Ion temperature profile stiffness: Non-linear gyrokinetic simulations and comparison with experiment

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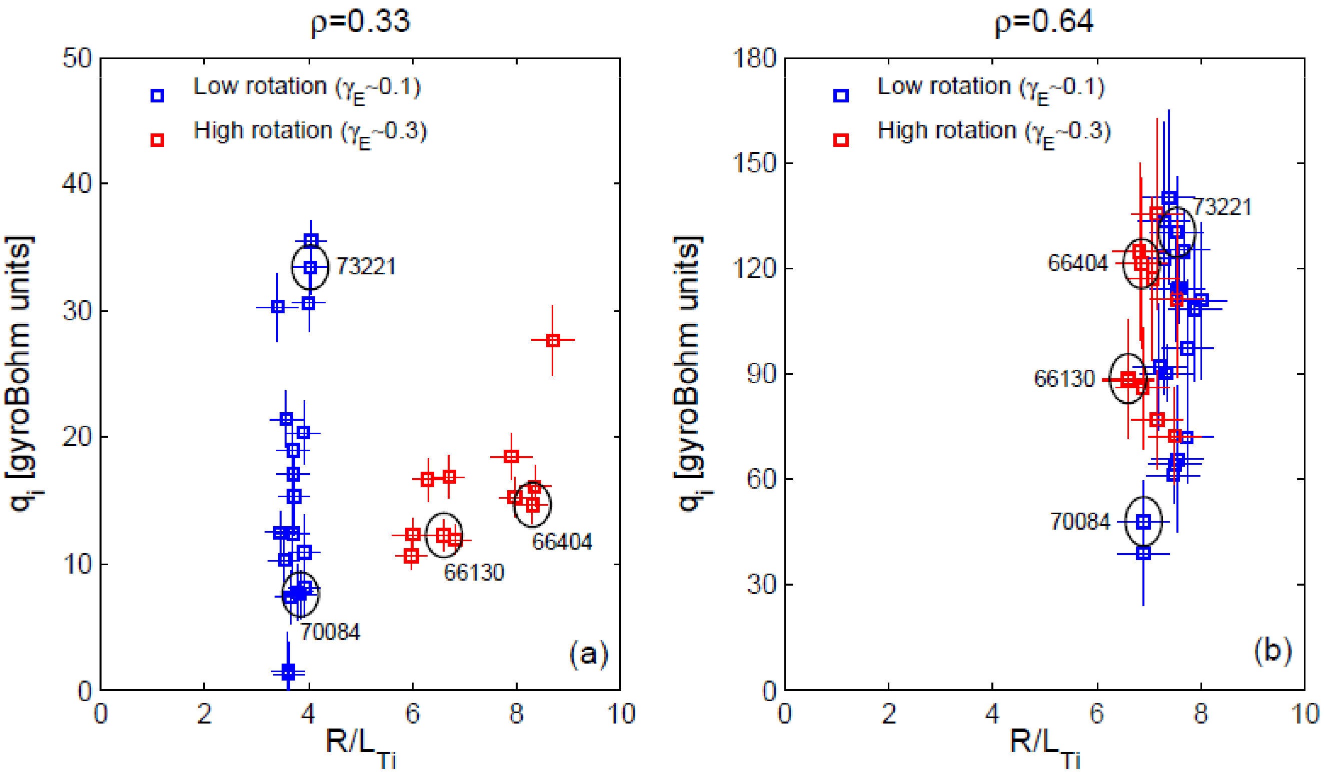
Motivation: primary claim from EXP

Mantica et al PRL 2009, 2011: striking experimental observations at JET

- Significant reduction in profile stiffness (slope of gradient length vs heat flux curve) is observed at higher rotation at low radii (ρ=0.33 – normalized toroidal flux coordinate). Hypothesized due to concomitant high flow shear and low magnetic shear

- At higher ρ (and magnetic shear), rotation observed to have no significant effect on ion temperature gradient lengths



$$q_{GB} = T_i^{2.5} n_i m_i^{0.5} / e^2 B^2 R^2$$

$$\gamma_E \equiv \frac{r}{q}\frac{d\Omega}{dr} / \left(\frac{v_{th}}{R}\right)$$

(pure toroidal rotation)

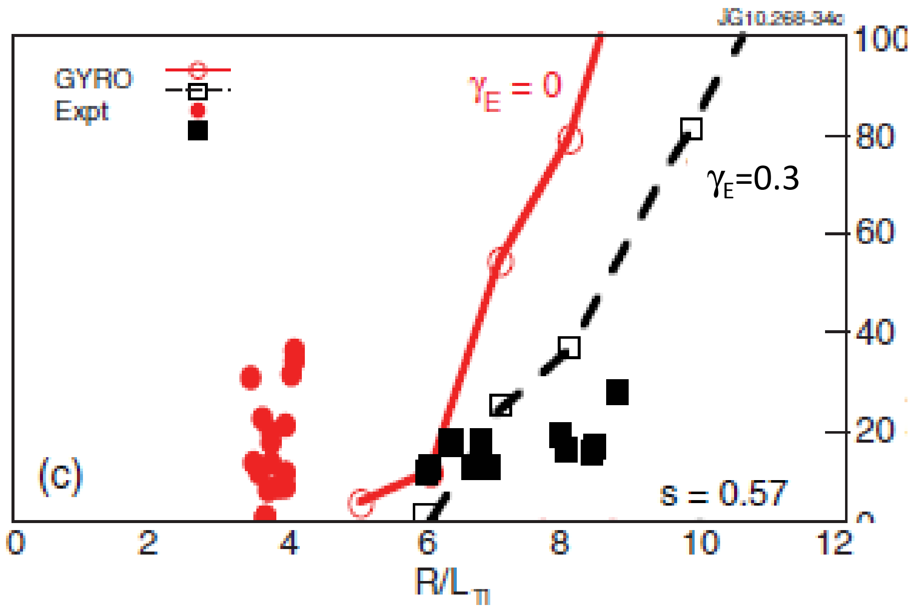
$$v_{th} \equiv \sqrt{T_e / m_i}$$

Motivation: secondary claims from EXP

Mantica et al PRL 2009, 2011: striking experimental observations at JET

- Compared with GYRO non-linear simulations (kinetic elec. collisions, electrostatic s/q=0.6/1.3, T_e/T_i =1, s-α geometry), experimental turbulence threshold agrees with linear threshold, not non-linear threshold. Raised questions regarding veracity of Dimits shift

- Stiffness of the 'low-rotation branch' higher than the GK non-linear simulations



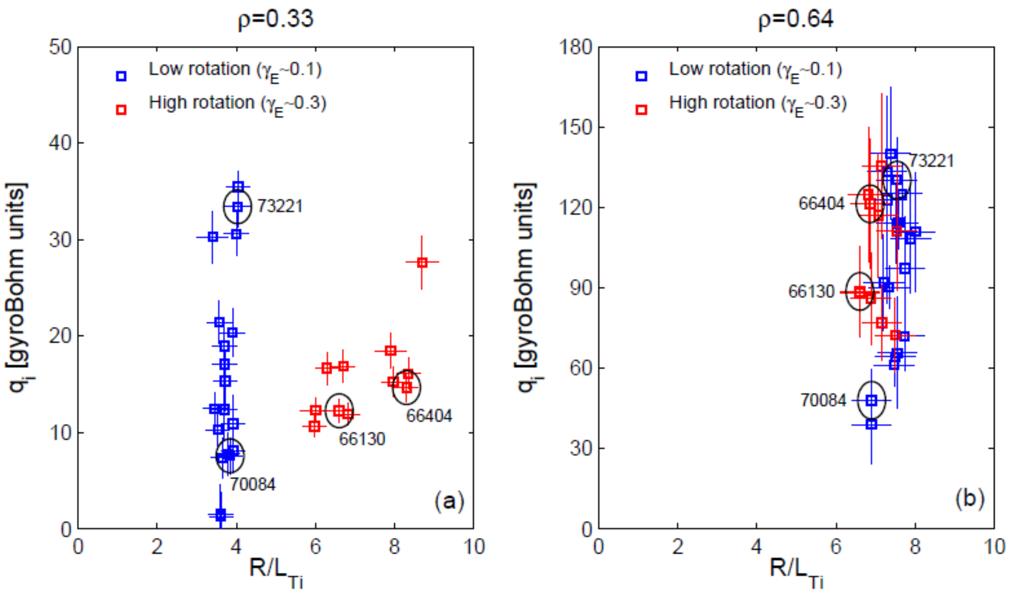
From Mantica et al PRL 2011

Our approach

• Detailed investigation of experimental discharges with GENE gyrokinetic linear and non-linear simulations.

• Underlying philosophy: in experimental – simulation comparisons, throw in everything, even the kitchen sink:
kinetic electrons, real geometry, electromagnetic effects, C species for Z_{eff}, fast particles, sensitivity studies around experimental variations and uncertainties
We assume though that local approximation holds ($1/\rho^* \sim 500$)

• Discharges circled below studied:
high and low stiffness branches at ρ=0.33, and also at ρ=0.64



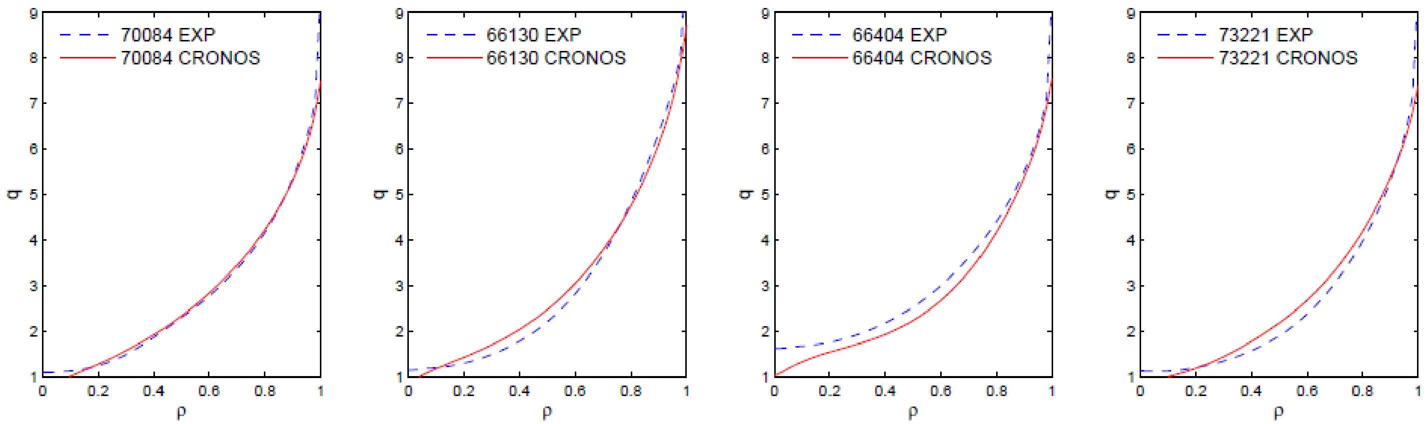
All cases first studied with CRONOS (Artaud et al NUFU 2010) integrated modelling interpretative simulations for q-profile validation, fast particle simulations (NEMO/SPOT, PION), and convenient study of experimental parameters and variations

