Microstability Properties of the Local Minimum |B| Regime in Pegasus

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PEGASUS
Toroidal Experiment

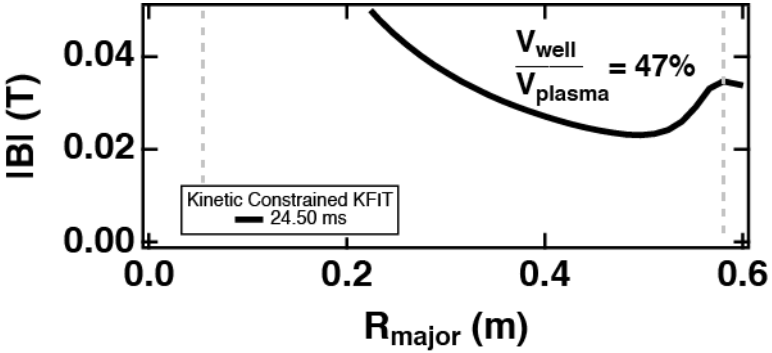
Abstract

A local **minimum |B| region**, or "magnetic well," was recently observed in the **low-A Pegasus device** in high-β scenarios with strong edge current peaking [1]. The **∇B reversal** within the magnetic well alters magnetic drifts and particle orbits associated with instabilities. Here, we report on the microstability properties of the magnetic well region with calculations from the **GENE gyrokinetic code** [2].

[1] D.J. Schlossberg et al., PRL, 2017;
D.J. Schlossberg, Ph.D. Thesis, 2017

[2] F. Jenko and the GENE Development Team,
http://genecode.org/

Magnetic well from
Pegasus equilibrium reconstruction [1]

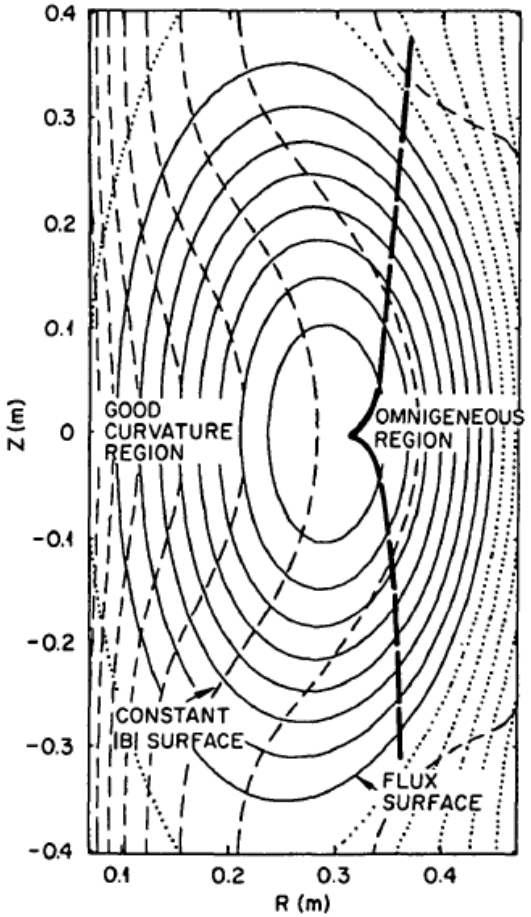


Outline

- Background
  - Confinement properties diamagnetic gyromotion and ST paramagnetism
  - ∇B reversal and drift wave stabilization
- Pegasus minimum |B| regime
  - $\beta_t \approx 100\%$ operation with HFS local helicity injection
  - Diamagnetic well in net-paramagnetic configuration
- Microstability properties of Pegasus minimum |B| regime
  - Microtearing modes at multiple scales identified with linear GENE simulations
  - Minimum |B| configuration is stabilizing relative to monotonic |B| configuration
  - In minimum |B| regime, low-k modes are highly sensitive to β and high-k modes are highly sensitive to ∇p drift term
  - Preliminary nonlinear simulation shows dominant electron electromagnetic thermal transport in $q_\perp$ and $q_\parallel$ moments
- Summary

Enhanced confinement with ST paramagnetism

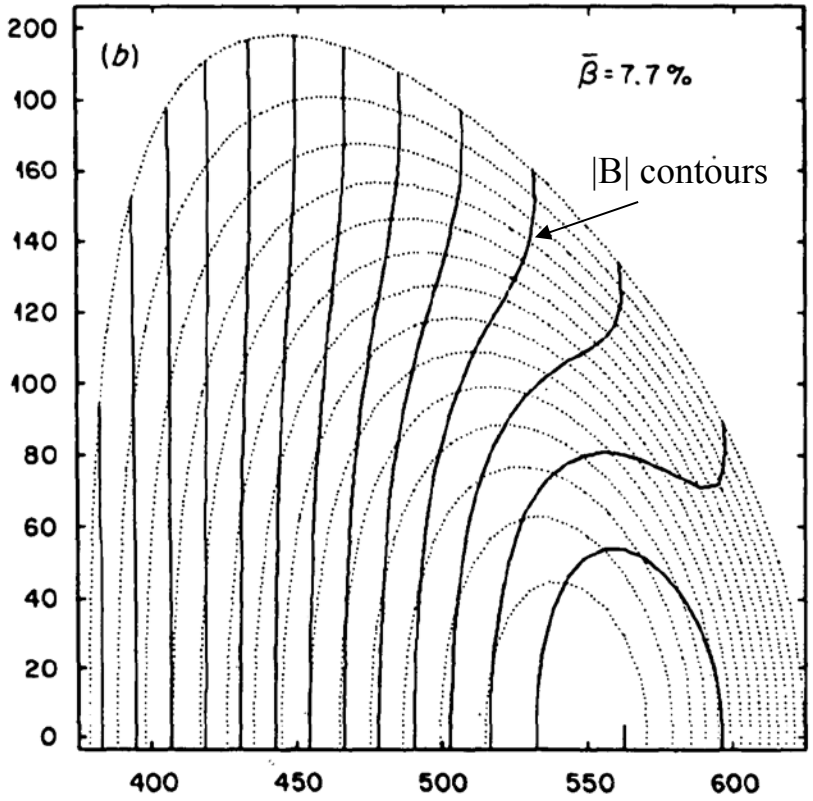
- STs are strongly paramagnetic due to large helical pitch and J_p
  - $\beta_p \sim 0.3$ (< 1 is paramagnetic)
- Omnigeneity in bad curv. region from paramagnetic $|B| \approx |B|(\psi)$
  - **Reduced neoclassical transport** due to vanishing banana orbit width



