Overview and open questions on electromagnetic effects on tokamak transport

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* See the Appendix of F. Romanelli et al., Proc. of the 25th IAEA Fusion Energy Conference 2014, St. Petersburg, Russia

DIFFER is part of FOM and NWO

Outline: will stick mostly with phenomology from simulations

EM effects can either enhance or reduce transport.
Not yet fully clear if all effects play a role in actual experiments

Transport reduction

- Electromagnetic stabilization of ITG turbulence. Enhanced by fast ions.
  Shown to play an important role at experimental parameters

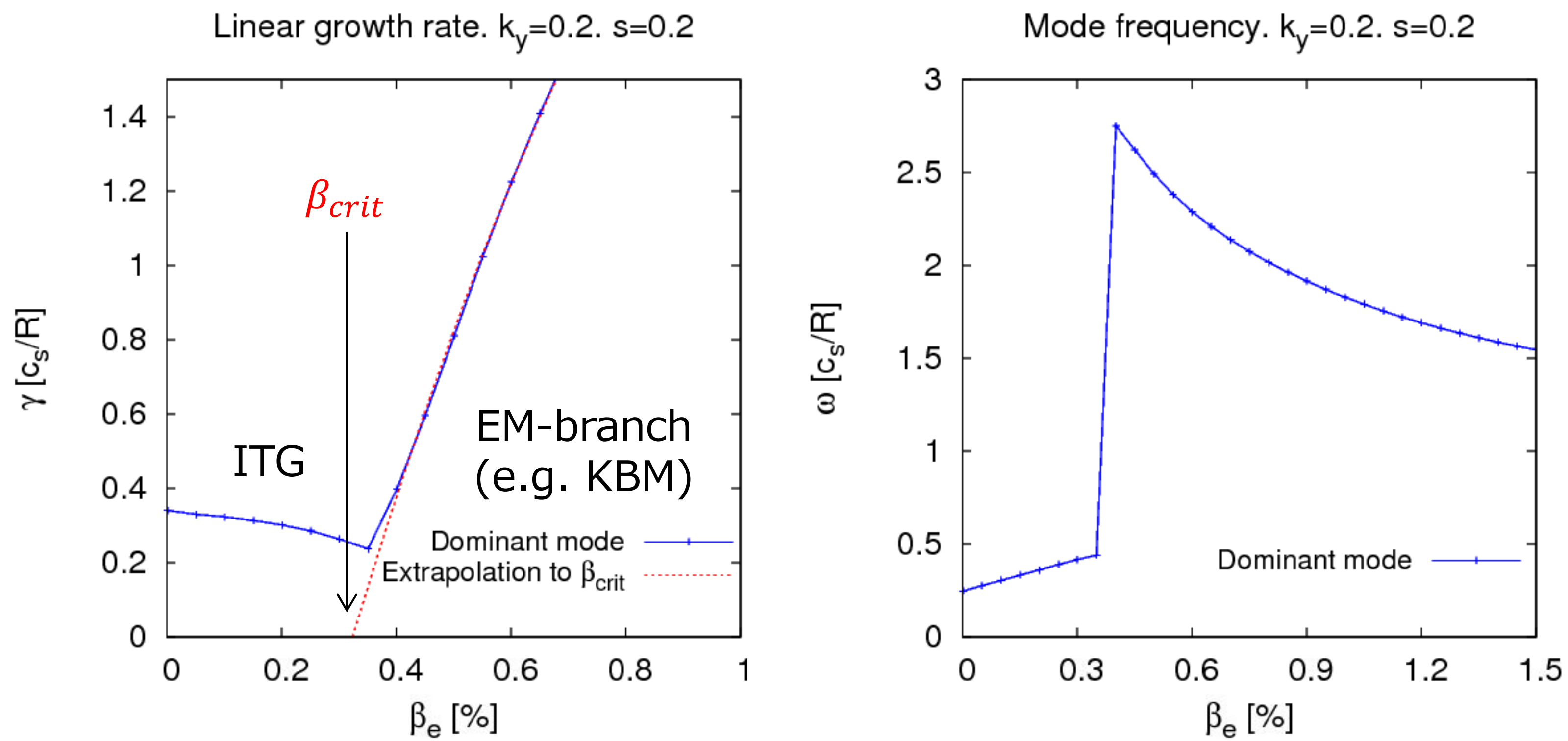
Transport enhancement

- Destabilization of “EM-branch” modes, e.g. Kinetic Ballooning Mode (KBM), or β-induced Alfvèn eigenmodes
- β-runaway effect. Zonal flows “short out” above a critical β
- Magnetic flutter electron heat transport due to microtearing. Can be due to nonlinear coupling even if linear MTM stable

New paper: “Overview of gyrokinetic studies of finite-β microturbulence”
Paul Terry et al., June 2015, Nucl. Fusion

EM-stabilization : Linear ITG stabilization below EM-branch limit

GENE Linear β scan for 'low stiffness' JET discharge 66404, at ρ=0.33



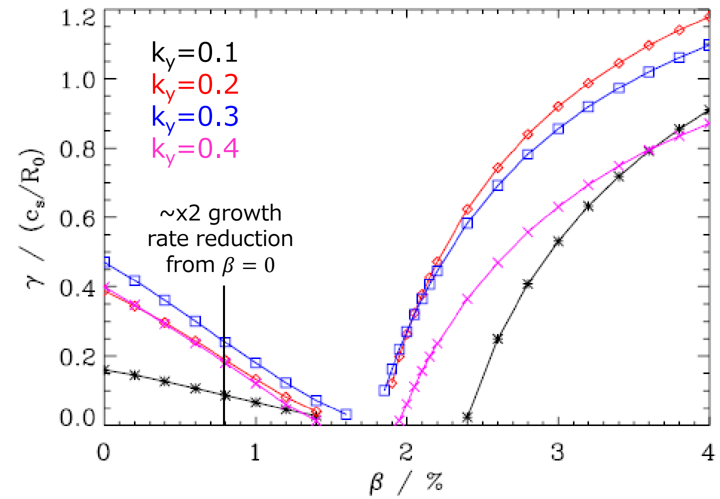
- Characterized by mode transition at β_{crit} from ITG to an electromagnetic branch
- Electromagnetic coupling stabilizes ITG below β_{crit}, (Kim, Horton, Dong PFB 1993, Hirose POP 2000).
- KBM limit typically lower than fluid BM limit (70% in CBC case), but not always

Note: All ion species β are scaled self-consistently with β_e which is used as the single input parameter

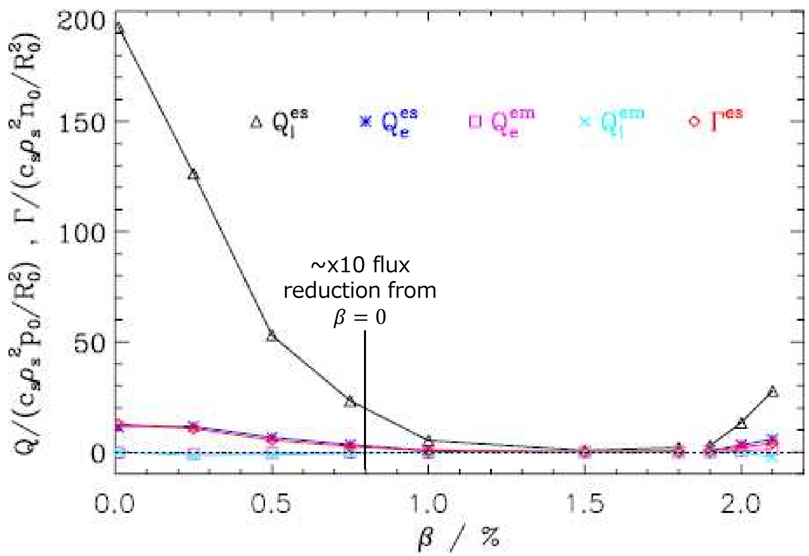
Electromagnetic-stabilization : Nonlinear stabilization stronger than linear

"Pure ITG" case based on CBC parameters with $R/L_{Ti}=8$, $R/L_n=1$. $R/L_{Te}=0$
GENE simulations. Modified from MJ Pueschel et al, POP 2010

Linear



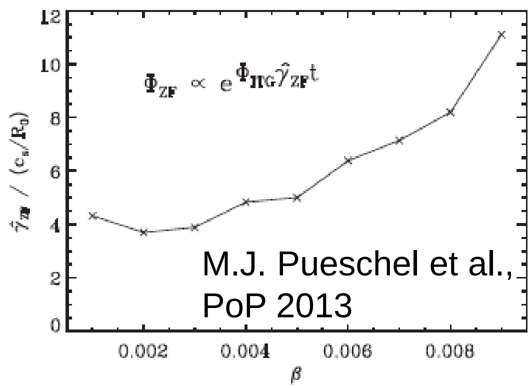
Nonlinear



Nonlinear EM-stabilization stronger than the linear stabilization!

