Global Turbulence Simulations of CYCLONE Base Case and MAST Plasmas

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Outline

- Previous flux-tube Gyrokinetic simulations for MAST
  - Brief summary of results
  - More recent developments
- Need for Global GK simulations

- Global gyrokinetic simulation results using ORB5
  - Cyclone base case
  - MAST

- (Global fluid simulations using Cutie)
- Conclusions and future directions

Gyro-kinetic Theory: Mathematical Model for Micro-instabilities

- Micro-instabilities have **low** frequency, **short** perpendicular wavelengths, but are **extended** along **B**, and satisfy:

$$\frac{\omega}{\Omega} \approx \frac{k_{ll}}{k_{\perp}} \approx \frac{\rho}{L} \approx \delta << 1 \quad \text{and} \quad \frac{f_1}{f}, \frac{e\delta\Phi}{T}, \frac{\delta B}{B} << 1$$

, Ω is gyro-frequency

- ω<<Ω, so can **'average'** the kinetic equation in 6-D **phase space** over small, rapidly gyrating **Larmor orbits** ⇒ 5-D "**gyro-kinetic equation**" (GK) for distribution function $f(\mathbf{R}, v_{||}, \mu)$:

$$\frac{df}{dt} = C(f) + S$$

$$\frac{d\mu}{dt} = 0$$

$$\frac{d\mathbf{R}}{dt} = \left.\frac{d\mathbf{R}}{dt}\right|_{||} + \left.\frac{d\mathbf{R}}{dt}\right|_{\nabla B} + \left.\frac{d\mathbf{R}}{dt}\right|_{E} + \left.\frac{d\mathbf{R}}{dt}\right|_{\delta E}$$

$$\frac{dv_{||}}{dt} = \left.\frac{dv_{||}}{dt}\right|_{\nabla B} + \left.\frac{dv_{||}}{dt}\right|_{E} + \left.\frac{dv_{||}}{dt}\right|_{\delta E}$$

- Electromagnetic fields are determined **self-consistently** from **Maxwell's** equations and the **charges** and **currents** given by *f*

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GS2 Solves the Gyro-kinetic Equation using Twisting slices in Toroidal Flux-Tube Geometry

• GS2 code was developed in the US, and solves **linear** & **nonlinear** GK equations in **toroidal** plasmas for arbitrary number of plasma **species**.

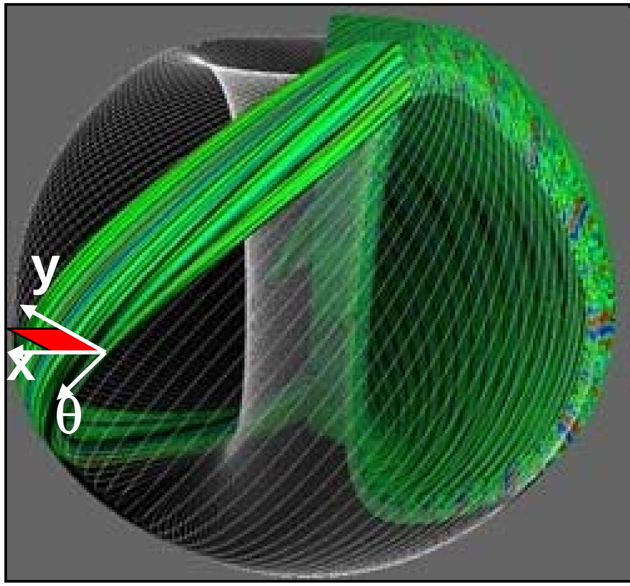
- **Advanced physics**: includes full $\delta\mathbf{B}$.

- **Geometry**: reduced volume "flux tube" aligned to follow equilibrium B field

- **Coordinates**: x is radial, y is in the flux surface $\perp$ to **b**, and θ is || to **b**

- **Numerical Scheme**: FFT in x, y; finite differences in θ, implicit for numerical stability

- **Flux-tube**: handles general toroidal tokamak equilibrium geometry



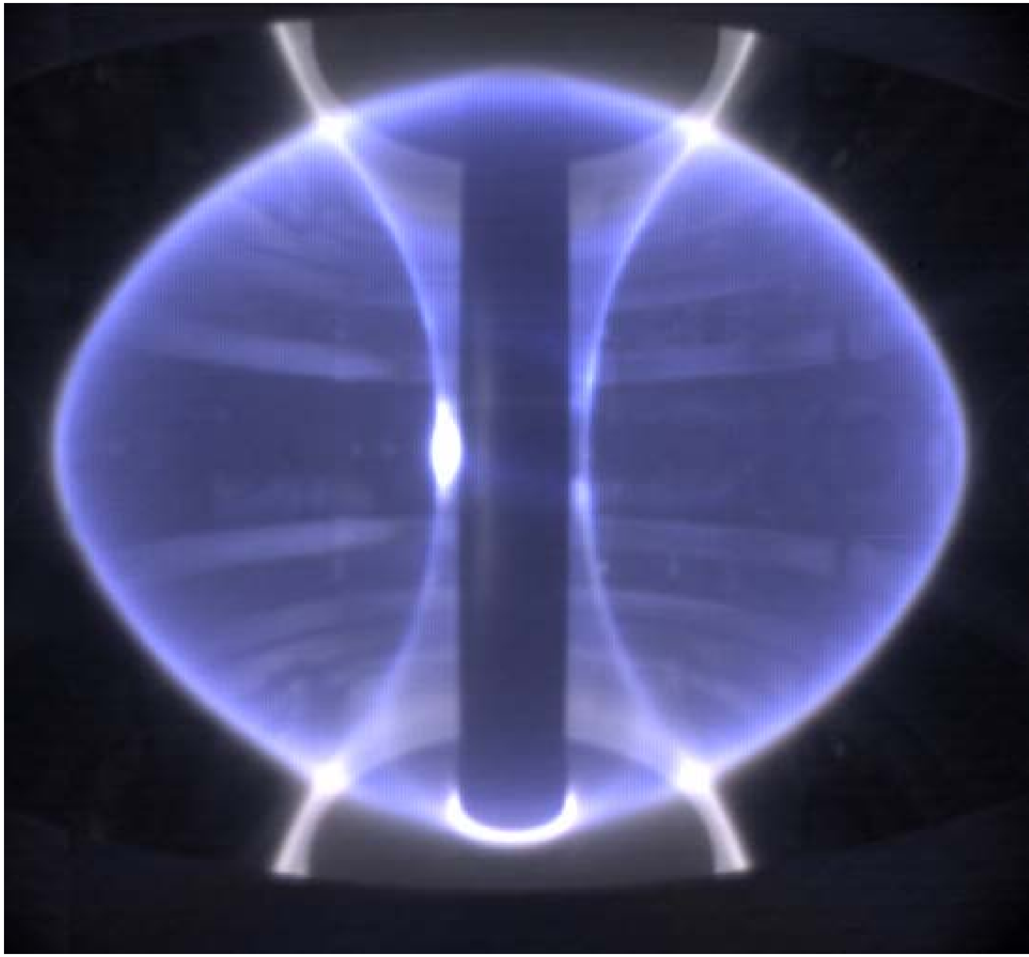
- **Parallelism:** Careful domain decomposition gives efficient parallel code. Good scaling with number of processors, essential in nonlinear calculations.

http://gs2.sourceforge.net

MAST spherical tokamak

- MAST parameters :
  - R=0.85m
  - a=0.65m
  - B_t=0.52 T
  - I_p=1.35 MA
  - P_{NBI}=3.3 MW

  - Small aspect ratio
    - A lot of trapped particles
  - A lot of NBI power for a small volume:
    - Fast rotation
  - “Effective” use of the magnetic field for confinement:
    - High β



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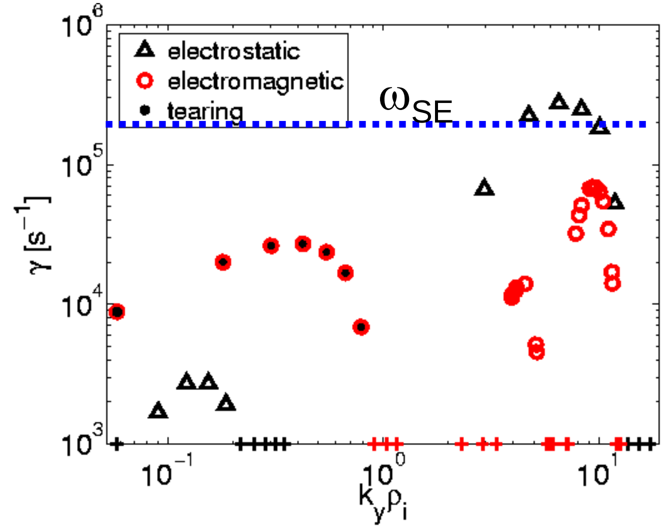
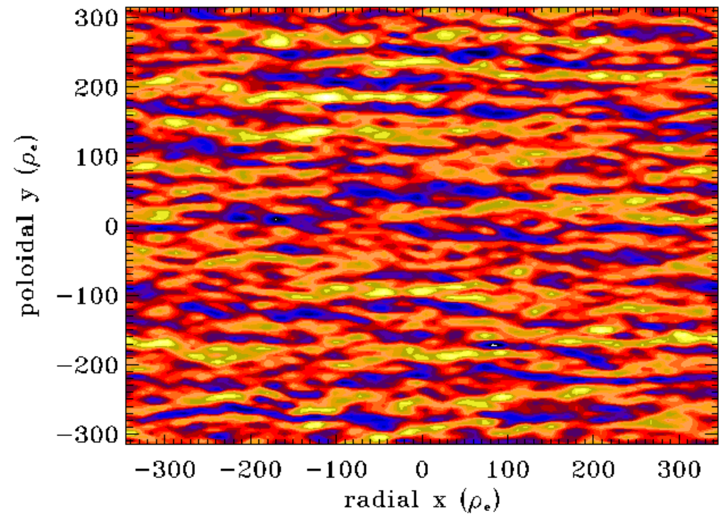
GS2 results for MAST so far

- Linear stability sensitive to electromagnetic effects
  - ETG, Micro-tearing, kinetic ballooning modes
  - ITG linear growth rate below the experimental ExB rotation shearing rate
  - C M Roach et al, PPCF **47**, B323, 2005
- Non-linear ETG turbulence can be simulated in a flux tube
  - Streamers with $\chi \approx \chi_{exp}$ (=5 m/s^2), much larger than $\chi=\gamma/k^2$ (<0.1 m/s^2).
  - N. Joiner et al. PPCF **48** (2006) 685

