OV/5-1

Overview of Gyrokinetic Studies on Electromagnetic Turbulence

P.W. Terry[1], D. Carmody[1], H. Doerk[2], W. Guttenfelder[3], D.R. Hatch[4], C.C. Hegna[1], A. Ishizawa[5], F. Jenko [2,6], W.M. Nevins[7], I. Predebon[8], M.J. Pueschel[1], J.S. Sarff[1], and G.G. Whelan[1]

[1]*University of Wisconsin-Madison*
[2]*Max Planck Institute for Plasma Physics, Garching, Germany*
[3]*Princeton Plasma Physics Laboratory*
[4]*Institute for Fusion Studies, University of Texas at Austin*
[5]*National Institute for Fusion Science, Japan*
[6]*University of California at Los Angeles*
[7]*Lawrence Livermore National Laboratory*
[8]*Conzorzio RFX, Padua, Italy*

Recent Discoveries from Gyrokinetic Studies of Turbulence and Transport at Finite β

This overview describes

- Discoveries concerning saturation of microinstabilities at finite β
  - Effect of stable modes
  - Effect of stable modes on magnetic fluctuations
  - Modifications of zonal flows
  - Effect magnetic configurations with short magnetic field scale lengths
- Comparative modeling across different magnetic configurations
  - Special focus: RFP <–> Tokamak
- Synthesis of saturation understanding, modeling and theory allow us to determine scaling behavior of critical β values for confinement effects

Key conclusions:

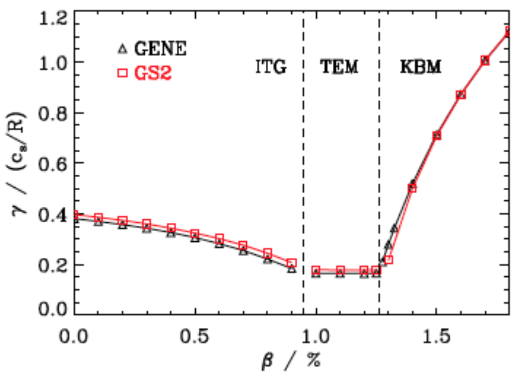
- Stable modes (nonlinearly excited) change saturation, transport
- Short magnetic length scales push critical β's and gradients to higher values

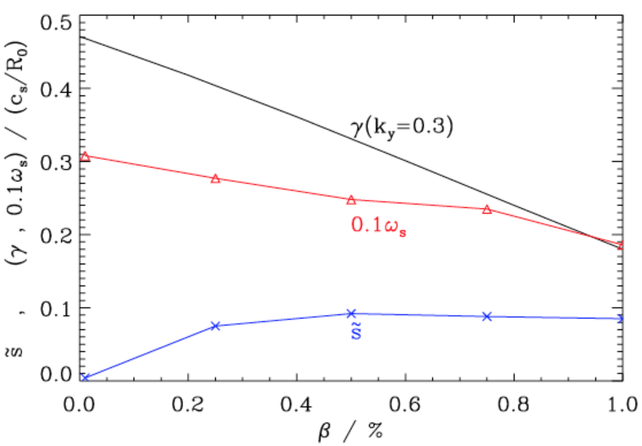
Background

Finite β operation is highly desirable for fusion

- Fusion reactions rates, bootstrap current benefit from high β

Finite β affects confinement as shown in prior gyrokinetic studies





Pueschel 2010

- Various instabilities arise
  - Kinetic ballooning mode (KBM)
  - Microtearing mode (MTM)
- Overtake electrostatic modes
  - Ion temperature gradient (ITG)
  - Trapped electron mode (TEM)
- Finite β affects saturation mechanisms
  - Zonal flows decrease more slowly with β than ITG growth rate
- Damped modes saturate ITG
  - What does finite β do to them?

Outline

Saturation Studies

- Tearing parity stable mode
- Non zonal transition
- KBM

Modeling

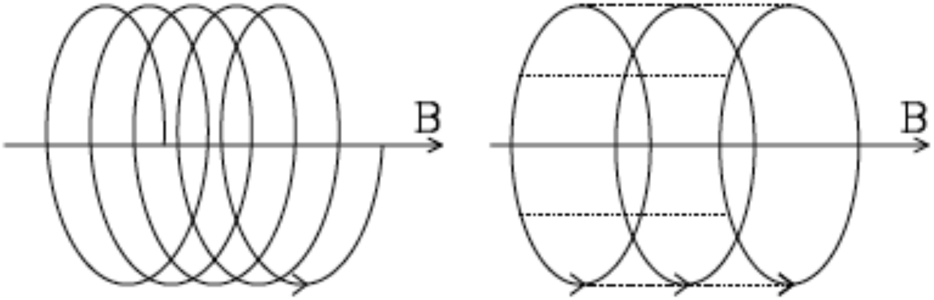
- MTM in NSTX
- MTM in RFX
- MTM in MST
- TEM/ITG in MST

Scaling Analysis

Introduction: Gyrokinetics

Gyrokinetics: eliminate the fast gyrophase from the equations of motion

$\Rightarrow$ significant speed up

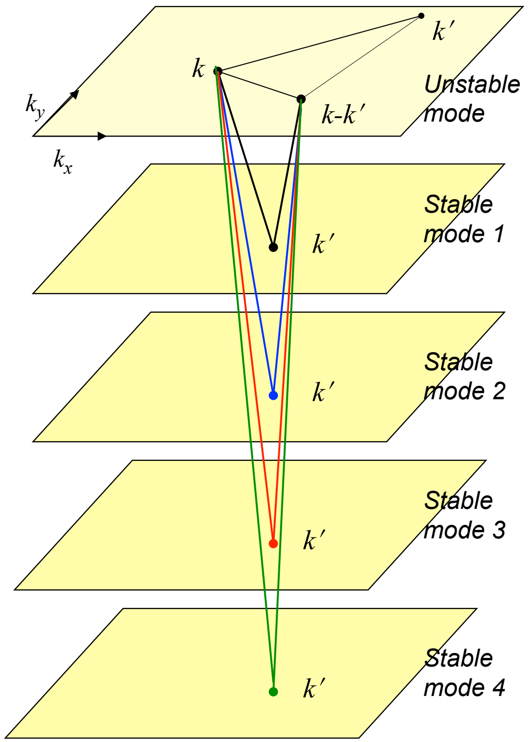


$\Rightarrow$ gyrokinetic Vlasov, field equations

Capabilities used:

- Nonlinear gyrokinetic equations
- Radially local simulations
- δf approach
- Multiple geometries and equilibria
- Electromagnetic, binary collisions
- Codes: GENE, GYRO, GS2, GKV

