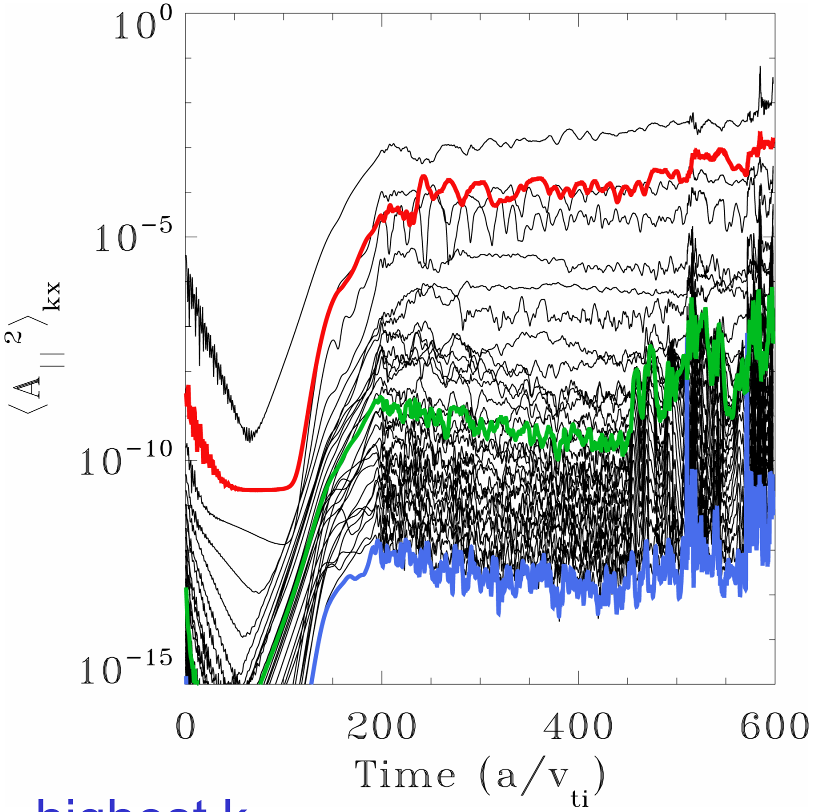
D J Applegate

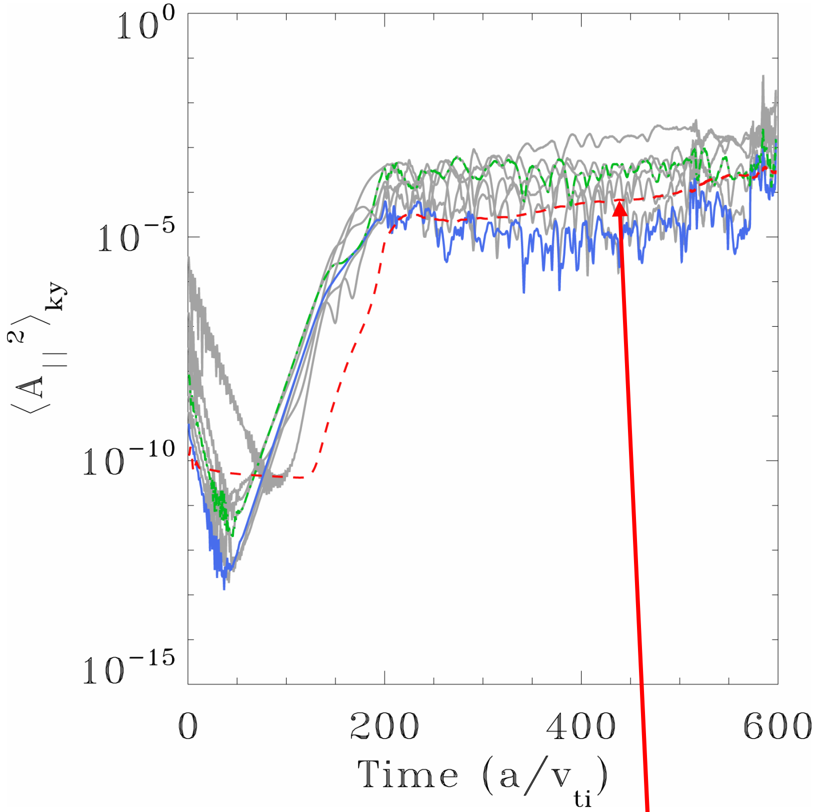
after spike event perturbed field wanders further, transport ↑