MAST H-mode ρ=0.4



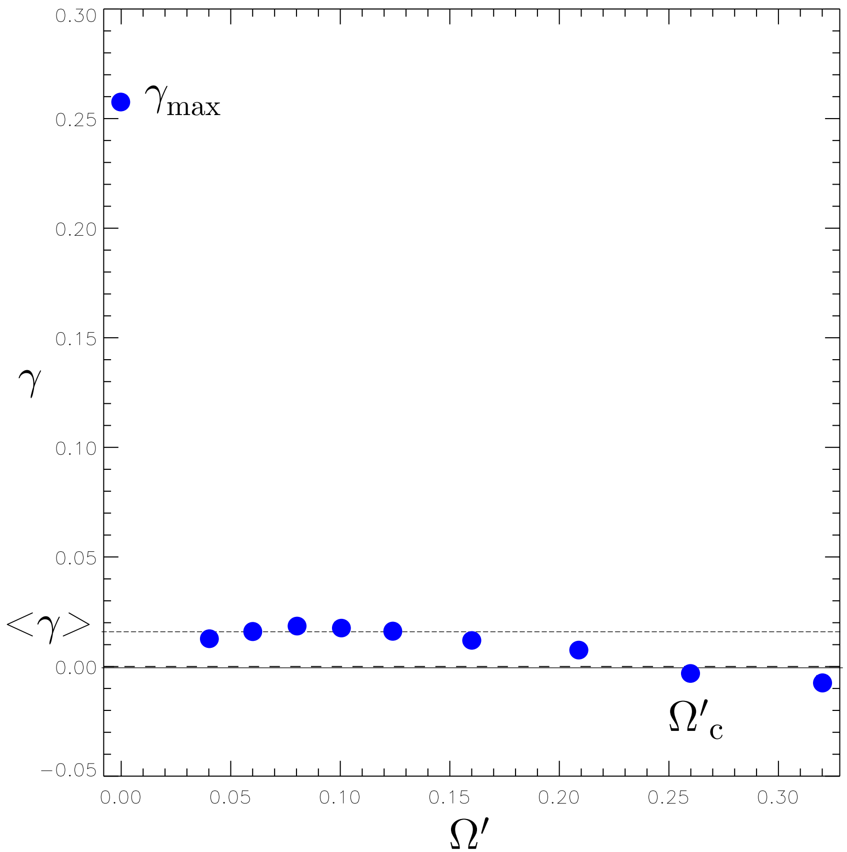
Non-linear ETG, ϕ



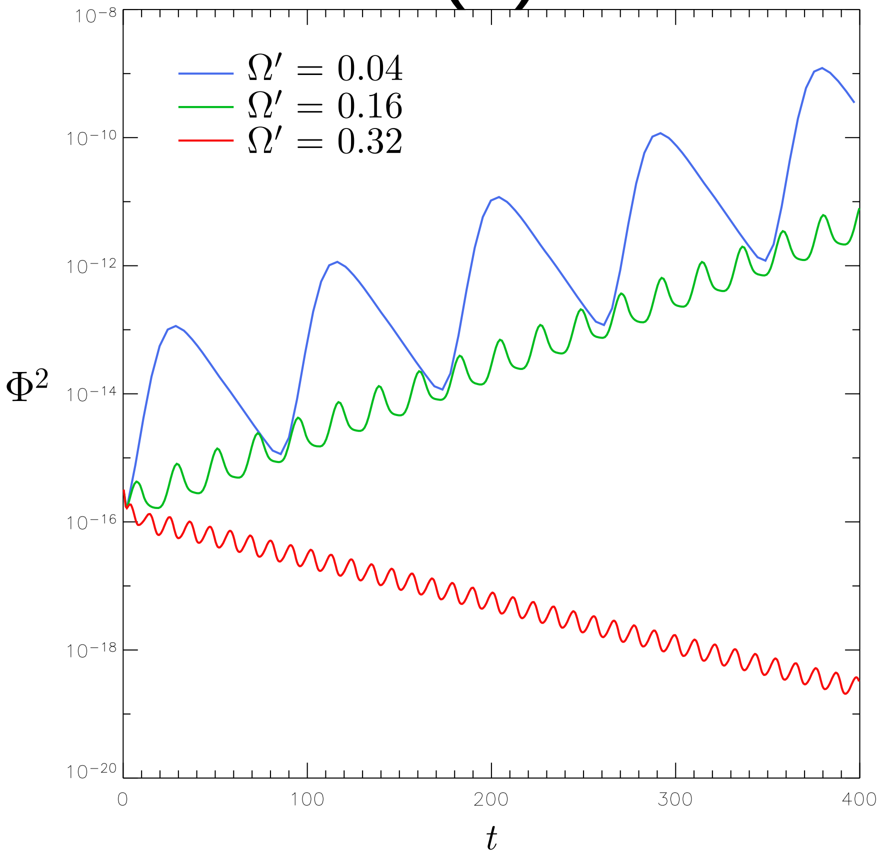
GS2 with sheared rotation (1)

- GS2 has been further developed by N. Loureiro, W. Dorland and G. Hammett to handle equilibrium rotation shear
  - Flow shear makes the radial wave number k_x a function of time.
  - Implicit response matrices in GS2 depend on k_x and would require recalculation every time step - very expensive.
  - Instead simulations are initialised with a range of k_xs, the change in k_x is tracked and the nearest point approximation is used.

GS2 with sheared rotation (2)



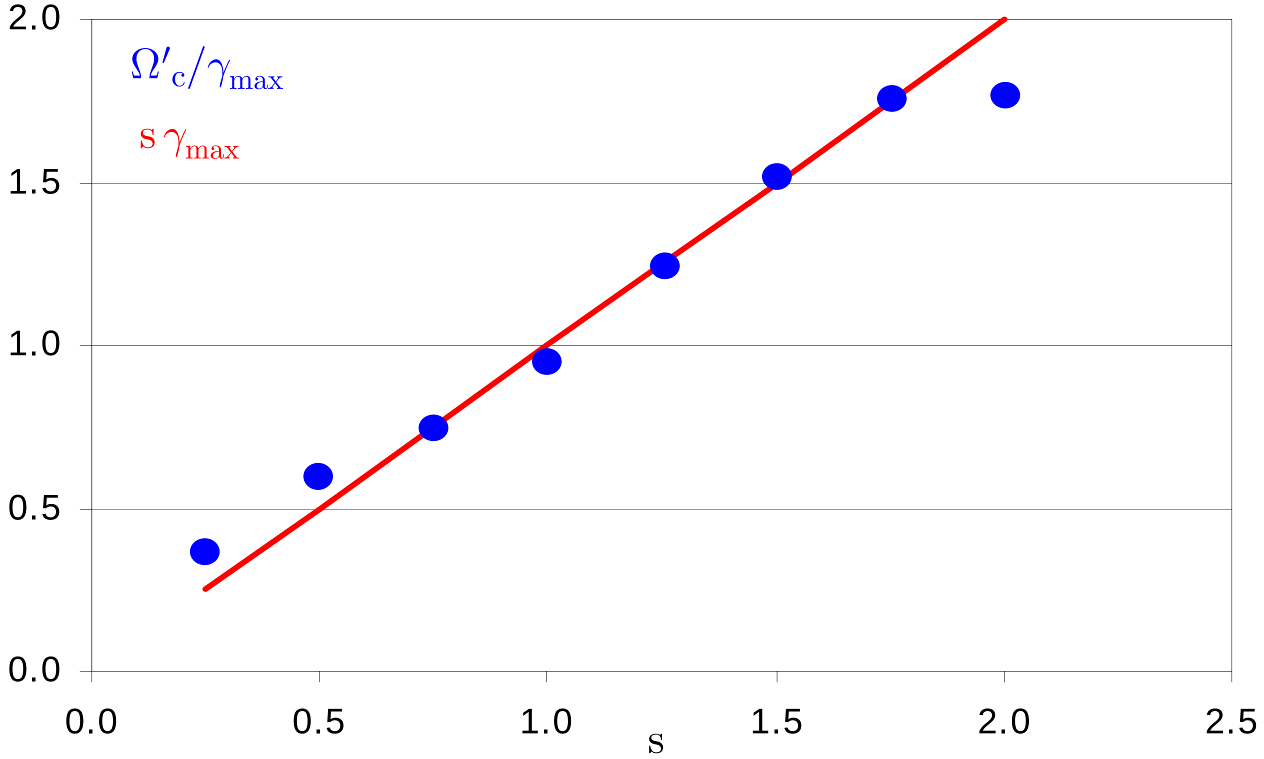
Linear growth rates γ versus the E×B shear rate Ω'. γ_{max} is the maximum growth rate at zero shear. $<\gamma>$ is the ballooning angle average growth rate. Ω'_c is the critical shear rate for marginal stability.



Time evolution of the squared amplitude of electrostatic potential Φ^2 for three levels of E×B shear rate Ω' having Floquet mode behaviour.

Sheared rotation and magnetic shear

The magnetic shear decreases the rotation shear stabilisation:



The ratio of the critical E×B shear rate Ω'_c over maximum growth rate at zero shear γ_{max} versus the magnetic shear *s*.

Microtearing Simulations using GS2

- GS2 calculations have found that microtearing modes are linearly unstable at mid-radius in MAST plasma conditions [1].

  [1] C M Roach et al, PPCF **47**, B323, 2005

- Extensive linear studies of microtearing mode properties [3] found:
  - drive sensitive to magnetic drifts, collisionality, ∇T_e, β
  - mode survives with energy independent collision operator
  - microtearing mode drive weakly reduces with r/R$\Downarrow$, still unstable at r/R~0.1

  [3] D J Applegate et al, PPCF **49**, 1113-1128, 2007

- Nonlinear calculations have proved difficult [4-6]

  [4] D J Applegate et al, PhD Thesis, Imperial College, awarded 2007.

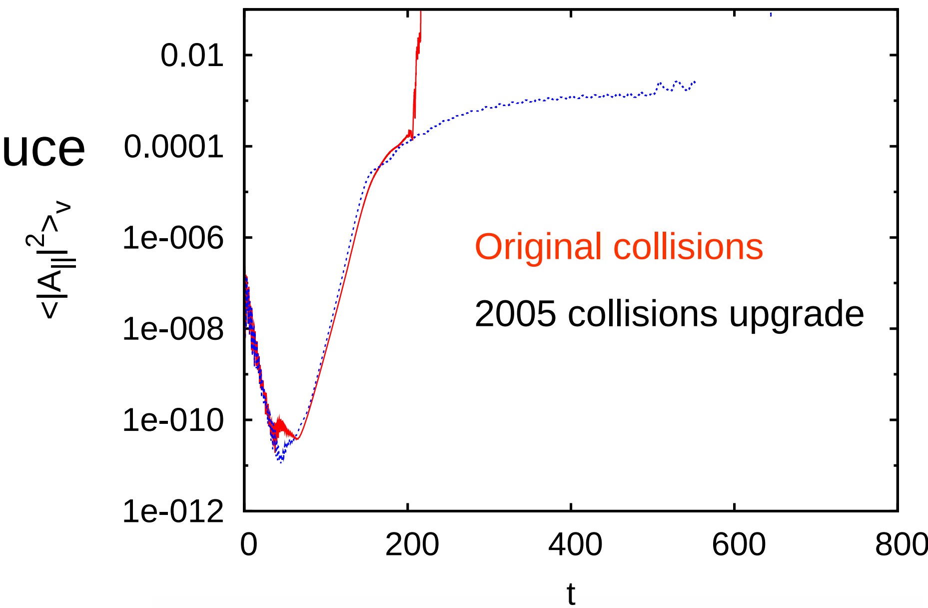
  [5] D J Applegate et al, 32nd EPS, Tarragona, ECA volume 29C, P5-101, 2005

  [6] C M Roach et al, 14th EFPW, Greoux-les-Bains, 2006.

Nonlinear GS2 Microtearing Simulations

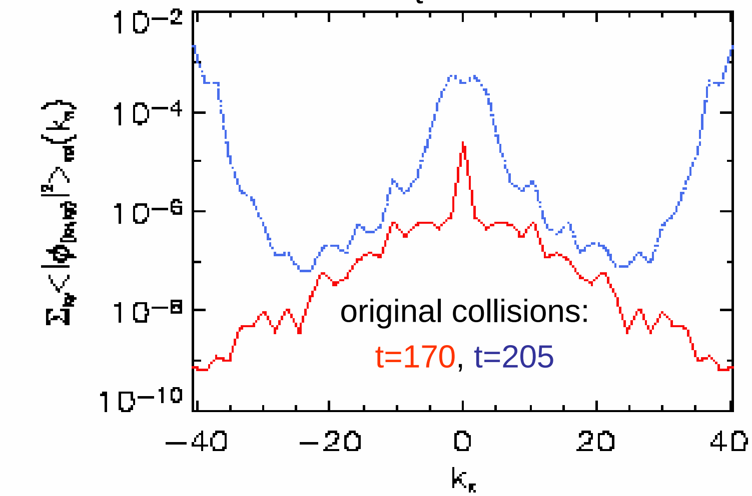
Cheaper NL μ-tearing runs with simplified artificial equilibrium to reduce mode extent || **B**, 4 k_y values:

$k_y \rho_i = 0, 0.2, 0.4, 0.6$



Results:

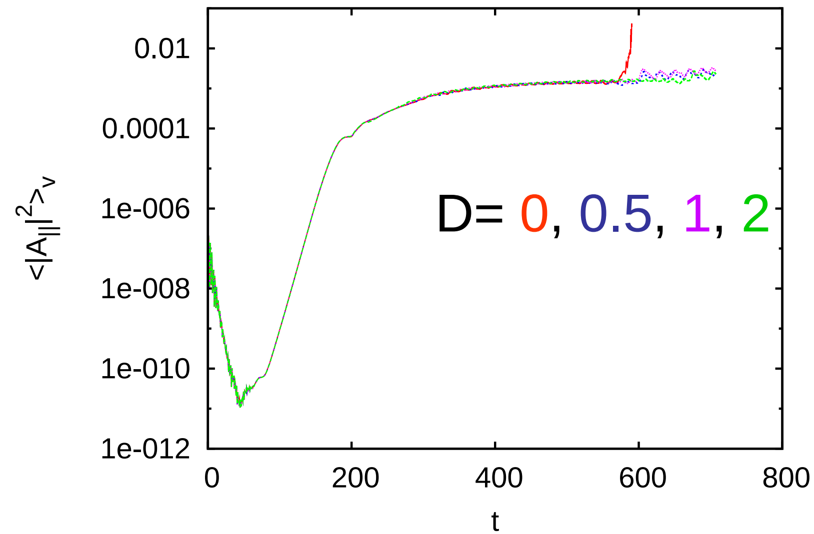
- pseudo-“saturation”, low transport
    - ➢ but blows up later at high k_x.
- improved GS2 collisions (2005) help
- but longer run proved that it
    - ➢ just postponed the problem ☹



Pragmatism Teaches Interesting Things

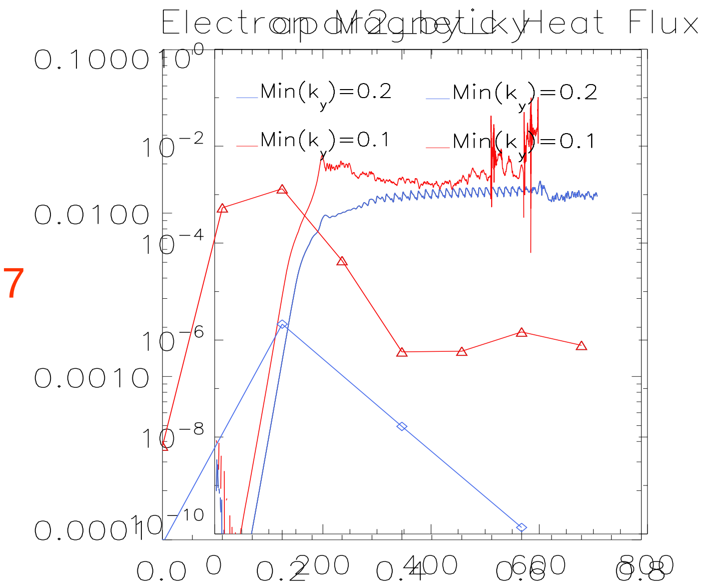
Include turbulent hyperviscosity D to dissipate high k_x prevents blow-up.