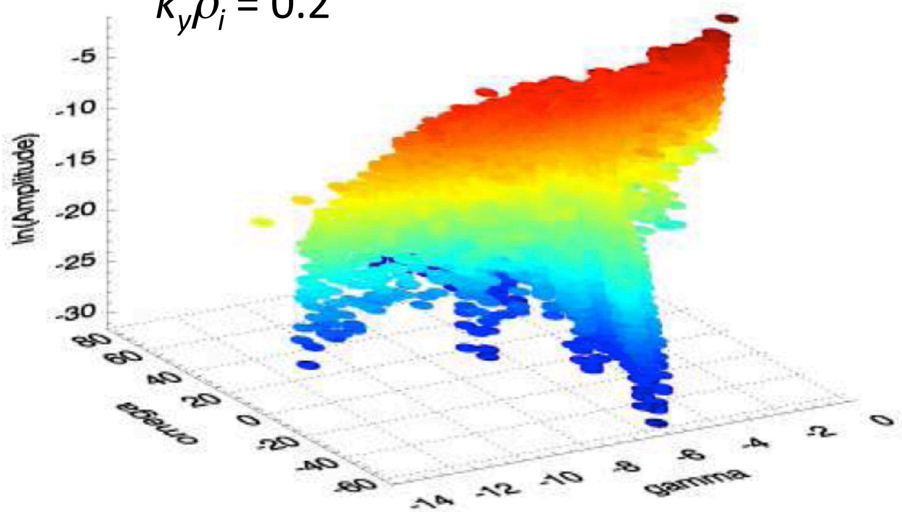
Nonlinearity excites damped modes in unstable k-space range



Energy transfer:
- High k modes (traditional cascade)
- Damped modes at same k

Damped modes:
- Thousands excited
- Significant sink for saturation

$k_y\rho_i = 0.2$

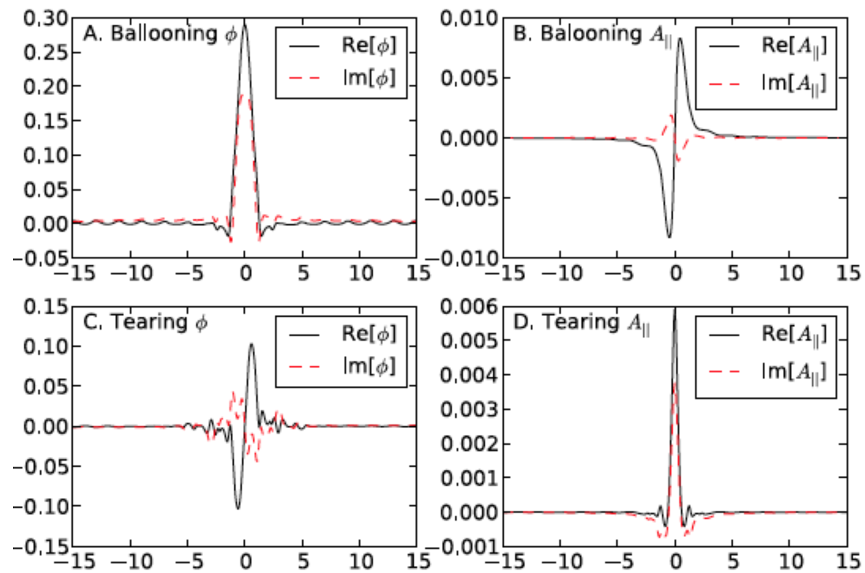


In CBC ITG turbulence:
$O(10^4)$ damped modes excited

Makwana 2014

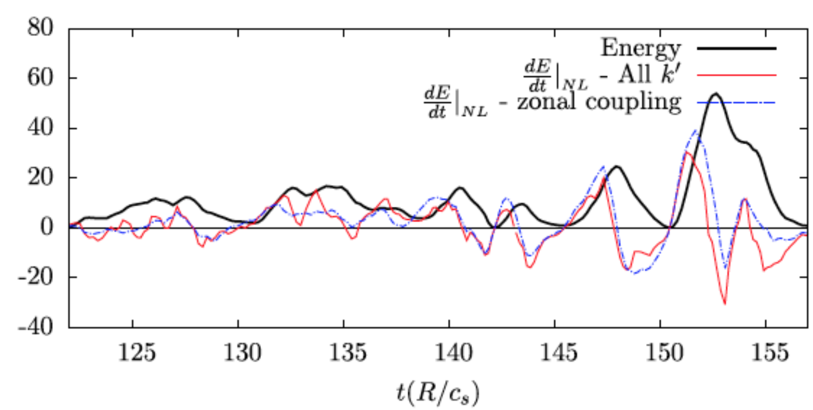
A significant subset of damped modes have tearing parity

- Damped modes sample z, $v_{||}$
- Unstable mode: ballooning parity
- Damped modes: ballooning, tearing, mixed parities