Y-K. M. Peng and D. Strickler, NF 1986

Enhanced confinement with diamagnetic |B| well

- At high β, plasma digs a diamagnetic |B| well
  - Gyromotion is diamagnetic
- Drift wave stabilization
  - ∇B reversal in magnetic drift
- Improved fast ion confinement
  - Expanded parameter space for:
    - fast ion trapping
    - co-and counter- fast ion confinement
- Reduced neoclassical transport
  - Smaller trapped particle fraction



J. Rome and Y-K. M. Peng, NF 1979

Drift wave stabilization with ∇B reversal

Toroidal ITG dispersion relation*

$$\omega^2 \frac{T_i}{T_e} - 2\omega_d \omega + \underbrace{2\omega_d \omega_{*T}}_{\text{key term}} - 7\omega_d^2 = 0$$

with $\omega_d = \vec{k} \cdot \overrightarrow{v_d}$, $\overrightarrow{v_d} = \frac{v_\parallel^2 + \mu B}{\Omega} \frac{\vec{B} \times \nabla B}{B^2}$, and $\omega_{*T} = -k_\theta \rho_i \frac{v_{ti}}{L_T}$.

Typically, $B(R) \propto 1/R$ with $\mathrm{sgn}(\omega_d) = \mathrm{sgn}(\omega_{*T})$ on LFS.

ITG instability ($\mathrm{Im}(\omega) > 0$) exists if L_T is sufficiently small.

***∇B* reversal** on LFS gives $\mathrm{sgn}(\omega_d) = -\mathrm{sgn}(\omega_{*T})$ and all modes are strictly **stable**

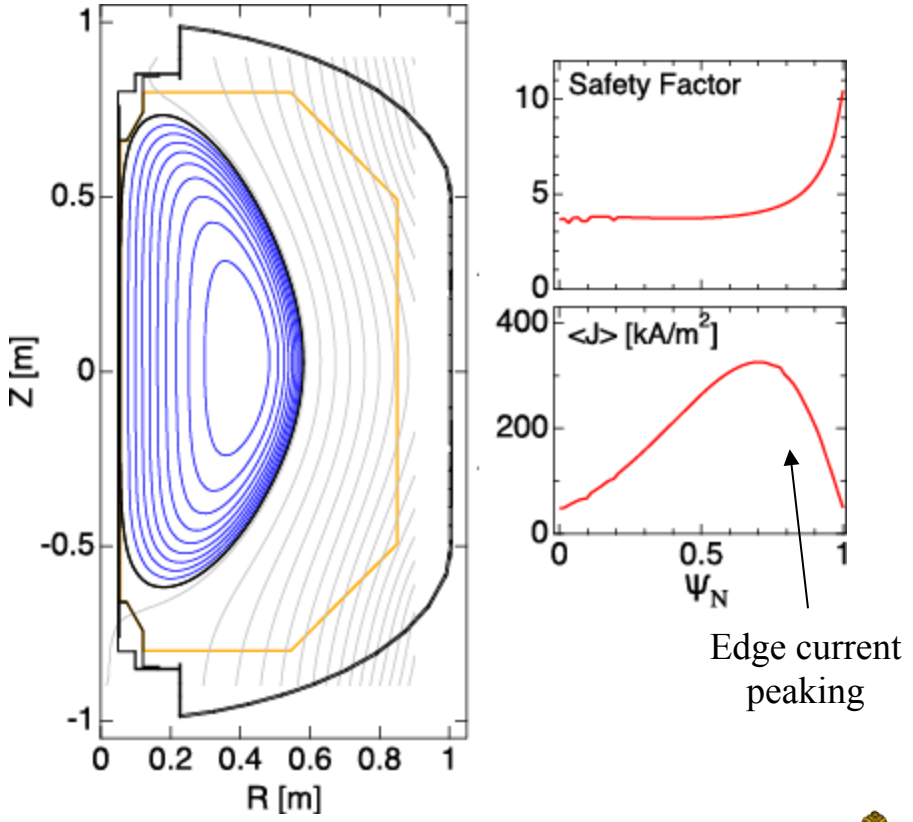
* neglect $k_\parallel$, assume $\omega \gg \omega_d$, and let $\nabla n \to 0$

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HFS LHI enables $\beta_t \approx 100\%$ regime in Pegasus

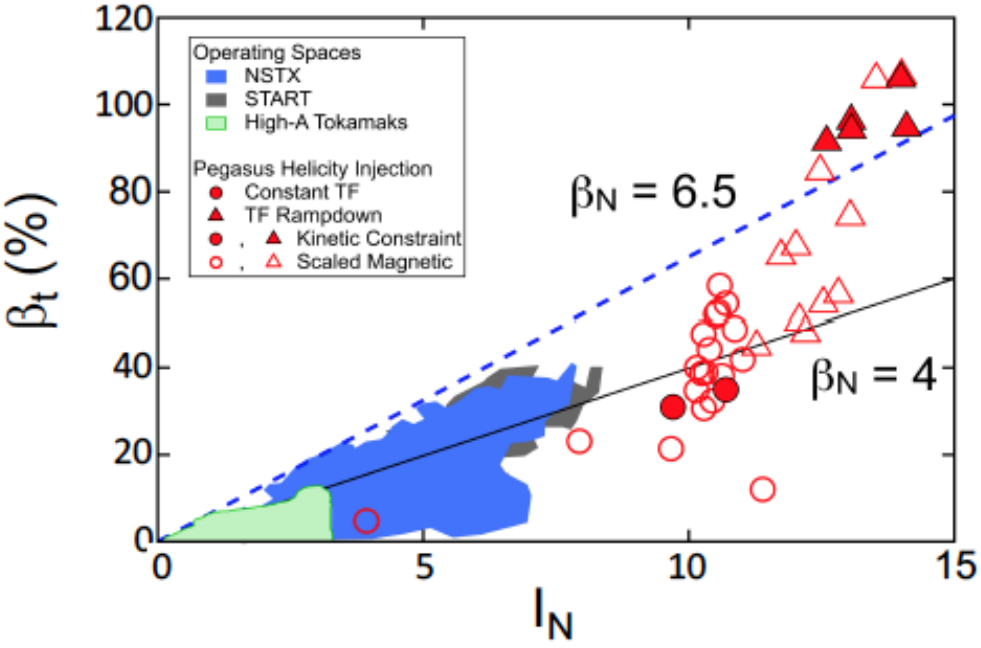
- Enhanced stability at low A (1.21) and high κ (2.6) in Pegasus
- Local helicity injection (LHI) with high field side (HFS) injectors
  - Reconnection ion heating ($T_{i0} > T_{e0}$)
  - Suppression of low-m tearing modes
  - Edge current peaking with low l_i (0.22)
- Kinetic-constrained equilibria