This has been linked with a relative increase in zonal flow pumping (GK ITG: Pueschel *et al.*, PoP 2008, 2010, 2013, Fluid ITG: Anderson *et al.*, PoP 2011)

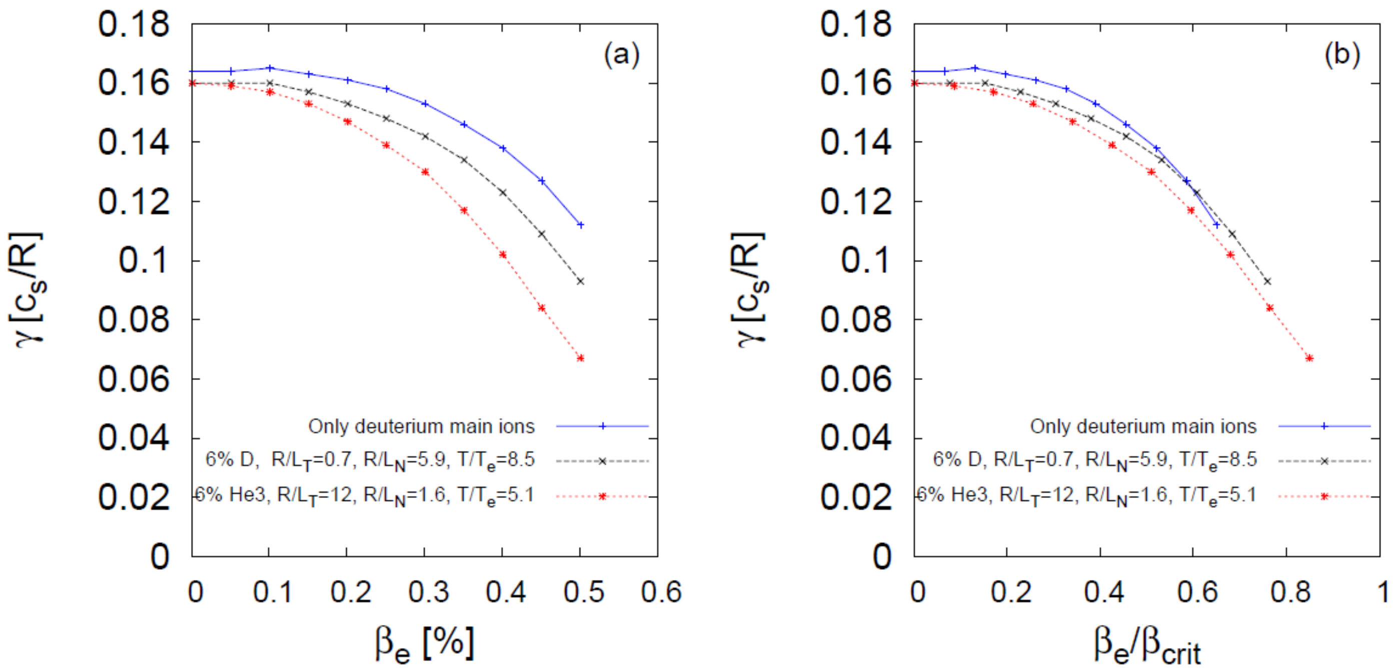
Zonal flow growth rate: Cyclone Base Case



Stabilization effect not dominated by pressure gradient effects on curvature drift and Shafranov shift

Electromagnetic-stabilization: Including fast ions increases EM-stabilization

Linear-GENE calculations of EM-stabilization in JET 66404 @ $\rho = 0.33$

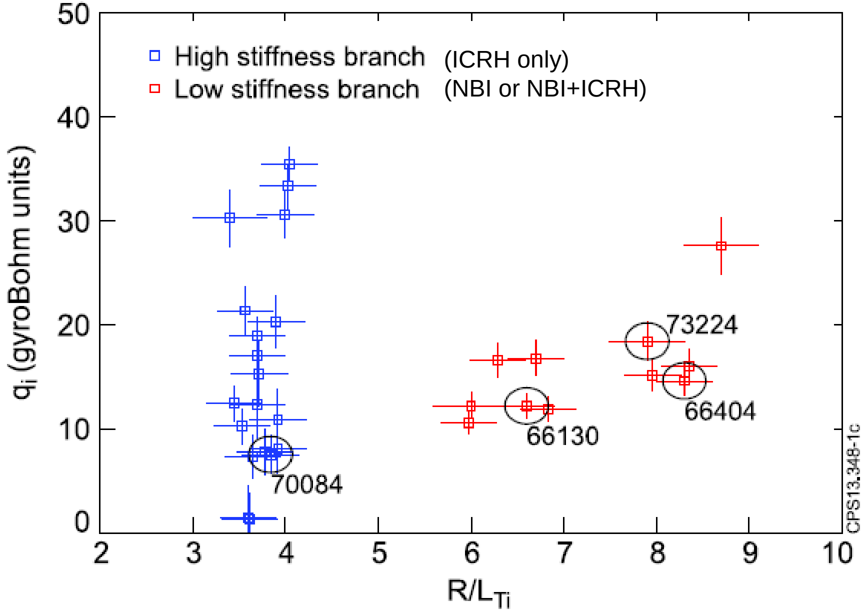


- Stabilization of ITG with fast ions increases with β, much beyond pure dilution ($\beta = 0$) effect
- Electromagnetic mode drive related to the ITG stabilization. β/β_{crit} is a valid parameter of merit for strength of stabilization effect. β_{crit} is the parameter dependent EM-mode limit
- Fast ion pressure gradients decrease β_{crit}, and increase ITG stabilization. Fast ions provide "free β'" that doesn't increase the ITG drive, but increases the EM-stabilization.

EM-stabilization of ITG invoked to explain strong ion temperature peaking in JET discharges

JET data-set in L-mode with a significant reduction in ion heat transport stiffness. Strongest stiffness reduction at lower magnetic shear. (P. Mantica PRL 2009, PRL 2011)

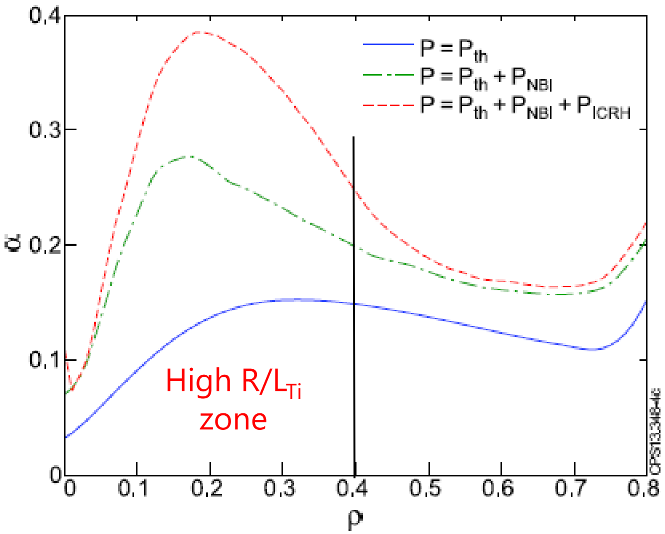
Ion heat flux (q_i) vs logarithmic ion gradient (R/L_{Ti}) at ρ=0.33



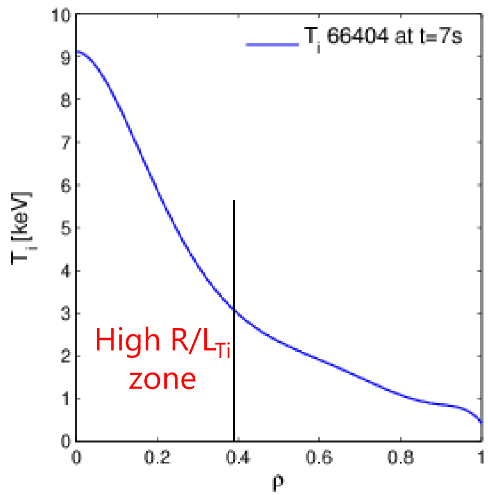
ITG EM-stabilization, enhanced by a significant fast ion fraction, necessary to explain “low stiffness branch”. Other effects ruled out (within the framework of local, gradient driven, GK). JC, PRL 2013, NF 2014

Extra slide: fast ion α-boost in low-β case

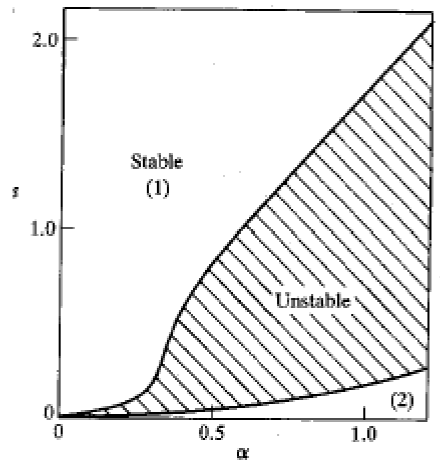
JET 'low-stiffness' discharge 66404: Pressure and α-profiles



Location of α-boost coincides with location of experimental R/L_{Ti} far above threshold

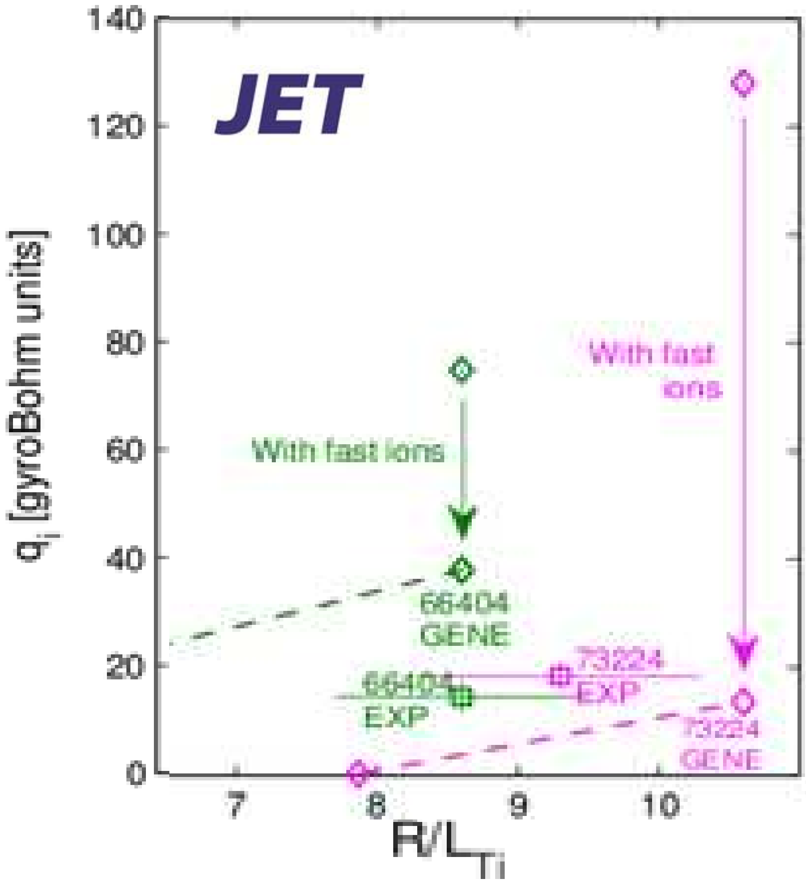


Fluid BM stability diagram (from Wesson)