Zonal flows catalyze transfer to tearing parity modes, leading to

- Stochastic field at low β
- Flutter-induced electron heat transport

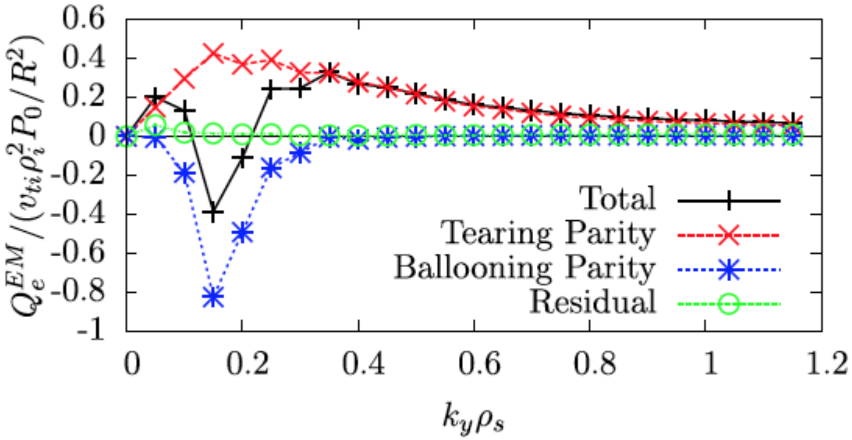


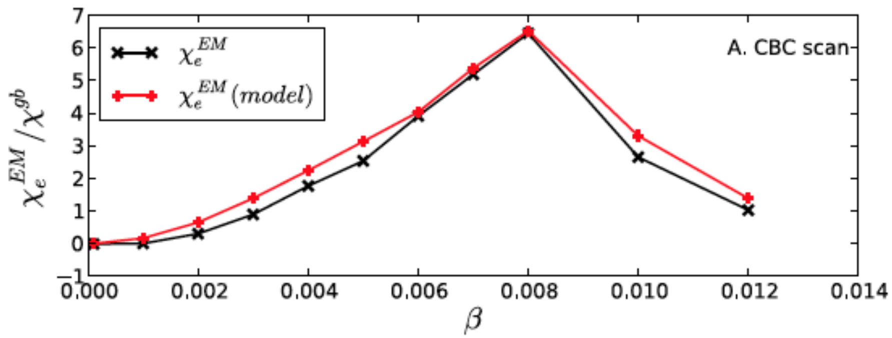
Hatch 2012, 2013

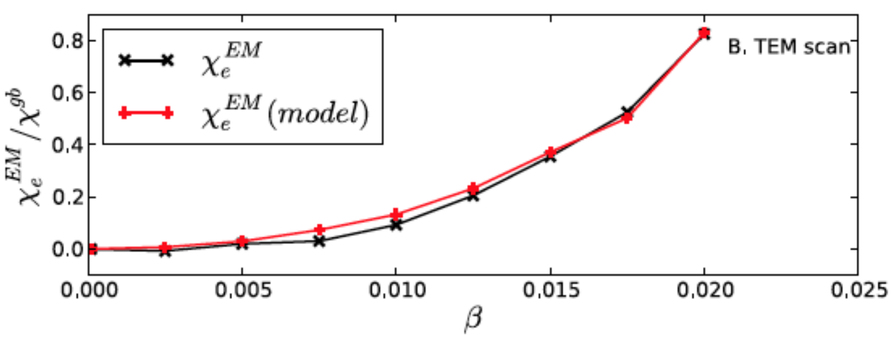
Tearing parity modes: outward magnetic fluctuation-induced electron heat flux

Unstable (ITG) mode: inward flux (low k)

Tearing parity modes: outward flux at lowest k's and high k







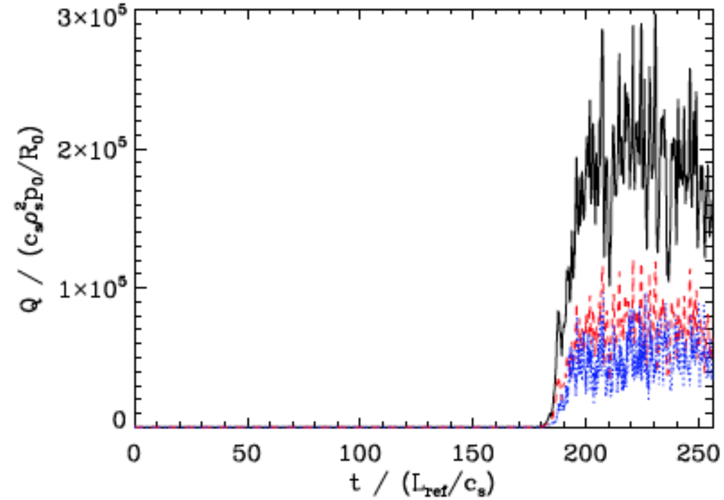
Away from $k_y\rho_s = 0.2$, flux not attributable to unstable mode

Not captured by quasilinear theory

Hatch 2013

Above a critical β zonal flows are disabled and transport 'runs away' to high values

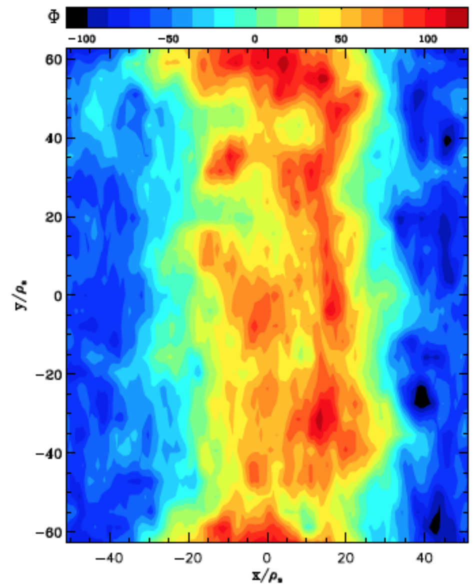
- Very large fluxes
- $\beta_{\text{crit}}^{\text{NZT}}$ ~ 0.9% Cyclone base case



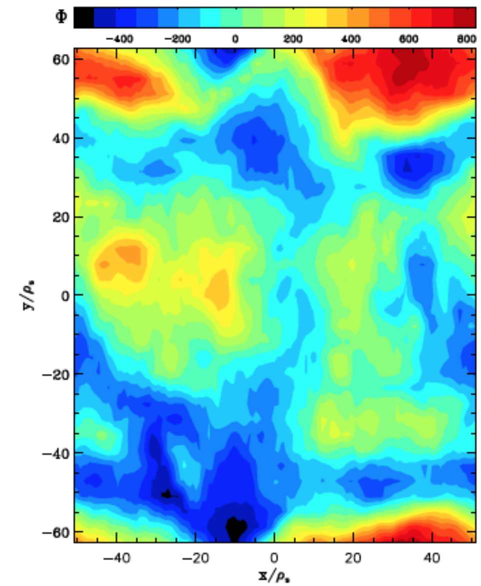
Zonal flows are disabled through magnetic field stochasticity

- Allows charge to stream from flux surfaces
- Confirmed by residual flow calculation

$\beta < \beta_{\text{crit}}^{\text{NZT}}$: strong ZFs



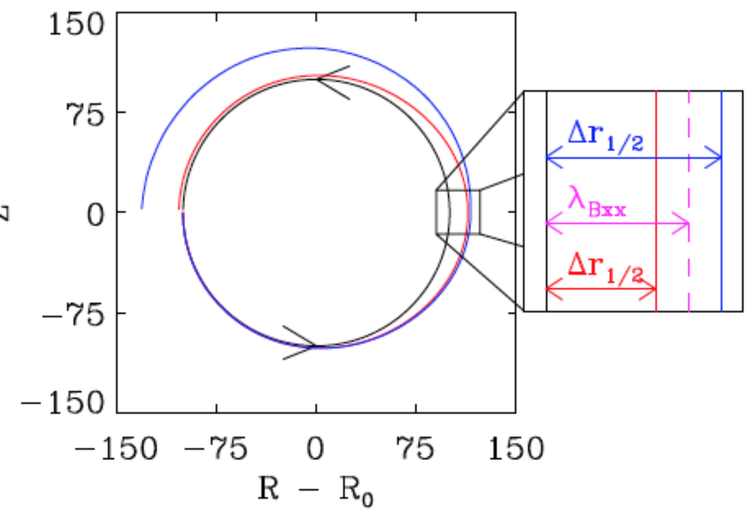
$\beta > \beta_{\text{crit}}^{\text{NZT}}$: ZFs break up