- no impact on linear physics
- saturation insensitive to D



y resolution and NL magnetic e heat flux:

- low flux with: $k_y\ \rho_i = 0, 0.2, 0.4, 0.6$
- larger with: $k_y\ \rho_i = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$



Large amplitudes low k_y

- Min($k_y\ \rho_i$) = 0.1 $\Rightarrow$ n ~4 for MAST ρ^*!

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Why go global?

- Local (flux tube) gyrokinetic simulations with GS2 can give insight on turbulence when the particle gyroradius is small compared with the plasma size, $\rho^* = \rho_i/a$
  - Flux tube ETG simulations are ok.
- When ρ^* is large, the particle orbit size becomes comparable with the equilibrium profile scale, i.e. T and ∇T are no longer constant in the simulation domain.
  - Flux tube approximation is no longer valid.
- In MAST $1/\rho^* \approx 50\text{-}100$
- Global simulations are required for MAST ITG

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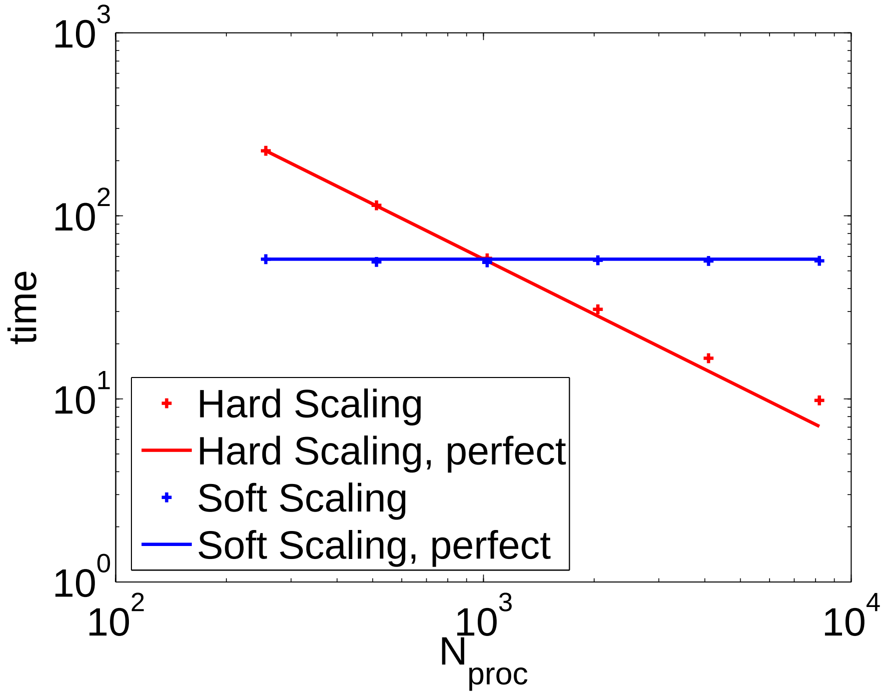
Introduction to ORB5

- Developed at CRPP, Lausanne by T.M. Tran, A. Bottino, P. Angelino, S. Jolliet
- Gyrokinetic PIC code, follows markers in phase space
- Electrostatic, adiabatic electrons, kinetic electrons in development.
- Uses δf-method and mode filtering to reduce noise.
- Scales to thousands of processors:



Benchmark: CYCLONE base case with trapped electrons, 512M particles.

Soft scaling = Increase the number of particles with the number of processors.
Hard scaling = Problem size kept constant.

Code comparison

Property	GS2	ORB5
Geometry	Flux tube	Global
Experimental equilibrium	Yes	Yes
Flow shear	Linear simulations ok, non-linear under development	Will have in the future
Magnetic perturbations	Yes	Possibly in the future
Collisions	Yes	No
Non-linear profiles	Fixed	Relax with turbulence. Sources possible in the new version.
Electron physics	Adiabatic or kinetic	Adiabatic, kinetic under development.

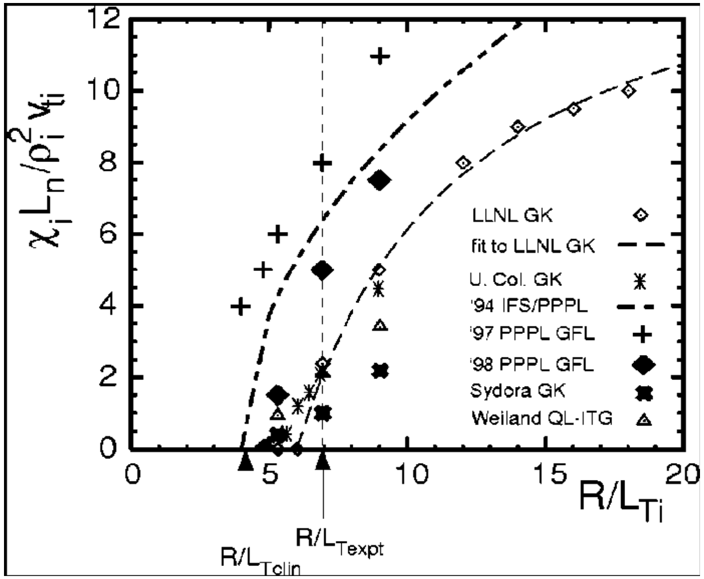
GS2 : Suitable for ETG and microtearing (difficult, but progress is being made), not suitable for non-linear ITG (flux tube limit).

ORB5 : Suitable for ITG, but not for microtearing (no collisions). ETG possible, but global simulations with experimental ρ_e* are very demanding.

CYCLONE test case

- US project to compare different codes in an identical equilibrium
  - Circular plasma
  - Global parameters
    - B = 1.91 T
    - a = 62.5 cm
    - R = 170 cm
  - Local parameters at mid radius
    - $n_e = 4.5 \times 10^{19}\ m^{-3}$
    - $T_e = T_i = 2$ keV
    - $R/L_T = 6.9$
    - $L_T/L_n = 0.321$
    - q = 1.4
    - shear = 0.78
    - $\rho^* = \rho_i/a = 1/184.7$

*Dimits et al. PoP **7** (2000) 969

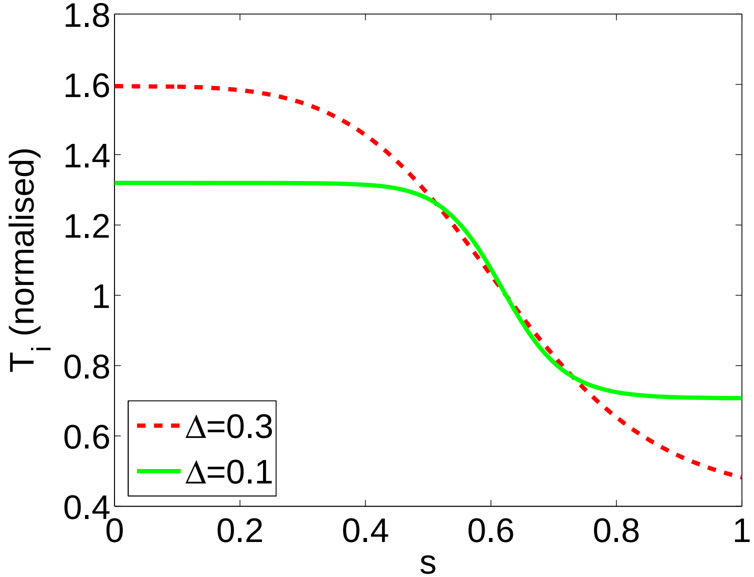


Flux tube (GS2) vs. global (ORB5)

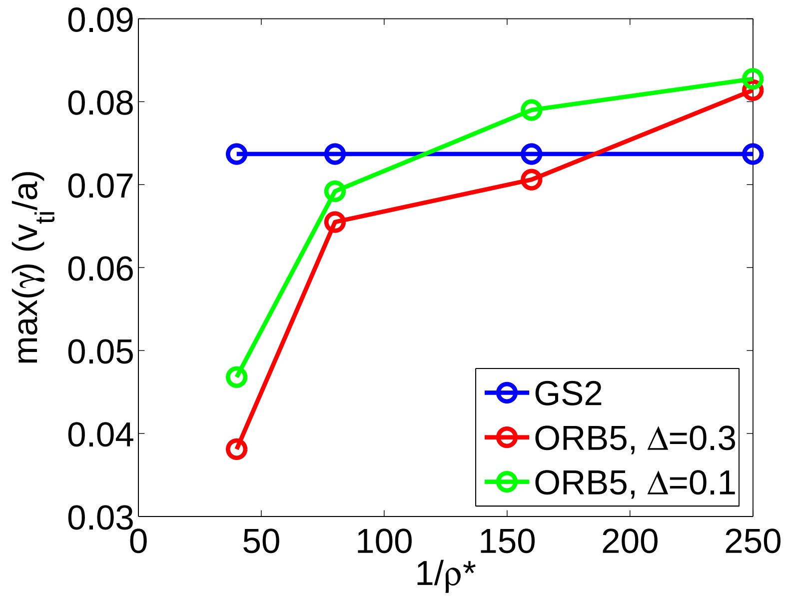
CYCLONE equilibrium,
linear ITG simulations, fixed R_0/L_T,
varying Δ (width of the gradient region).

$$\frac{1}{T}\frac{dT}{d\psi} = -\frac{a}{L_T}\frac{\left[\cosh^{-2}\left(\frac{s-s_0}{\Delta}\right) - \cosh^{-2}\left(\frac{s_0}{\Delta}\right)\right]}{\left[1-\cosh^{-2}\left(\frac{s_0}{\Delta}\right)\right]}$$

$$s = \sqrt{\psi_N}$$



Linear growth rates:

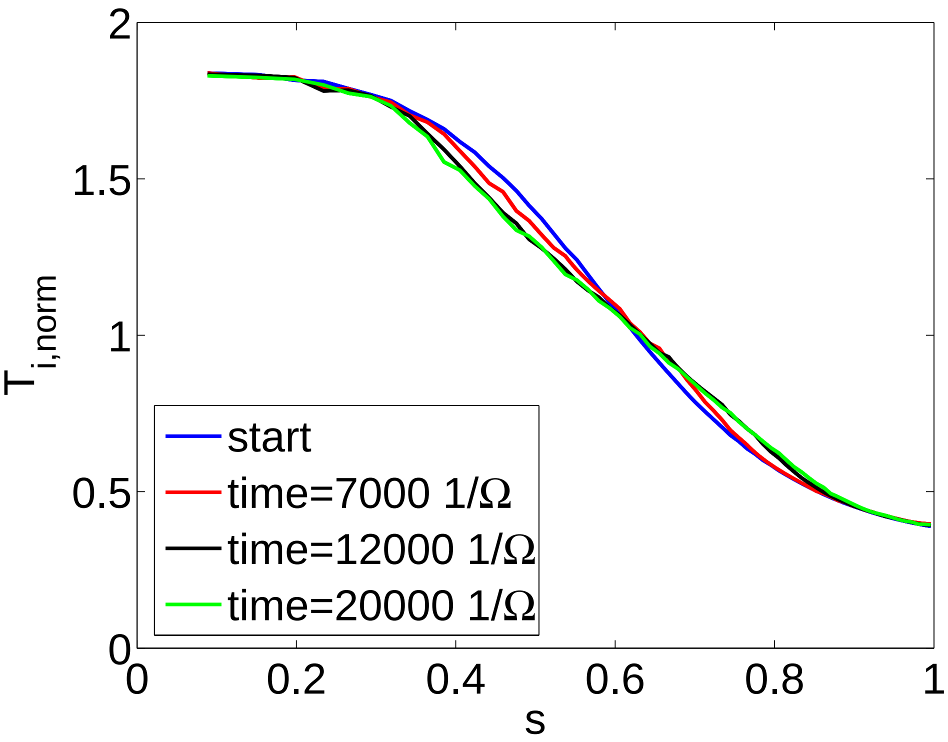


ORB5 linear growth rate deviates from flux tube code as ρ^* increases.