D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017



High β_t at high I_N (aI_p/B_{t0}) in Pegasus

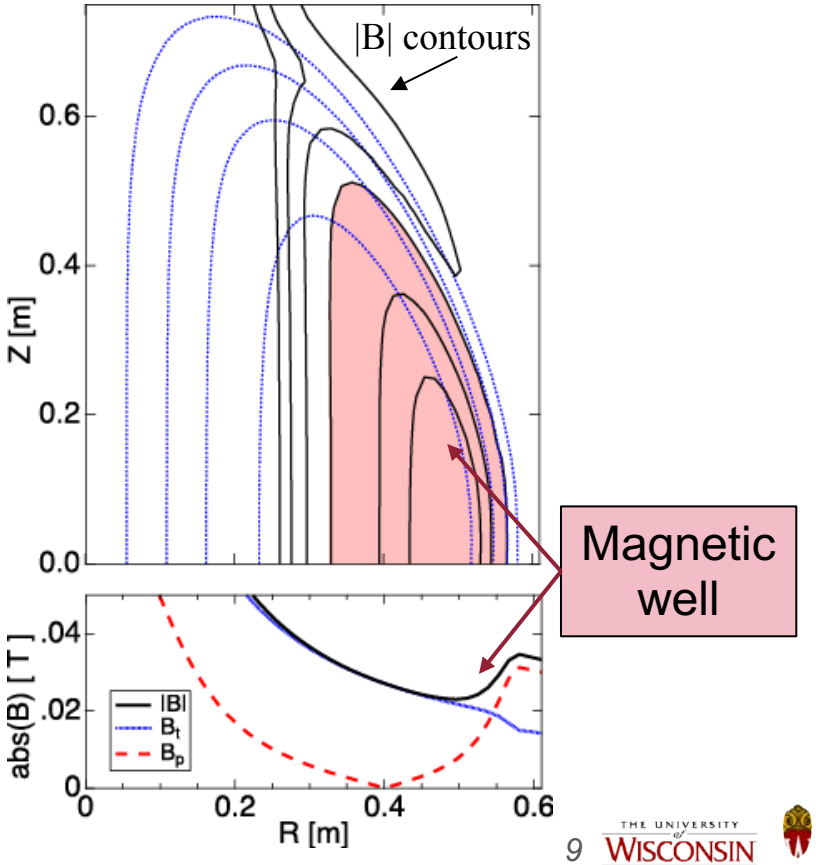
- Sykes-Troyon scaling
  - $\beta_{t,max} \propto aI_p/B_{t0}$
  - Normalized current: $I_N \equiv aI_p/B_{t0}$
  - Normalized beta: $\beta_N \equiv \beta_{t,max}/I_N$
    - Higher β_N accessible at lower A and/or higher κ
- I_{TF} ramp-down to access high I_N
  - $I_N \propto I_p/I_{TF}$



D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

Diamagnetic |B| well in net-paramagnetic Pegasus

- Strong ST paramagnetism diminished by diamagnetic well
  - $\beta_p = 0.45$
- Magnetic well depth increases at higher β_p or lower B_t

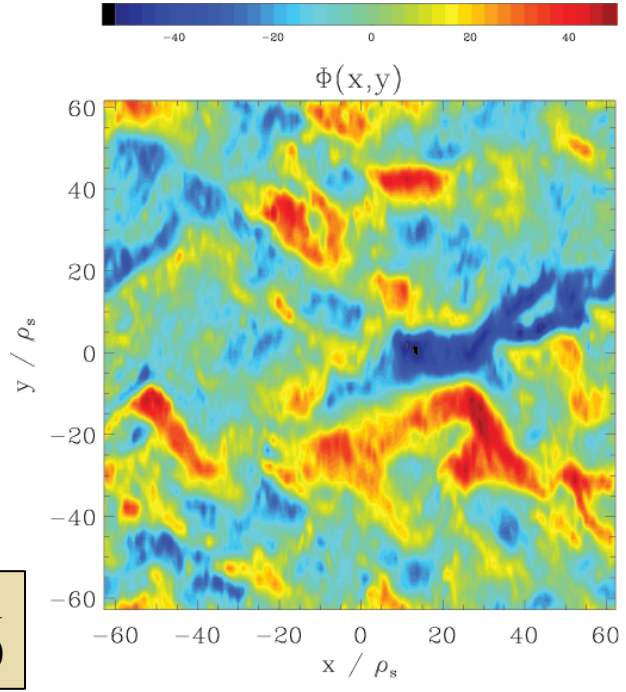


D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

Gyrokinetic simulations with *GENE*

- *GENE* evolves gyrokinetic equations in 5-dimensional phase space
  - Electromagnetic with $A_{\parallel}$ (and $B_{\parallel}$ if needed)
  - Local flux tube or global profiles
  - Linear/nonlinear initial value solver or linear eigenvalue solver (subdominant modes)
  - **F. Jenko et al, http://genecode.org/**

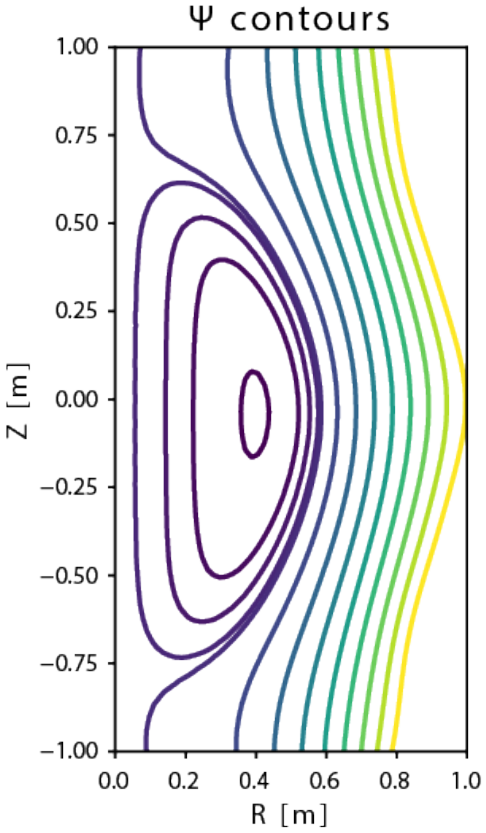
Example GENE simulation of finite-β TEM turbulence at A = 5.5