Brief discharge summary

Previous GYRO study assumed that all discharges in data-set maintained same other dimensionless parameters as low R/L_{Ti} discharge 70084 (apart from γ_E). However, we see significant changes in T_e /$T_{i,}$ R/L_n , β_e, fast particles

Profiles averaged over energy confinement time. Errors only statistical! s, q from CRONOS interpretative simulations

Shot no.@location	$\hat{s}$	q	T_e/T_i	R/L_{Ti}	R/L_{Te}	R/L_{ne}	β_e [%]	ν^*	$\langle Z_{eff}\rangle$	$M[v_{tor}/c_s]$
$70084@\rho = 0.33$	0.7	1.7	1.08 ± 0.04	3.5 ± 0.5	3.8 ± 0.6	1.4 ± 0.4	0.19 ± 0.01	0.07	2.2 ± 0.1	0.09
$66130@\rho = 0.33$	0.7	1.8	1.25 ± 0.13	6 ± 0.4	6.5 ± 1	2.4 ± 1	0.46 ± 0.09	0.04	1.8 ± 0.1	0.31
$66404@\rho = 0.33$	0.4	1.8	1.14 ± 0.06	8.6 ± 0.9	5.5 ± 0.8	3.8 ± 0.4	0.35 ± 0.07	0.02	2.2 ± 0.1	0.19
$73221@\rho = 0.33$	0.7	1.5	1.33 ± 0.02	3.8 ± 0.4	5.4 ± 0.2	2.8 ± 0.3	0.2 ± 0.02	0.055	2.2 ± 0.1	0.07
$70084@\rho = 0.64$	1.3	3	1.18 ± 0.05	7.2 ± 0.2	6.4 ± 1	1.8 ± 0.8	0.096 ± 0.01	0.16	2.2 ± 0.1	0.03
$66130@\rho = 0.64$	1.5	3.5	1.1 ± 0.2	6.8 ± 0.3	8.5 ± 3	1.8 ± 1.4	0.18 ± 0.04	0.1	1.8 ± 0.1	0.23
$66404@\rho = 0.64$	1.4	2.9	1.23 ± 0.13	6.9 ± 0.4	10 ± 1.6	2.1 ± 0.9	0.08 ± 0.01	0.05	2.2 ± 0.1	0.15

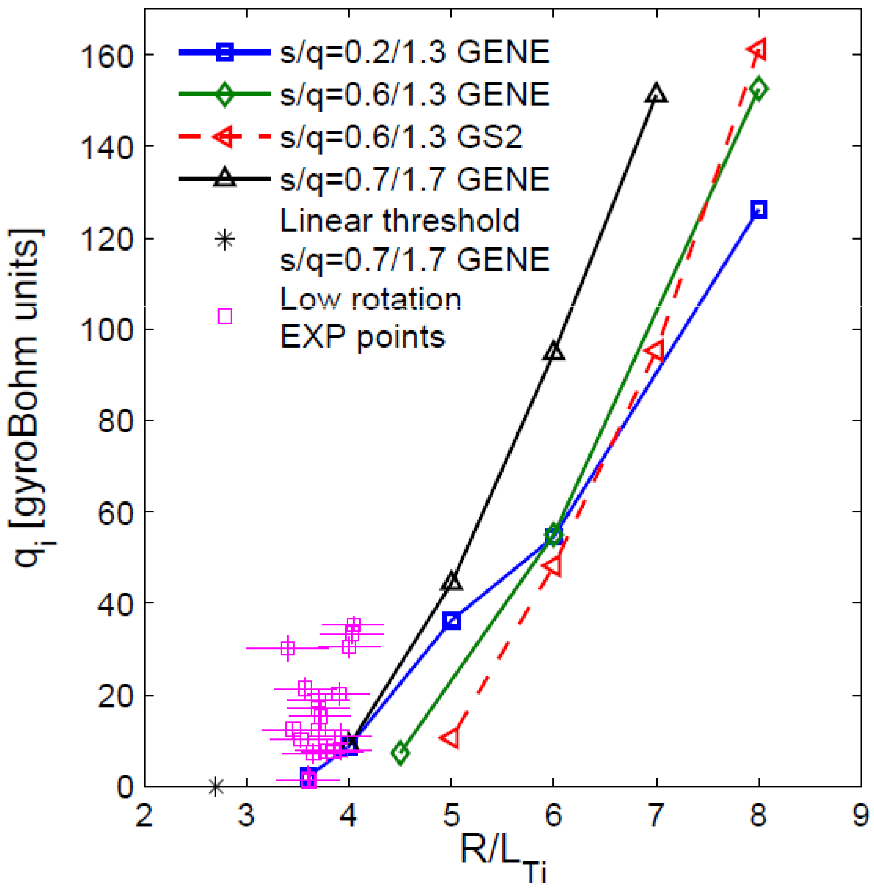


EXP (polarimetry or MSE constrained EFIT) and CRONOS q-profiles agree within ~15% EXP error estimate

Note: previous GYRO simulations assumed s/q=0.6/1.3 for 70084 … recent EFIT+Faraday rotation reprocessing + CRONOS interpretative simulations point to q=1.7. SIGNIFICANT DIFFERENCE (as will be seen)

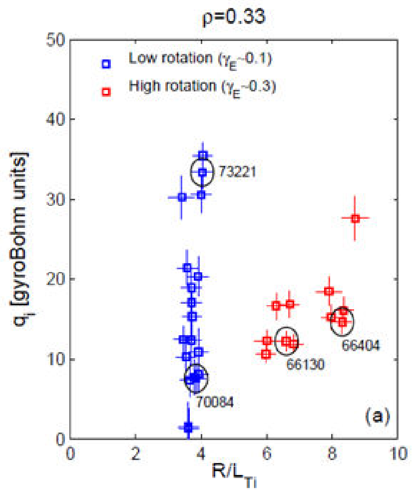
q and s sensitivity of threshold and stiffness

Collisionless, electrostatic simulations based on low-rotation discharge 70084



- GENE-GS2 benchmark agree for s/q=0.6/1.3 Mantica PRL 2011 parameters (apart from low R/L_{Ti} - likely due to s-α vs circular geometry)
- Simulations for various s/q values to assess reasonable range of variation of actual values. Stiffness reduced at low-s (likely due to increased impact of zonal-flows, J.Citrin et al POP 2012)
- For the new 'base value' of s/q=0.7/1.7, the Dimits shift now agrees very well with the experimental threshold! Opposite conclusion from Mantica PRL 2011. Due to strong threshold sensitivity between q=1-2

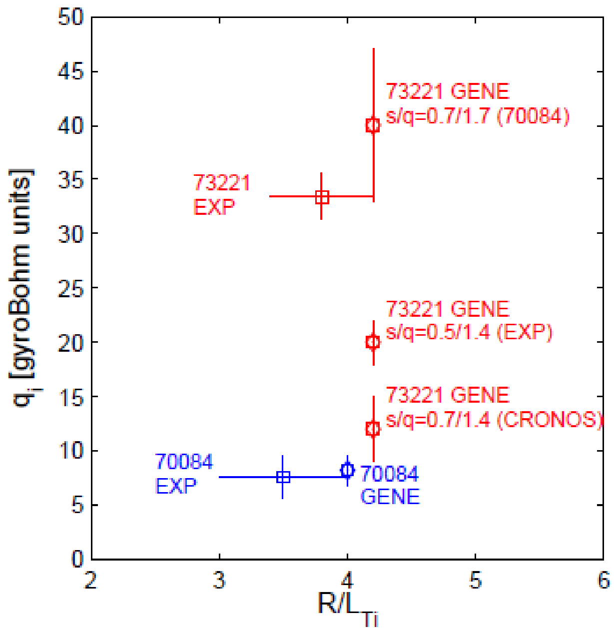
Study of ‘high-stiffness branch’



Seeming high stiffness ‘wall’ not reproduced by simulations assuming constant T_e/T_i. However, T_e/T_i for high flux cases is – following recent ECE recalibration – higher than previously thought (1.3 instead of 1.1).

Major impact on ITG threshold through $(1+T_i/T_e)$ scaling

GENE NL simulations. Z_{eff} =1.9, e-i collisions, electromagnetic, real geometry

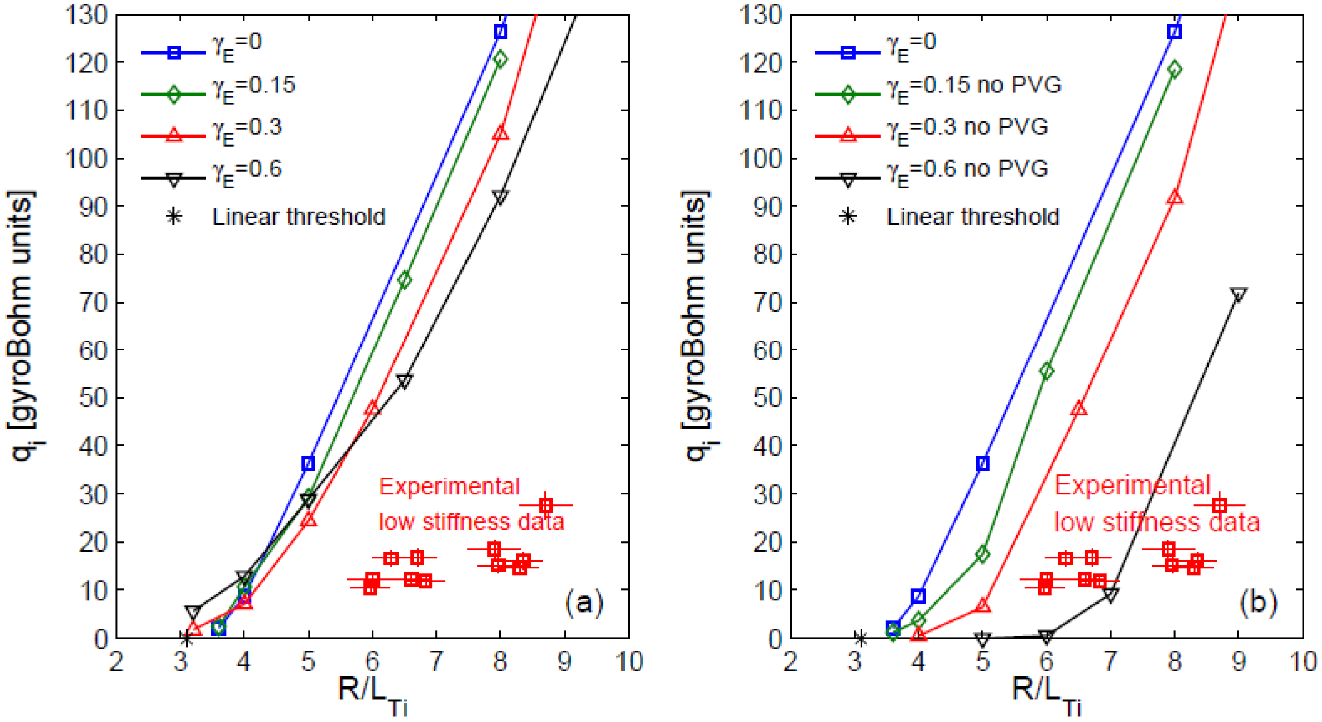


Within reasonable range of q-profile uncertainty (~15%), the ‘wall’ can be reproduced.