Location of fast ion α-boost coincides with location of steep experimental T_i peaking. Suggests increase in EM-stabilization due to increased proximity to $\frac{\beta}{\beta_{crit}} \sim 1$. Lower magnetic shear also helps

Experimental ion heat flux reached when including fast ions in EM simulations



Simulations with flow shear, EM, and **fast ions** (D from NBI & ICRH ^{3}He minority), carbon impurities

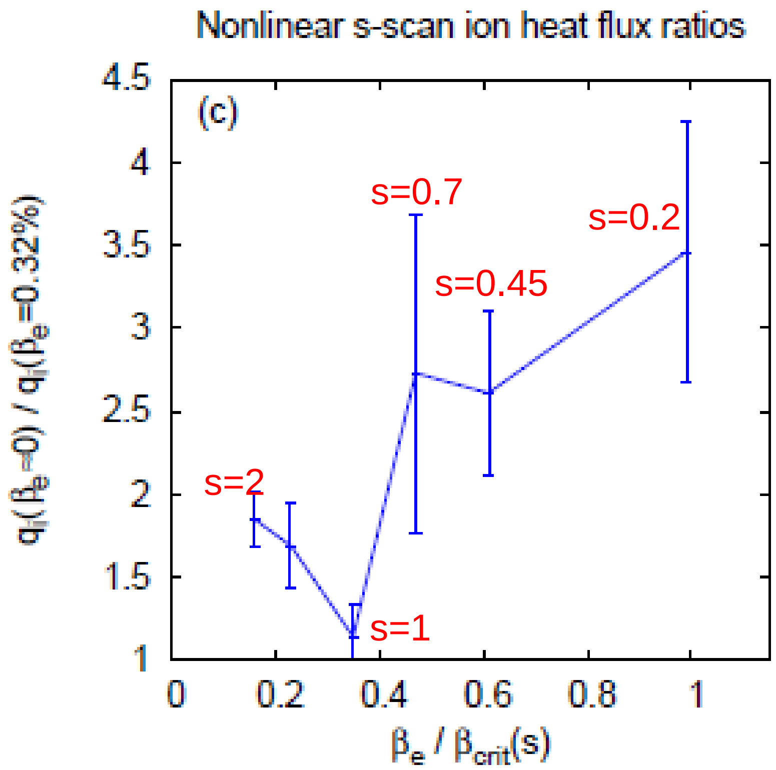
- Agreement between EXP and NL simulations drop to within $\approx \times 2$
- Full agreement can be reached with reasonable variations around input parameter uncertainties (e.g. $\frac{R}{L_{Ti}}, s, q, Z_{eff}$)
- Caveat: Maxwellian fast ions. GS2 linear results with slowing down distribution show similar results (Wilkie)

Inclusion of fast ions yields strongly reduced fluxes and low stiffness, but only in nonlinear electromagnetic simulations!

Result also consistent with GYRO modelling of DIII-D QH mode (C. Holland *et al.,* Nucl. Fusion 2012)

Electromagnetic-stabilization: Magnetic shear dependence in line with observed trend

(GENE nonlinear simulations based on 66404 base parameters: 2 species, T_i/T_e=1, circular geometry)



- Clear trend towards stronger EM-stabilization at low-s. In line with experimental trend
- Likely related to decrease of β_{crit} of KBM at low-s
- At higher radius, high-s. Thus expect weak EM-stabilization at high ρ since ($s \propto \beta_{crit}$)

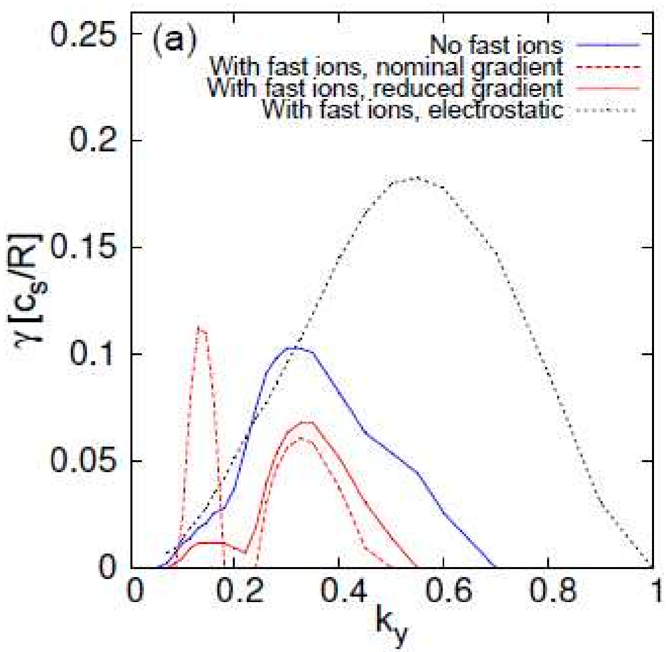
EM-stabilization in hybrid scenarios

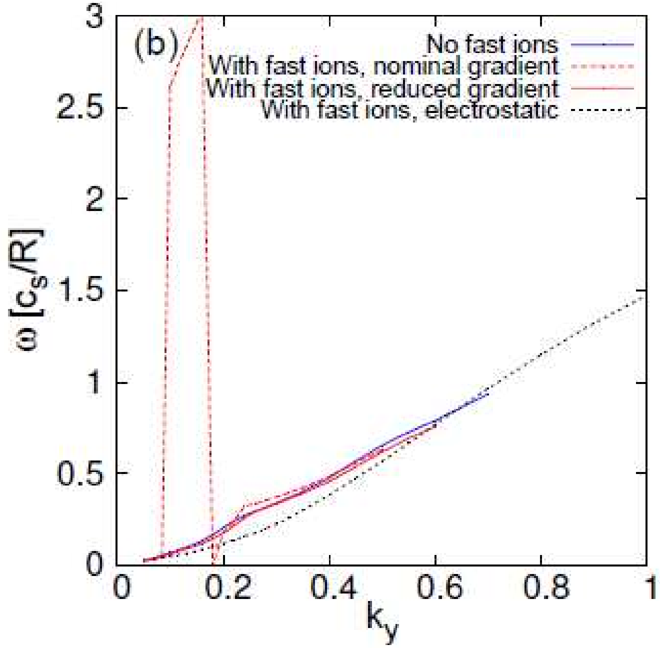
How does the fast ion enhanced EM stabilization effect generalize to reactor-relevant high-β plasmas?

- Which elements characterize this effect? High-β, significant fast ion fraction, low magnetic shear $(\hat{s})$ → hybrid scenarios
- Extensive GENE linear and nonlinear analysis of representative high confinement C-wall JET hybrid scenario 75225 (J.Hobirk et al., PPCF 2012) at $\rho = 0.33$ and $\rho = 0.64$.
- T_i peaking experimentally observed in inner half-radius
- Similar scale to previous study. $\approx$10 million CPU hours including convergence checks. Runs expensive due to high-β, low-$\hat{s}$.
- $\delta B_\parallel$ now included (with ∇P included in vertical drift frequency)
- Fast ion driven modes now play a role

Linear study in inner half-radius: Strong EM stabilization, enhanced by fast ions