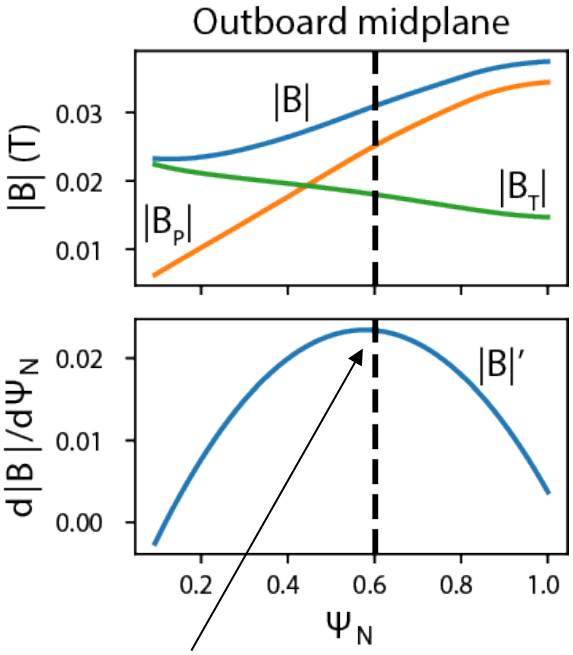


M. J. Pueschel and F. Jenko, PoP 2010

Simulation parameters for Pegasus diamagnetic well

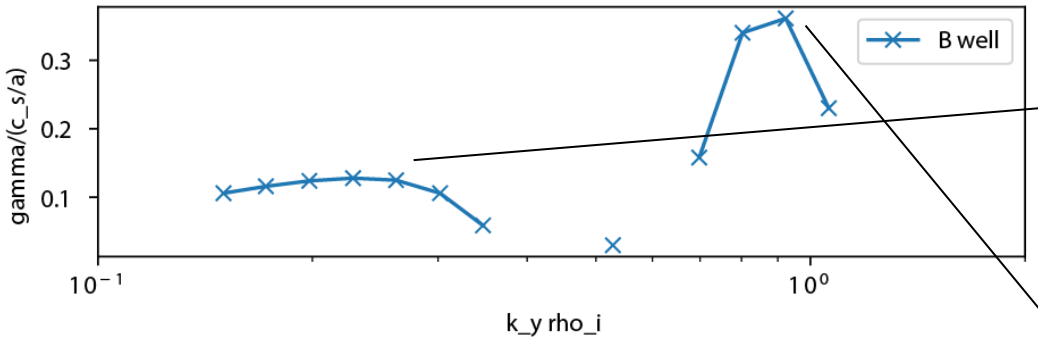
- Flux tube
  - $\Psi_N = 0.6$ @ max ∇B reversal
  - $q = 3.5$ and $\hat{s} = 0.55$
- Physics model
  - ϕ and $A_{||}$ (no $B_{||}$)
  - $m_e/m_d = 1/400$ (heavy ele.)
  - $\nu_i^* = 0.07$
  - $\beta_e = 27\%$
- Species' profiles
  - $a/L_n = 1.9$
  - $a/L_{Ti} = a/L_{Te} = 4.2$
  - $T_e = T_i$

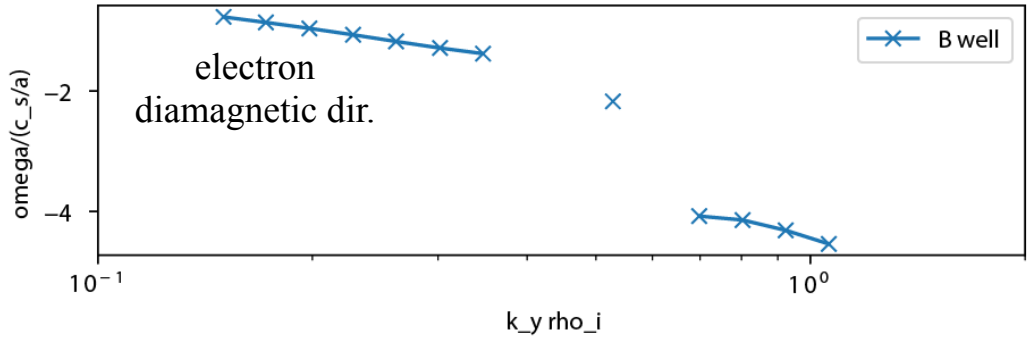


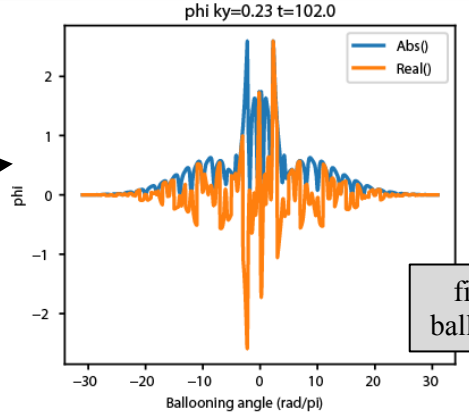


max ∇B reversal

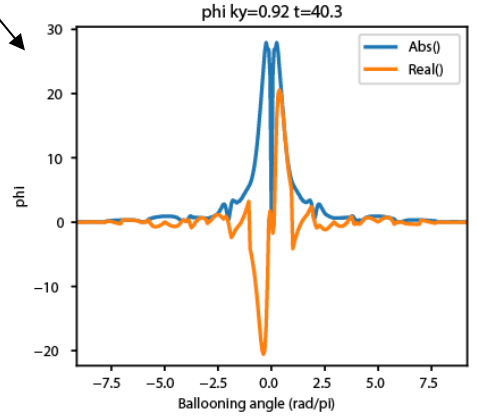
Tearing-parity electron modes in diamagnetic |B| well