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

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





highest k

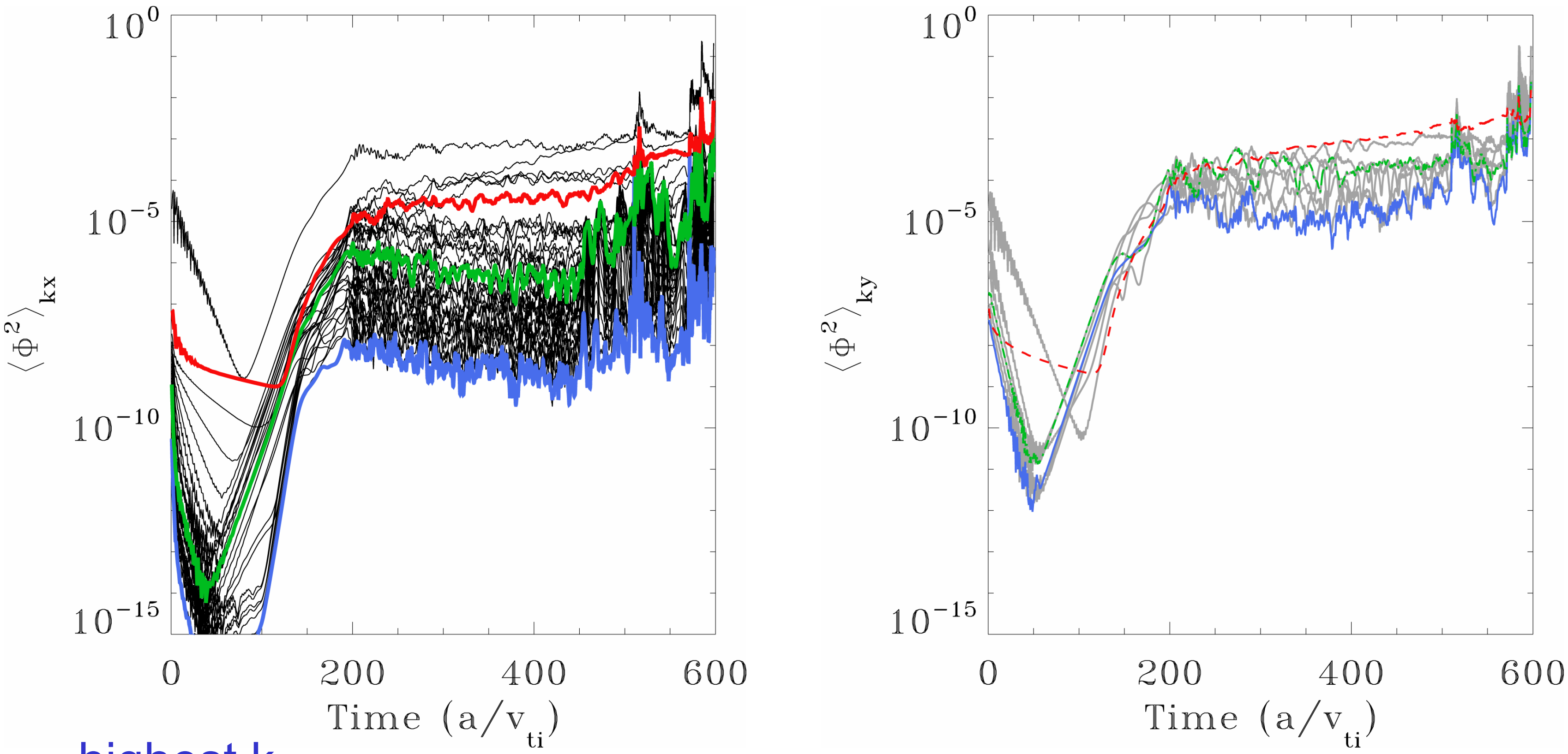
middle k

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?

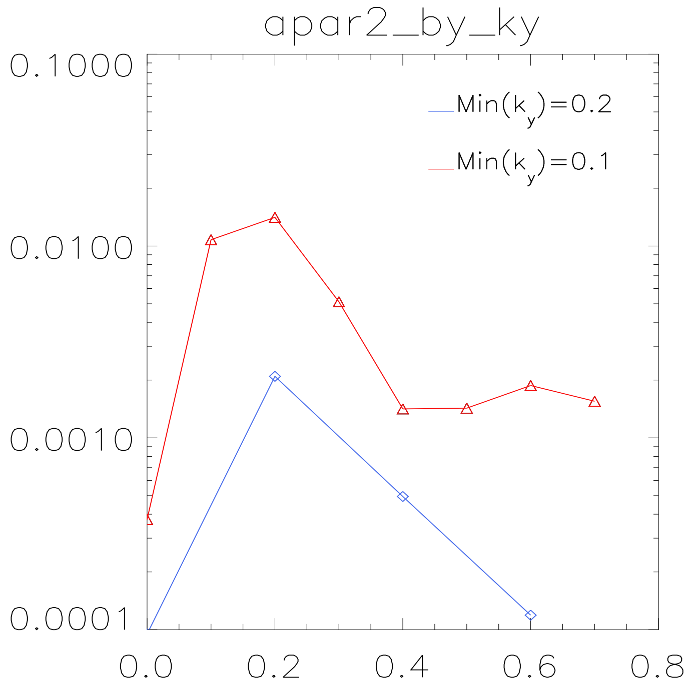
Flux-Tube equilibrium?

