Microtearing instabilities, ∇B reversal, and magnetic drifts in the Pegasus local minimum |B| regime

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PEGASUS
Toroidal Experiment

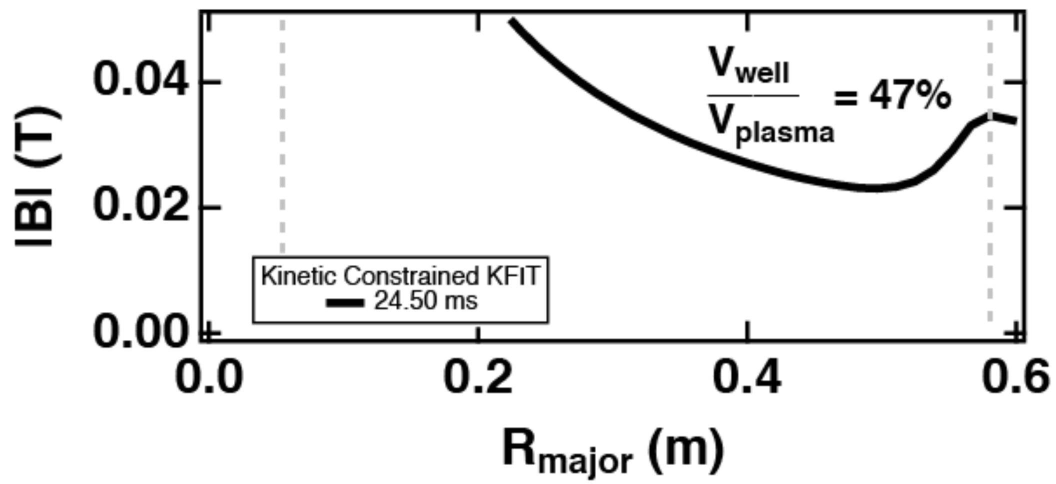
Abstract

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]

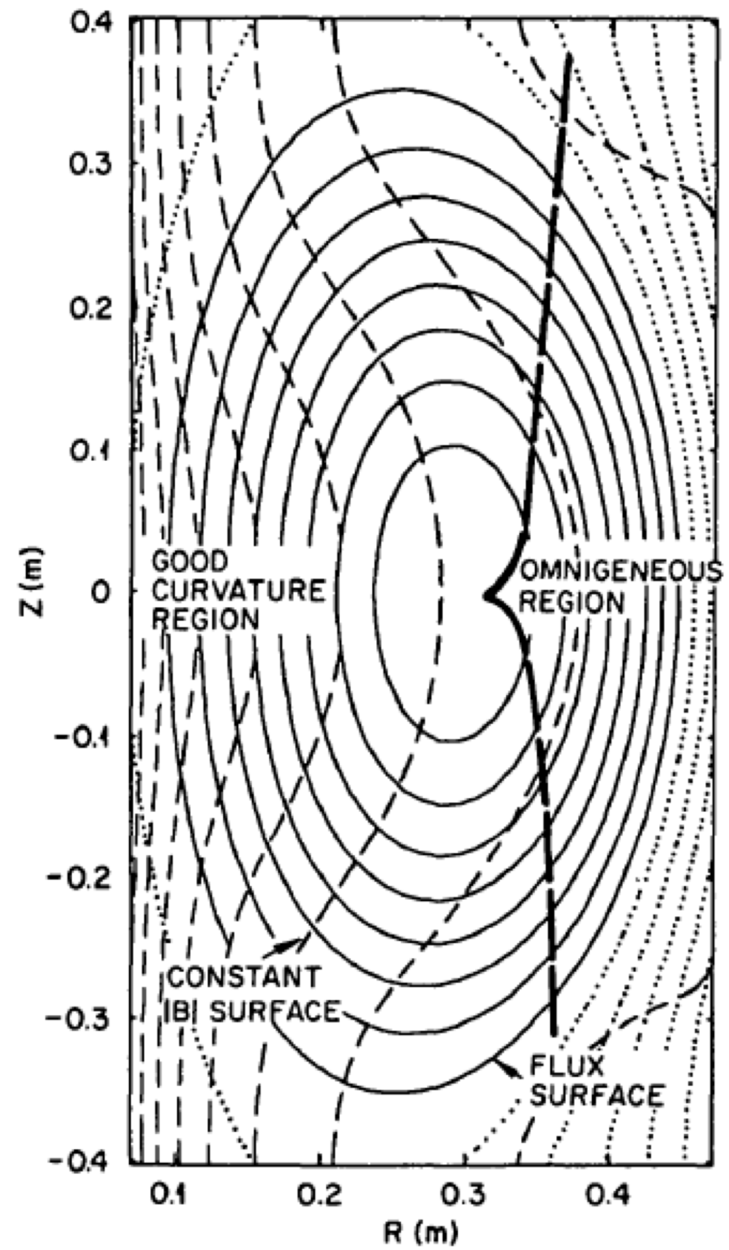


Outline

- 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
  - Initial nonlinear simulation shows dominant electron electromagnetic thermal transport with radially narrow, poloidally elongated $j_{||,e}$ structures
- Summary