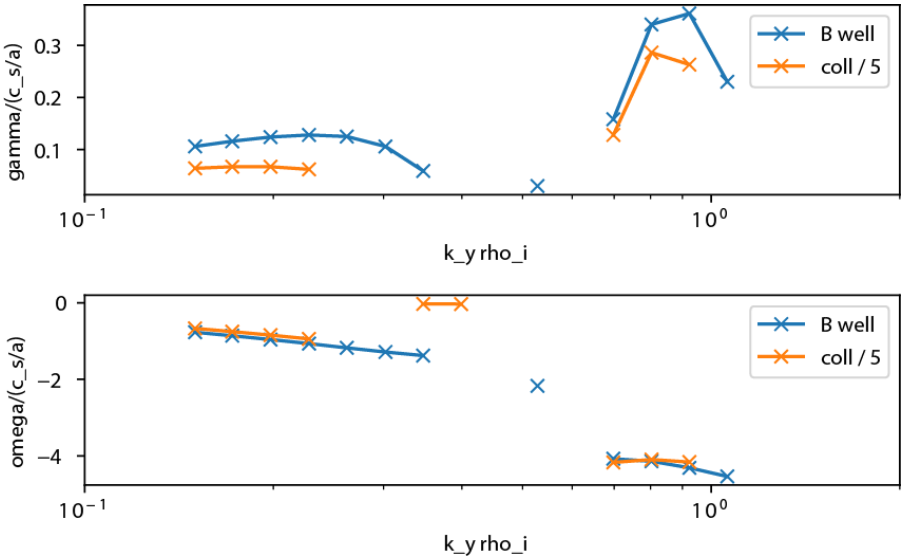
field-aligned ballooning angle



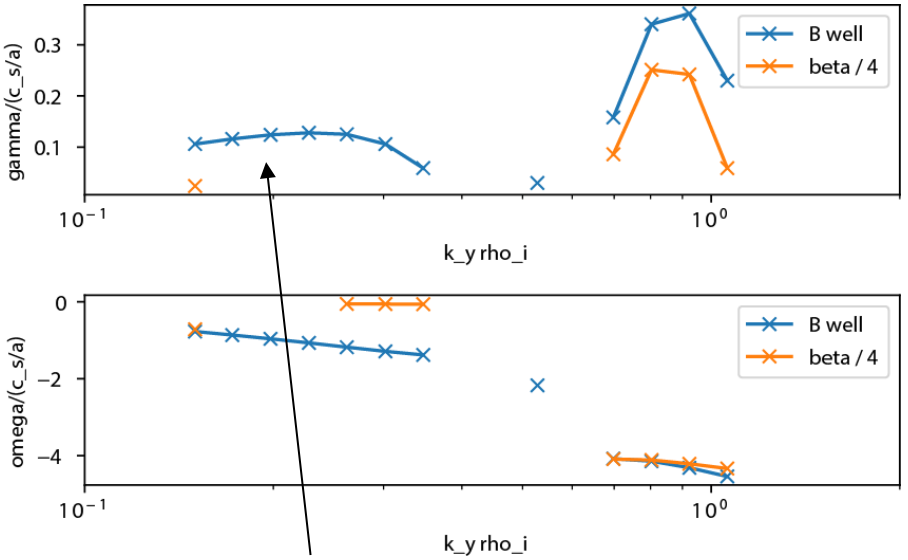
Linear initial value calculations

Destabilized by collisionality and $\beta \rightarrow$ microtearing modes

Comparison with 1/5th collisionality



Comparison with 1/4th beta

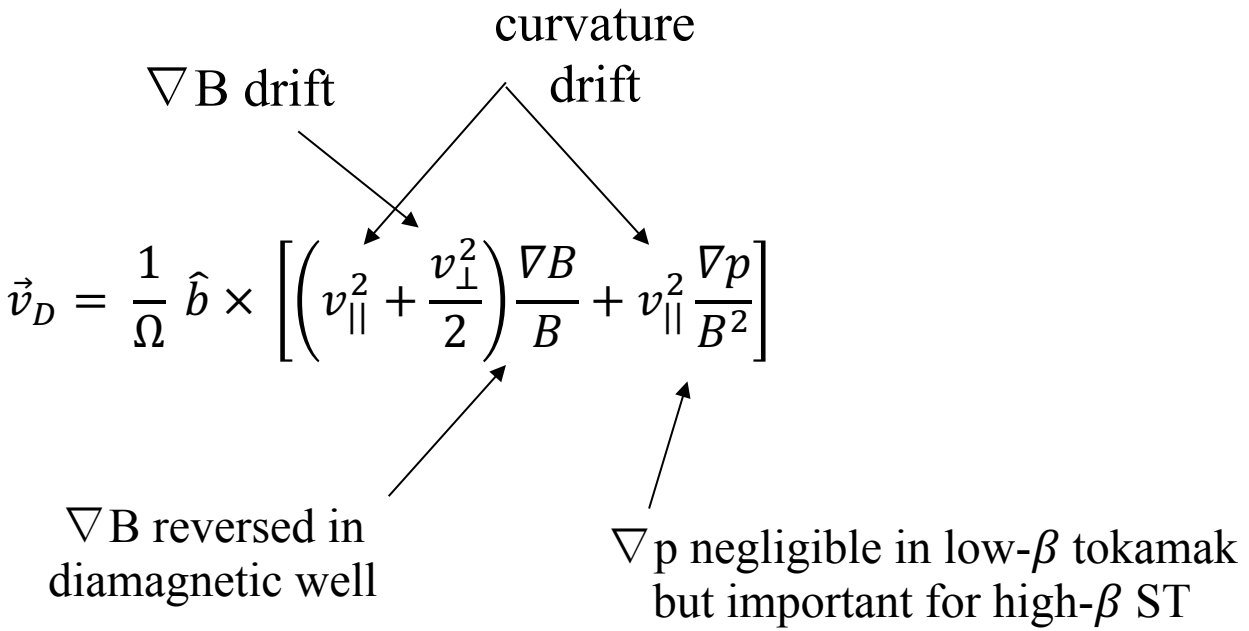


Low-k modes fully stabilized at beta/4

Also, modes destabilized with ∇T_e

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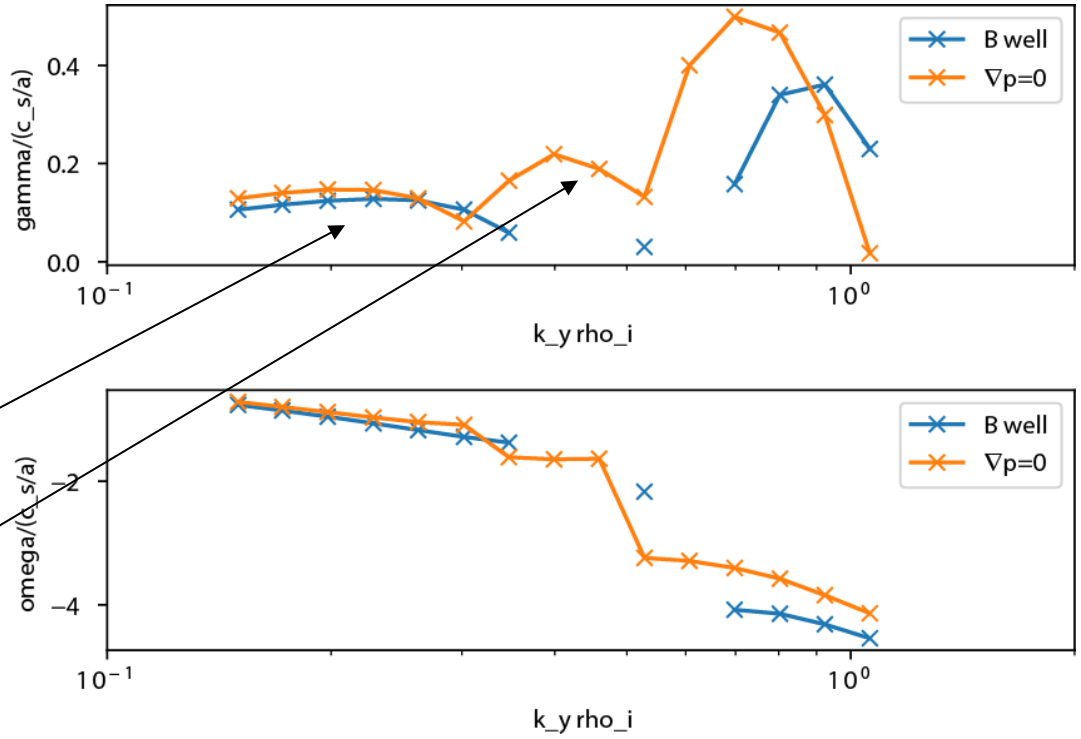
Magnetic drifts and pressure contribution