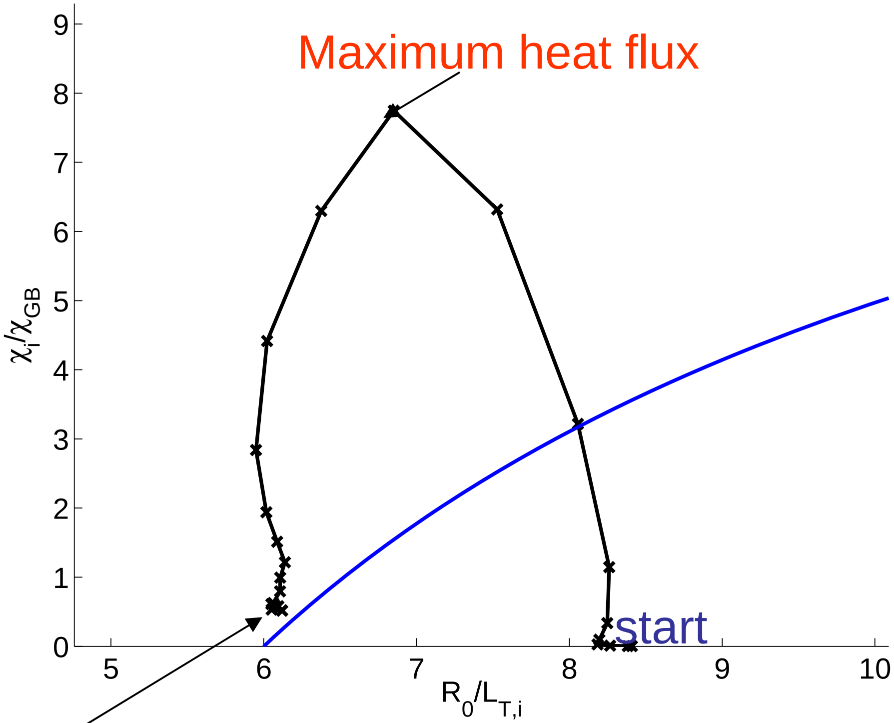
The width of the gradient region does not affect this trend.

Global effects in non-linear ITG simulations (1)

Temperature profile evolution



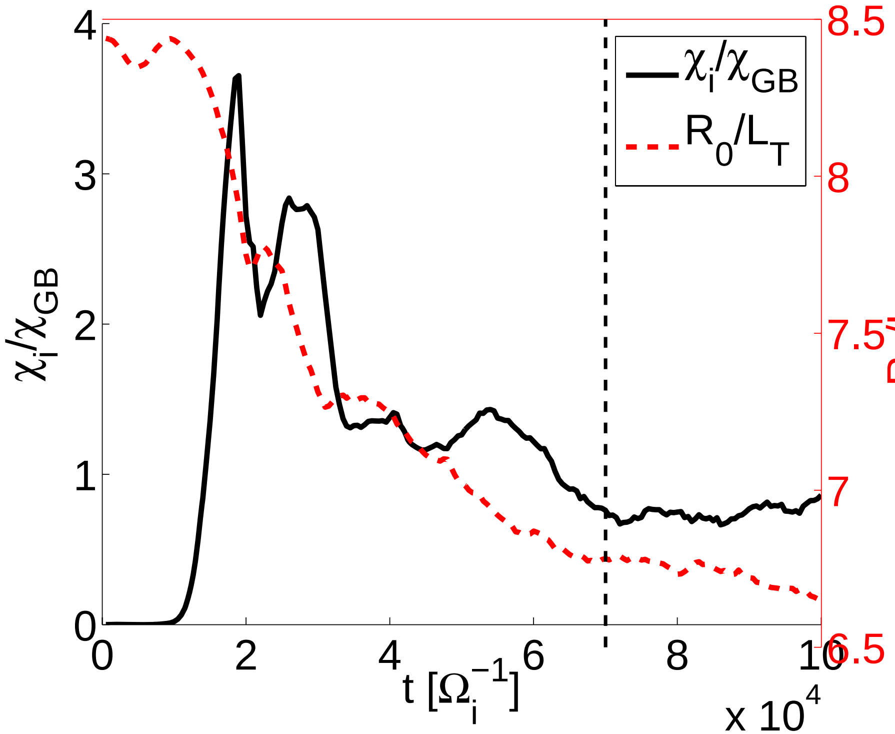
χ/χ_{GB} vs. R_0/L_T, "Dimits curve"



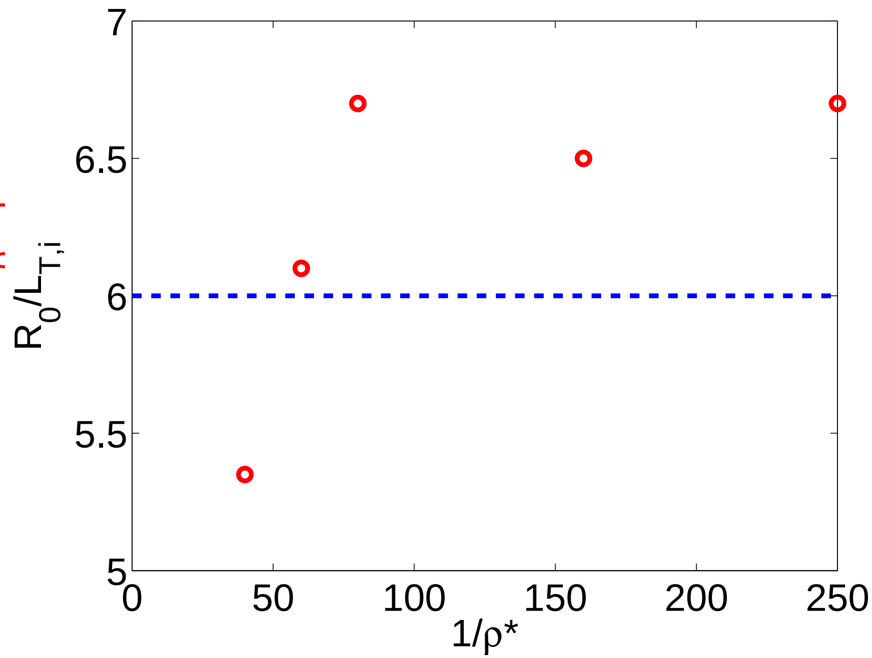
Non-linear stability limit, χ and R_0L_T practically constant for t=12000-20000 1/Ω

Global effects in non-linear ITG simulations (2)

- During the non-linear phase, the gradient relaxes (no sources).
- We define the non-linear stability threshold (in R_0/L_T) when χ does not decrease any more.

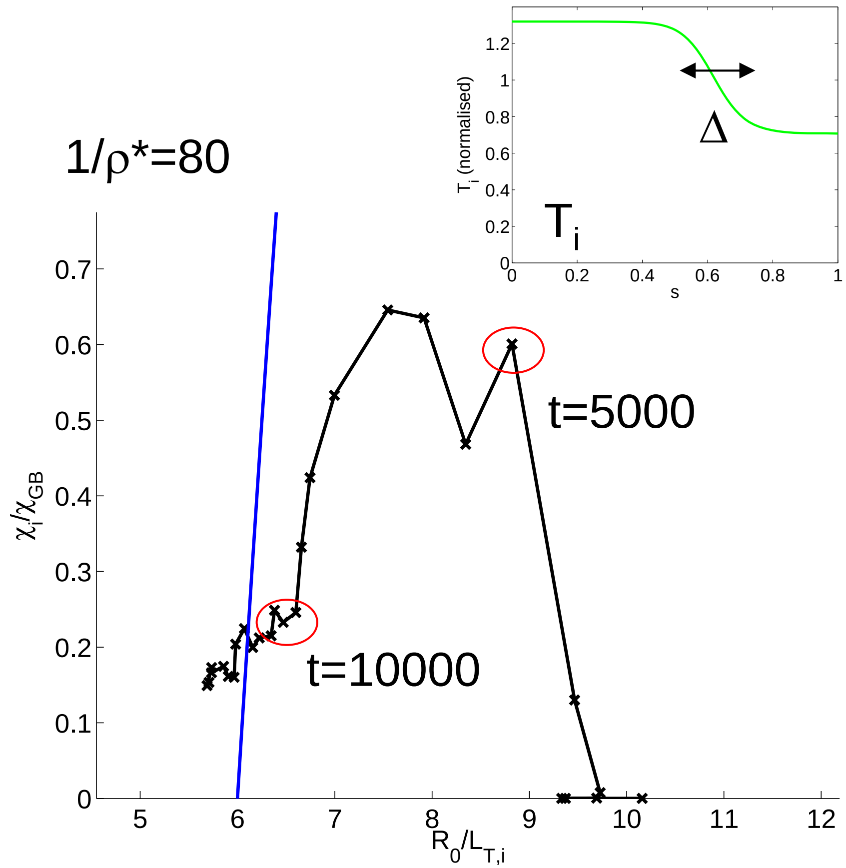


R_0/L_T at the non-linear stability threshold, ····· Dimits plot at χ=0

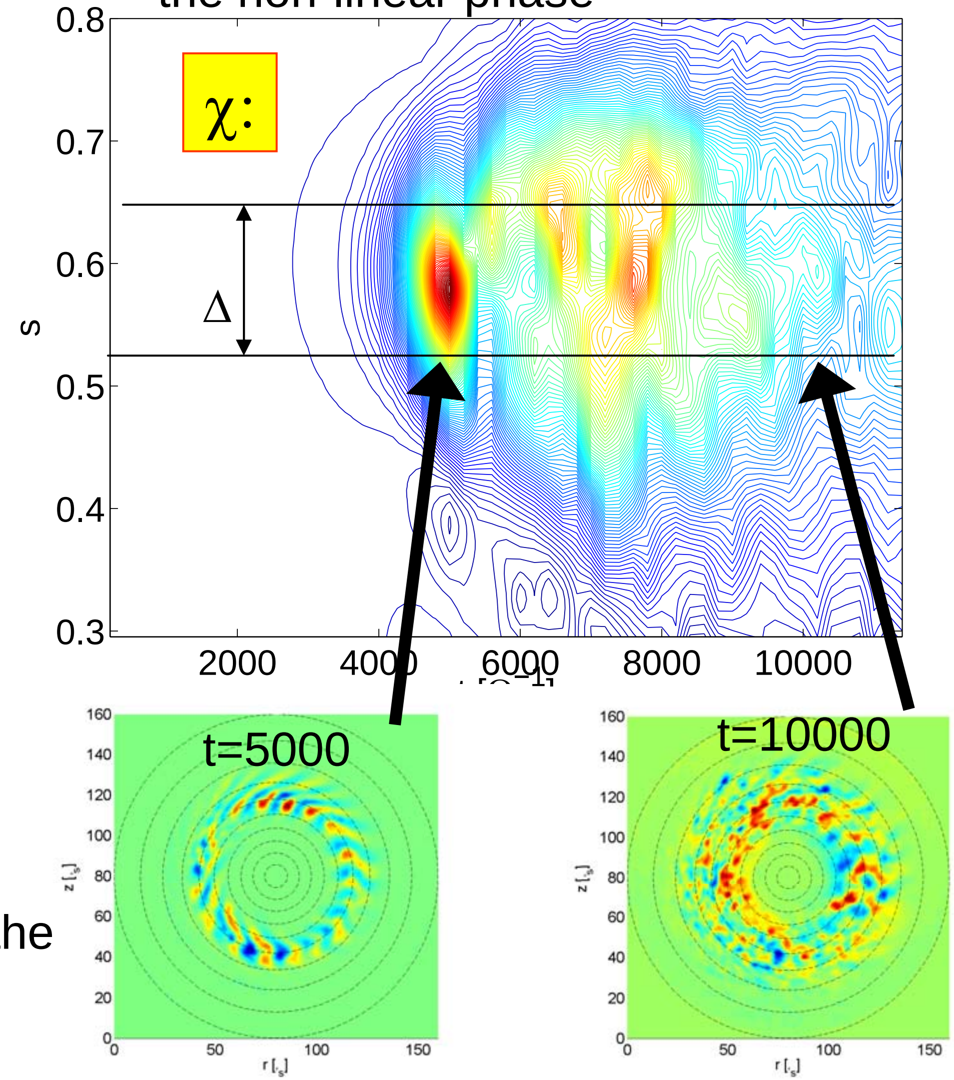


- Non-linear stability threshold stays close to the Dimits curve even for $1/\rho^* = 40$.
- Similar results obtained with the full-f code GYSELA : V. Grandgirard, et al. PPCF 2007

Global non-linear simulations, narrow profiles



Turbulence spreads during the non-linear phase



Even for non-linear simulations with a narrow gradient region at the start of the simulation the non-linear threshold is close to the Dimits curve.