R/L_{Ti} taken at edge of error bar, otherwise simulations are stable. Uncertainty also in Z_{eff} profile has strong impact.

Study of low-stiffness branch. sensitivity study to various parameters: **Flow shear**

Collisionless, electrostatic GENE non-linear simulations based on 70084 with circular geometry

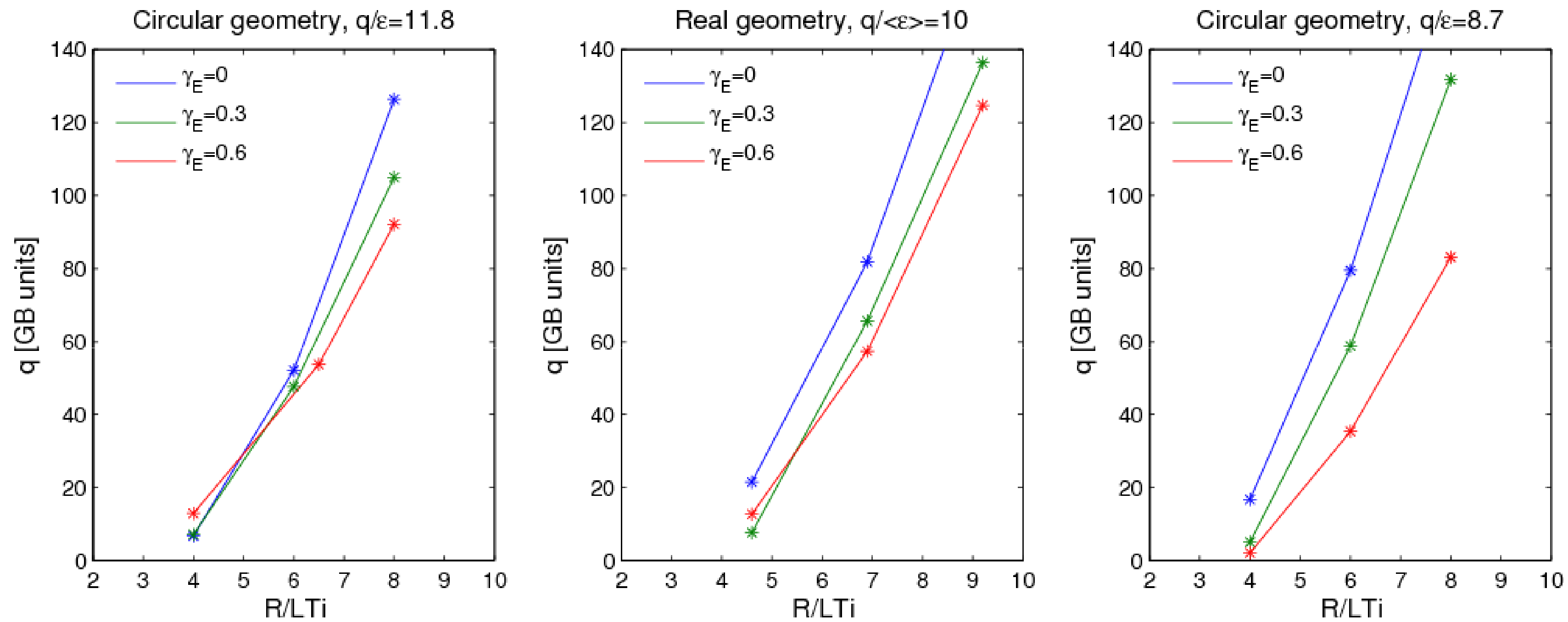


PVG effects are very apparent

- Leads to no shift of threshold, and even destabilization and reduced stiffness in vicinity of threshold.
- Regular 'Waltz-rule' is restored at all R/L_{Ti} when removing PVG from system.

Study of low-stiffness branch. sensitivity study to various parameters: **Flow shear**

q/ε dependence of PVG drive: $\gamma_p = q/\varepsilon * \gamma_E$ for pure toroidal rotation



PVG effects are reduced when decreasing q/ε. This case seems to be on the boundary of a 'zero-turbulence-manifold' at lower range of R/L_{Ti} (PRL E.Highcock 2012).

- Even for real geometry, toroidal rotation cannot explain the measured ITG stabilisation due to PVG drive and insufficient flow shear (reminder: γ_E = 0.3 is the experimental 'high-flow-shear' value).

- Impact of centrifugal force on magnetic geometry investigated and found negligible

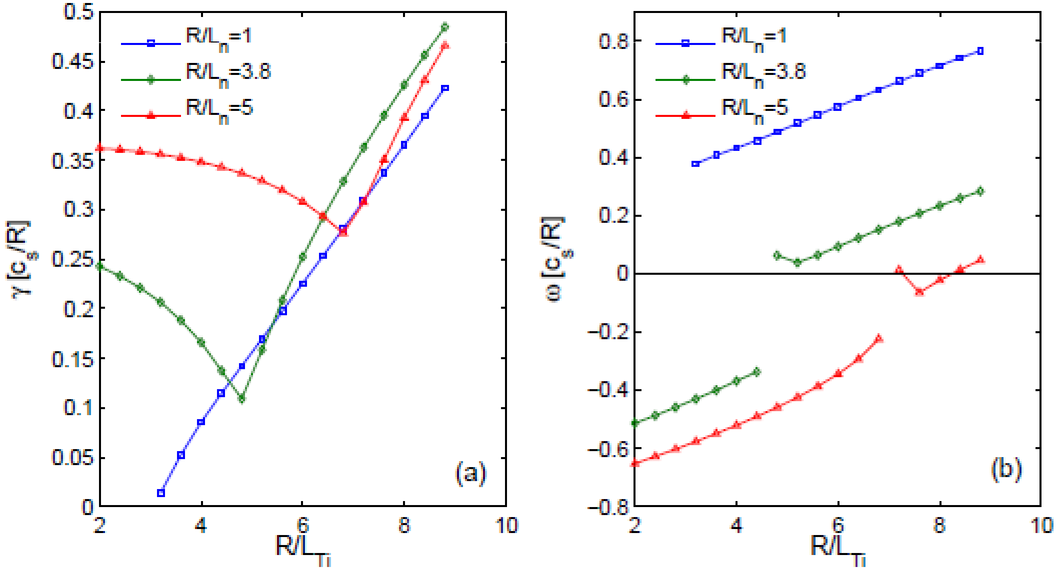
Study of low-stiffness branch. sensitivity study to various parameters: R/L_n

Higher R/L_n associated with the 'low stiffness' discharge:
$R/L_n = 3.8$ for high $R/L_{Ti} = 8$ discharges, and $R/L_n = 1$ for low $R/L_{Ti} = 4$ discharge

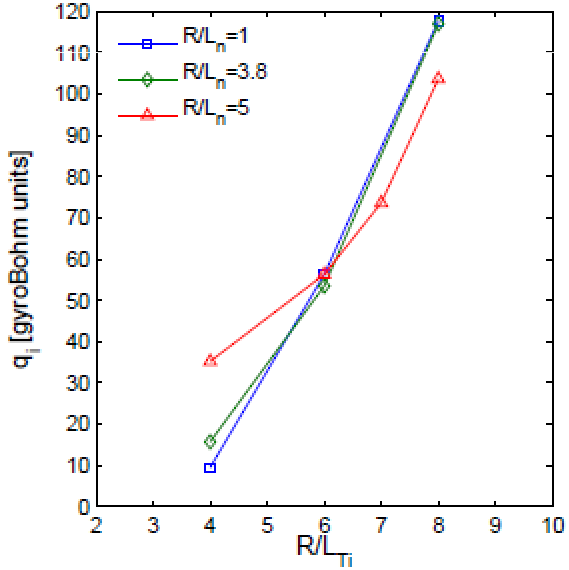
Question whether non-linear TEM-ITG interplay could reduce flux (Merz and Jenko Nucl. Fusion 2010)

Collisional, electrostatic GENE simulations based on 70084 with circular geometry

Linear growth rates and frequencies



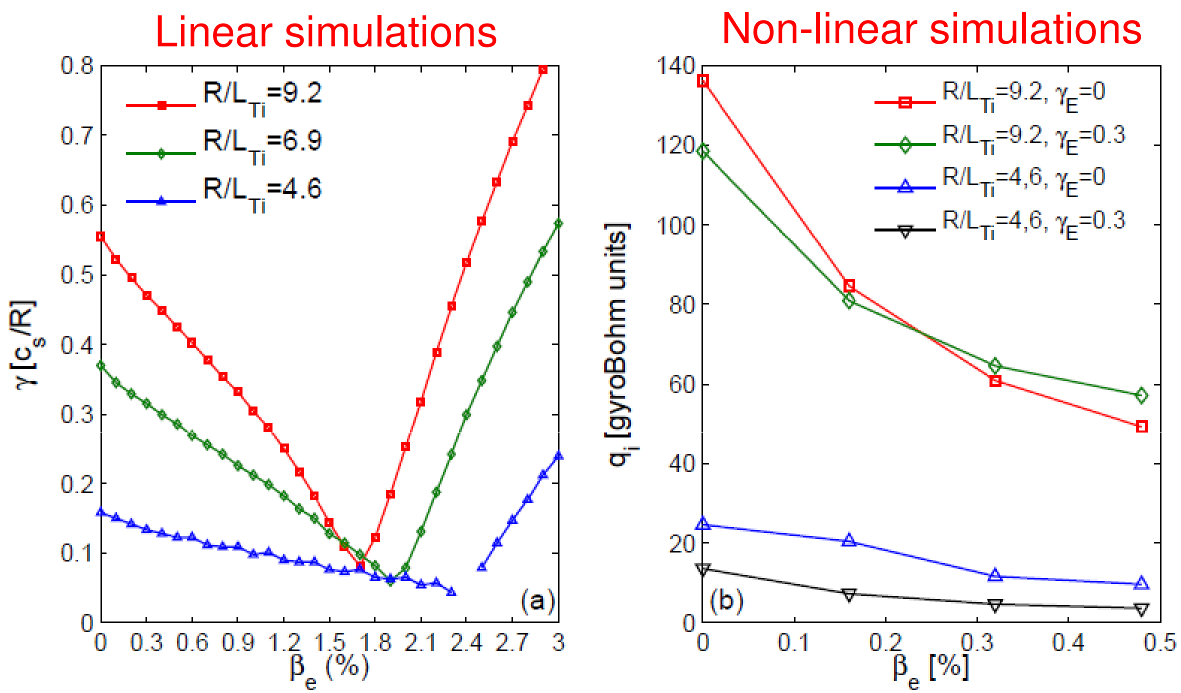
Non-linear simulations



At experimental high R/L_n, ITG takes over at R/L_{Ti} ~ 5, much less than experimental R/L_{ti}

Conclusion: R/L_n differences unlikely to have significant impact

Study of low-stiffness branch. sensitivity study to various parameters: β_e



Collisional, electromagnetic GENE simulations based on 66404 with real geometry

As long as we are below the KBM limit (see linear graph), electromagnetic effects can stabilize ITG (see also Pueschel et al POP 2008, 2010).