Eliminating ∇p from curvature drift is destabilizing for high-k modes

$$\vec{v}_D = \frac{1}{\Omega}\,\hat{b} \times \left[\left(v_{||}^2 + \frac{v_\perp^2}{2}\right)\frac{\nabla B}{B} + v_{||}^2 \frac{\nabla p}{B^2}\right]$$

$\nabla p \to 0$



little effect on low-k modes

all tearing-parity electron modes

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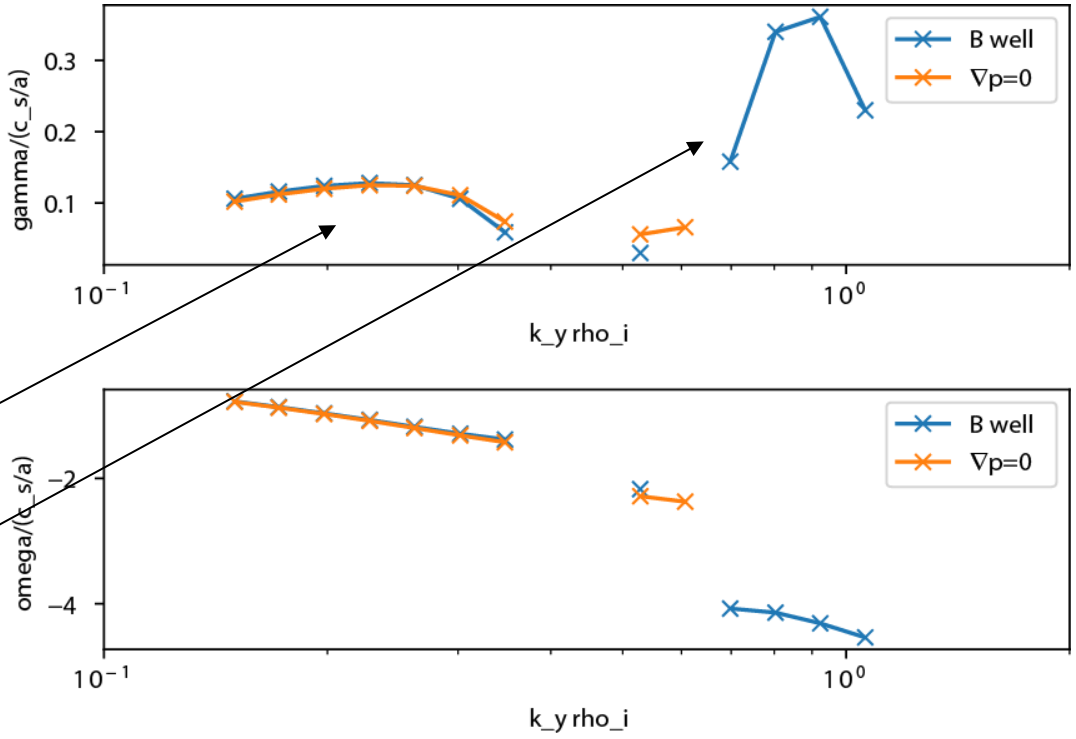
Eliminating ∇p from ∇B drift is stabilizing for high-k modes

Recast drifts to κ form

$$\vec{v}_D = \frac{1}{\Omega}\,\hat{b} \times \left[\left(v_{||}^2 + \frac{v_\perp^2}{2}\right)\vec{\kappa} - \frac{v_\perp^2}{2}\cancelto{0}{\frac{\nabla p}{B^2}}\right]$$