Pueschel 2013, Terry 2013

$\beta_{\text{crit}}^{\text{NZT}}$ set by a form of overlap criterion

- When $\Delta r_{1/2} \approx \lambda_{Bxx}$
  - $\Delta r_{1/2}$ is radial displacement of perturbed field <B_x> in ½ poloidal turn
  - λ_{Bxx} is radial correlation length

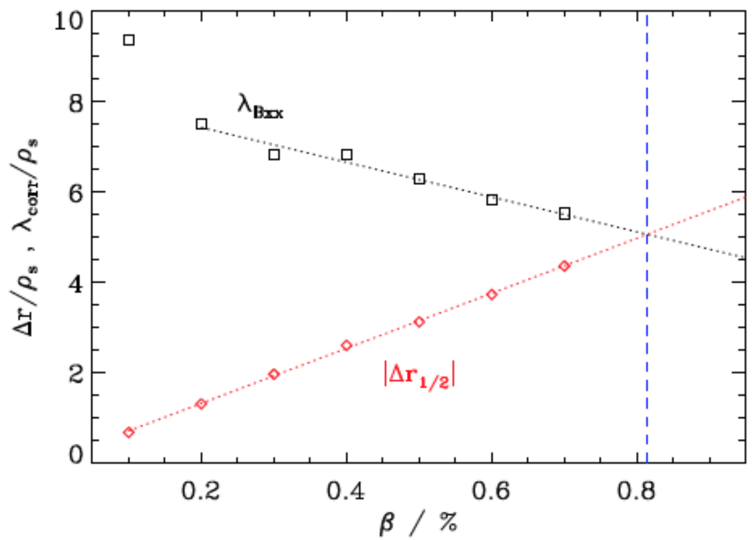


- $\Delta r_{1/2}$ depends on gradients through <B_x>

=> $\beta_{\text{crit}}^{\text{NZT}}$ increases with weaker gradients

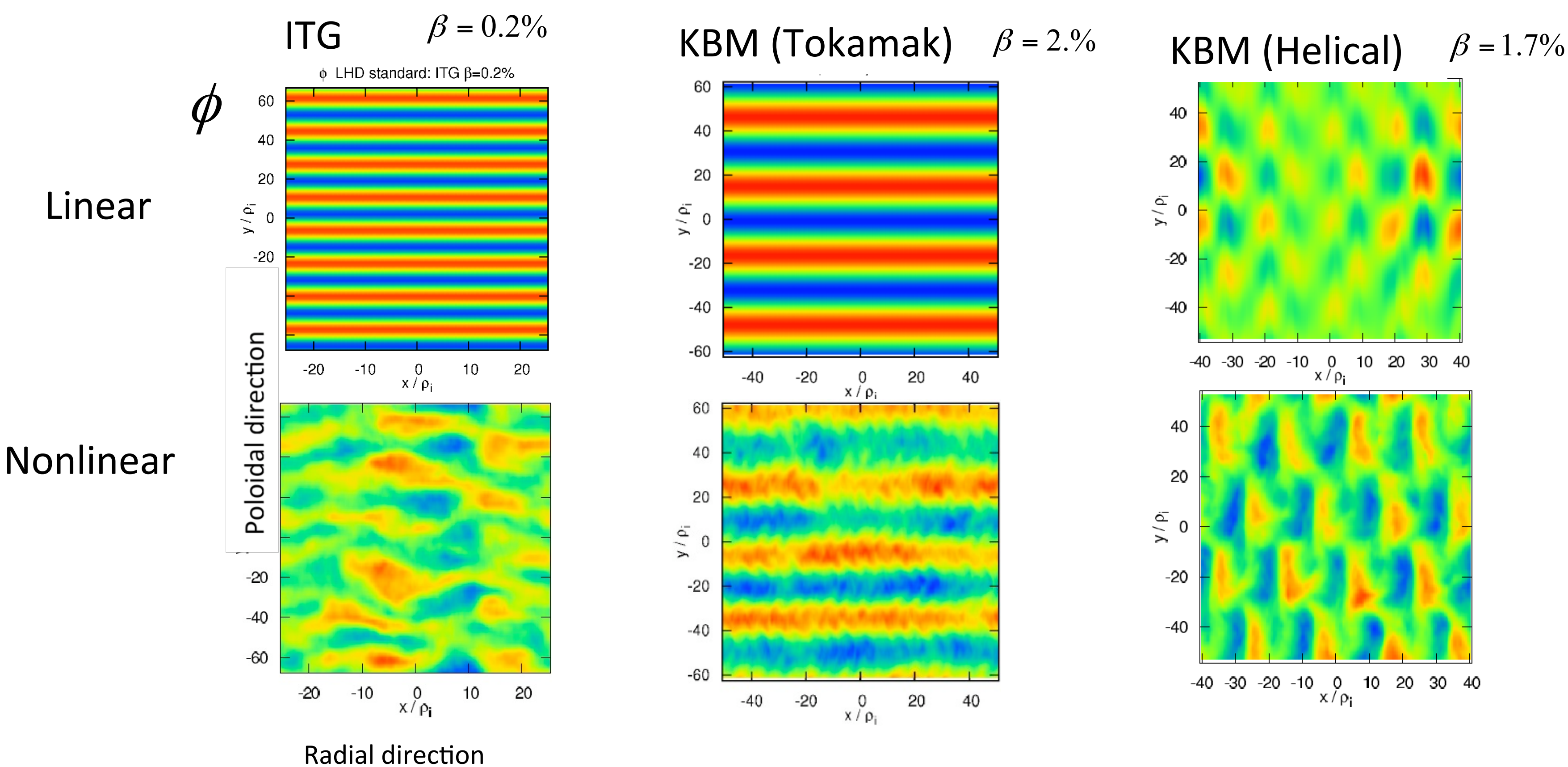
$$\frac{\beta_{\text{crit}}^{\text{NZT}}}{\beta_{\text{crit}}^{\text{KBM}}} \propto \frac{1}{(\omega_T - \omega_{T,\text{crit}})^{\xi/2}} \qquad (0.5 < \xi < 1)$$