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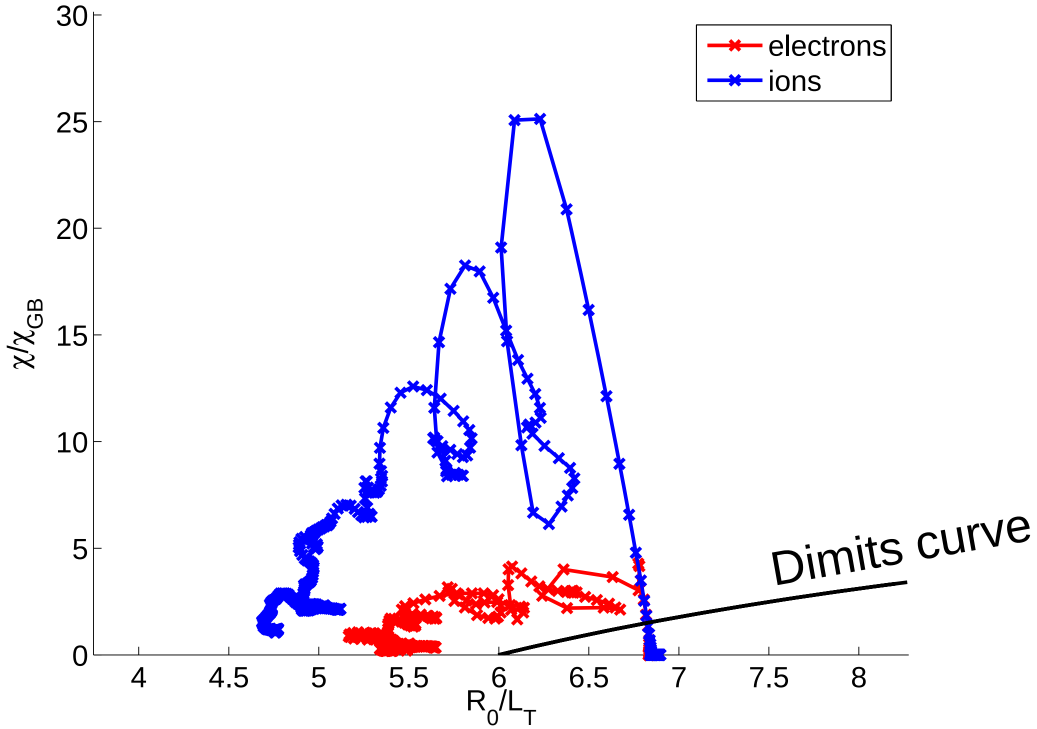
Trapped electron effects

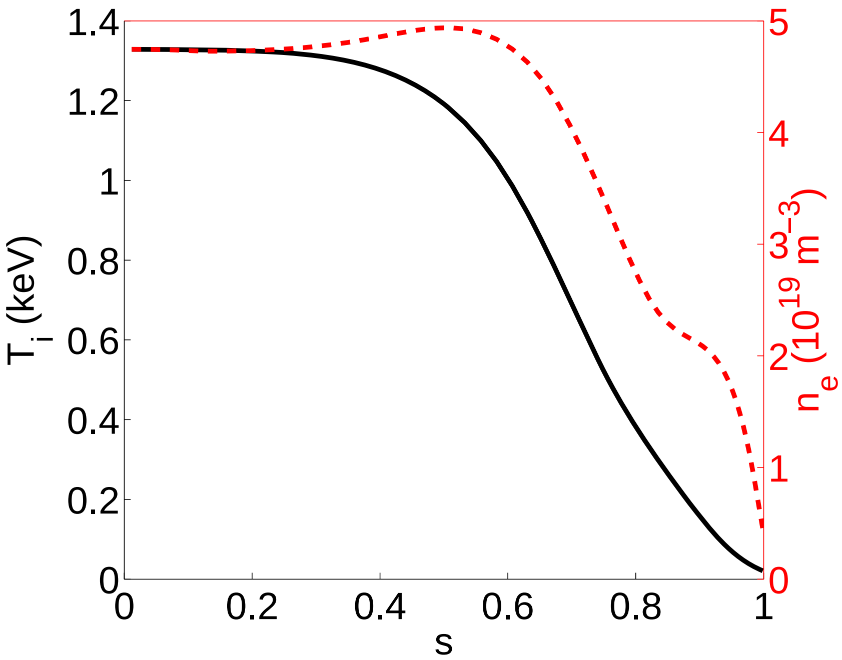
CYCLONE base case, but instead of adiabatic electron response, trapped electrons are simulated kinetically as well as ions.
The code still in development, so the results are preliminary.

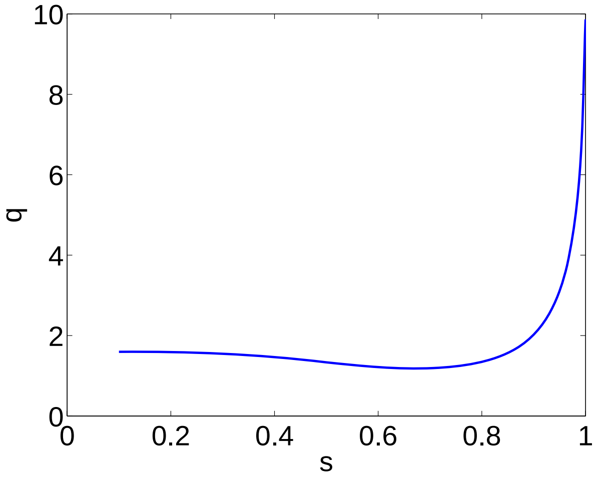


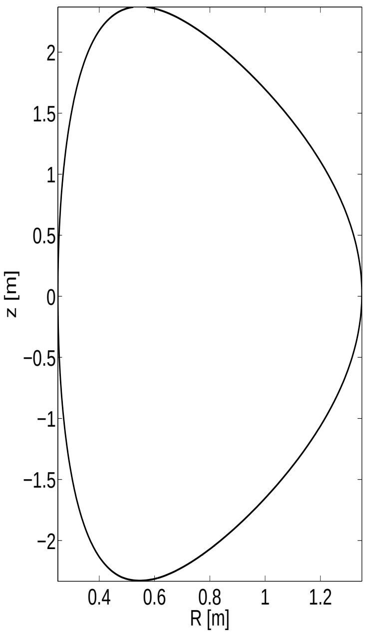
500M particles
130 000 CPU hours
on HECToR

- Including trapped electron physics (instead of adiabatic response) lowers the ITG non-linear threshold.
- The increased turbulence is in agreement with Sydora et al. PPCF **38** (1996) A281

MAST L-mode plasma #12556 (I)







I_p=730kA
B_T=0.41T
Ptot=2MW

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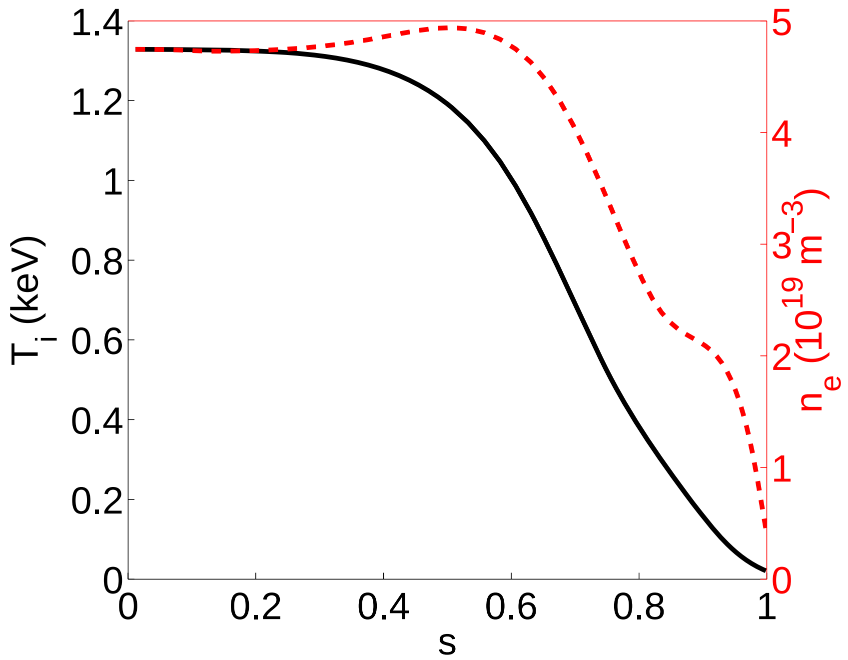
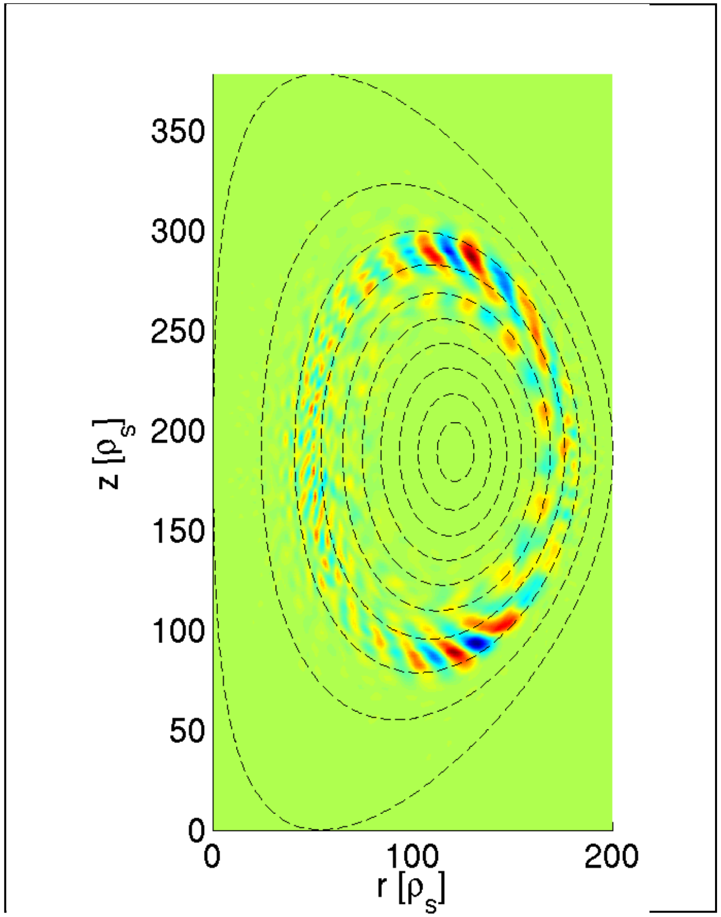
MAST L-mode plasma #12556 (II)



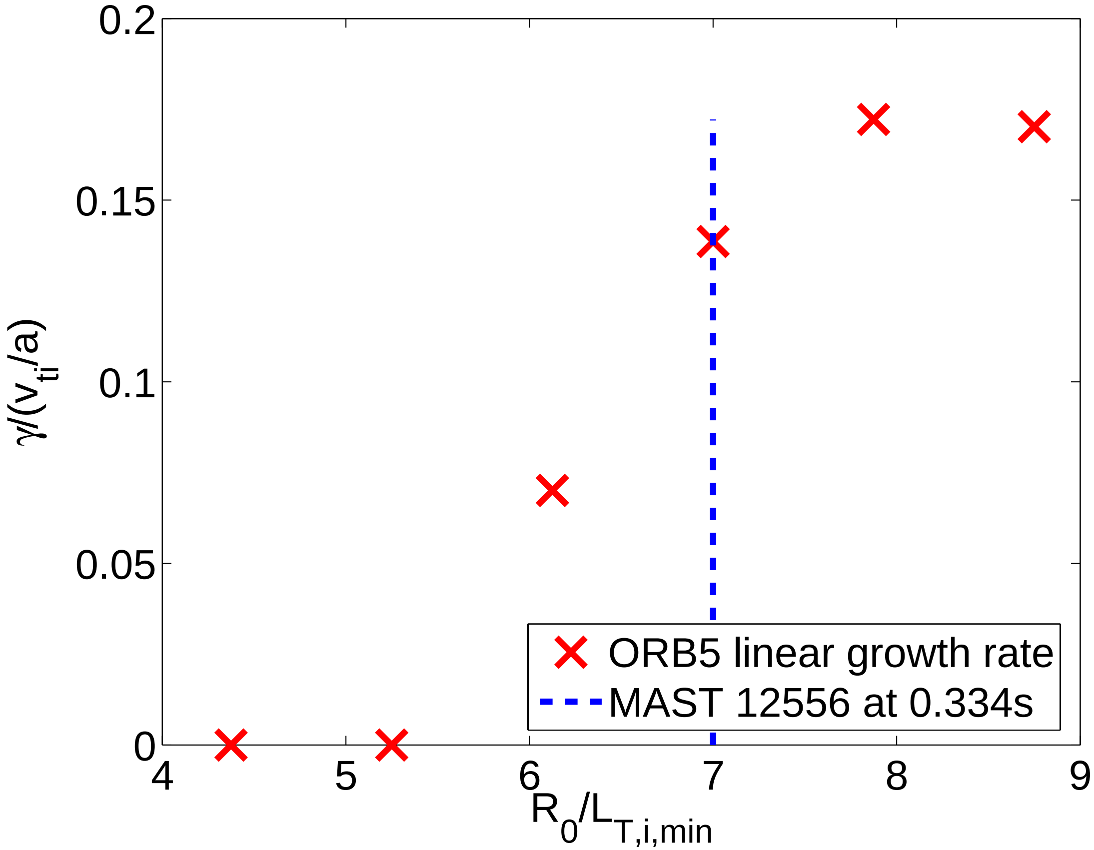
I_p=730kA
B_T=0.41T
Ptot=2MW

Fastest growing mode:
n=25, $k_\theta \rho_i \approx 0.25$



Linear mode NOT ballooning !