Linear spectra of JET 75225 hybrid scenario @ $\rho = 0.33$

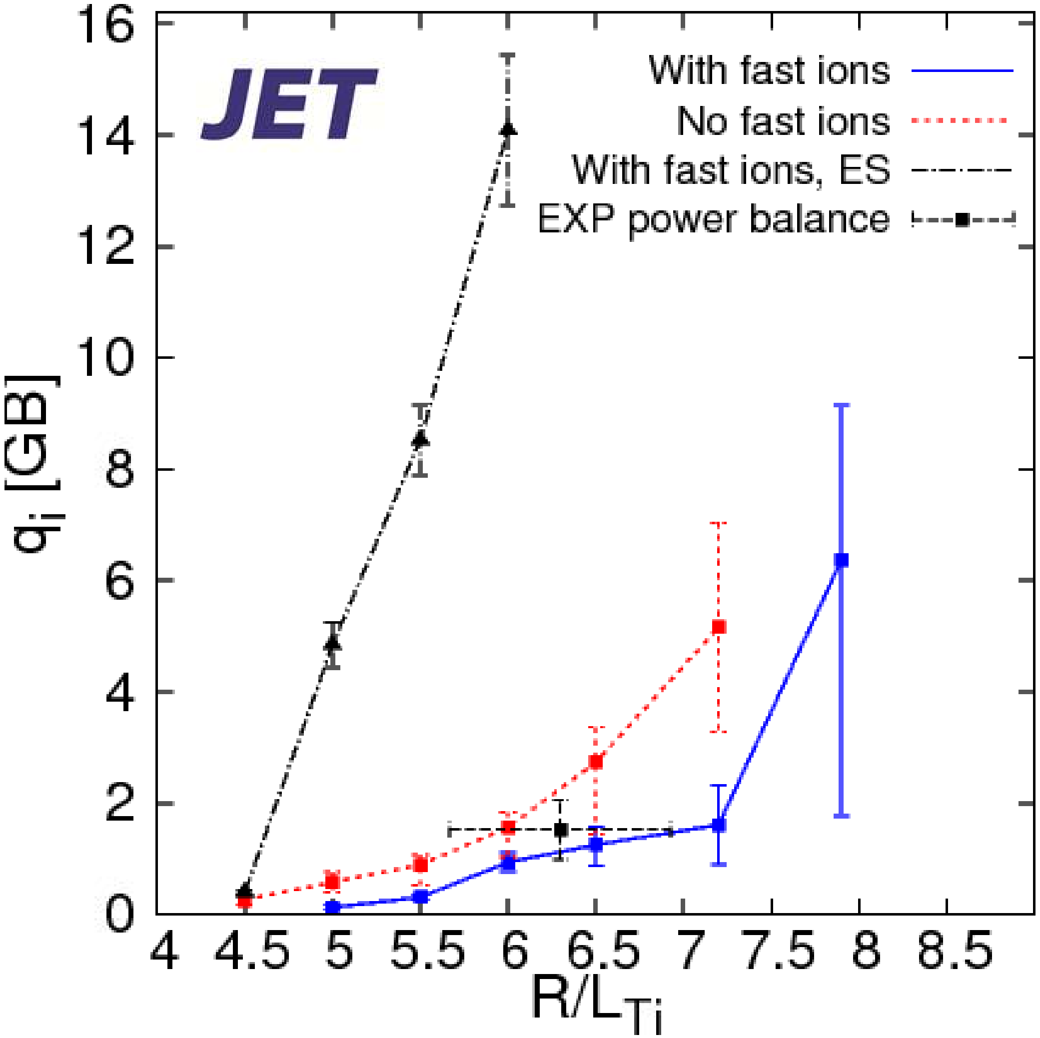




- Significant EM-stabilization of ITG modes. Enhanced by fast ions.
- With nominal fast ion pressure (CRONOS/SPOT), fast ion modes at $k_y < 0.2$
- Fast ion mode at n~10. Frequency within 5% of GAM frequency. Seems consistent with beta induced Alfven Eigenmode (BAE)? Stabilized by $\approx 30\%$ reduction of ∇P_{fast}
- $\beta/\beta_{crit} \approx 1$, thus significant nonlinear EM-stabilization is also expected

Nonlinear study in inner half-radius: EM-stabilization of critical importance

GENE nonlinear simulations of JET 75225 @ $\rho = 0.33$. 4 ion species, finite-β, collisions, real geometry, rotation.

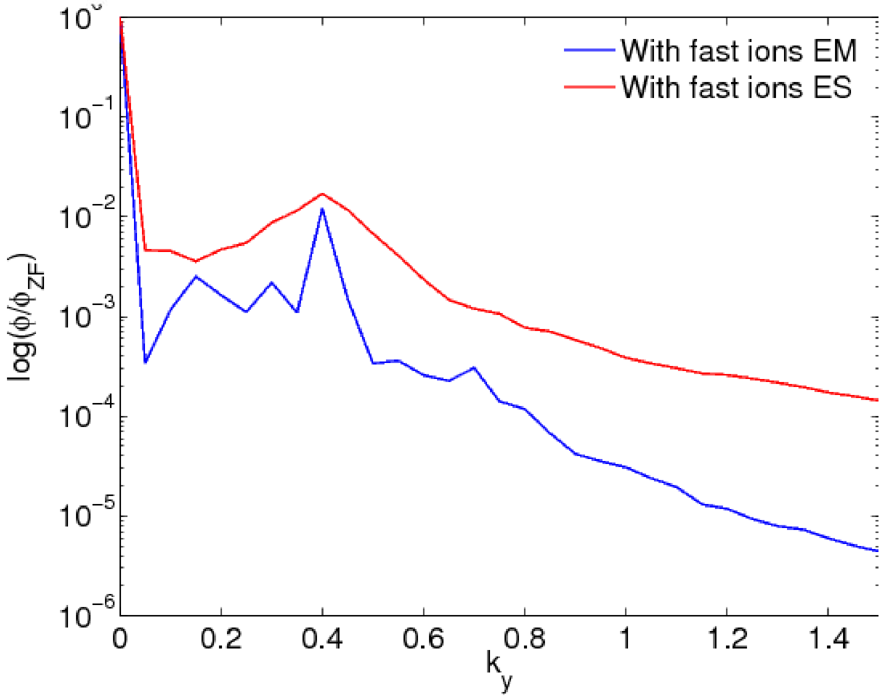


- EM-stabilization is a key factor in reaching power balance fluxes! Main effect is stiffness reduction.
- Fast ion enhancement of effect significant, but not dominant as in low-β data set (consistent with lower suprathermal fraction here)

JC, PPCF 2015
J. Garcia, NF 2015

Evidence for increased impact of ZF

Nonlinear amplitude spectra from GENE simulations of JET 75225 at $\rho = 0.33$



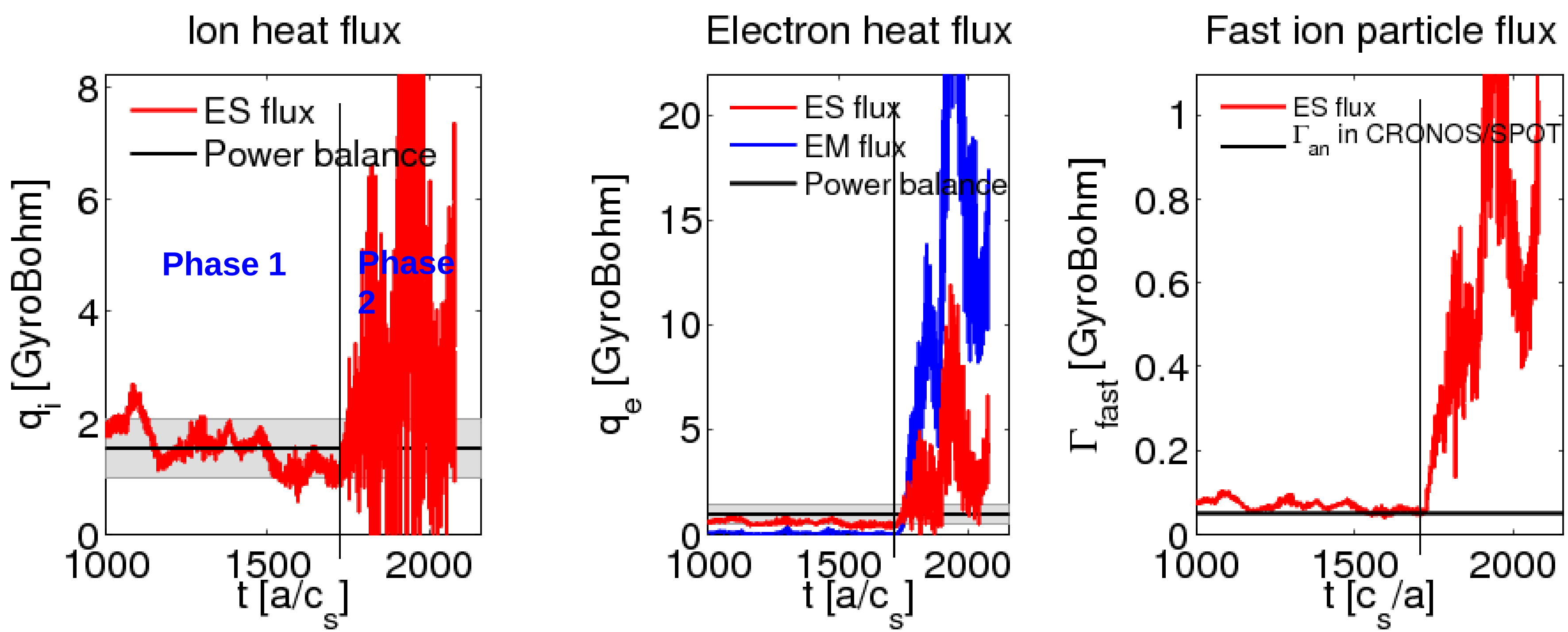
Reduced fluxes in EM cases correlated with increased proportion of zonal flow energy in system

$$\frac{\phi_{ZF}}{\sum_{k_y>0}\phi_{DF}} = \begin{cases} 39.1 - \text{with fast ions EM} \\ 31.7 - \text{without fast ions EM} \\ 10.6 - \text{with fast ions ES} \end{cases}$$

Consistent with increased Zonal Flow drive with increasing β, as in M.J. Pueschel et al., Phys. Plasmas 20, 102308 (2013)

When including fast ion mode in NL simulation, fluxes far above power balance levels