where $\omega_T = \frac{\partial T}{\partial r}\frac{R_0}{T}$



Pueschel 2013

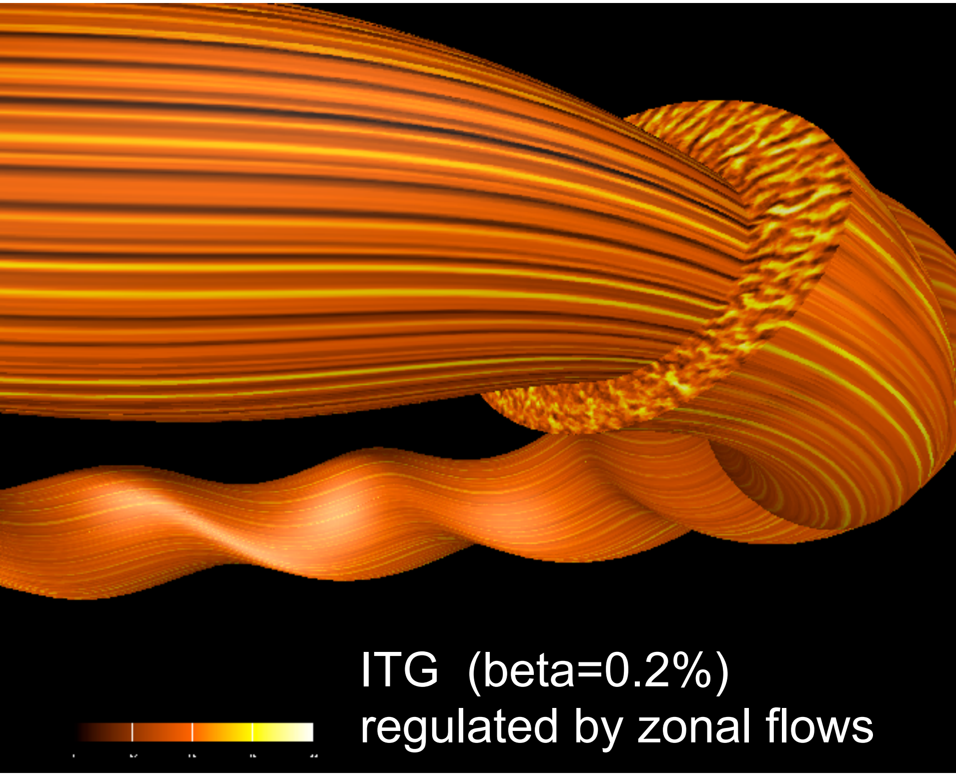
In absence of zonal flows (high β) kinetic ballooning mode saturates by developing particular structures



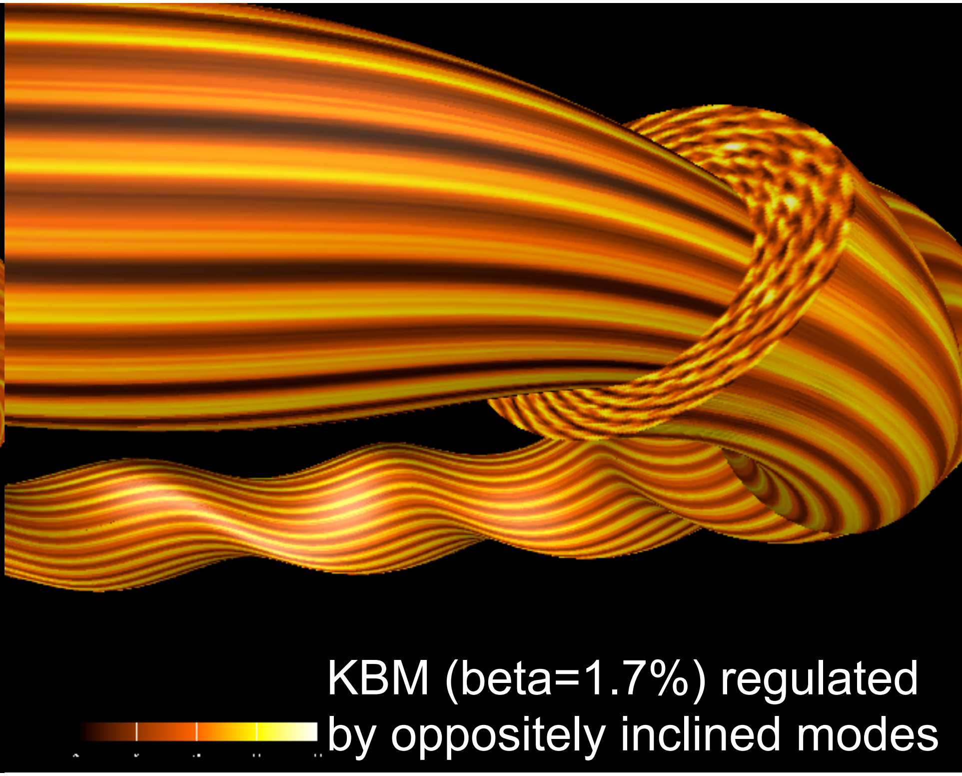
Ishizawa 2013

- Tokamak: twisted modes along the field line saturate KBM
- LHD: most unstable KBM has finite radial wavenumber, k_r

=> Saturation caused by nonlinear interactions between oppositely inclined finite k_r modes



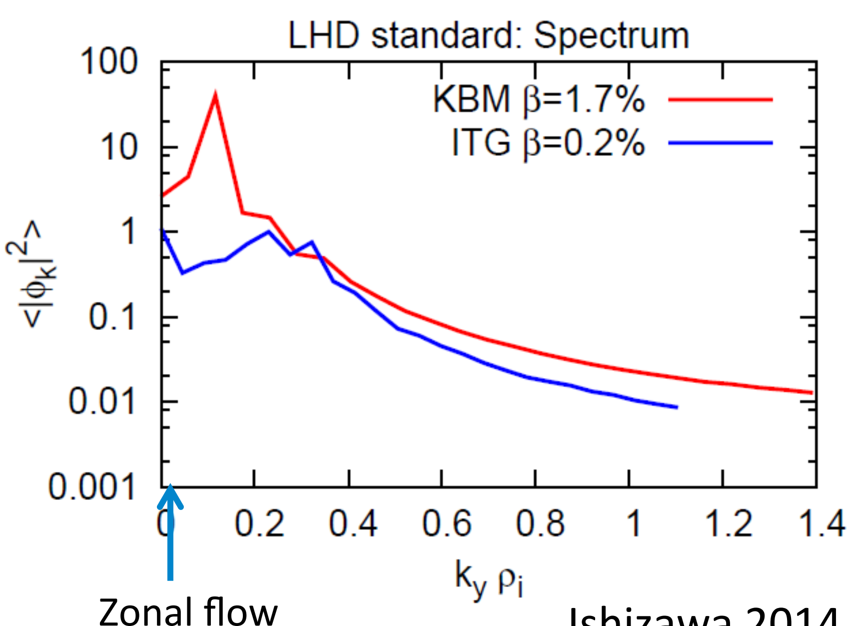
ITG (beta=0.2%) regulated by zonal flows