Enhanced confinement with ST paramagnetism

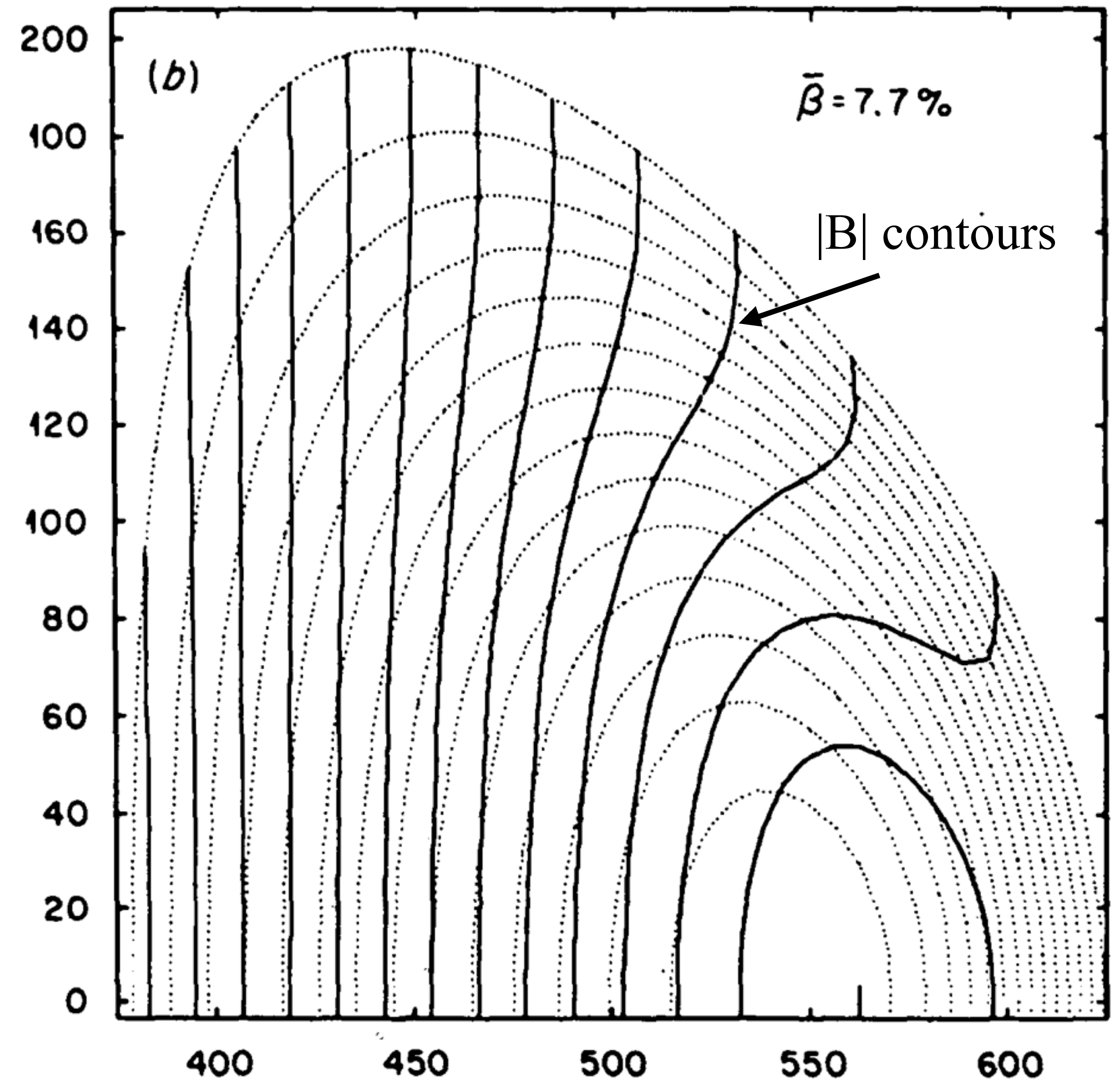
- STs are strongly paramagnetic due to large helical pitch and J_p
  - $\beta_p \sim 0.3$ (< 1 is paramagnetic)
- Omnigeneity in bad curv. region from paramagnetic $|B| \approx |B|(\psi)$
  - **Reduced neoclassical transport** due to vanishing banana orbit width



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.

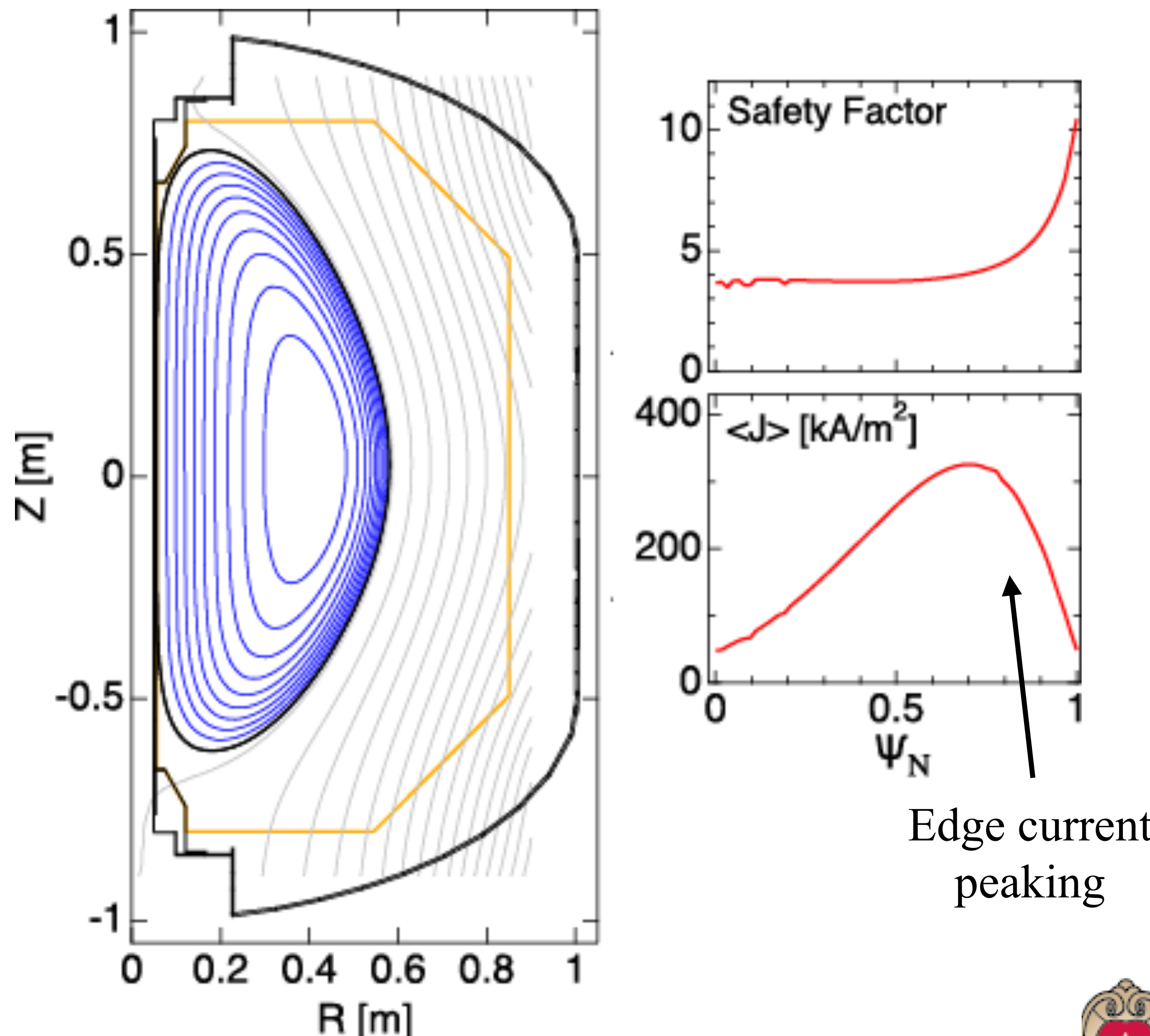
∇B reversal on LFS gives $\mathrm{sgn}(\omega_d) = -\mathrm{sgn}(\omega_{*T})$ and all modes are strictly **stable**