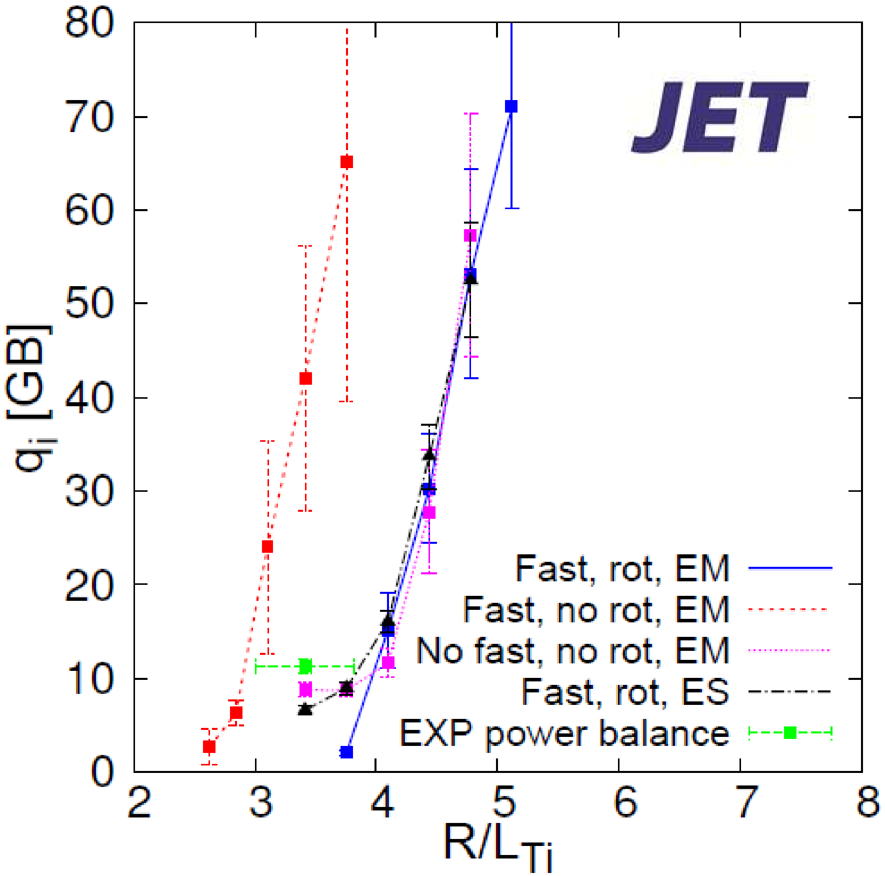
What happens nonlinearly if we allow the BAE-like modes to be unstable?



Phase 1: With 30% reduced fast ion pressure (no BAE-like mode)
Phase 2: increase to nominal fast ion pressure and restart simulation

- System with fast ion mode has fluxes clearly above power balance values. Limit cycles? Robustly maintained below limit? Needs further study.
- Supports use of a “stiff” fast ion transport model in reduced modelling frameworks

At outer half-radius: EM effects not important, flow shear is important



Similar core analysis as at $\rho = 0.33$ carried out for $\rho = 0.64$

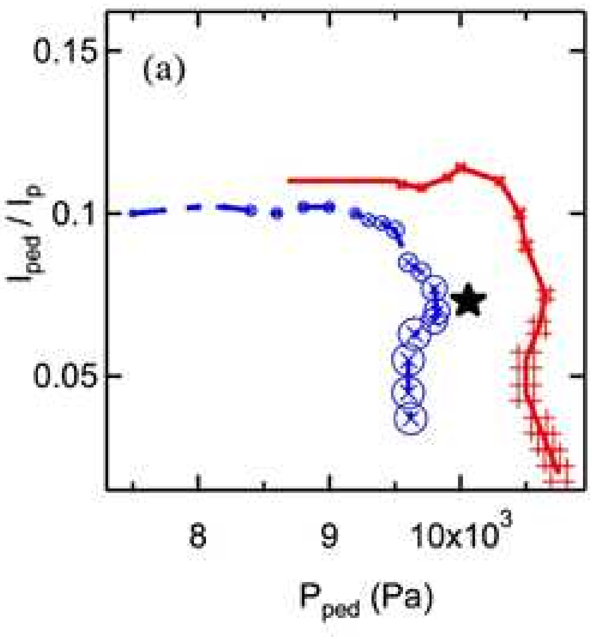
- Weak impact of EM-stabilization
- $E \times B$ shear leads to significant stabilization
- Partial results at $\rho = 0.5$ hint at a smooth transition from EM to $E \times B$ dominated stabilization with increasing ρ

Much weaker EM-stabilization at $\rho = 0.64$ likely linked to the lower $\frac{\beta}{\beta_{crit}} \approx 0.3$ value

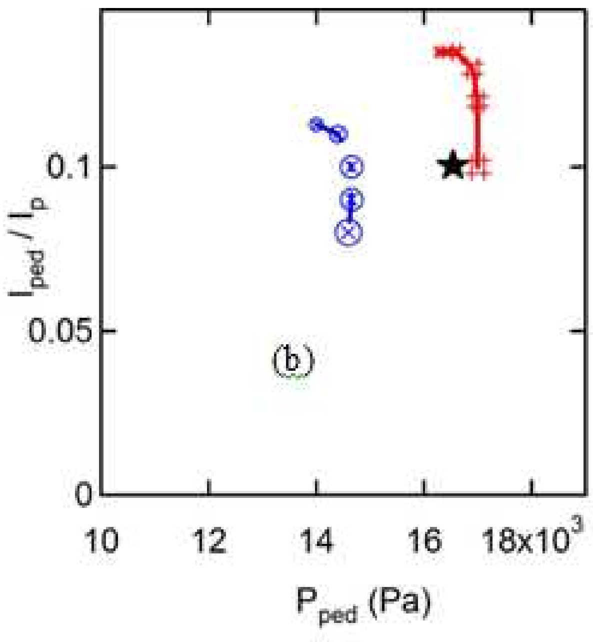
Implications for power scaling (β scaling)

- Pedestal confinement improves with increasing total β (due to Shafranov shift)
- Feedback effect: EM-stabilization in core increases β → improved pedestal confinement → higher core β and more EM-stabilization
- Fast ions amplify this loop by ratcheting up both core and edge stability
- Significant improvement in total energy confinement then achieved

JET 75225 (low δ)



JET 77924 (high δ)



MISHKA edge ballooning-peeling stability limit

RED: With total β
BLUE: With thermal β
*: Measured value

J. Garcia NF 2015

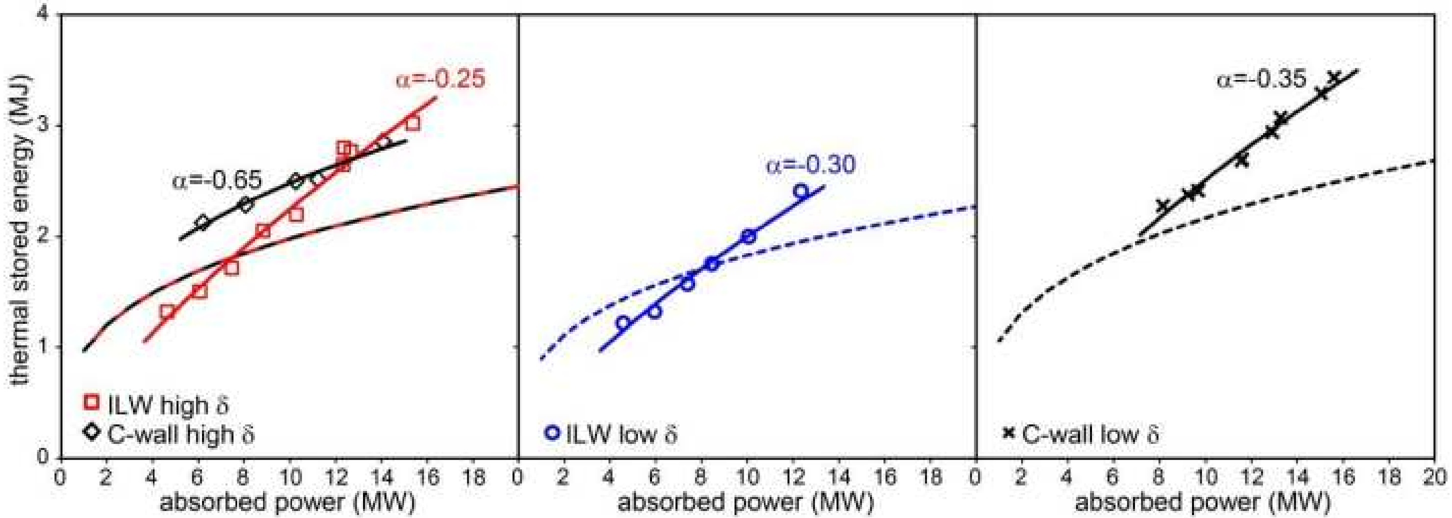
Positive feedback loop at high-β could help explain JET power scan results

- EM-stabilization and feedback loops to edge all invoked to explain observations of a *lack* of serious confinement degradation in JET hybrid scenario power scans. Good news for high-β high-performance scenarios.