- Non-linear stabilisation ~ x3 stronger than linear stabilisation!
- For our parameters, the effect is quite strong and ***significantly reduces stiffness.***
- This effect is general and has implications for transport modelling. Should be incorporated into mixing length rule in quasi-linear models, for example

Note: PVG modes seem stronger with finite beta (or ExB stabilisation weaker)… Not understood

Speculation (and future work): mechanisms for non-linear β-stabilisation

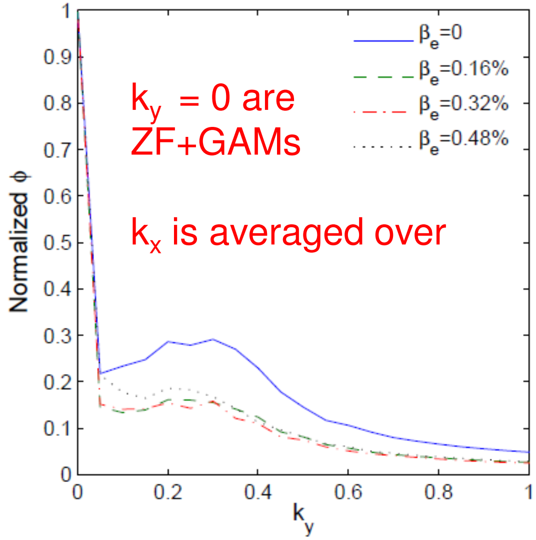
• ITG stabilization due to finite beta seems correlated with increased relative strength of zonal flows (Pueschel et al 2010)

• Alfven waves acting as a 'catalyst' for increased non-linear coupling of DW to ZF has been proposed (Millitello et al NUFU 2011)

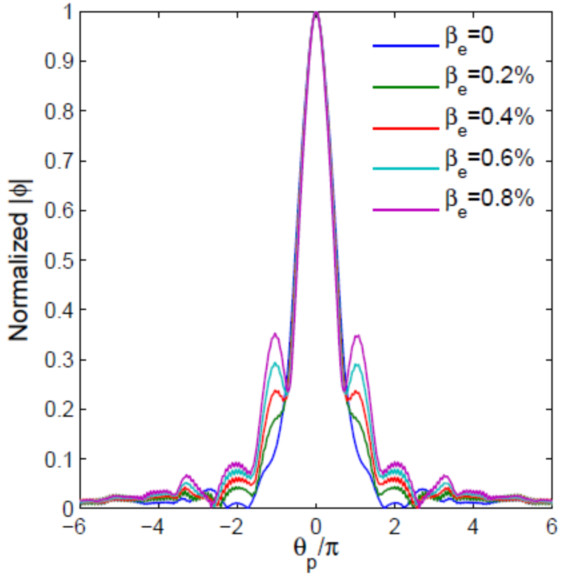
• In our scan, increased relative strength of ZF to DW is observed when going from electrostatic to electromagnetic cases

• Linear eigenmode structure widens in ballooning space as β_e increases. Facilitates coupling to ZF since DW modes are more poloidally symmetric? Same mechanism seen at low-s (J.Citrin et al POP 2012)

Potential field amplitude potential from the non-linear β_e scan



Linear eigenmodes from beta-scan



Study of low-stiffness branch. sensitivity study to various parameters: **Fast particles**

Discharges studied are low density and collisionality. NBI driven ‘high-rotation’ discharges can have significant fast particle population. Can stabilise ITG turbulence through 3 general mechanisms:

• Dilution of main ion species

• Geometric effect: increased Shafranov shift due to suprathermal pressure alters drift frequencies and can stabilise ITG (see e.g. Bourdelle et al NF 2005)

• Stabilisation by finite-β effects. Suprathermal pressure adds to thermal β and β' . Can locally stabilise turbulence where fast ions have strong gradients (M.Romanelli PPCF 2010)

We have studied all 3 mechanisms in detail. GENE simulations based on high R/L_{Ti} discharge 66404:

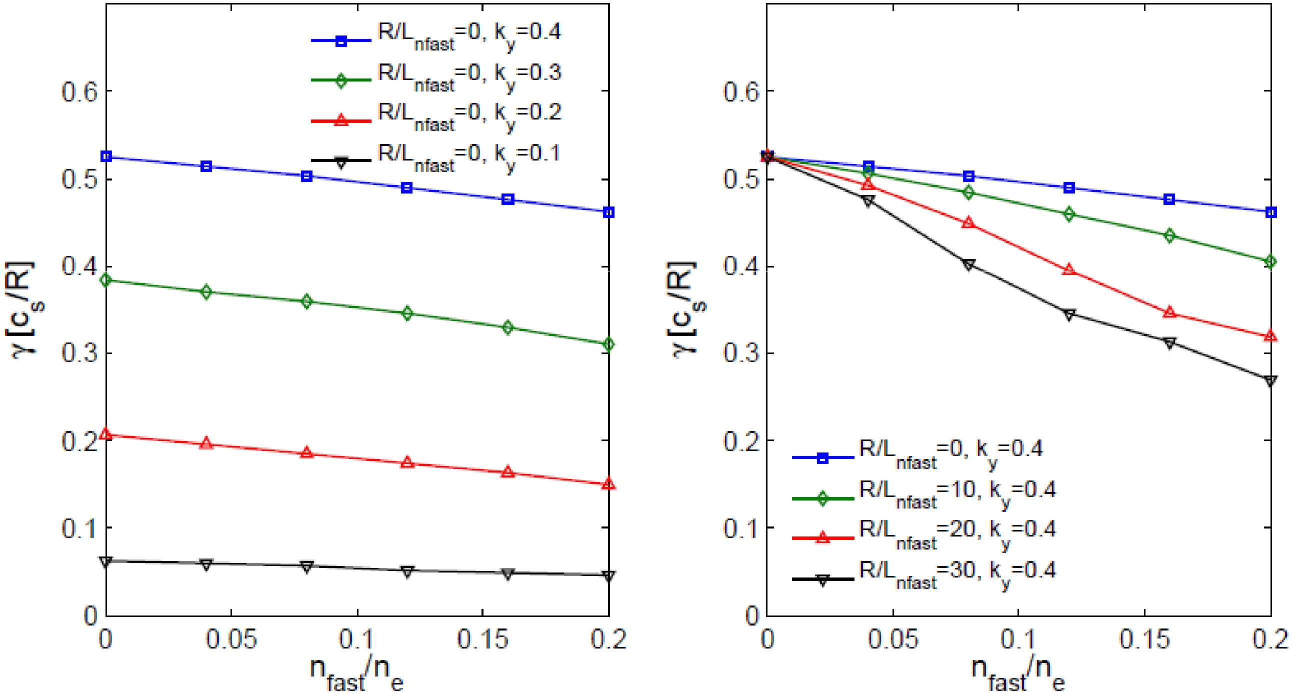
Fast particle energy distribution and densities calculated by Monte Carlo modelling (CRONOS with NEMO/SPOT (M.Schneider et al NF 2010).

Study of low-stiffness branch. sensitivity study to various parameters: **Fast particles**

Collisional, electromagnetic GENE linear simulations based on 66404 with real geometry

No fast ion pressure gradient: main ion dilution only

$R/L_{nfast} \approx 15$ from NBI modelling

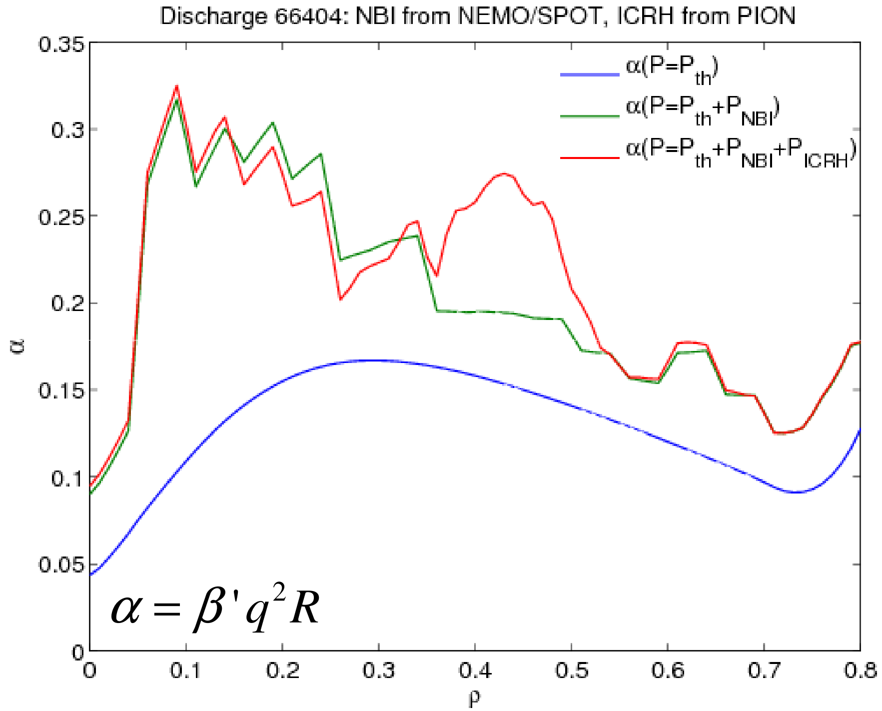


According to NEMO/SPOT modelling, $n_{fast} / n_e = 0.1$. Ion dilution effect thus negligible

Interpolated linear stabilisation due to fast-particle β-effect is ~15%.
However, as with the thermal β-effect , we can expect enhanced non-linear stabilisation!