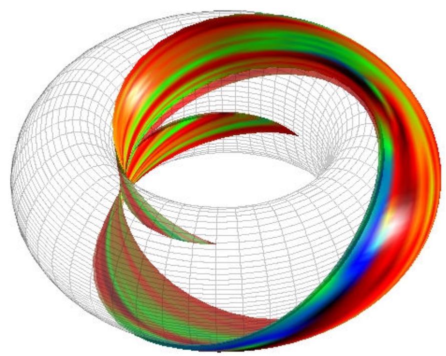
• as reduce Min($k_y\ \rho_i$), we go to low n

• $s^{SIM} = 5\ s^{MAST}$ so L_x artificially small

• at lower k_y and s, flux-tube gets fatter, to challenge local approximations

More work needed!



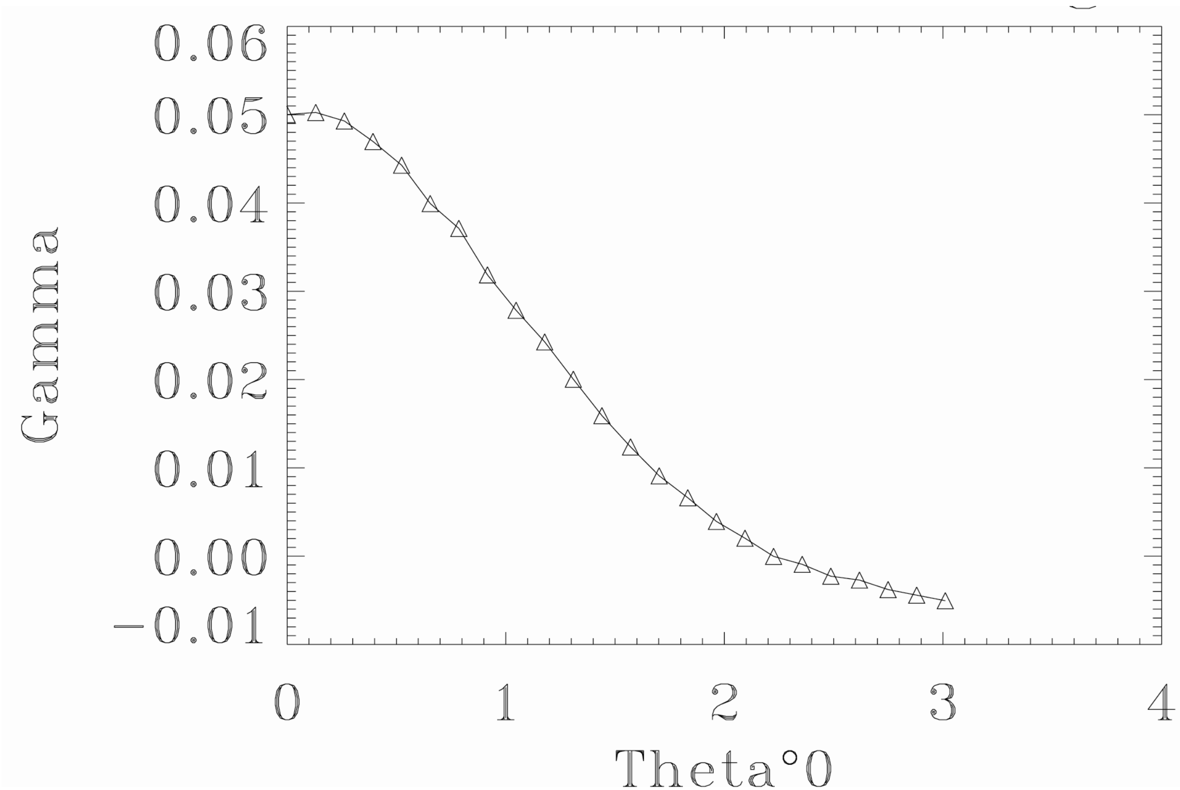


Do Microtearing Modes Matter in MAST Anyway?

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 γ 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?