- C-wall high-δ outlier suspected to be due to different plasma shape and divertor configuration resulting in strong neutral influx

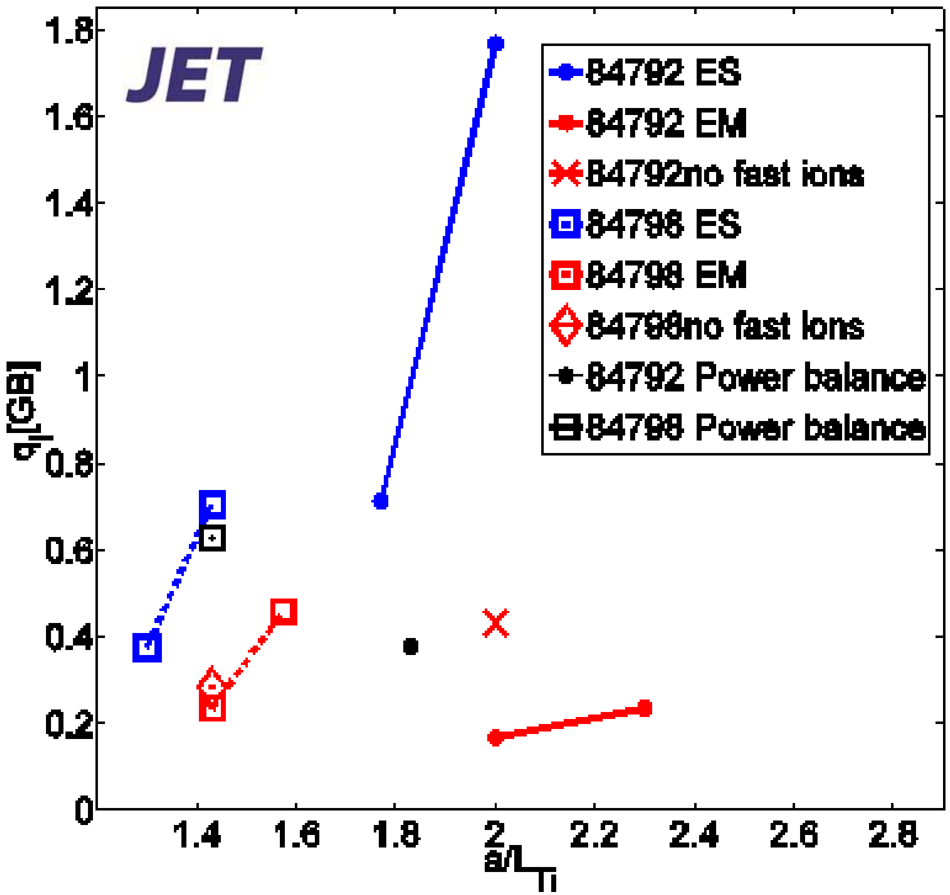
- Revision of IPB98 scaling law? Original dataset poorly represented at high-β

JET hybrid scenario power scans vs IPB98 expected scaling



C. Challis
NF 2015

JET ILW hybrid scenario power scan trends recovered in gyrokinetic nonlinear simulations



J. Garcia NF 2015
H. Doerk

- At low NBI power, β and fast ions leads to low level of EM stabilization
- At high NBI power, β and fast ions leads to significant EM stabilization

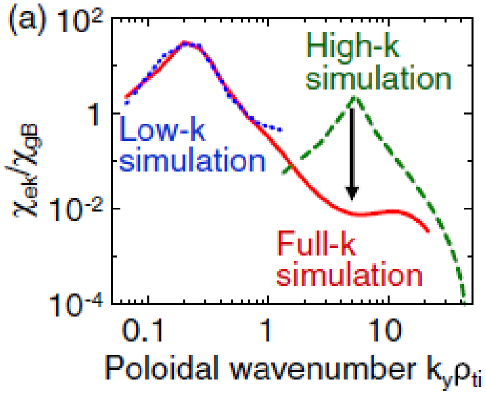
Summary of EM-stabilization

- Significant EM-stabilization relevant for experimental cases. Needs to be invoked to explain power balance in Ti peaked regimes.
- Nonlinear stabilization stronger than linear. Related to ZF physics
- Fast ions provide "free β" which enhances stabilization while not increasing drive.
- Core-edge feedback loop related to β can strongly improve total confinement
- Consistent with recent JET hybrid scenario results showing a lack of power degradation at high-β
- Need to revise IPB98 scaling law?
- Extrapolation to high-β reactors more optimistic

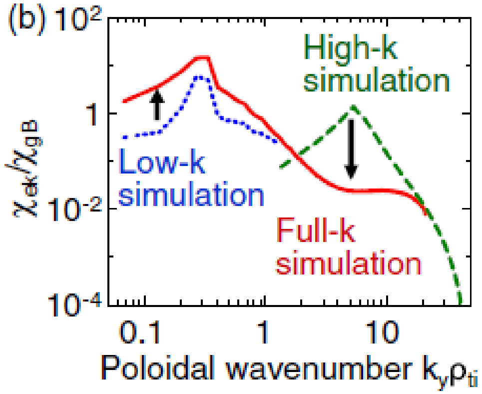
Destabilization effects: Multiscale simulations

Cyclone-Base-Case (CBC) EM ($\beta = 2.0\%$) multiscale simulations
Maeyama PRL 2015

ES case

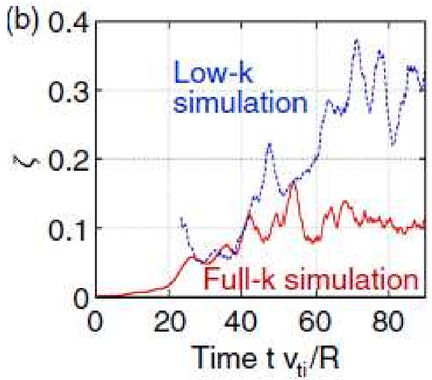


EM case



- Degradation of nonlinear EM-stabilization in multiscale simulations
- Factor 2-3 increase in flux
- Correlates with a decrease in relative zonal mode energy

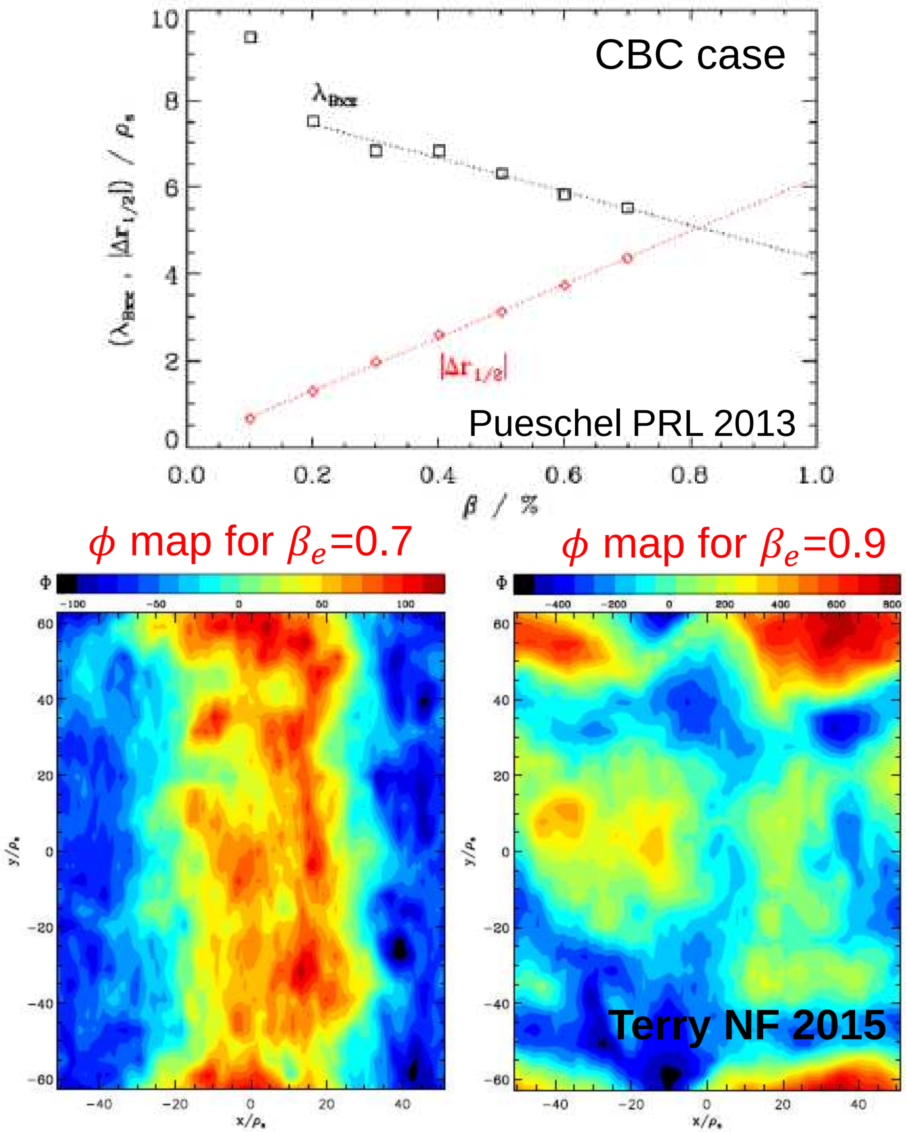
Ratio of zonal to nonzonal field energy



Ramifications?

- EM-stabilization for experimental cases was so strong, that a factor 2-3 increase is “digestible”
- Nevertheless, how universal? CBC much stronger driven than experimental cases. Should repeat for EXP cases

Destabilization effects:
The “non-zonal-transition”

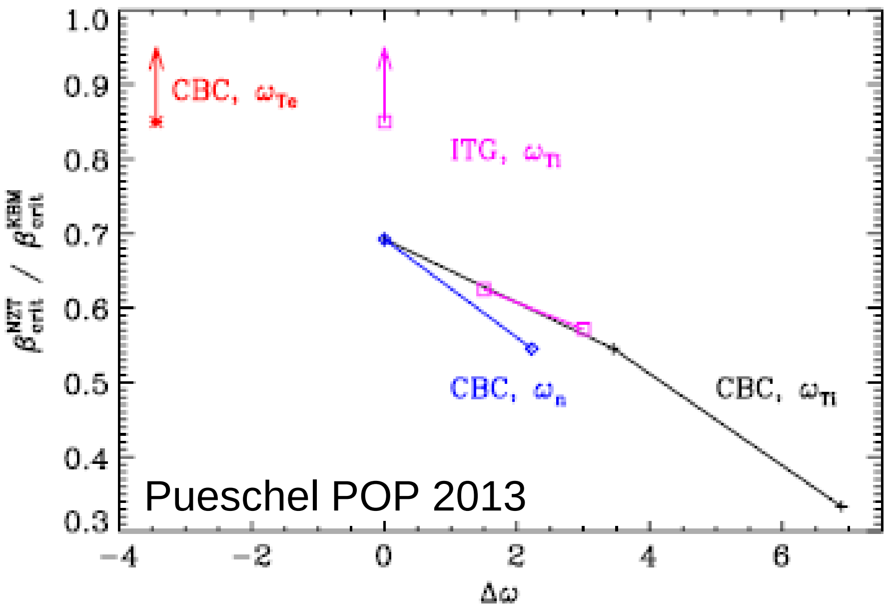


β-runaway effect (non-zonal-transition, NZT)
Pueschel PRL 2013, POP 2013

- When field line displacements exceed radial B-field correlation length, ZF “shorted out” by electron flow
- This increases field line displacements, leading to a runaway effect. Final saturation values are huge and unphysical
- This new β_{crit} (β_{NZT}) can be lower than β_{KBM}

Destabilization effects: The "non-zonal-transition"

Sensitivity of β_{NZT}/β_{KBM} to input gradients



"ITG case" is similar to CBC, but with R/Lti=8, R/Lte=0, R/Ln=1

Pertinent question: is the β_{NZT} relevant for experimental cases?