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

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

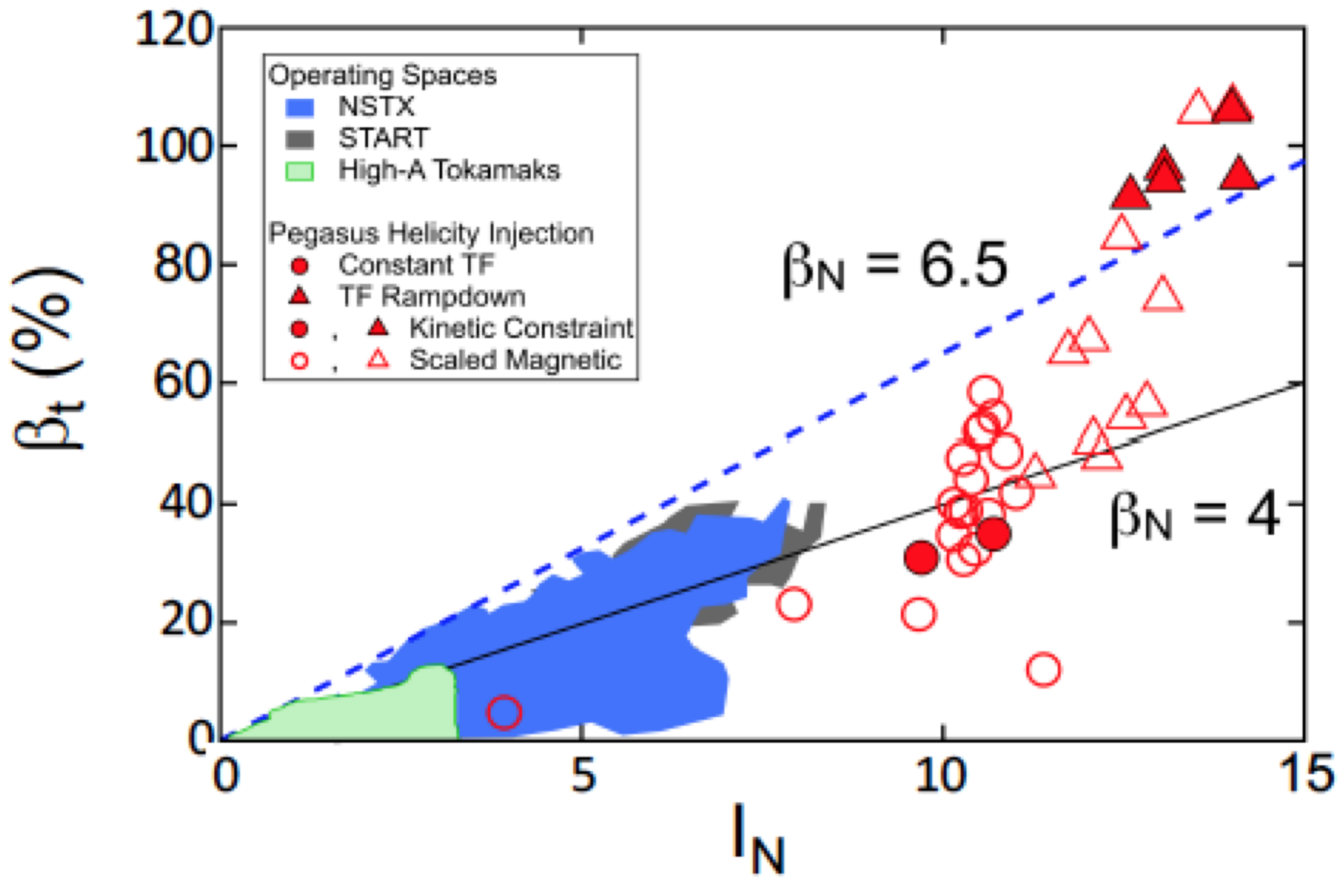
- Enhanced stability at low A (1.21) and high κ (2.6) in Pegasus
- Local helicity injection (LHI) with high field side (HFS) injectors
  - Reconnection ion heating ($T_{i0} > T_{e0}$)
  - Suppression of low-m tearing modes
  - Edge current peaking with low l_i (0.22)
- Kinetic-constrained equilibria

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
  - $I_N \propto I_p/I_{TF}$