MAST L-mode discharge #12556, linear stability

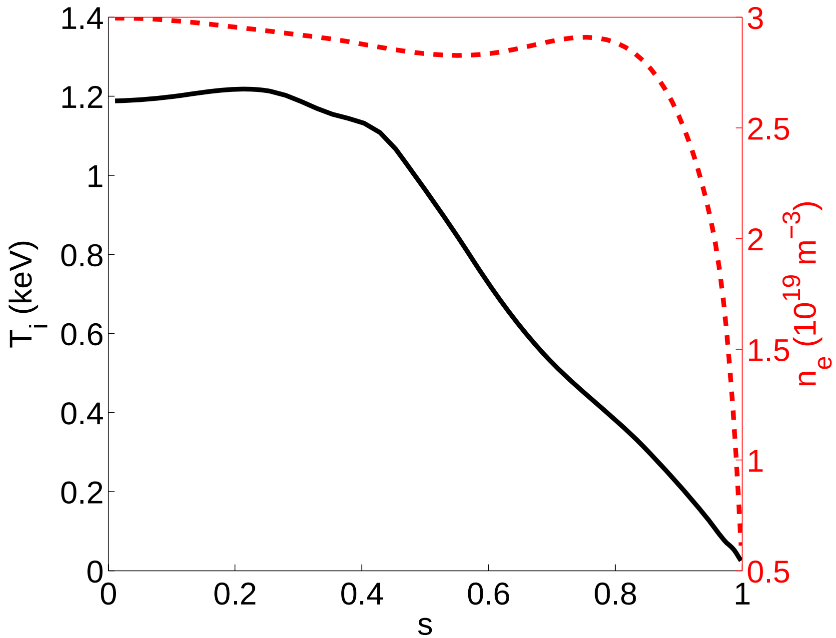


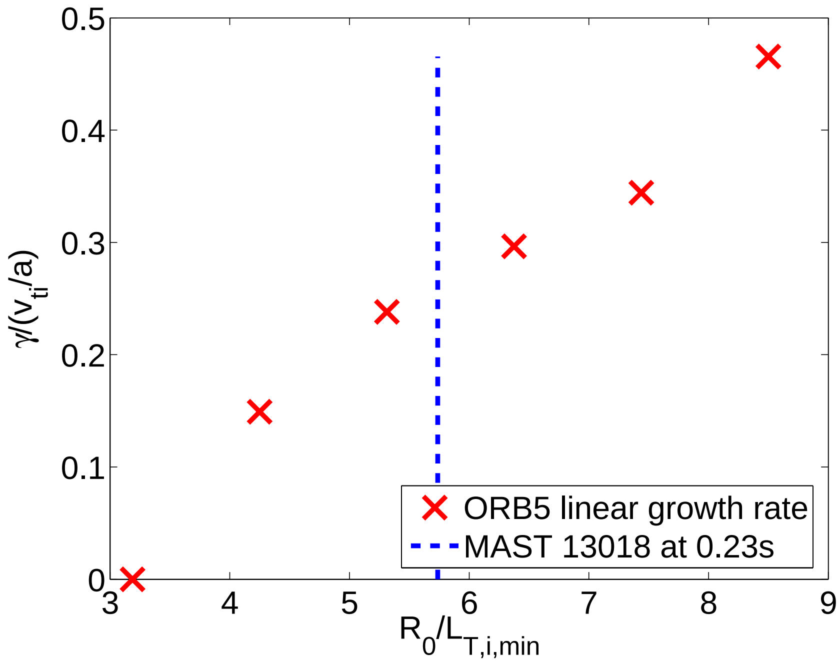
•MAST above the ORB5 linear stability limit

•Electromagnetic and equilibrium flow effects not yet captured by ORB5. They can be significant.

H-mode, #13018

Main difference to the L-mode: Flat density profile in the core.



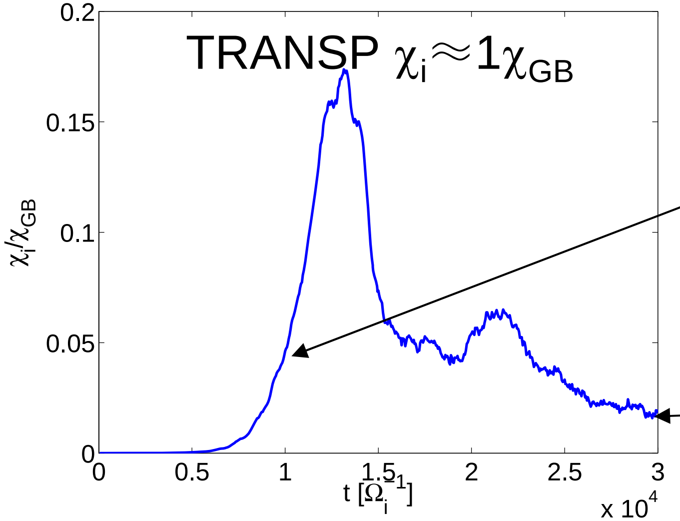


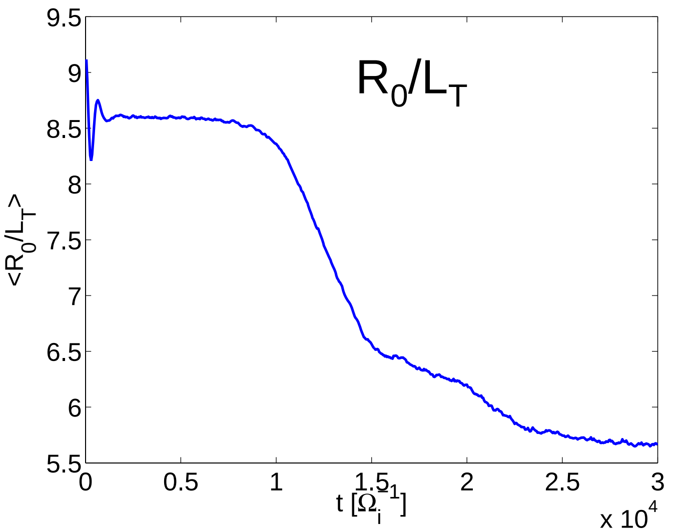
I_p=730kA
B_T=0.41T
Ptot=2MW

As in L-mode, the experimental H-mode temperature profile is above the linear stability limit.

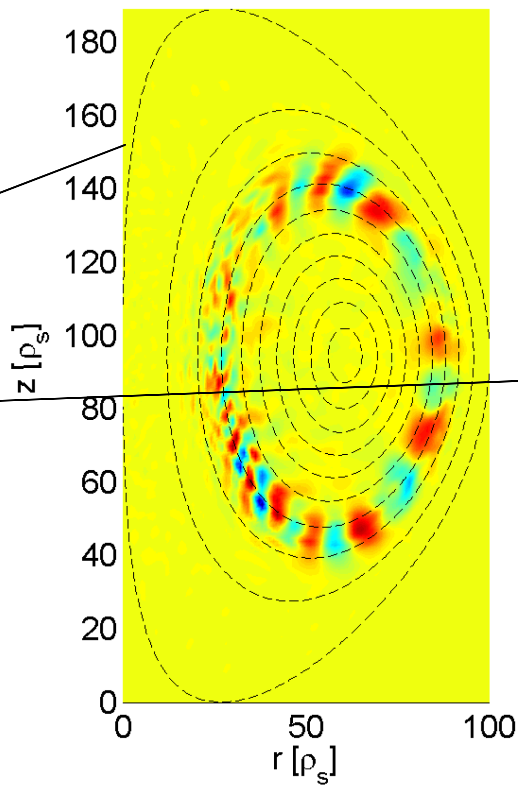
Non-linear MAST simulations (1)

Radial heat flux

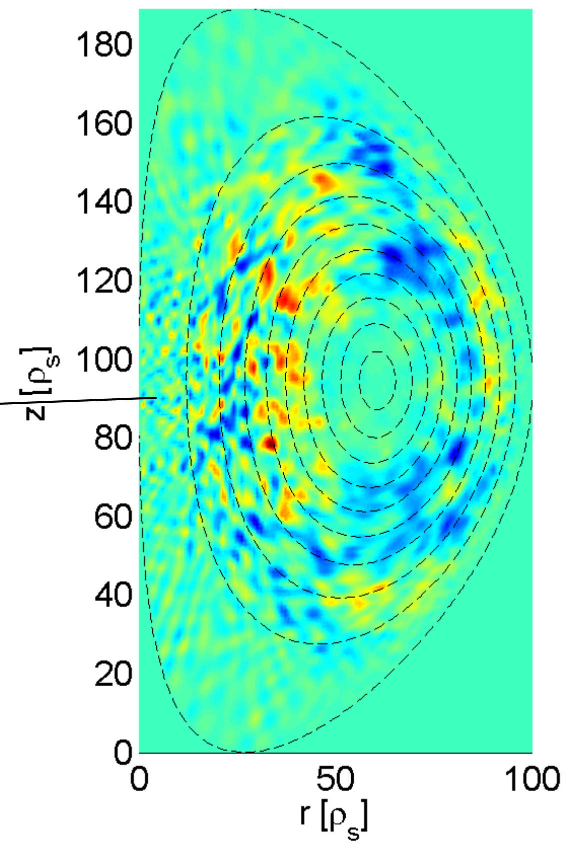




$\phi - <\phi>$, linear phase



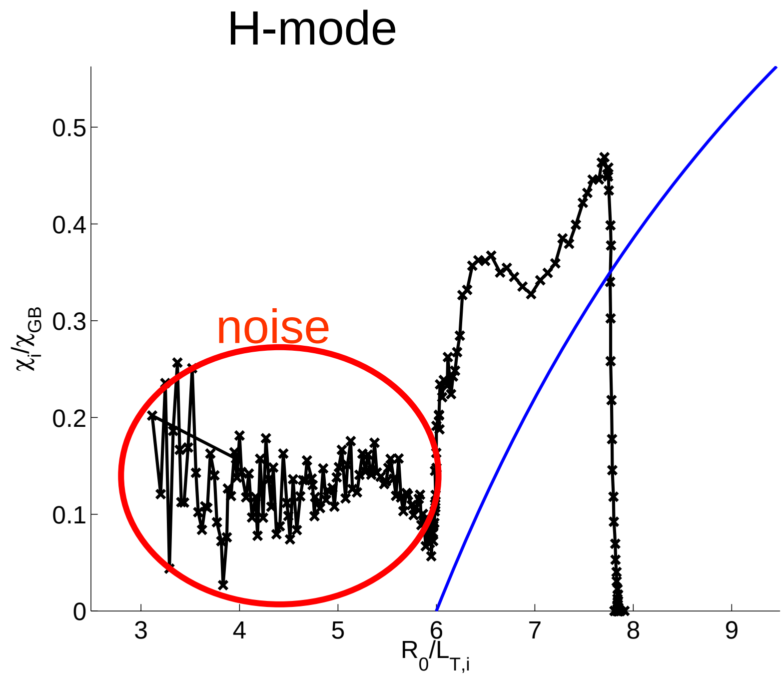
$\phi - <\phi>$, end of simulation

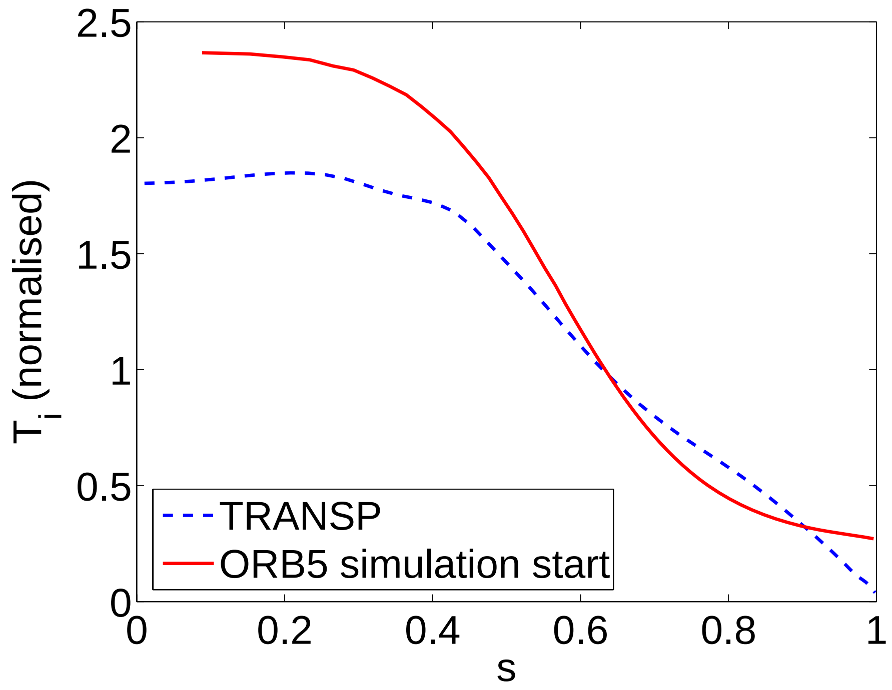


Noise becomes a problem in the end part of the simulation. This should improve with the new version of the code: McMillan et al. PoP 15 (2008) 052308