- β_{NZT}/β_{KBM} increases for higher drive
- $\beta_{NZT}/\beta_{KBM} > 1$ in all experimental cases studied thus far (e.g. JET L-mode and hybrids)
- Hopefully it's not experimentally relevant (otherwise bad news for high-beta scenarios). Still an open question

Note: much study of EM effects has been carried out at highly driven CBC case. This opens up valid questions as to the relevance of effects observed for experimental parameters.

Destabilization effects: KBM turbulence

When $\beta_{NZT} > \beta_{KBM}$, then KBM sets the upper β limit of the ITG EM-stabilization

Some open questions:

- Saturation level and saturation mechanism of KBM modes
  - $\beta_{KBM} < \beta_{MHD}$ always?

Disparate results

- GENE: JET hybrid scenario, high KBM saturation level immediately following β_{KBM}. Hard limit to EM-stabilization (JC PPCF 2015)
- GKV: CBC with η_e=0. Maeyama POP 2014, Ishizawa POP 2014. Low KBM saturation level compared with similar growth rate ITG. Saturation due to elongated mode structure and coupling between connected modes through parallel boundary condition. However, increasing flux tube to [-2π,2π] reduces this coupling and significantly increases KBM saturation.
- GYRO global: $\beta_{KBM}(global) \gg \beta_{KBM}(local)$ at low magnetic shear (S. Moradi)

Destabilization effects: Microtearing modes

"micro-destruction" of magnetic surfaces, leading to Rechester-Rosenbluth magnetic flutter transport for electron heat

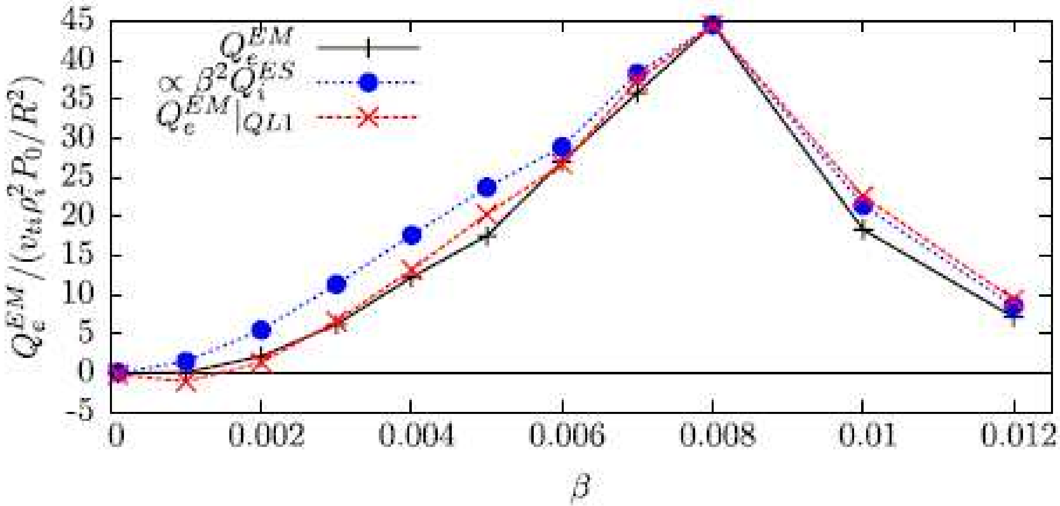
Linearly unstable MTM

- Considered more important for spherical tokamaks than conventional tokamaks.
- In NSTX and MAST, collisional MTM a candidate to explain the observed $1/\nu^*$ scaling of electron heat confinement (e.g. Guttenfelder NF 2013)
- In conventional tokamaks, pure MTM simulations have shown experimentally relevant electron heat flux levels (Doerk PRL 2011). However, coupled ITG-MTM simulations show very weak magnetic flutter in spite of linearly unstable MTM (Doerk)

Destabilization effects: Microtearing modes

Linearly stable MTM, but nonlinear coupling to tearing parity modes

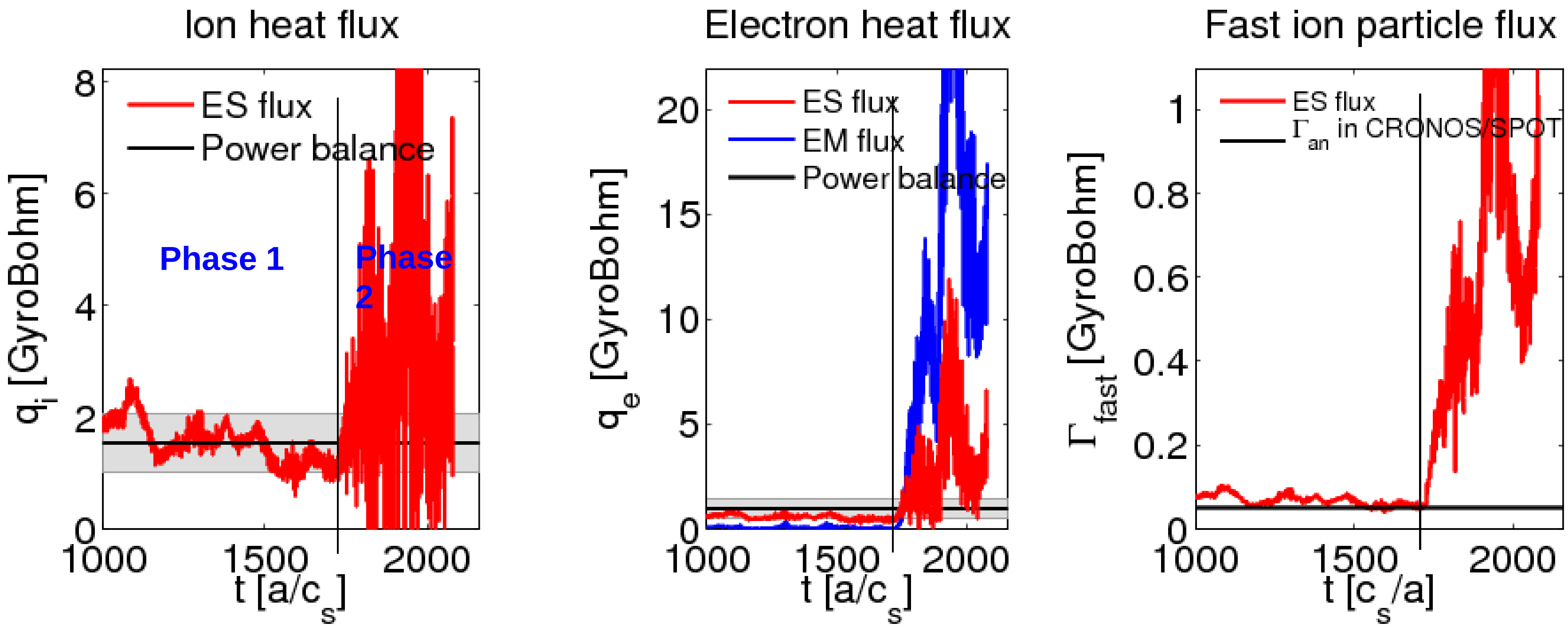
- Extensive study in CBC regime (Pueschel POP 2008, POP 2010, Nevins PRL 2011)
- General saturation mechanism of coupled via zonal flows to linear damped modes, and dissipation through Landau damping (Hatch PRL 2011, POP 2011)
- These coupled damped modes also include MTMs, which have sufficient amplitude to lead to significant magnetic flutter transport (Hatch PRL 2012)
- Observed to have a ${Q_e}^{EM} \propto \beta^2 Q_i^{ES}$ scaling



Destabilization effects: Microtearing modes

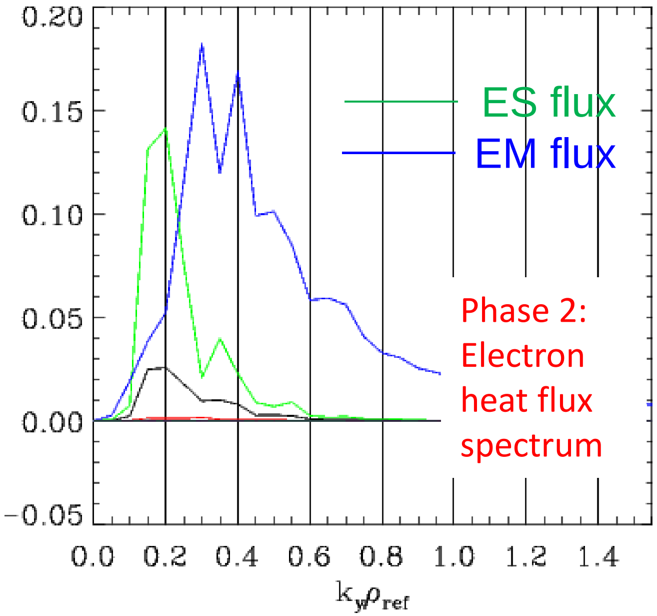
Is this experimentally relevant?