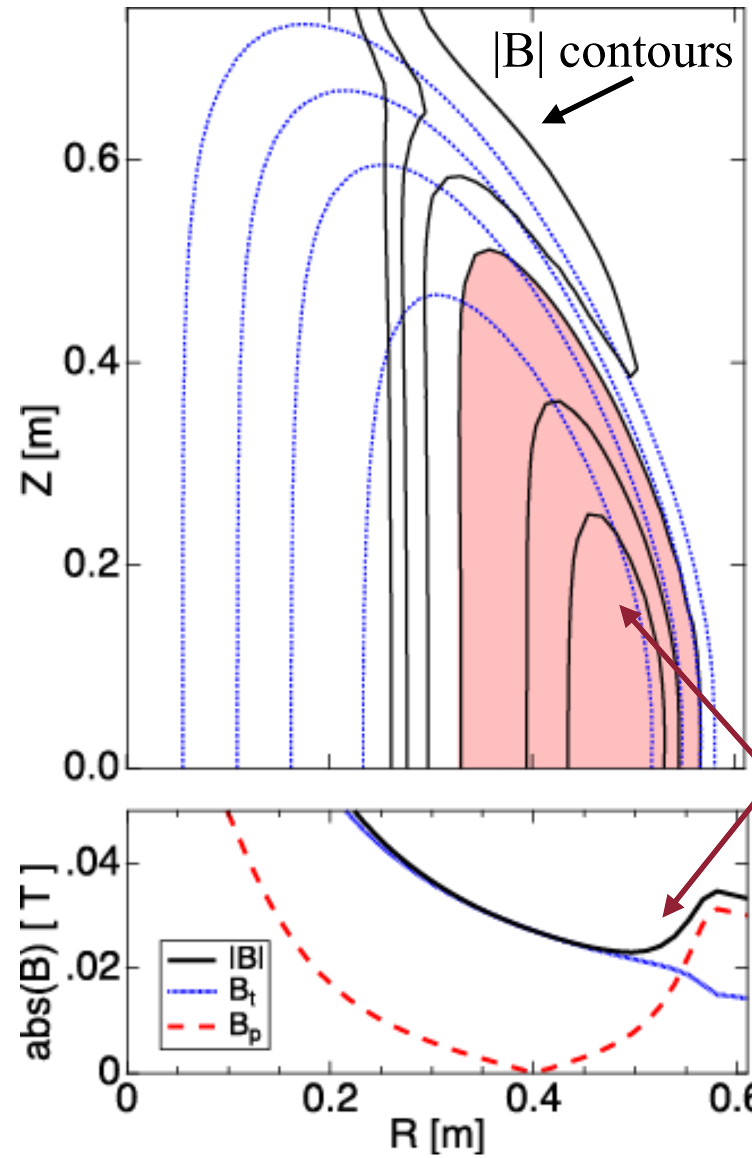


D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

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



Magnetic well

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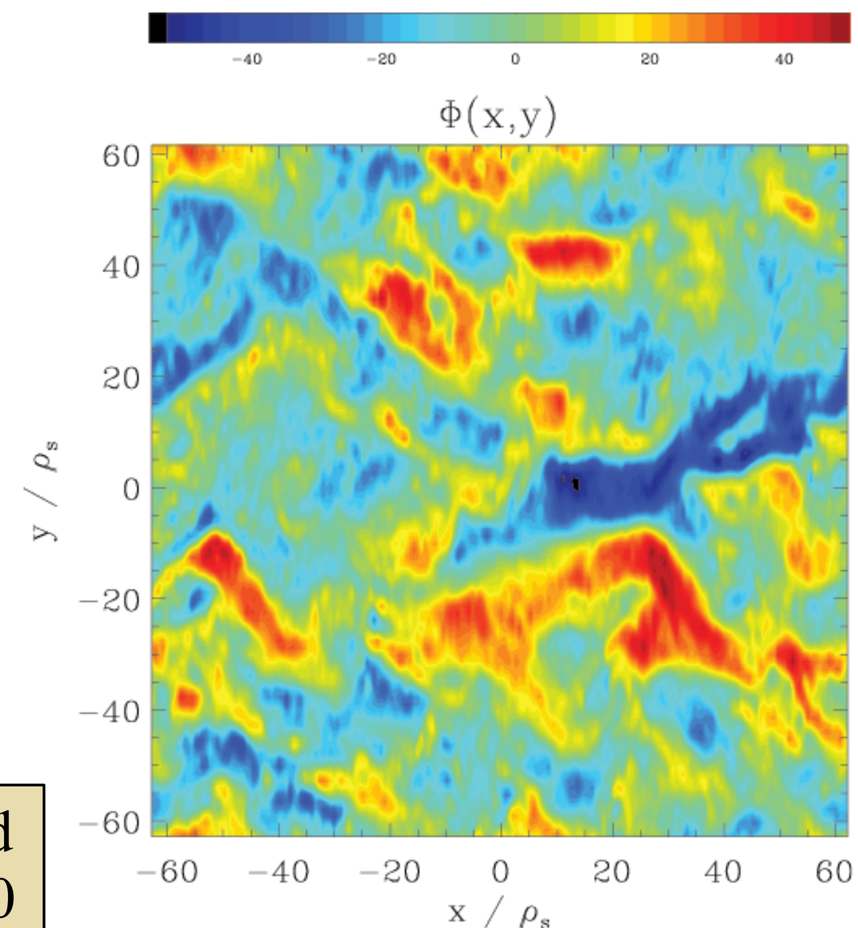
Gyrokinetic simulations with *GENE*