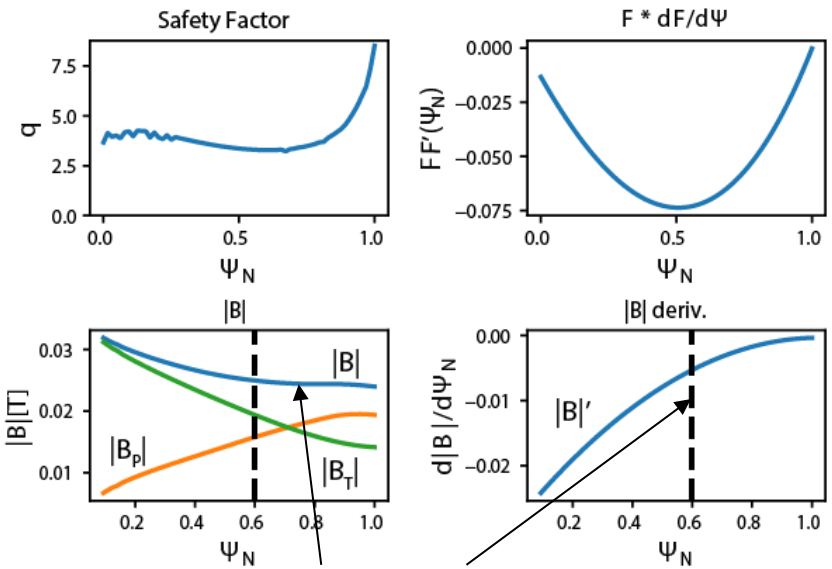
no effect on low-k modes

high-k fully stabilized

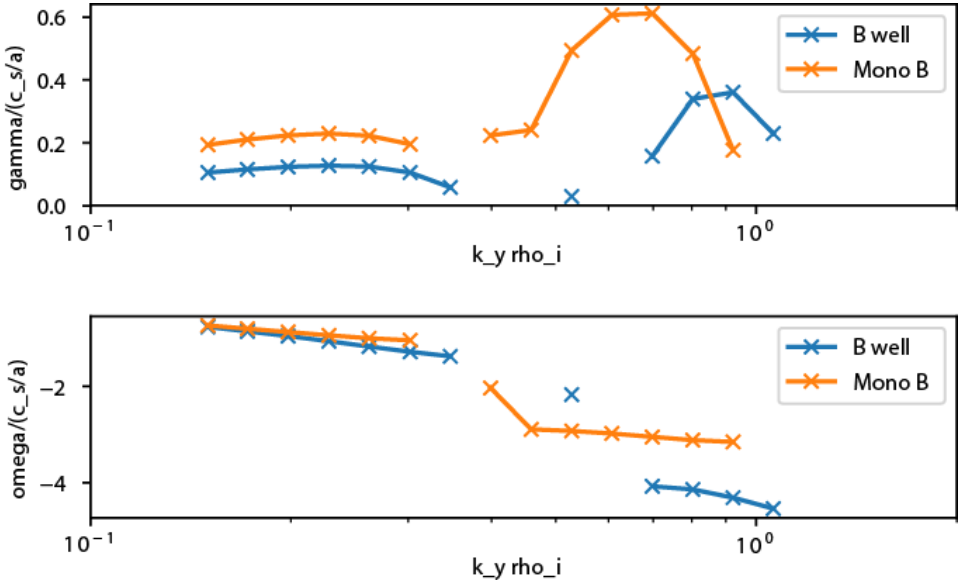


▽B reversal in diamagnetic well is stabilizing

Monotonic |B| configuration



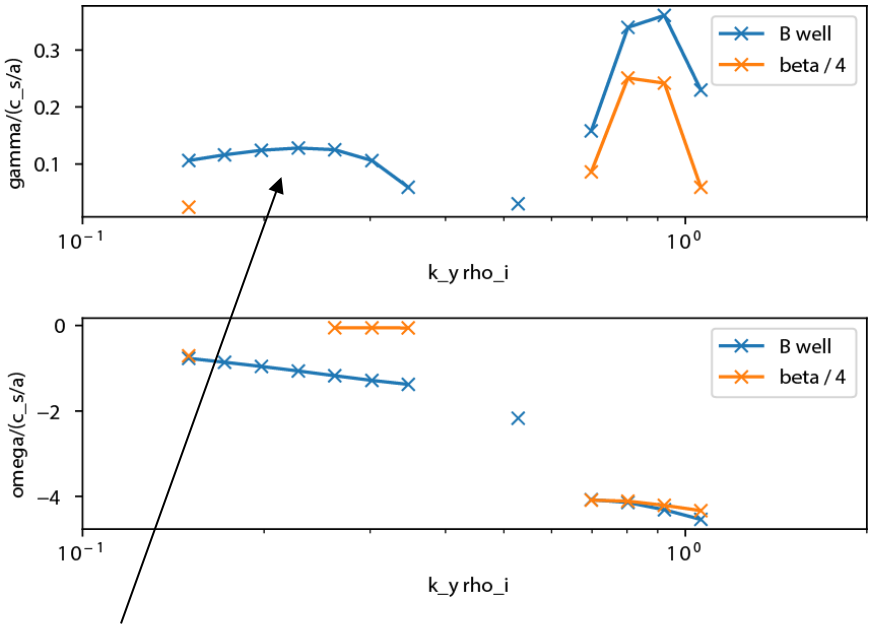
Modes are more unstable with monotonic |B|



Monotonic |B| and |B|′< 0 (cf. pg. 11).
Slight RS and less edge current (cf. pg. 7).

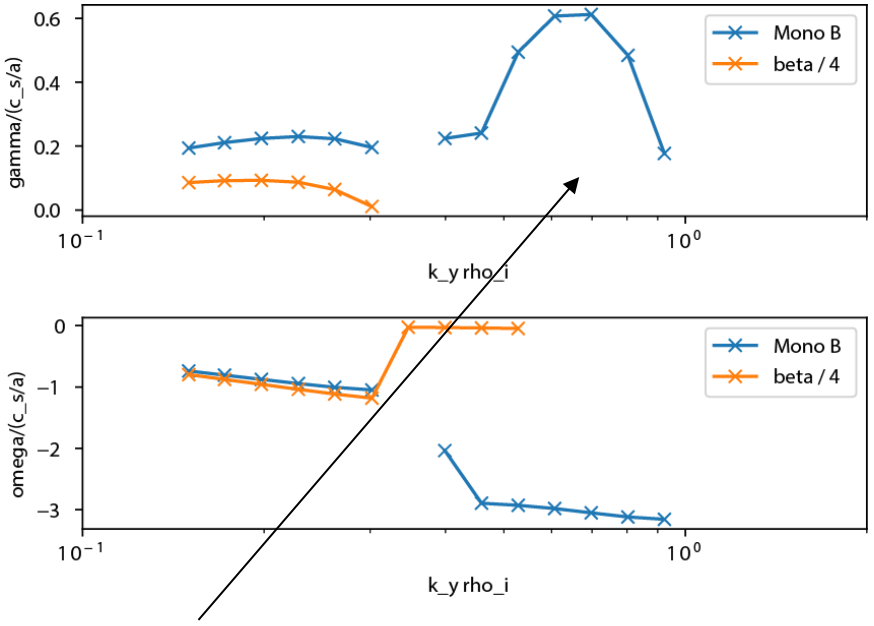
Low-k modes in min. |B| regime are strongly suppressed at low β in contrast to high-k suppression in monotonic |B|

|B| well



Low-k modes fully stabilized at $\beta/4$

Monotonic |B|



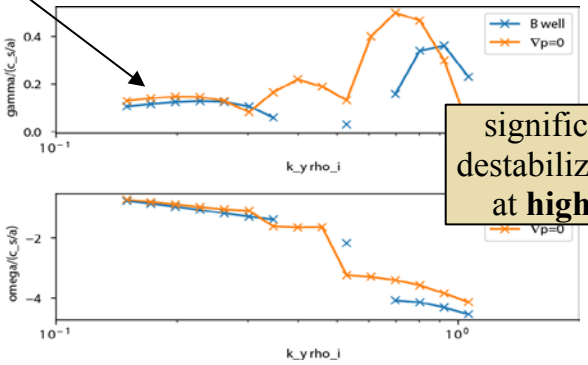
High-k modes fully stabilized at $\beta/4$