Study of low-stiffness branch. sensitivity study to various parameters: Fast particles

Discharge 66404 also has some ICRH:
sharp spatial gradients in ICRH distribution function

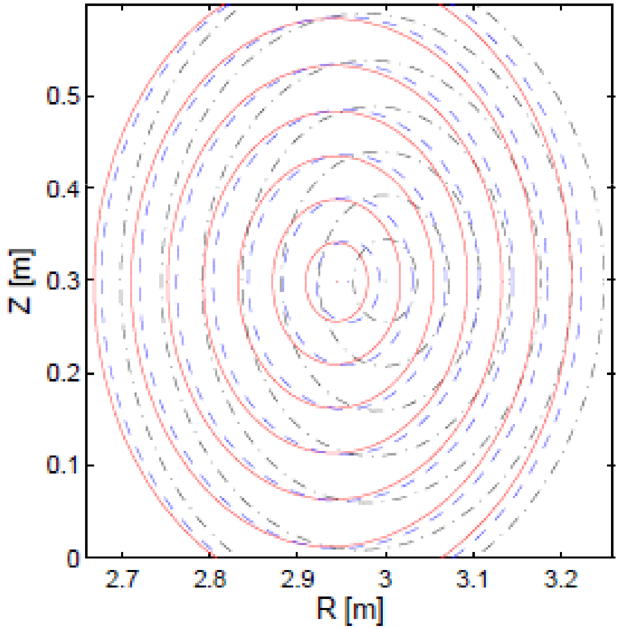


- According to PION modelling no impact on ρ=0.33. But what are modelling uncertainties?
- Δρ=0.1 variation in suprathermal pressure gradient could ~double the fast-particle β-stabilisation
- Check of profile from SELFO ICRH modelling planned

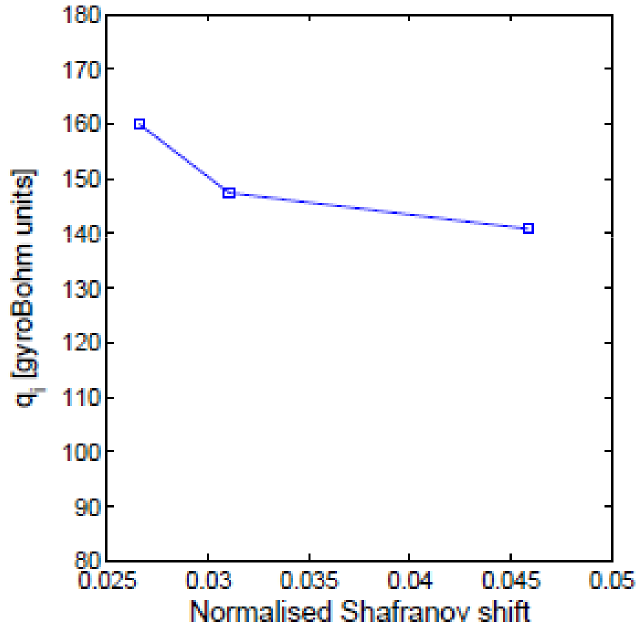
Study of low-stiffness branch. sensitivity study to various parameters: **Fast particles**

ITG stabilisation due to increased Shafranov shift

CRONOS flux surface solutions (from HELENA), with:
Thermal pressure of discharge 70084
Thermal pressure of discharge 66404
Total pressure of discharge 66404



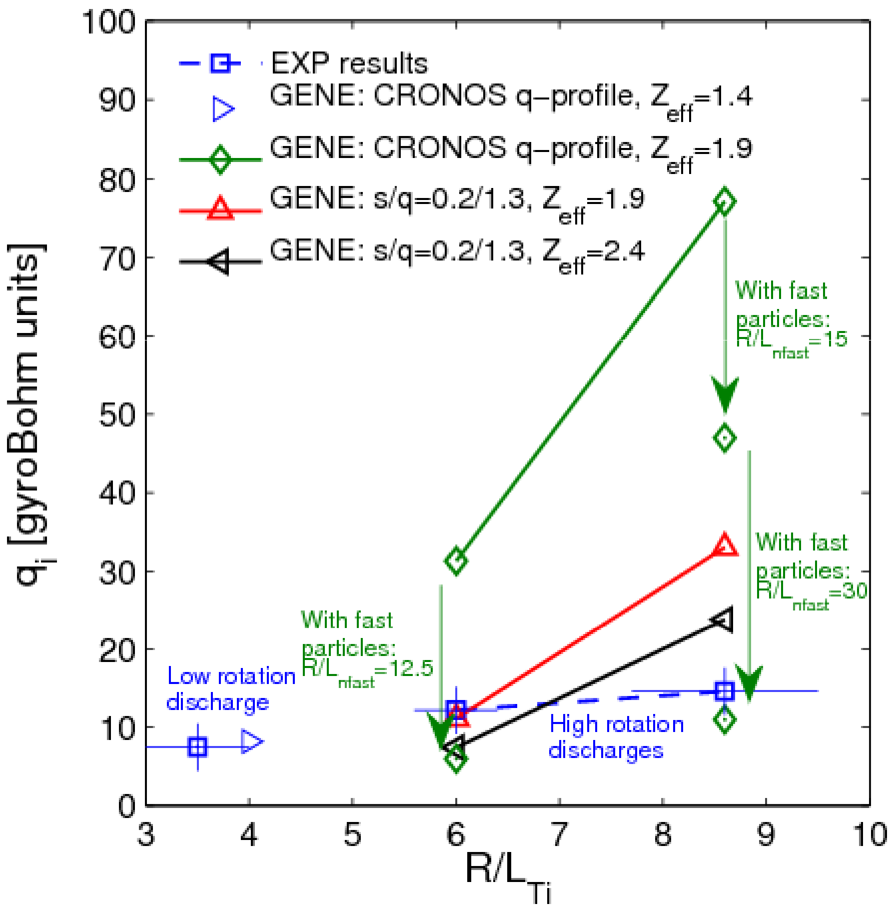
Non-linear simulations transitioning between the 3 equilibria



Linear β-effect, and Shafranov shift effect gives a total of 30% stabilisation (~45% if there is indeed a mismatch in the modelled ICRH profile).
Non-linear β-effect expected to be stronger… Fast particles cannot be ignored!

Full comparison between measured ion heat flux and GK simulations at ρ=0.33

GENE NL simulations: collisional, electromagnetic, up to 4 species (C and fast), real geometry. Sensitivity tests done for 'reasonable' variations of input parameters



Shot number	Z_{eff}	R/L_{Ti}	T_e/T_i	$\hat{s}$	q	q_i [gyroBohm units]
66130	1.4	6	1.25	0.2	1.3	19.4
66130	1.4	6	1.12	0.2	1.3	12.3
66130	**1.9**	**6**	**1.25**	**0.7**	**1.8**	**31.3**
66130	**1.9**	**6**	**1.25**	**0.2**	**1.3**	**11.1**
66130	**2.4**	**6**	**1.25**	**0.2**	**1.3**	**7.5**
66404	1.4	8.6	1.14	0.2	1.3	53.2
66404	**1.9**	**8.6**	**1.14**	**0.4**	**1.8**	**77.1**
66404	**1.9**	**8.6**	**1.14**	**0.2**	**1.3**	**33**
66404	2.4	8.6	1.14	0.4	1.8	47
66404	**2.4**	**8.6**	**1.14**	**0.2**	**1.3**	**23.8**
66404	2.4	7.7	1.08	0.2	1.3	13.7

Non-linear β stabilisation from *both* thermal and suprathermal components the key factor for reducing ion-heat-flux

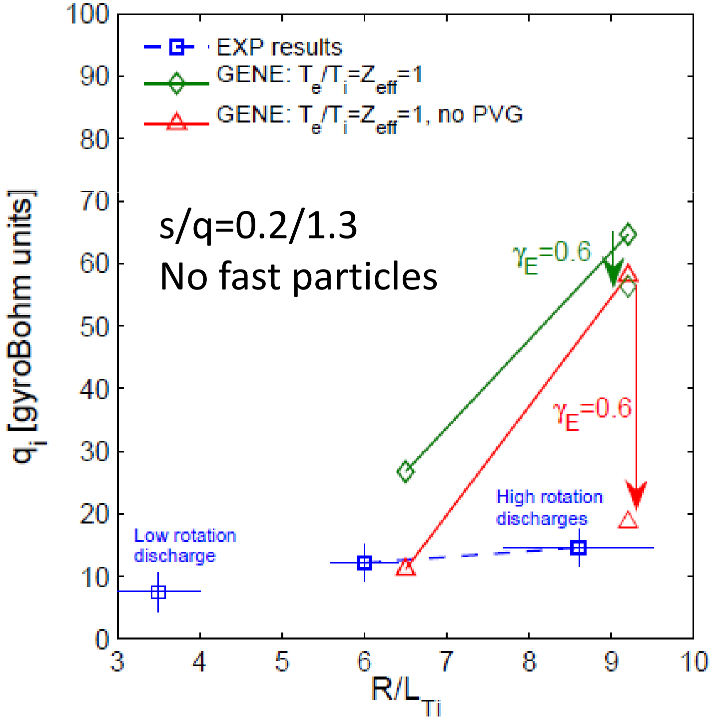
Full agreement for 66130.

For 66404, simulated flux x3 higher for NBI fast ions only. Within range of agreement given reasonable input parameter variations. Assuming ICRH suprathermal pressure mismatch also provides agreement

Full comparison between measured ion heat flux and GK simulations at ρ=0.33

Relaxing ‘constraint’ of pure toroidal rotation

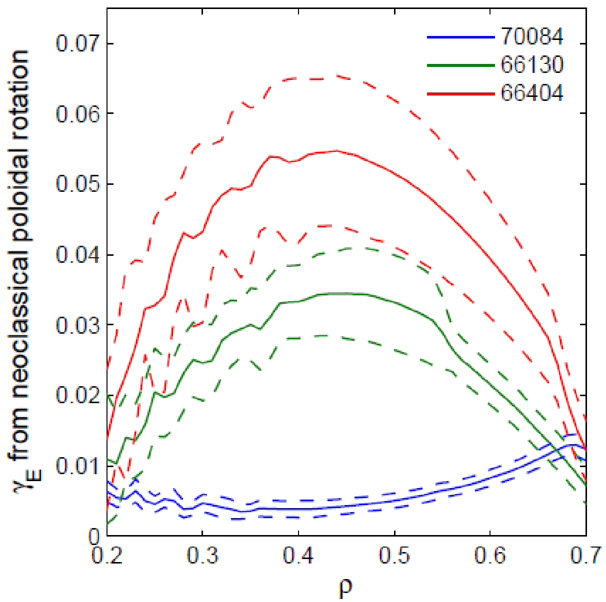
Significant stabilisation can be observed if we assume no PVG. Decoupling γ_E and γ_P of equivalent to assuming non-negligible poloidal rotation



Significant poloidal rotation measured in JET ITBs (Crombé et al PRL 2005).
Diff. between EXP and NCLASS C and D poloidal rot. measured at DIII-D (Solomon et al POP 2006, Grierson et al POP 2012)

Could the zero-poloidal-rotation assumption be wrong?
Factor ~10 more than NCLASS predicted γ_E needed