- *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

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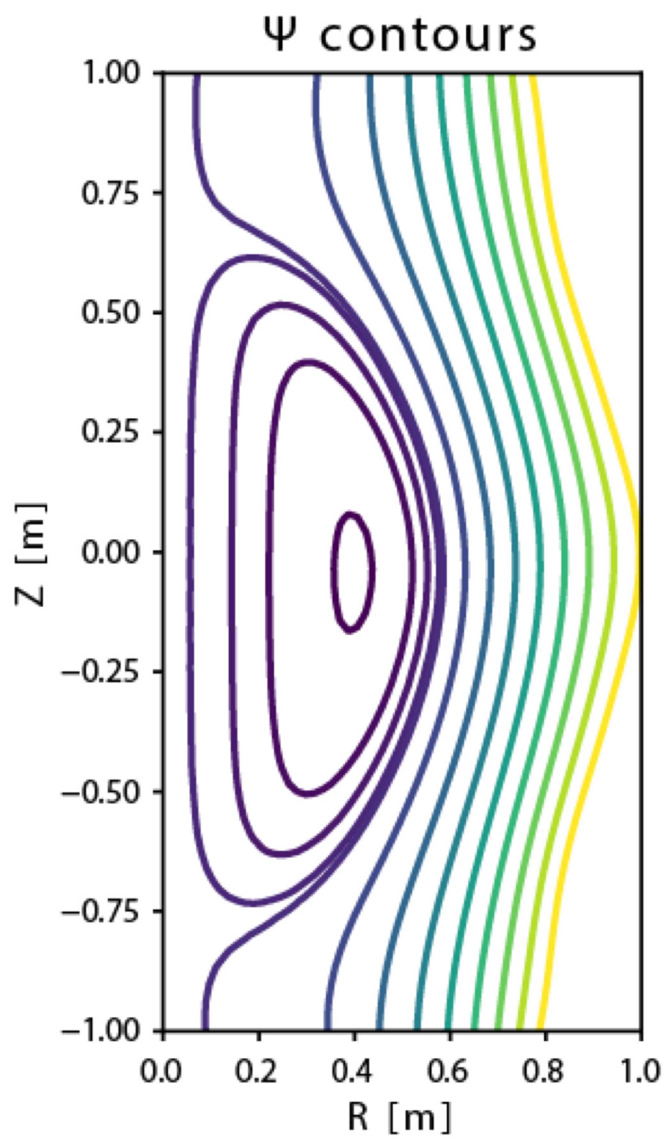
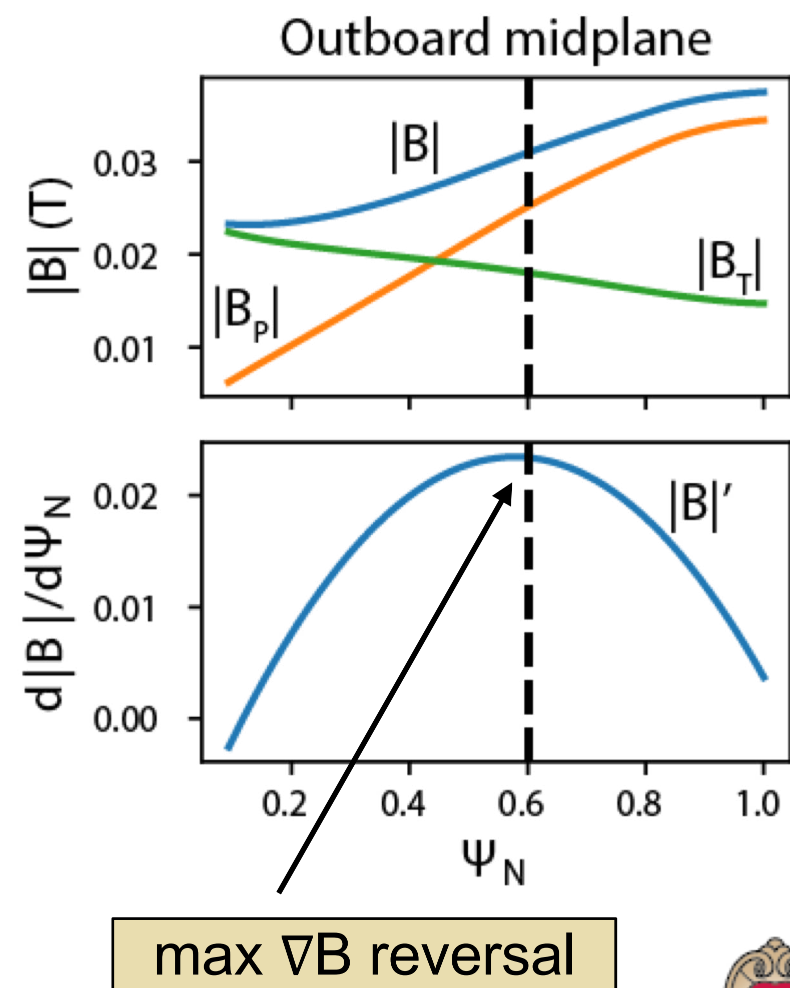
Simulation parameters for Pegasus diamagnetic well

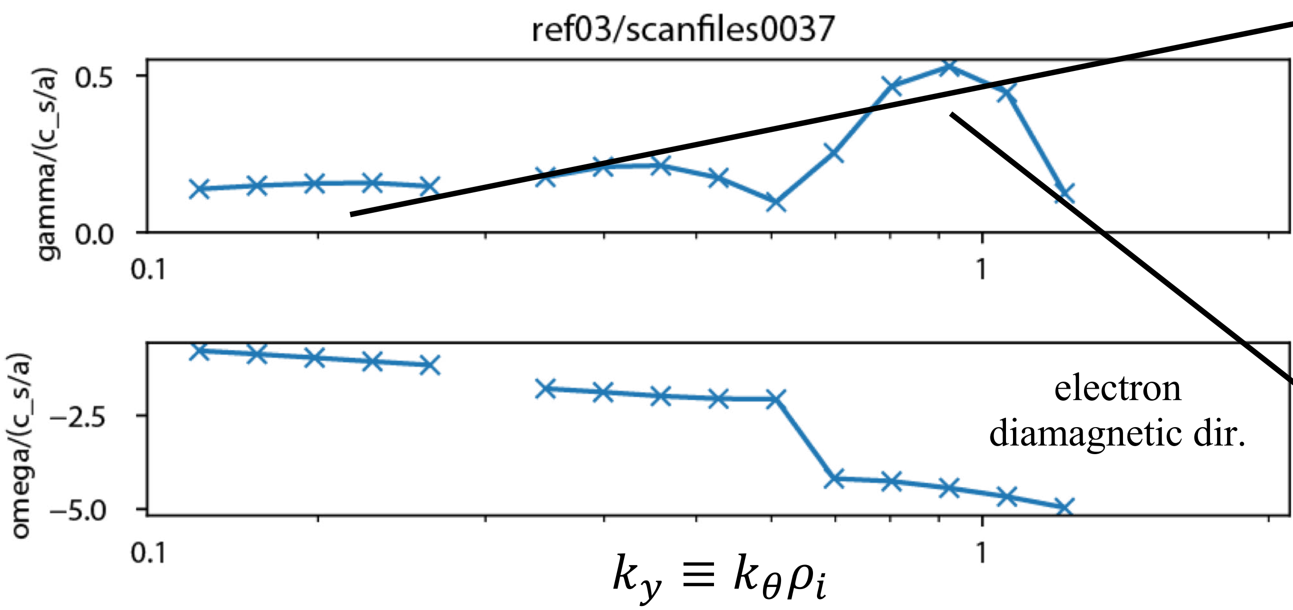
- Flux tube
  - $\Psi_N = 0.6$ @ max ∇B reversal
  - $q = 3.5$ and $\hat{s} = 0.55$
- Physics model
  - ϕ and $A_{||}$ ($B_{||}$=0)
  - $m_e/m_d = 1/400$ (heavy ele.)
  - $\nu_i^* = 0.07$
  - $\beta_e = 27\%$
- Species
  - $a/L_n = 1.9$
  - $a/L_{Ti} = a/L_{Te} = 4.2$
  - $T_e = T_i$