Non-linear MAST simulations (2-I)

- Start simulations with steep gradients.





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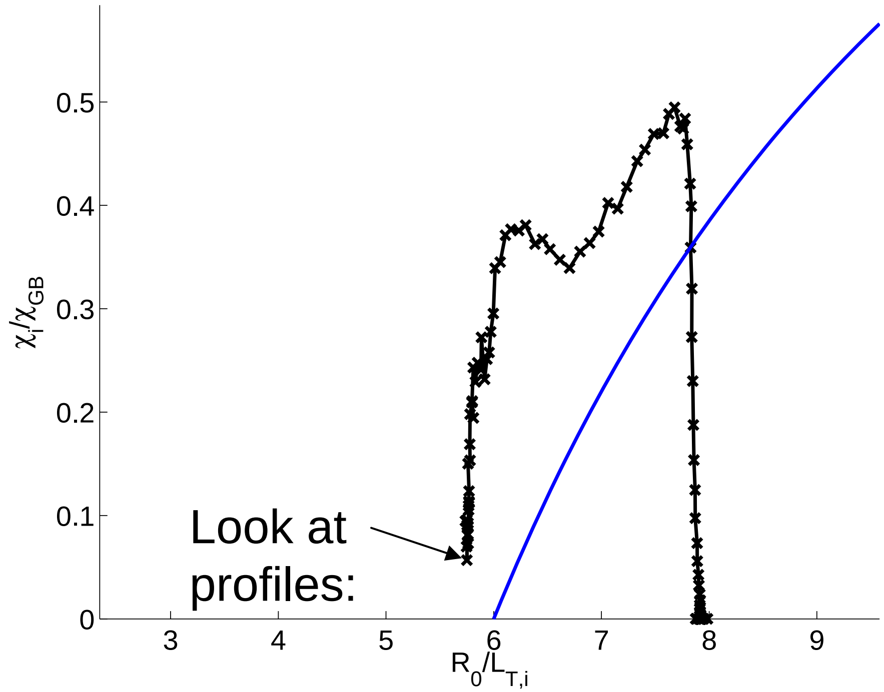
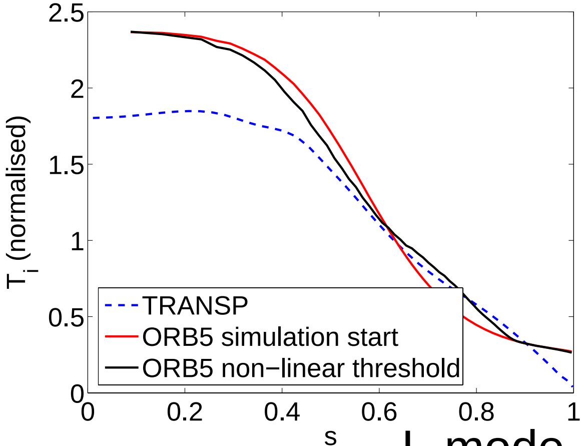
Non-linear MAST simulations (2-II)

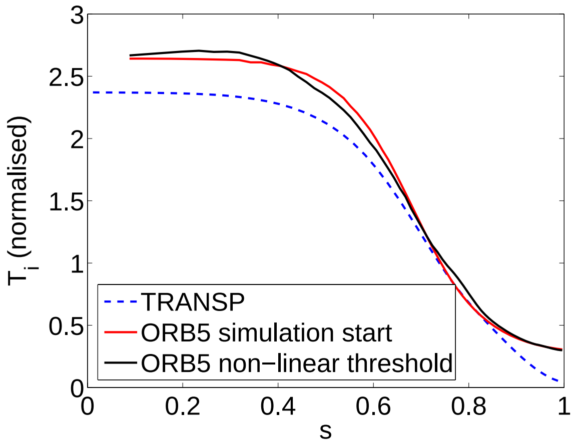
- Start simulations with steep gradients.
- Finish once χ reaches quasi-steady state.



H-mode



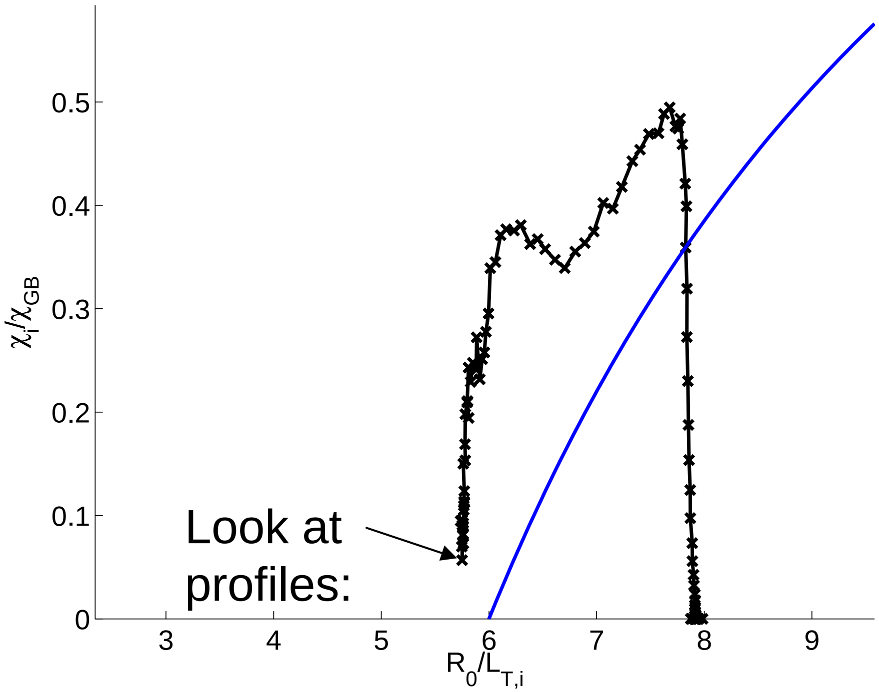
L-mode



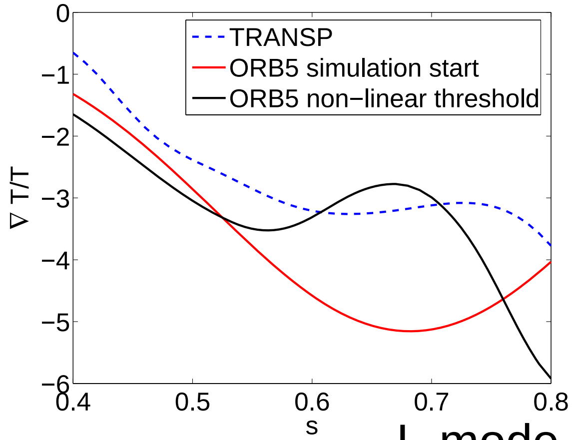
- Turbulence relaxes the profiles close to the Dimits curve.
- Relaxed T_i gradients quite similar to MAST profiles.
- Note: no rotation shear effects, no sources, no EM effects!

Non-linear MAST simulations (2-III)

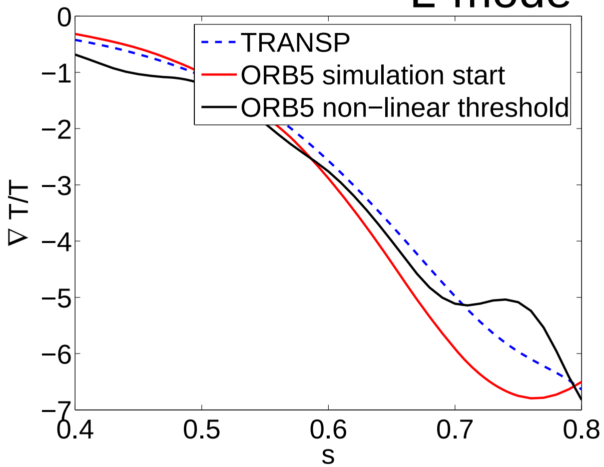
- Start simulations with steep gradients.
- Finish once χ reaches quasi-steady state.



H-mode



L-mode

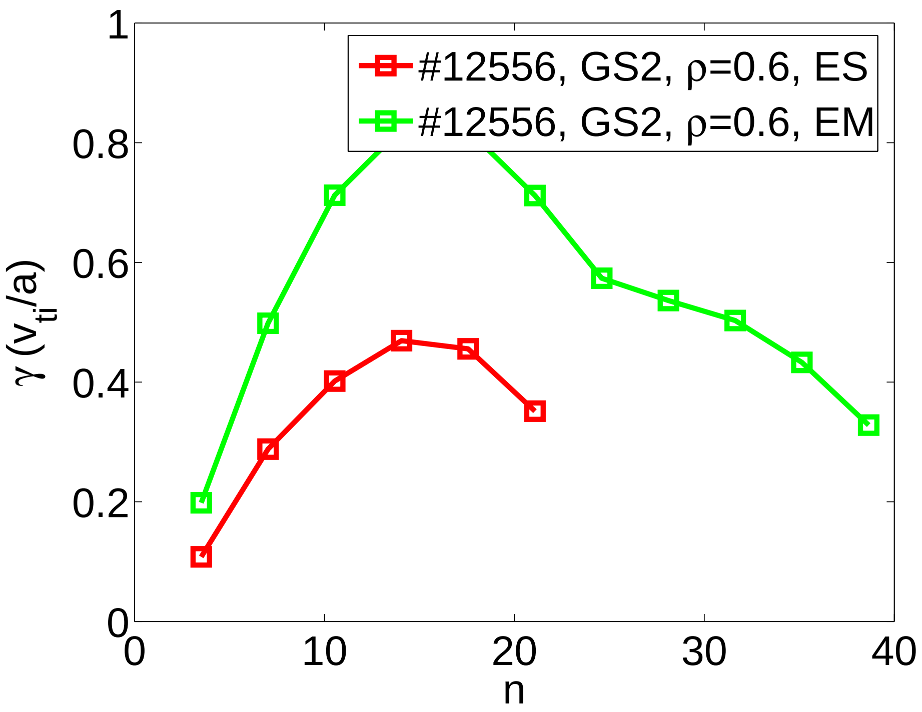


- Turbulence relaxes the profiles close to the Dimits curve.
- Relaxed T_i gradients quite similar to MAST profiles.
- Note: no rotation shear effects, no sources, no EM effects!

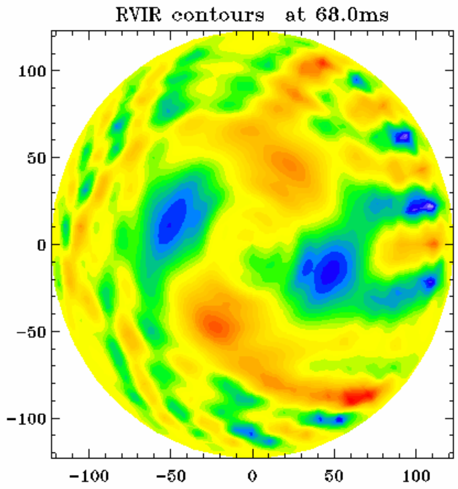
Future directions with ORB5 for MAST

- In MAST the equilibrium rotation shear is significant. Sheared rotation will be included in future ORB5 simulations.
- As shown by local GS2 simulations, high β plasmas of an ST require electromagnetic treatment.
- ORB5 with sources will make it possible to compare steady state fluxes with the experiment.