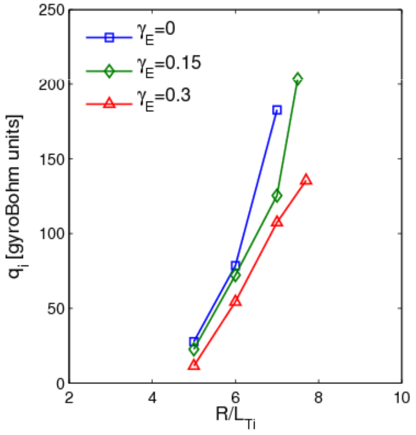
NCLASS predicted γ_E from neoclassical poloidal rotation (and error boundaries)

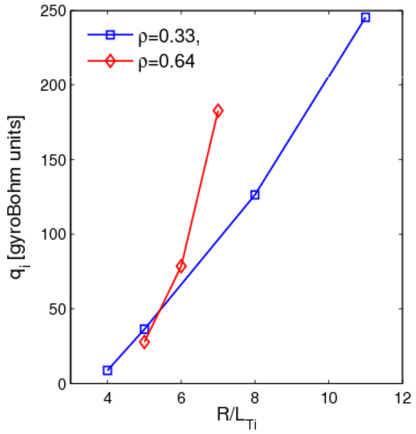


Full comparison between measured ion heat flux and GK simulations at ρ=0.64

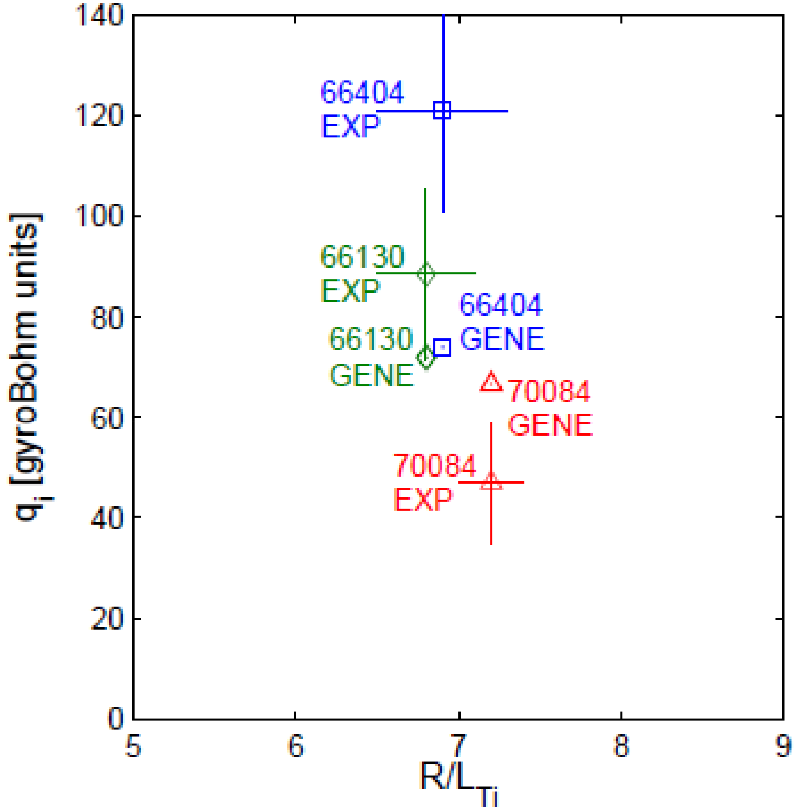
Effect of rotation small. Stiffness much higher than at ρ=0.33 as measured – due to s and q. Also for EM simulations will hold since β lower and typically no fast particles

Based on 70084. Electrostatic simu, no colls, Z_{eff} =1





Full non-linear simulations



Full comparison is successful. Agreement for each case within ~50%, easily explainable by input parameter uncertainties (Z_{eff}, R/L_{Ti}, T_e/T_i).

70084 simu. doesn't include far off-axis ICRH which should improve agreement

Conclusions

- Comprehensive linear and non-linear simulations with GENE carried out to investigate experimental observations and claims on JET data-set: low-stiffness with rotation and low-s, lack of Dimits shift, high stiffness at low rotation (beyond code predictions)

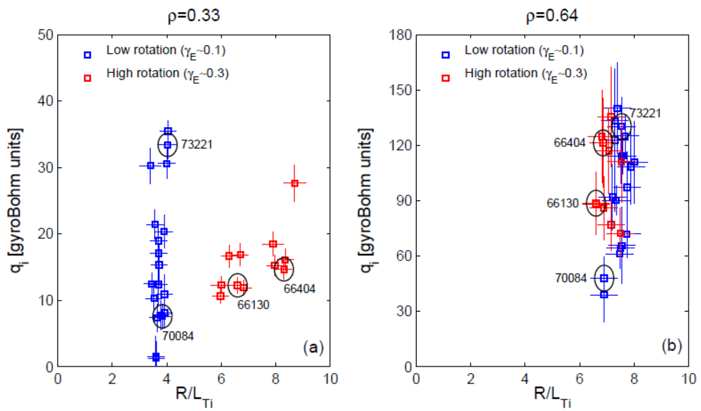
- Agreement with NL threshold (Dimits shift) and EXP threshold 'recovered' following reanalysis of measured q-profile, in agreement with CRONOS interpretative simulations

- 'High-stiffness' branch likely due to increased T_e / T_i impact on threshold in high flux low-rotation discharges following ECE recalibration (shows sensitivity of conclusions to input parameters)

- Pure toroidal rotation does not reduce stiffness in this data-set due to PVG and insufficient γ_E

- 'Enhanced' non-linear β-stabilization by both thermal and suprathermal pressure the key factor for flux reduction and lowered stiffness. Physics of enhanced non-linear stabilisation still open question. Has general implications for transport modelling.

- All 7 experimental ion-heat-flux points studied agree with NL predictions within reasonable variations of input parameters around experimental uncertainties



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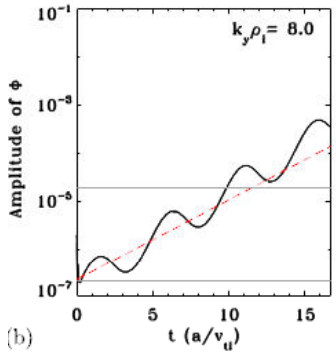
1. Novel method for calculating growth rates in presence of flow shear

2. Study of differences in flow shear suppression of linear instabilities with adiabatic and kinetic electron formulations

Novel growth rate calculation method (1)

How to define linear growth rates in the presence of flow shear? Is there a physically meaningful description?



1. Simple average through the fluctuations of the Floquet mode. Probably not physically meaningful

2. Define γ over a time until a defined amplitude amplification is reached. Assumes that then non-linear phase reached (PPCF Roach et al 2009)

Another suggestion: define γ over a time window corresponding to an estimated non-linear decorrelation time

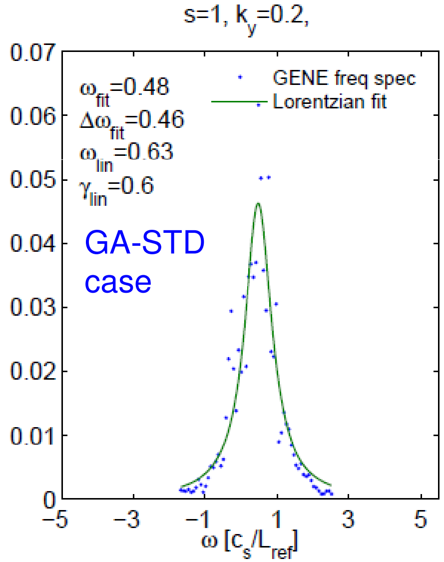
(e.g. estimation such as $\tau_{NL}=O(1)\gamma^{-1}$)

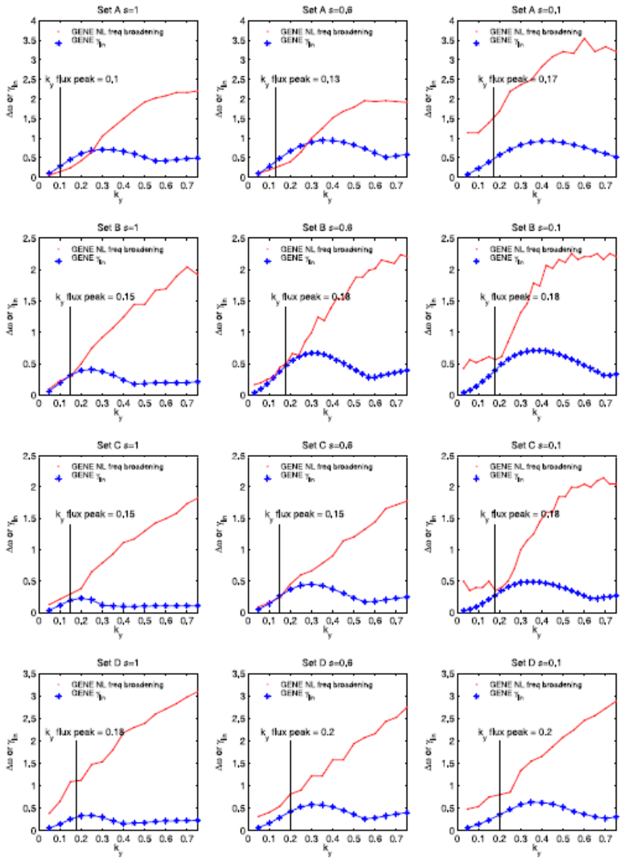
Novel growth rate calculation method (2)

Citrin et al POP 2012

TABLE I. Input parameters for the GENE magnetic shear scans.

Set name	R/L_{Ti}	R/L_{Te}	R/L_n	T_i/T_e	q
A (GASTD)	9	9	3	1	2
B	7.6	6.7	4	1.4	1.4
C	6.3	5.5	3.3	1.4	1.4
D	7.6	6.7	4	1.4	1





k-dependent non-linear decorrelation time (inverse freq. width) found to be $\tau_{ac} = 1/\gamma_k$ over range in parameter space at transport relevant k_y (but not at low-s or low-q: decorrelation due to ZF?) Agrees with simple linear response renormalization.

Motivates calculating γ_k over a time window corresponding iteratively to $1/\gamma_k$!