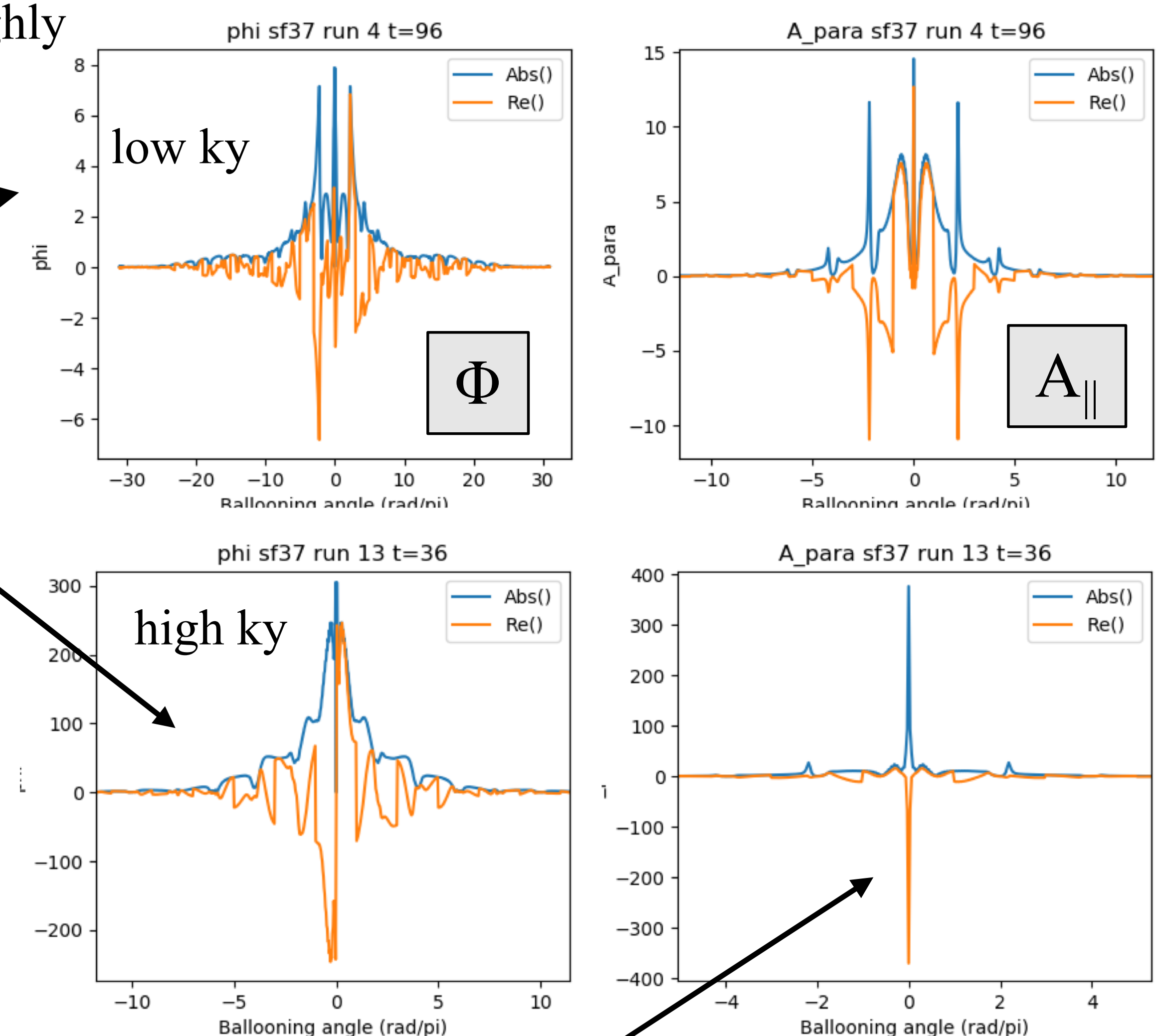




Tearing-parity electron modes in diamagnetic |B| well

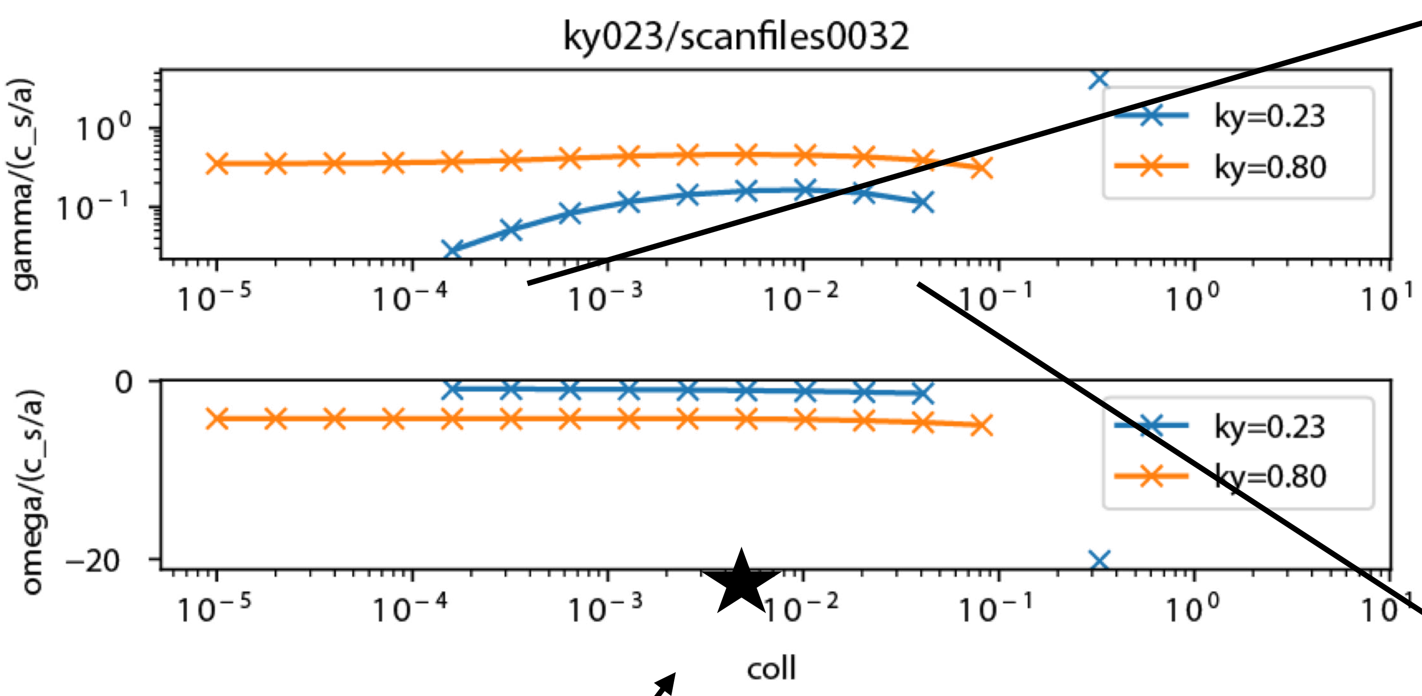
Low ky mode structure is highly extended along fieldline