KBM (beta=1.7%) regulated by oppositely inclined modes

Transport at finite-beta

- Zonal flow of KBM turbulence is much weaker than that of ITG turbulence
- KBM turbulence is less effective in driving transport than ITG turbulence

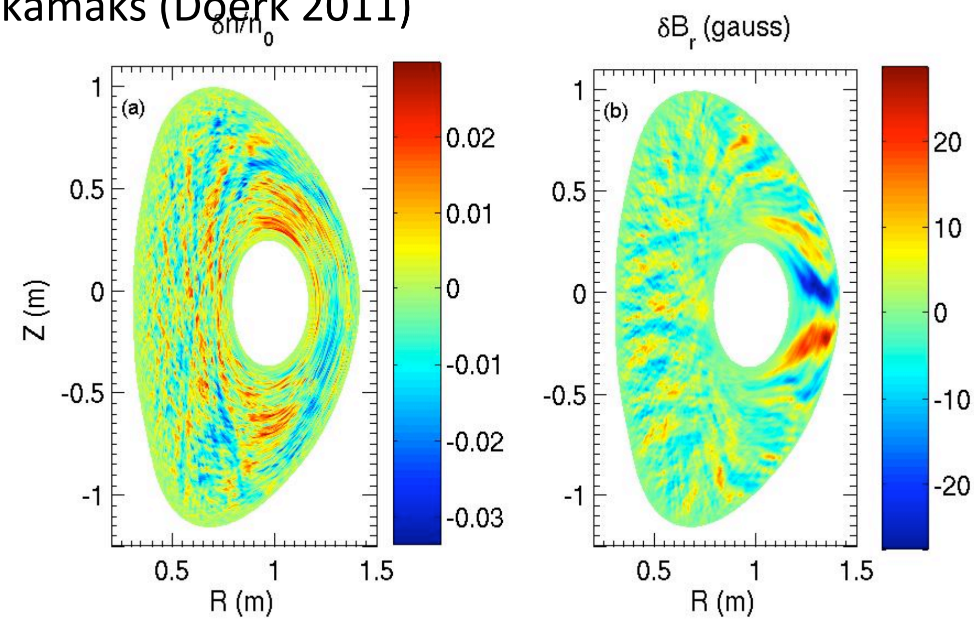


ITG $Q_i = 5 n_0 T_i v_{Ti} \rho_i^2 / L_n^2$

KBM $Q_i = 3 n_0 T_i v_{Ti} \rho_i^2 / L_n^2$

Ishizawa 2014 , IAEA-FEC TH/P6-40

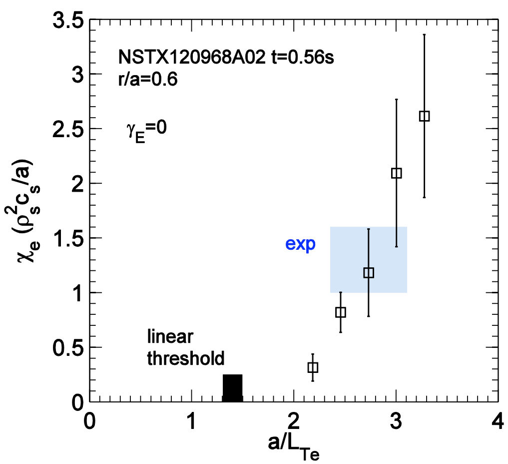
Gyrokinetic simulation: MTM in standard tokamaks (Doerk 2011)

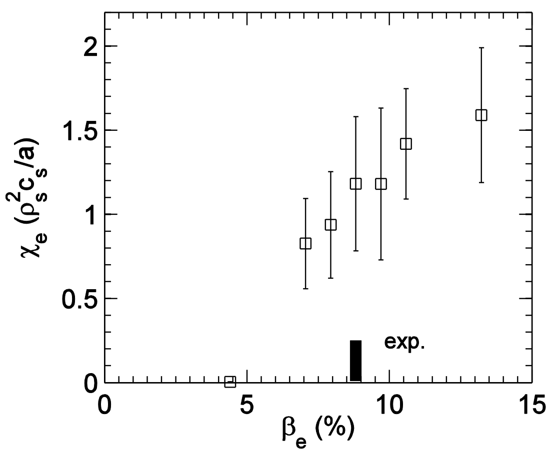


NSTX: MTM drives large χ_e (high β , high ν)

- Transport from magnetic "flutter"
  $\chi_{e,em} \sim v_{||,e} \delta B_r$
- Unclear what sets overall saturation and scaling of δB_r

- Threshold in ∇T_e, or β_e
- γ and χ_e depend on ν_e (time-dependent thermal force)
- $\chi_e \sim \nu_e$ consistent with global confinement trends $\Omega\tau_E \sim \nu_*^{-1}$





Guttenfelder 2013

- MTM: most unstable mode in transport barriers of helical states (QHS)

- Quasi-linear collisionless form of $\chi_e \sim (\rho_e/L_{Te})\, v_{th,e} L_c$, in good agreement with experiment

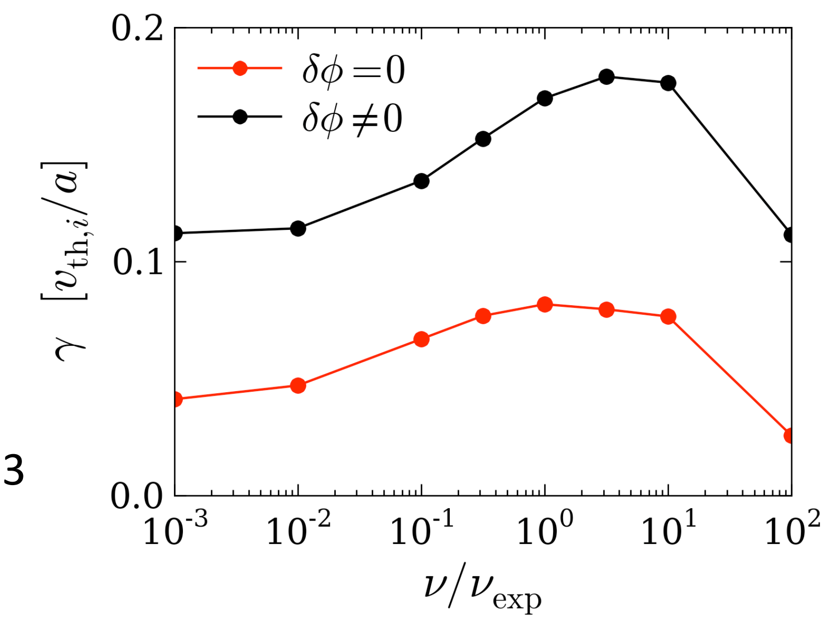
- Unstable for $a/L_{Te} \sim 2.5 - 3$ for typical values of β

MTM in the RFP is sensitive to grad-B/ curvature drifts in ω_d.