γ_k calculation method

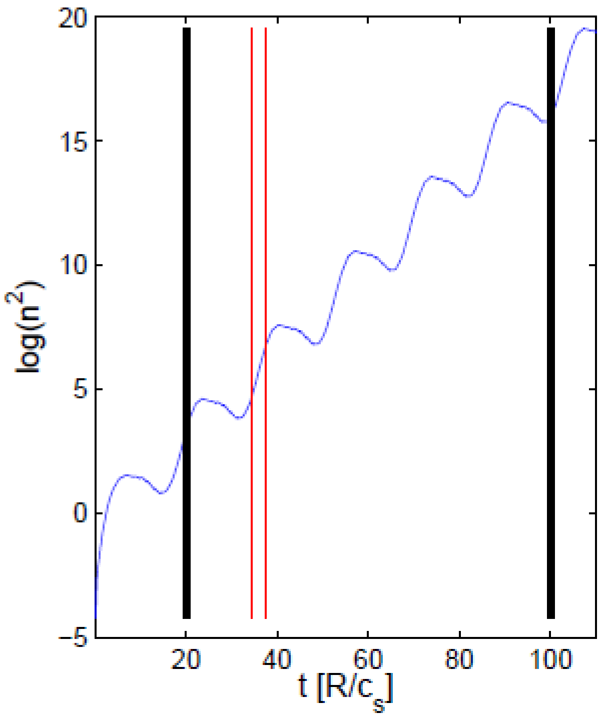
1. For a given time window Δt, a 'local' γ can be calculate for every point on the Floquet mode

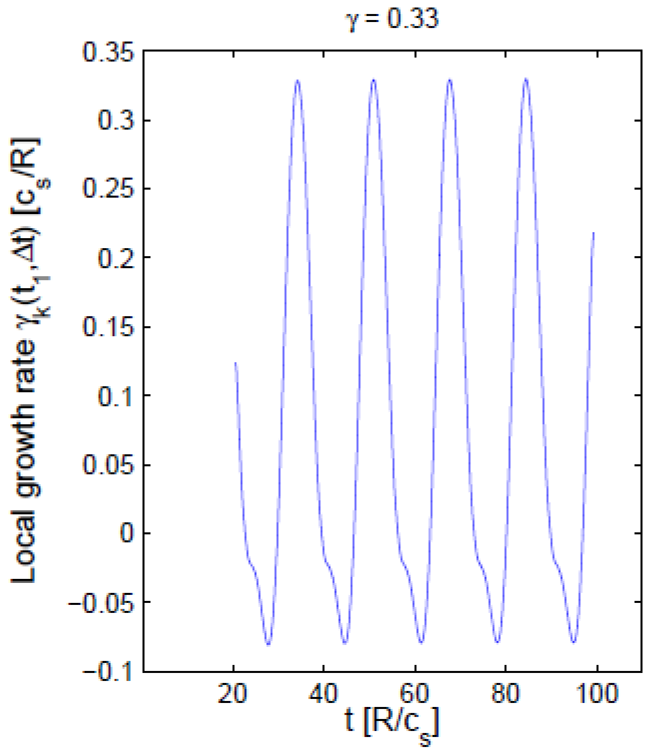
$$\gamma_k\left(t_1, \Delta t\right) = ln\left(\frac{n(t_1+\Delta t)}{n(t_1)}\right) / \left(\Delta t\right)$$

2. From the average of the peaks of the 'local' γ, a $\gamma(\Delta t)$ can be defined

3. If $1/\gamma(\Delta t) \neq \Delta t$, then Δt is iteratively adapted until $1/\gamma(\Delta t) = \Delta t$ – the presumed NL decorrelation time

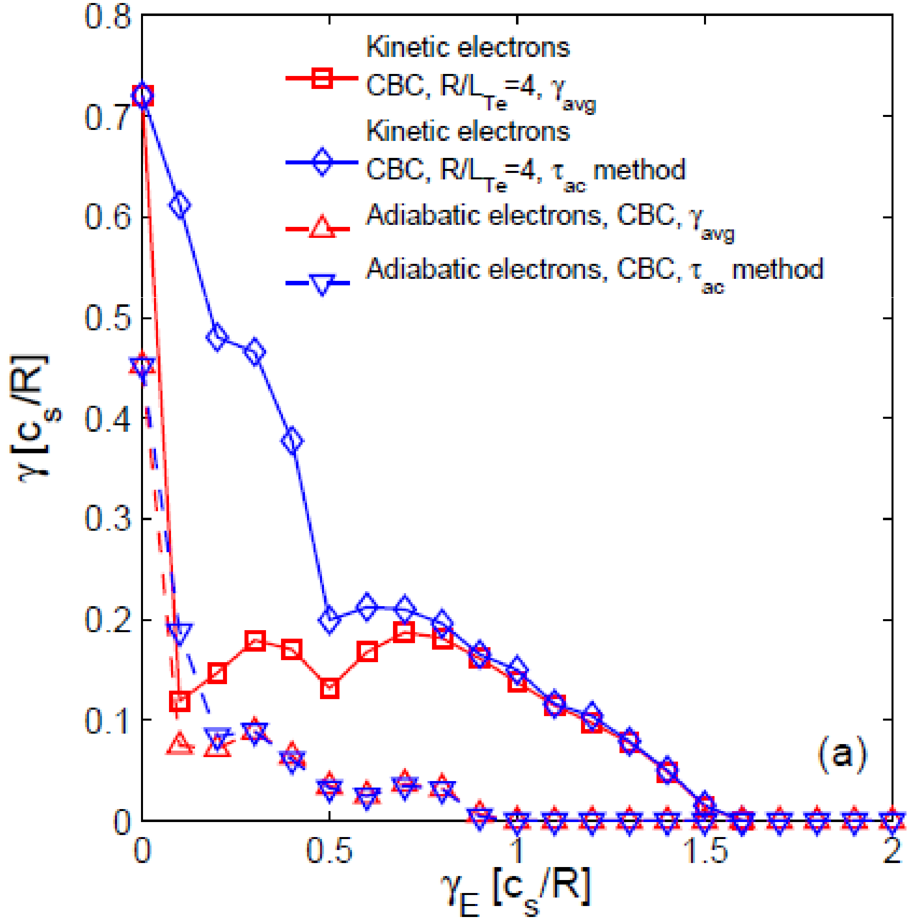
   Can easily generalize to $1/\gamma(\Delta t) = C\Delta t$, with C a function of plasma parameters capturing the NL frequency broadening





τ_{ac} method example, compared with simple averaging

GENE linear simulations
Cyclone Base Case



- Sharp drop for small γ_E avoided

- For large γ_E growth rates converge with values for averaging, as expected since $1/\gamma$ is large

- Steady drop (e.g. for kinetic electron case) reminiscent of 'classic' quench rules in quasi-linear modelling to fit non-lineat simulations, e.g:

$$\gamma_{eff} = \gamma_k \left(1 - \alpha \frac{\gamma_E}{\gamma_k}\right)$$

with $\alpha \approx 0.5\text{-}1$

Mode quench at low-s

In work by Highcock et al (PRL 2012) at zero-magnetic-shear, sub-critical turbulence arises from PVG. No linear modes since for γ_E / s > 1, eddy convection is faster than sound speed. We thus examine flow-shear quenching at low-s, to determine threshold of this behaviour. Note that this work was done with adiabatic electrons

Eddy convection due to flow shear in slab (Newton et al PPCF 2010)

Toroidal analogy

$$u_f = V_0 \frac{L_s}{L_v} \hat{\mathrm{e}}_{\mathrm{v}} \cdot \hat{\mathrm{y}} = \frac{dV_{tor}}{dr} \frac{Rq}{s} \frac{\epsilon}{q}$$

If u_f > c_s assumed that instabilities cannot arise

Solving for γ_E:

Normalized ExB shear rate for pure toroidal rotation

$$\gamma_E = \frac{\epsilon}{q} \frac{dV_{tor}}{dr} / \frac{c_s}{R}$$

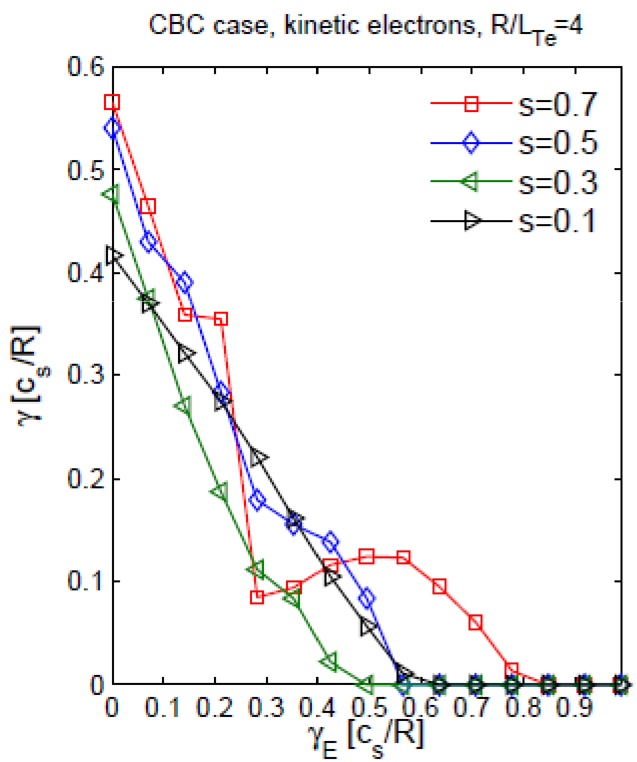
Stability criterion

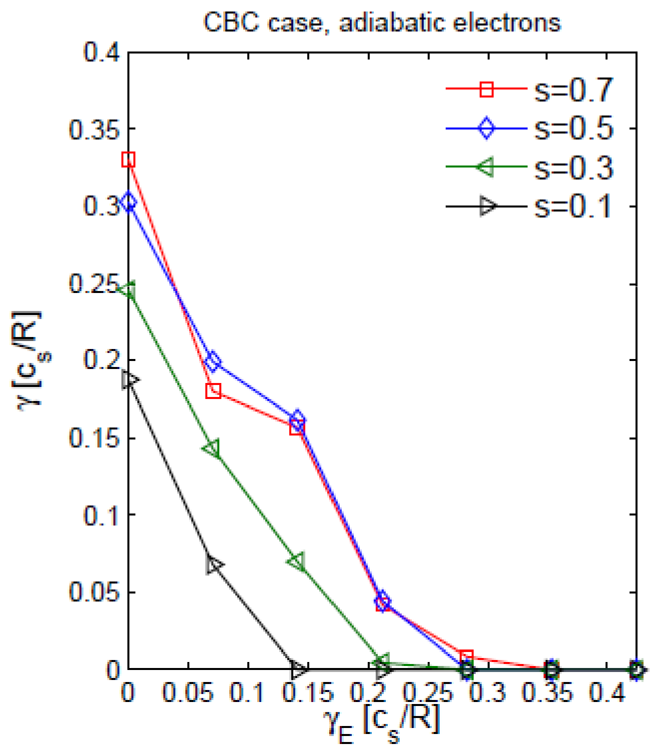
$$\gamma_E > \frac{s}{q}$$

Let's examine it with both adiabatic and kinetic electrons!