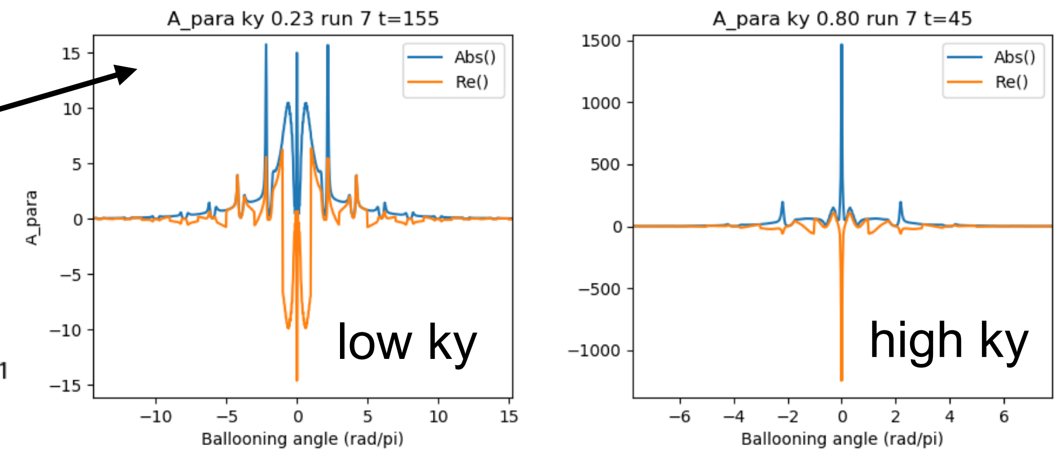
High ky mode structure looks like a “conventional” MTM

Low (high) ky mode is collisional (collisionless)

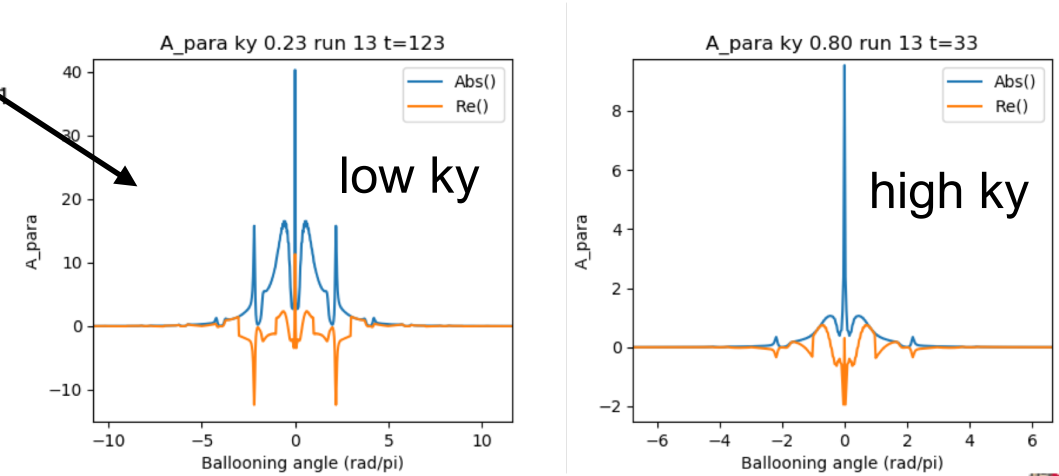


exp't value

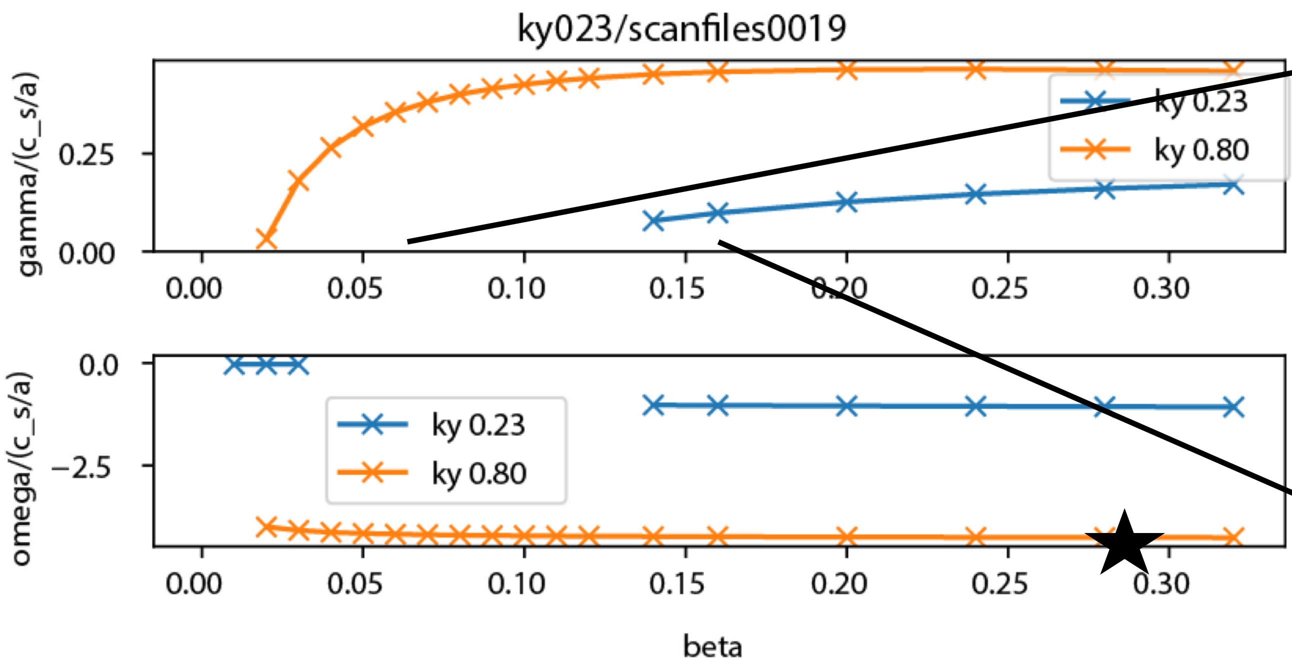
A$_{||}$ mode structures at low coll ~ 6e-4