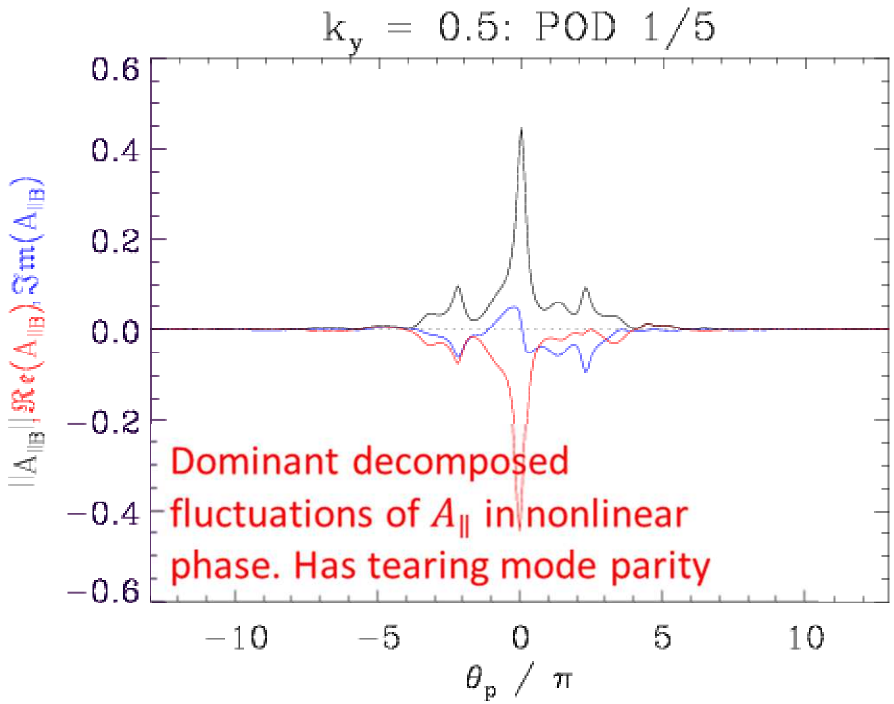
Perhaps! In the vicinity of $\beta \sim \beta_{KBM}$, JET hybrid scenario observed to have significant magnetic flutter transport (JC PPCF 2015)



Phase 1: With 30% reduced fast ion pressure (no BAE-like mode)
Phase 2: increase to nominal fast ion pressure and restart simulation

Destabilization effects: Microtearing modes





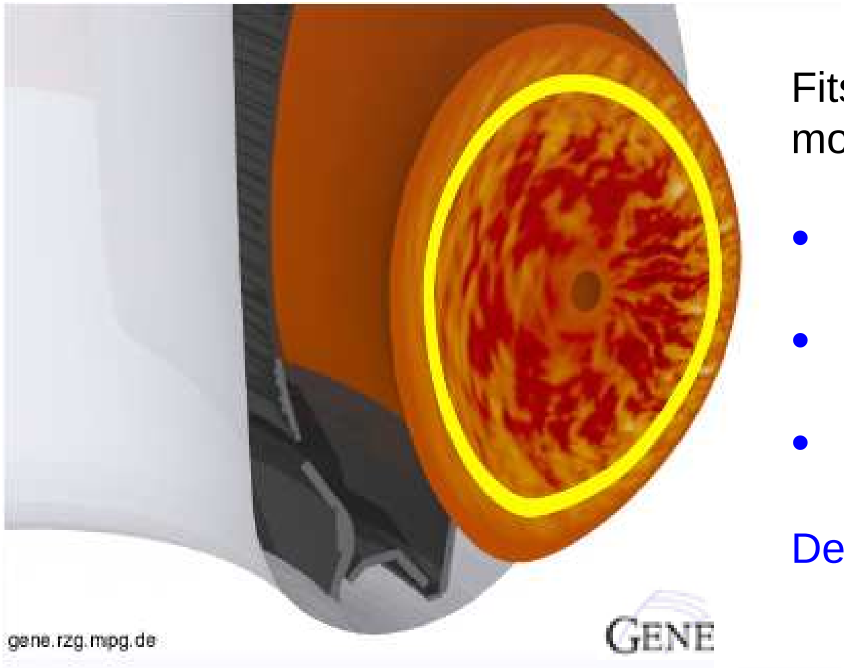
- Tearing parity dominates as seen by POD analysis
- Linearly stable MTM coupled in system, in experimentally valid parameters
- Only significant in this case only as β approaches $\beta_{KBM-BAE}$
  At lower β, no EM-transport seen. This doesn't agree with β^2 scaling of EM-transport seen in CBC case. Yet can still be relevant for experiments.

Open questions

- Analysis of multi-ion electromagnetic ITG system. Understand precisely how fast ions can stabilize ITG in EM system
- Why is nonlinear ITG EM-stabilization stronger than linear stabilization? How are ZFs more strongly pumped? Are there also reduced tertiaries?
- How universal is the multiscale reduction of ion-scale zonal flows?
- Is $\beta_{NZT} < \beta_{KBM}$ for all or most experimental cases?
- How does KBM saturate? What are the saturation levels, or, what is the stiffness level of KBM turbulence?
- Are nonlinearly coupled MTMs relevant in actual experimental cases?
- When are linearly stable MTMs relevant to set electron heat transport?

Extra slide: Choice of assumptions and workflow

- We include: kinetic electrons, experimental geometry, electromagnetic effects, active C species, active fast ions (D from NBI, ^{3}He minority from ICRH)
- Local (flux tube) approximation ($1/\rho^* \sim 500$)
- Only $\delta B_\perp$ fluctuations kept due to low $\beta_e \approx 0.4\%$. Lack of sensitivity to $\delta B_\parallel$ verified
- Caveat: fast ions approximated by hot Maxwellians



Workflow

Fits of raw data fed into CRONOS [4] integrated modelling suite. Interpretative run carried out.

- Current diffusion. HELENA for magnetic equilibrium
- NEMO/SPOT [5] for NBI fast ion calculation
- SELFO [6] for ICRH fast ion calculation

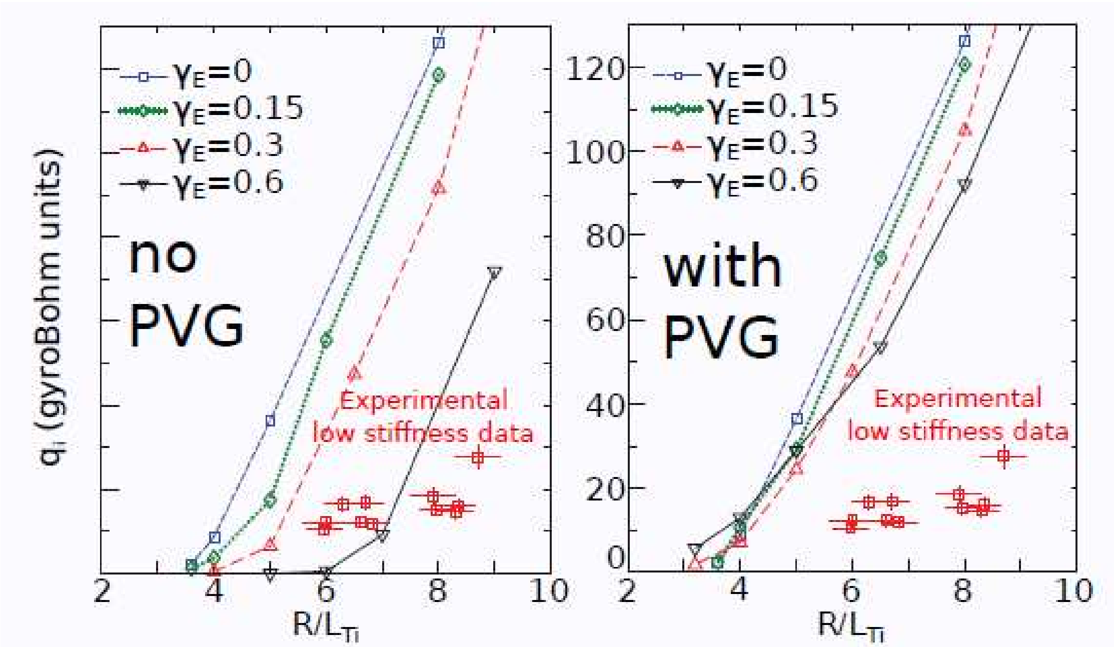
Defines input into GENE simulations

[4] J.F. Artaud et al., Nucl. Fusion **50**, 034001 (2010)
[5] M. Schneider et al., Nucl. Fusion **51**, 063019 (2011)
[6] J. Hedin, T. Hellsten, L.-G. Eriksson and T. Johnson Nucl. Fusion **51**, 063019 (2011)

Extra slide: Flow shear does not explain observations

Simulation of low rotation JET discharge 70084 at ρ=0.33

Increase flow shear and see if low stiffness can be reached



Stabilizing perpendicular flow shear rate (toroidal rotation)

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

- Compare stiffness for various γ_E, with and without PVG term
- Experimental “high rotation” value is $\gamma_E = 0.3\ c_s/R$

- With PVG, stiffness only slightly reduced near threshold. Experimental observations cannot be explained by flow shear
- With no PVG, classic “Waltz-rule” threshold shift recovered