Low-s stability study (1)

All growth rates calculated with the new 'τ_{ac} method'.
Magnetic shear scans around the CBC case carried out

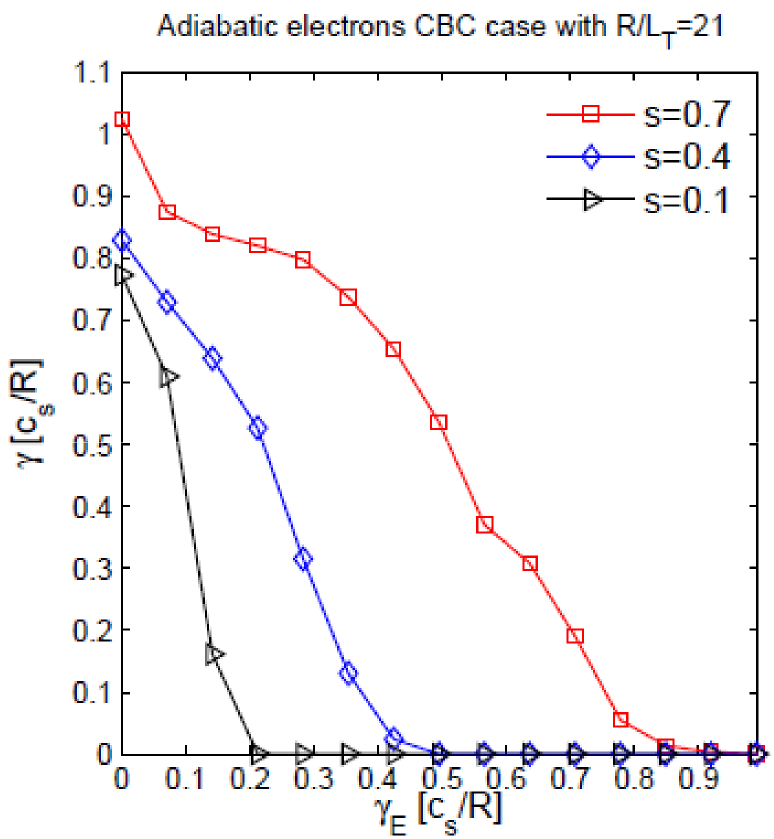




(Last minute apology – just realized that c_s includes sqrt(2) for γ_E normalisation but not γ for all subsequent graphs. Influences interpretation of quench point)

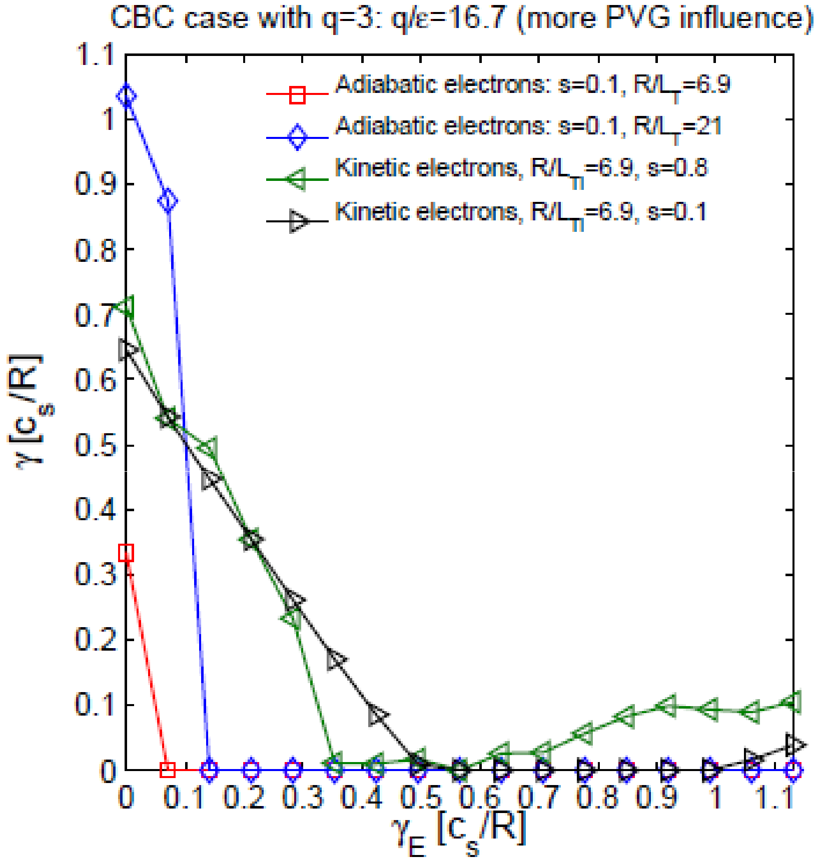
Kinetic electron cases clearly not following $\gamma_E > s/q$ quench rule
Adiabatic cases not clear for these parameters: could also be consistent with $\gamma_E > \alpha\gamma_0$ quench rule (with α=1-2)

Low-s stability study (2)



At higher R/L_{Ti} (and thus higher γ_0) the adiabatic cases do now seem consistent with $\gamma_E > s/q$ quench rule!

Low-s stability study (3)



At higher q, adiabatic electron case quench occurs even faster, again consistent with $\gamma_E > s/q$ quench rule. Kinetic electron cases are oblivious to this.

What's going on? Why this difference? Important for interpretation and validation of sub-critical turbulence in low-s regimes!

Conclusions

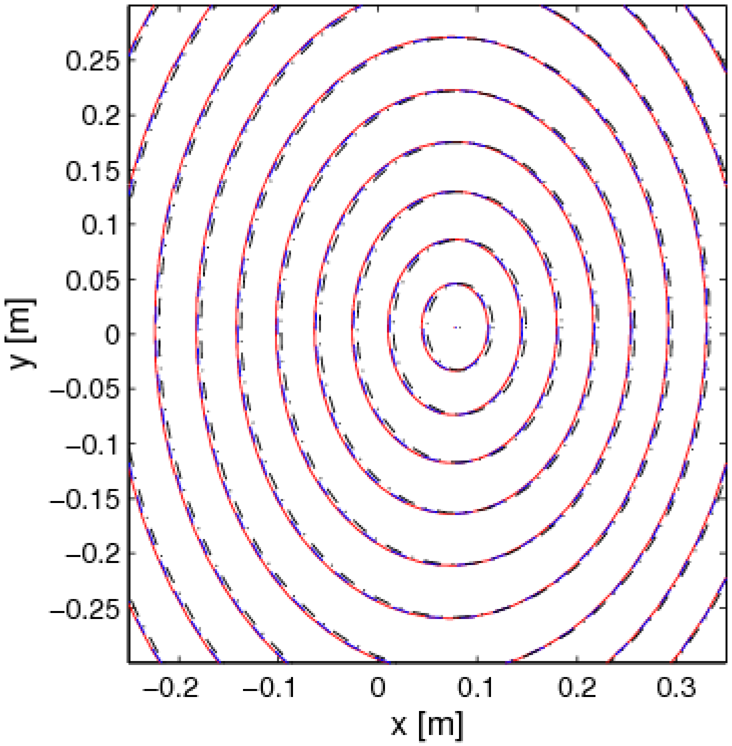
• Novel growth rate calculation method in presence of flow shear introduced. Calculates growth rates over an assumed non-linear decorrelation time: $\gamma=1/\tau_{ac}$ Involves an adaptive time window for calculation

• New method used to analysis flow shear supression of ITG modes at low magnetic shear, to test γ_E > s/q quench rule (eddy convection faster than sound speed)

• Rule seems to hold for adiabatic electrons but not for kinetic electrons! Difference not yet understood. Has implications for the validation of sub-critical turbulence in low-s regimes.

Sensitivity of equilibrium to rotation

FINESSE (A.J.C. Beliën - J. Comp. Phys (2002), based on HELENA) code solves generalized Grad-Shafranov equation with toroidal flow. We calculated real geometry including flow and examined sensitivity of heat flux.

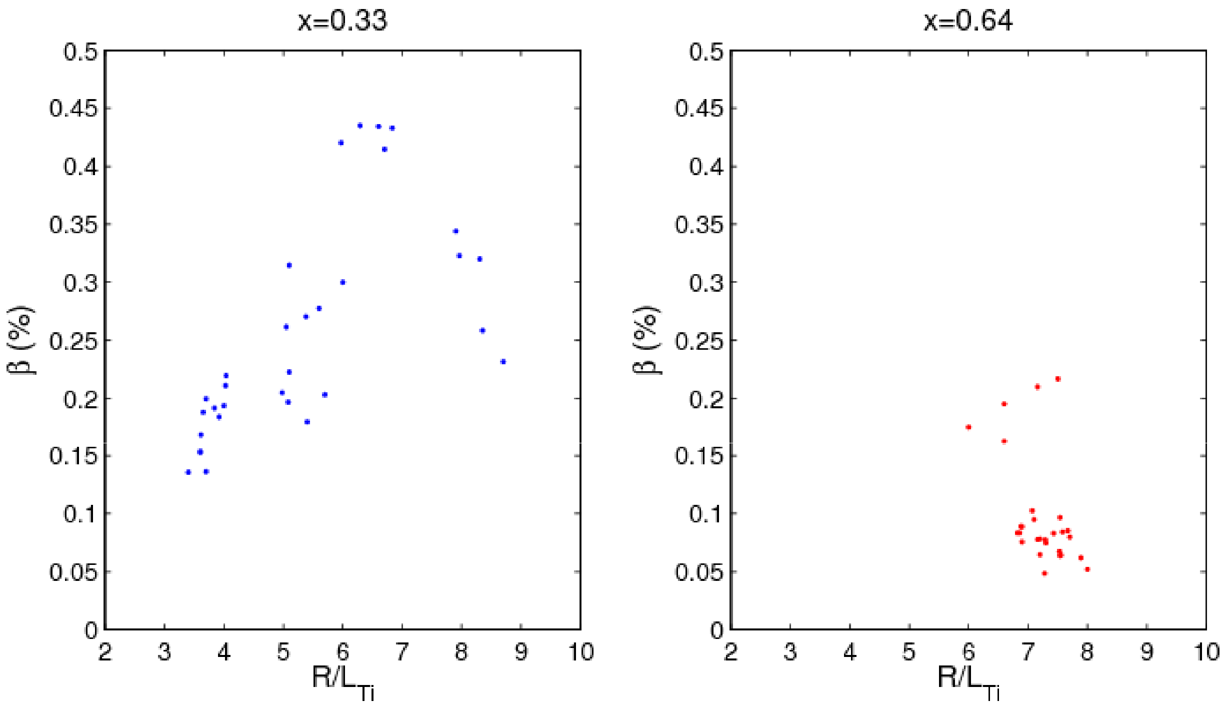


Bottom line: Shafranov shift only increases by ~10% in even for γ_E=0.6 case. Sensitivity of heat flux also ~10% (decreases)...

Not responsible for significant decreased stiffness.

Rotation in dataset from Mantica 2011 actually not that high!

Correlation of beta to R/LTi



Beta correlated with R/Lti. While this is a trivial statement, perhaps thus explains part of the decreased stiffness.

Could rotation add to this effect by increasing the ‘push’ up the R/Lti-beta slope?