Collisionless MTMs exist, even neglecting trapped electron dynamics.

Retaining $\delta\phi$ is always destabilizing.

Predebon 2013



MTM is unstable in standard MST discharges at low θ

$$\Theta = \langle B_\theta \rangle^{\text{wall}} / \langle B_\phi \rangle^{\text{vol}}$$

(low θ => low magnetic shear)

Study with toroidal Bessel function equilibrium

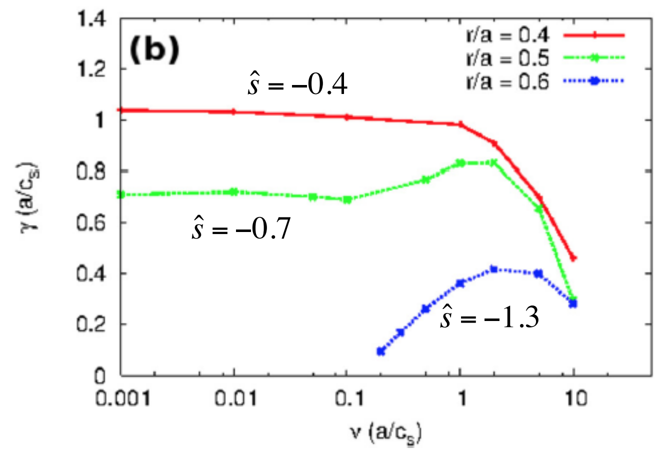
Thresholds: β = few %
a/L_{Te} = 3 - 4

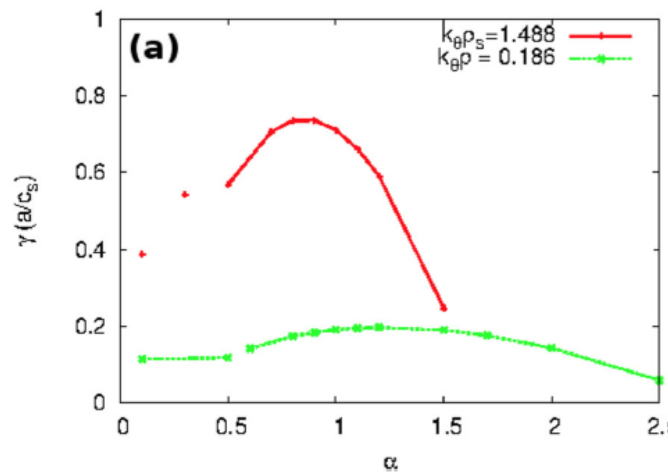
Finite growth rate as collisionality -> 0

Requires weak to moderate shear

Theory:

- Start with DKE, take high freq. fluid limit
- Instability as ν -> 0 if $\phi \neq 0$
- Enabled by ω_{De}
- (ω_{De} in RFP is larger than tokamak value by R/a)



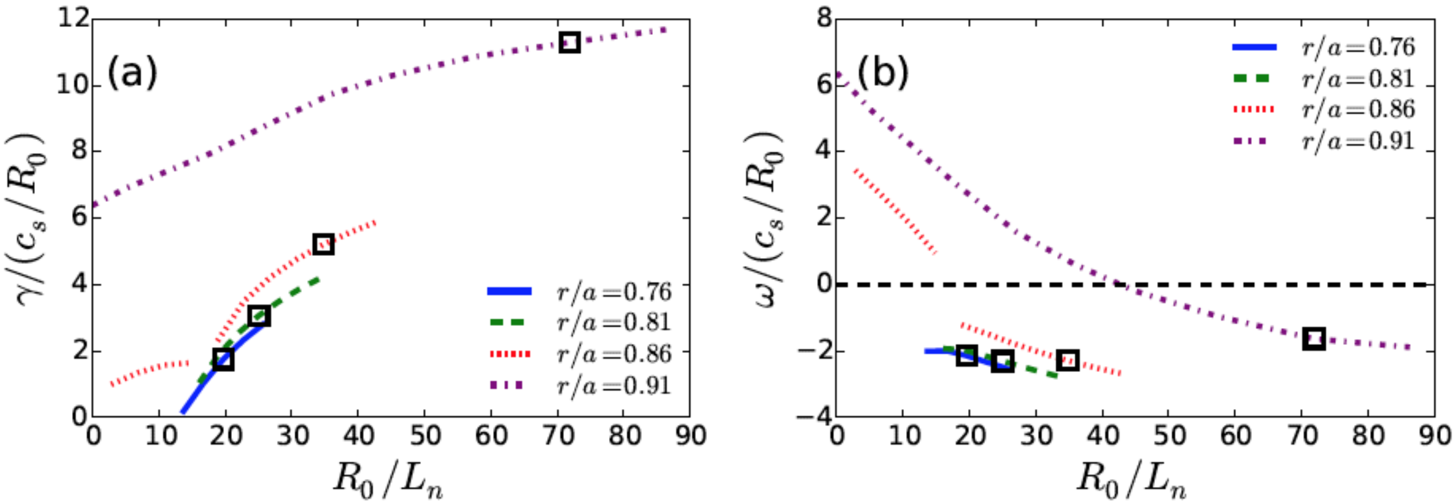


Carmody 2013

MST enhanced-confinement discharges show surprising absence of electrostatic turbulence

Flat current profile (reduce global tearing)
High θ (high shear)
Instability in outer region (β small)

Gyrokinetic modeling (fitting experimental equilibrium): TEM/ITG



- Density gradient driven TEM (frequency in electron direction)
- At β ~ 1 – 2%, discharge is below critical β for MTM, NZT, etc.