Electromagnetic effects in GS2:



CUTIE global cylindrical electromagnetic (EM) two fluids code for plasma transport



Two-Fluid Evolution Equations

$$\frac{\partial n}{\partial t} + \nabla.(n\mathbf{v}) = S_p$$

$$m_i n \frac{d\mathbf{v}}{dt} = -\nabla(p_i + p_e) + \mathbf{j} \times \mathbf{B} + F_{eff}$$

$$\frac{3}{2} n \left[\frac{\partial T_{i,e}}{\partial t} + \mathbf{v}_{i,e}.\nabla T_{i,e}\right] + nT_{i,e}\nabla.\mathbf{v}_{i,e} = -\nabla.q_{i,e} + P_{i,e}$$

$$\mathbf{E} + \mathbf{v}_e \times \mathbf{B} = -\nabla p_e / en + \mathbf{R}_e$$

• Authors: A. Thyagaraja, P. Knight and M. Romanelli

- Time independent cylindrical magnetic surfaces: concentric circles in the poloidal plane (low β).
- Toroidal periodic boundary conditions.
- Toroidal curvature effects included in the fluctuation equations.
- q profile evolved but Ip and B toroidal fixed.
- dr,dm,dn -> (100,64,32) from MHD scales to ITG
- Ref. to CUTIE: A. Thyagaraja et al. PoP 12 (2005) 090907.

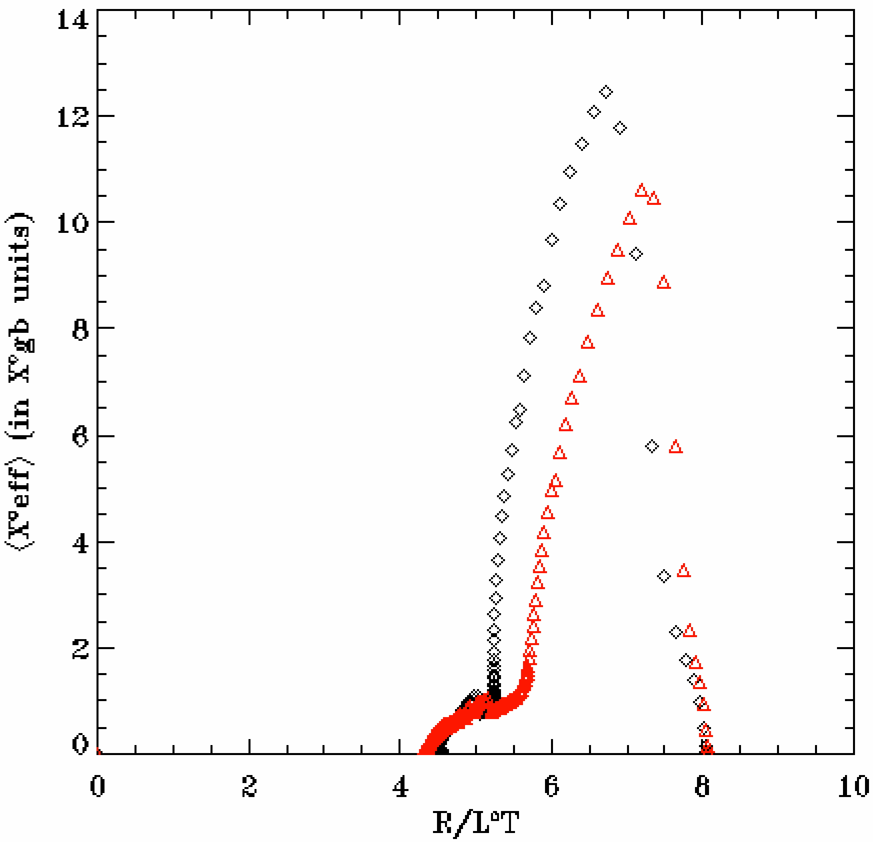
Generic Transport Equation & Flux

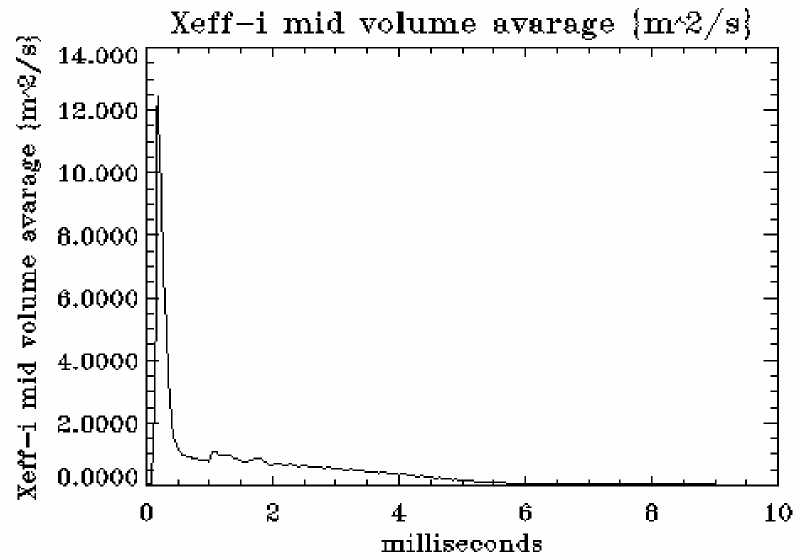
$$\frac{\partial F_0}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_F) + S_F$$

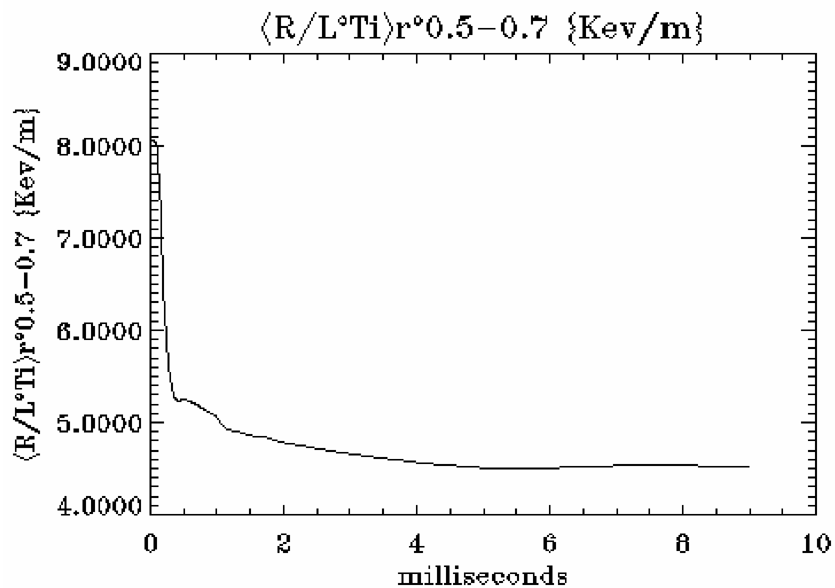
$$\Gamma_F(r,t) = \Gamma_F^{coll} + \Gamma_F^{turb}$$

$$\Gamma_F^{turb} = -<\tilde{F} \times \frac{c}{B}\left(\frac{1}{r}\frac{\partial\tilde{\Phi}}{\partial\theta}\right)>_{\theta,\zeta}$$

CUTIE Cyclone case





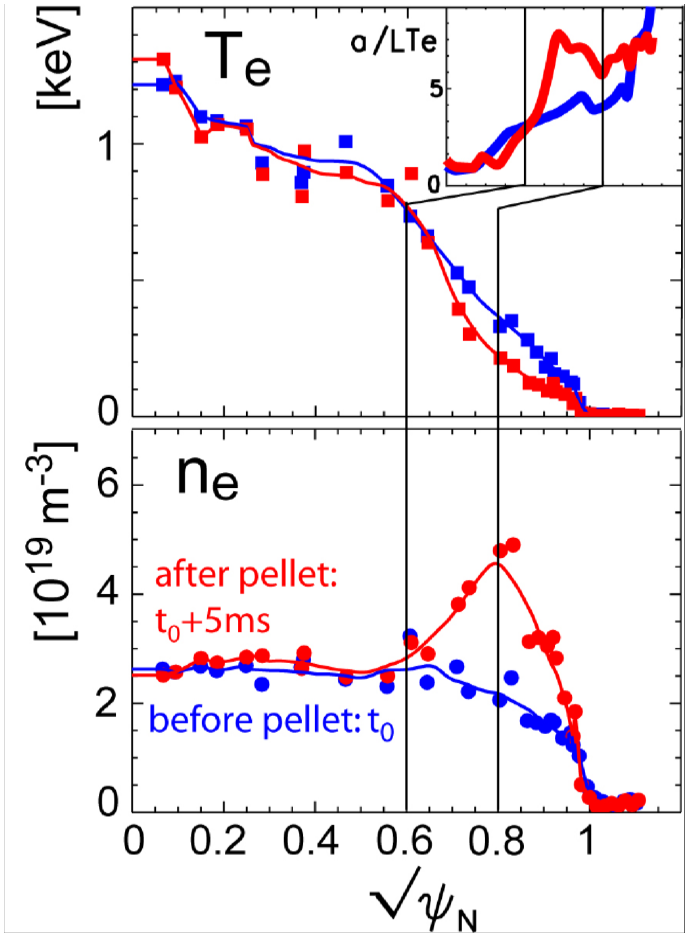


Ions – black

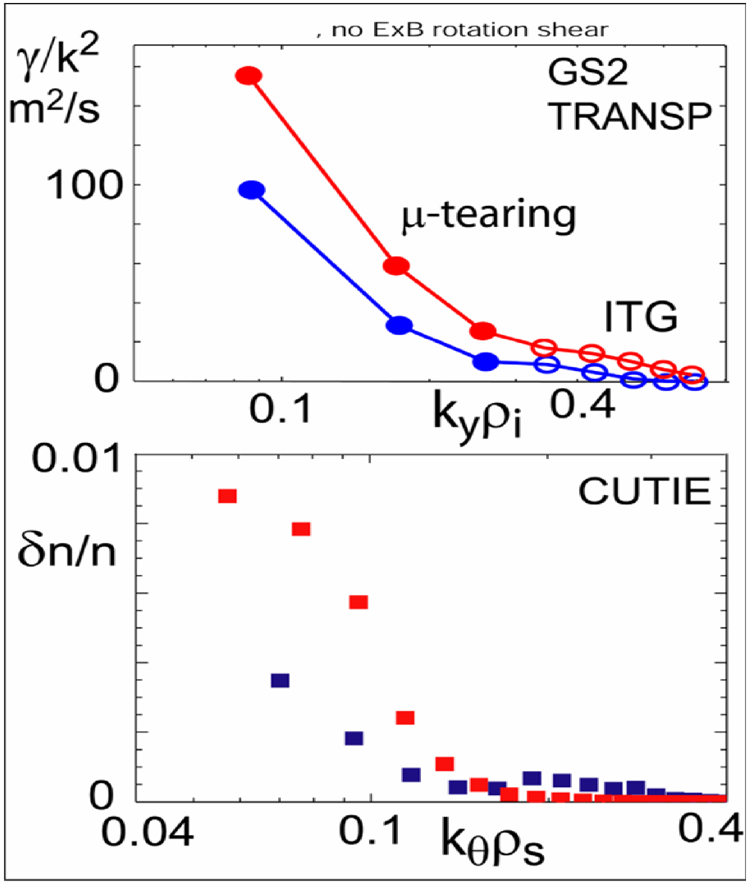
Electrons – red

$\rho^* = 1/184.7$

Cutie simulations of pellet-fuelled MAST plasma



M. Valovic et al. NF **48** (2008) 075006



The pellet creates a distinct zone: $\nabla n_e > 0$, doubled $\nabla \ln T_e$.

Both quasi-linear GS2 diffusivity ($\chi=\gamma/k^2$) and CUTIE fluctuations in saturated stage show increased transport in this region at long wave length modes.

Conclusions from global simulations

- ORB5 growth rates of linear ITG in CYCLONE base case deviate from flux tuber results at high ρ^*.
- With small ρ^* flux tube result is reproduced regardless of the width of the gradient region.
- Non-linear stability threshold is weakly affected by ρ^*.
- Experimental L- and H-mode MAST plasmas are well above the linear stability limit for ITG.
- Non-linear stability threshold is reached close to experimental MAST temperature profiles.
- Cutie and quasi-linear GS2 both show increased turbulence at low k_y after a pellet.