High-k modes in |B| well are highly sensitive to ∇p drift terms

all **low-k** show little sensitivity

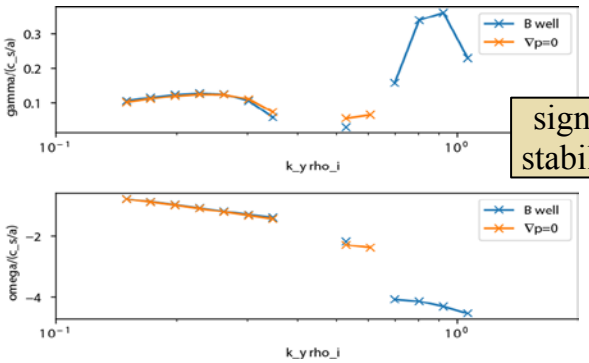
|B| well

∇p in curv. drift



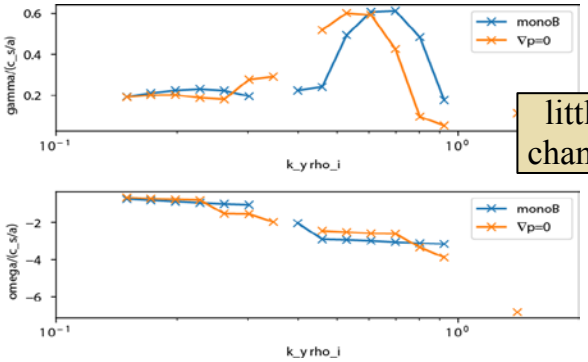
significant destabilization at **high-k**

∇p in ∇B drift

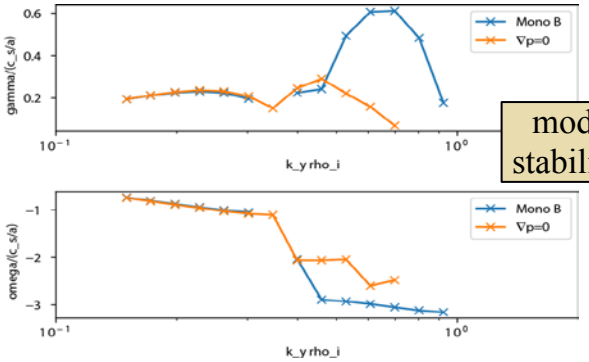


significant stabilization

Monotonic |B|



little change

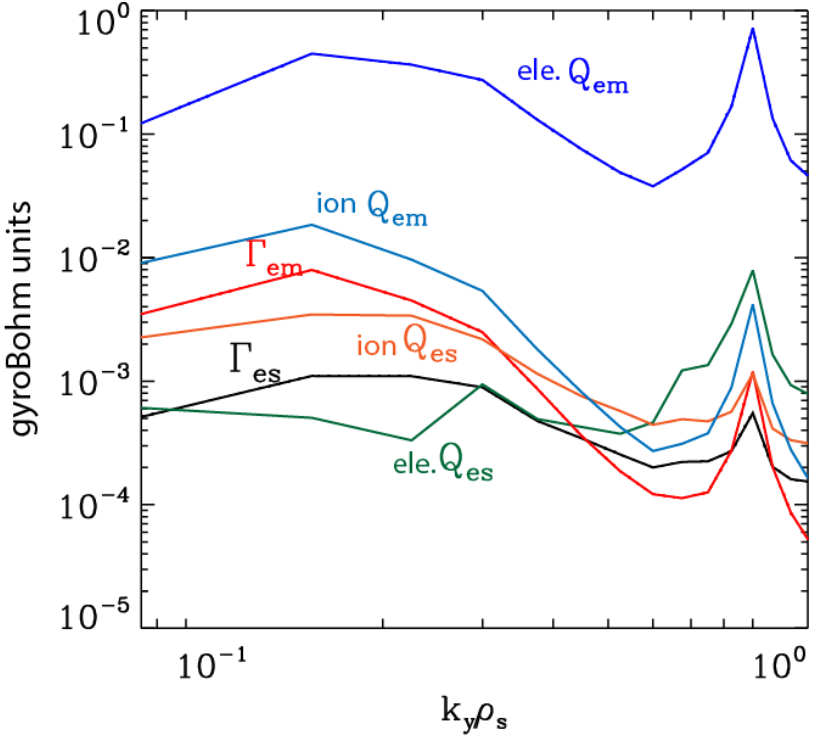


moderate stabilization

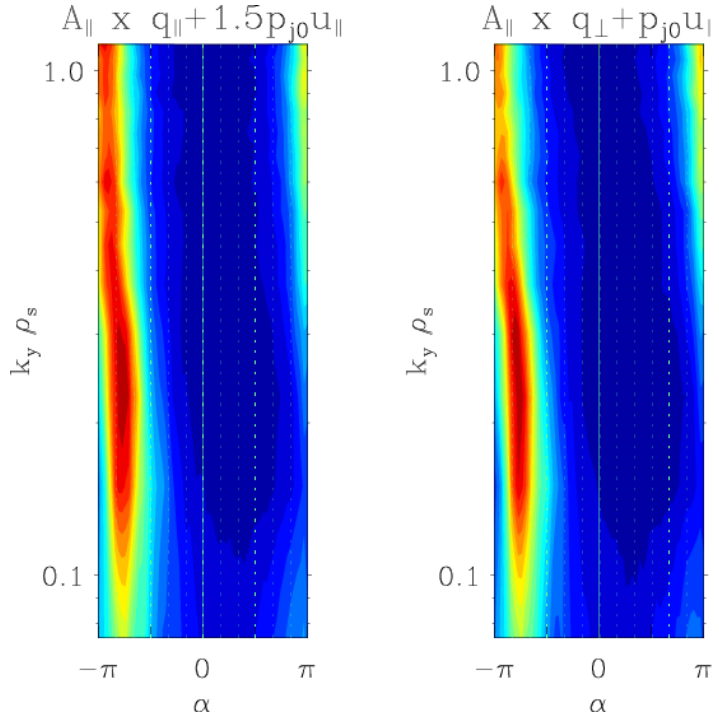
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Preliminary nonlinear simulation of min. |B| regime shows dominant electron electromagnetic thermal transport

Flux spectra



Electron crossphases



plots from GENE diagnostic tool

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Summary

- ST paramagnetism and diamagnetic wells have favorable confinement properties
  - Drift wave stabilization with ∇B reversal in diamagnetic well
  - Reduced neoclassical transport with paramagnetic |B| omnigeneity
- Pegasus $\beta_t \approx 100\%$ regime exhibits diamagnetic well while remaining net-paramagnetic
  - Edge current peaking with HFS local helicity injection
  - D.J. Schlossberg et al., PRL 2017
- Microtearing instabilities in min-|B| region
  - ∇B reversal is stabilizing relative to monotonic |B|
  - $k_y\rho_i \sim 0.7$ modes are highly sensitive to ∇p drift term
  - Low-k modes are strongly suppressed at low β, in contrast to monotonic |B| configuration
  - Dominant electron electromagnetic thermal transport

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