Saturated turbulence:

Large zonal flows

Large Dimits shift

Transport rates: weaker than experiment by x10

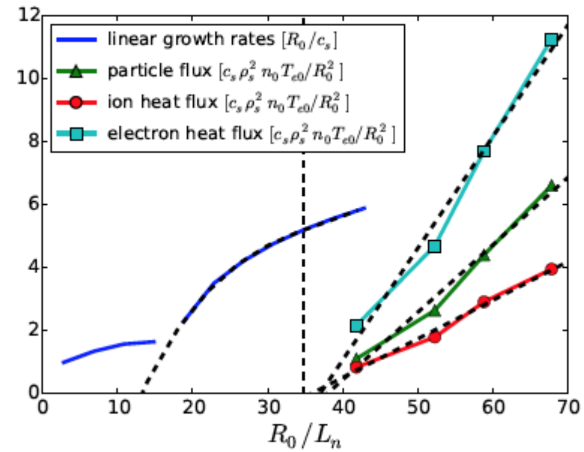
Mock up tearing mode activity using external magnetic perturbation at experimental level

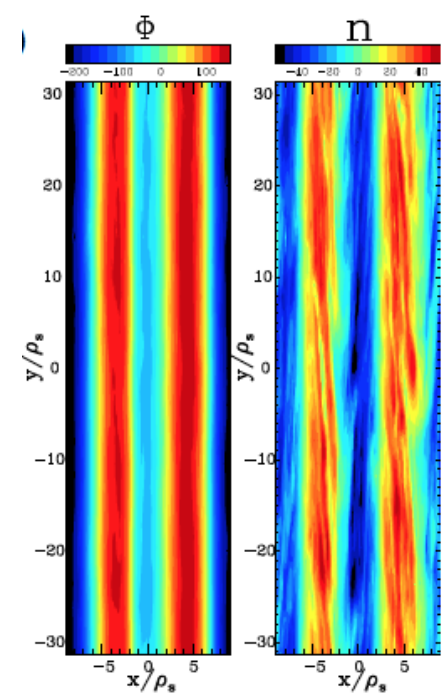
- Weaker zonal flow
- Lower Dimits shift – close to exp. gradient
- χ_e at experimental level

Key issue:

Despite relatively high β, RPF is below critical β for electromagnetic effects

Why?



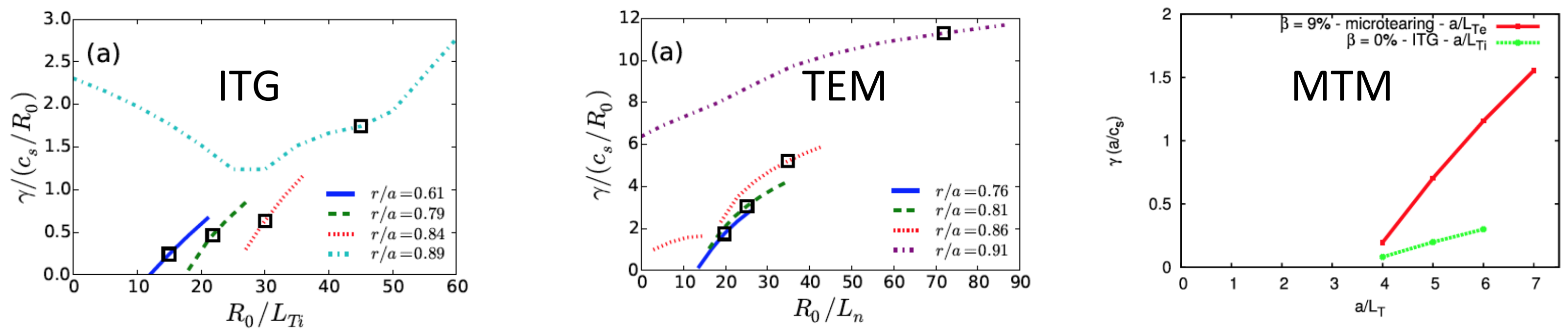


RFP equilibrium has smaller length scales than standard tokamak

	Equilibrium	Scale of variation	Connection length	Safety factor q
Tokamak	$B_\phi >> B_\theta$	R	qR	q > 1
RFP	$B_\phi \approx B_\theta$	r	r	q < 0.2

Smaller equilibrium scales generally push instability thresholds to higher values

Gyrokinetics: $$\frac{1}{L_{crit_{RFP}}} \approx \left(\frac{R}{r}\right)\frac{1}{L_{crit_{tok}}}$$ (for both electrostatic and electromagnetic)



In RFP all β thresholds for electromagnetic effects pushed to much higher values

Primary causes:

Shorter magnetic shear scale lengths: $$\frac{L_{S_{Tok}}}{L_{S_{RFP}}} \sim q_{Tok} q_{0_{RFP}} \left(\frac{R}{r}\right)^2 \sim \mathrm{O}\left(\frac{R}{r}\right)$$

Smaller *q*

ITG stabilization $$\beta \geq \varepsilon_n \varepsilon_T^2 \tau^2 \left[1 + \left(\varepsilon_T / q_0\right)^2\right]^{-1} q_0^{-2} \left[(\tau + 2\varepsilon_n)(\tau + 1) + \tau^2 \eta_e\right]^{-1} \sim \mathrm{O}\left(\frac{R}{r}\right) \beta_{crit_{Tok}}$$

NZT $$\frac{\beta^{NZT}_{crit_{RFP}}}{\beta^{NZT}_{crit_{Tok}}} \propto \left(\frac{R_0}{r}\right)^{1+\xi/2} q_{0_{Tok}}$$

KBM $$\beta^{KBM}_{crit_{RFP}} \sim 0.6 \frac{\left(\frac{R}{r}\right)}{q\left[\frac{R_0}{L_n} + \frac{R_0}{L_{T_e}} + \left(\frac{R_0}{L_n} + \frac{R_0}{L_{T_i}}\right)\frac{T_i}{T_e}\right]} >> \beta^{KBM}_{crit_{Tok}}$$

Larger shear, smaller *q* push electromagnetic effects to higher β

Higher critical gradients allow steeper gradients in experiment

Conclusions

Microturbulence at finite β subject to new effects

- Stable tearing parity fluctuations excited by ITG => electron heat transport
- Magnetic fluctuations can disable zonal flows => much higher transport
- New instabilities arise (microtearing, kinetic ballooning mode)
- Shorter magnetic scale lengths push these effects to higher gradients, beta

Saturation of microturbulence at finite β involves complex feedback loops, especially with zonal flows and magnetic fluctuations (both stable and unstable)

Have demonstrated:

- How interplay between instability, nonlinearly excited stable modes, zonal flows affects saturation and transport (variation of β changes balances to reveal physics)
- Magnetic field scales push critical gradients and β to higher values