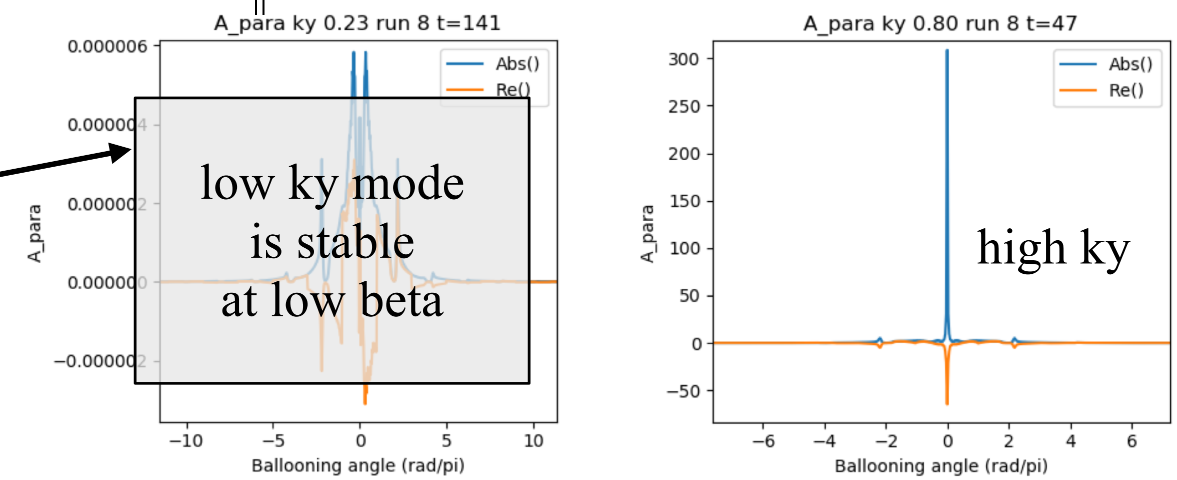
A$_{||}$ mode structures at high coll ~ 4e-2



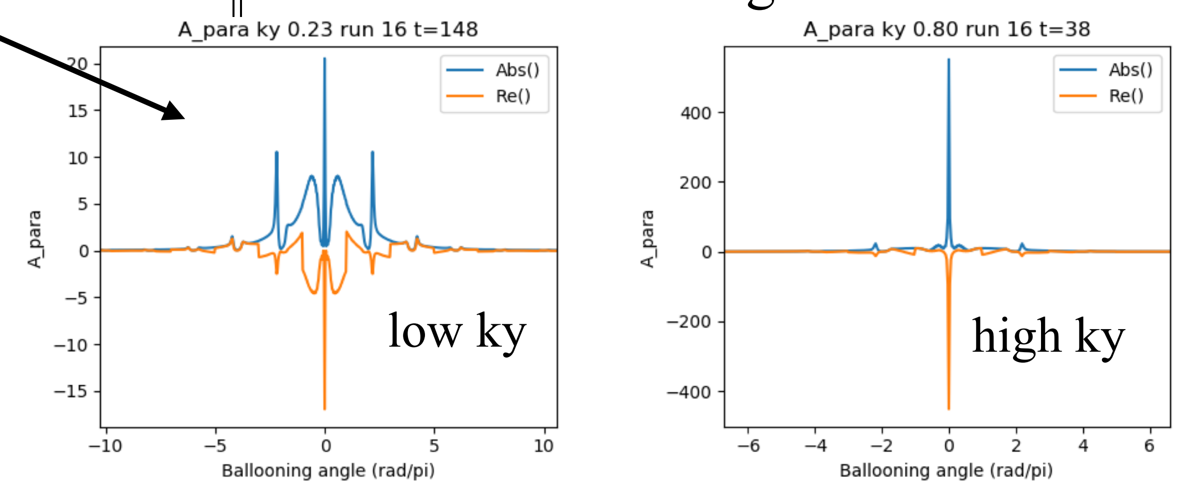
Beta scan reveals distinct critical betas



$A_{\|}$ mode structures at low beta ~ 6%



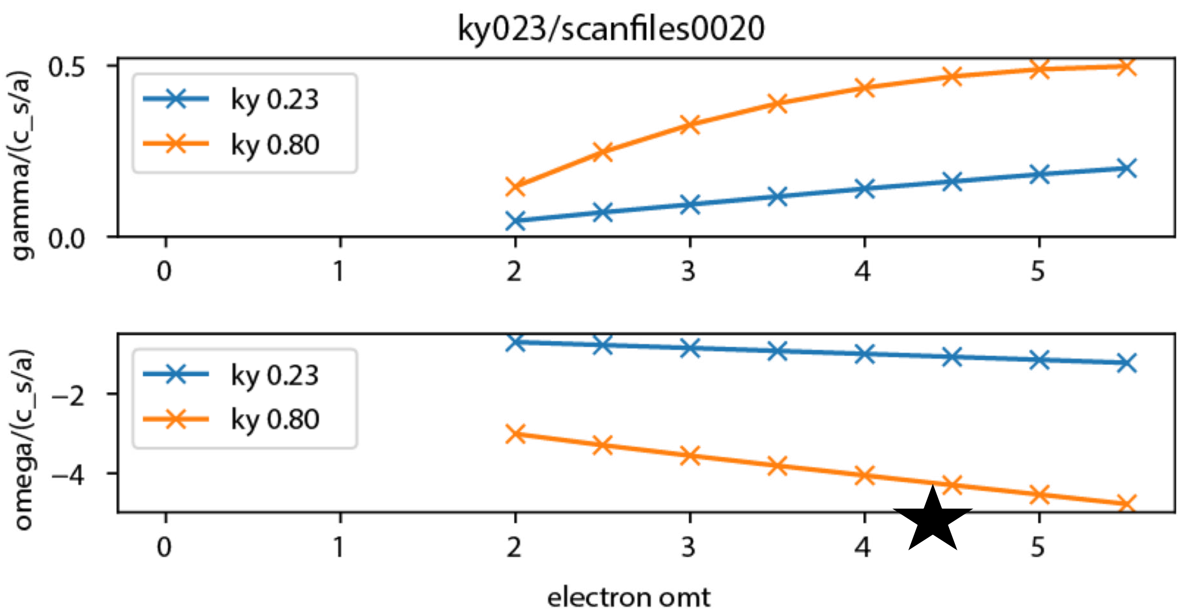
$A_{\|}$ mode structures at high beta ~ 16%



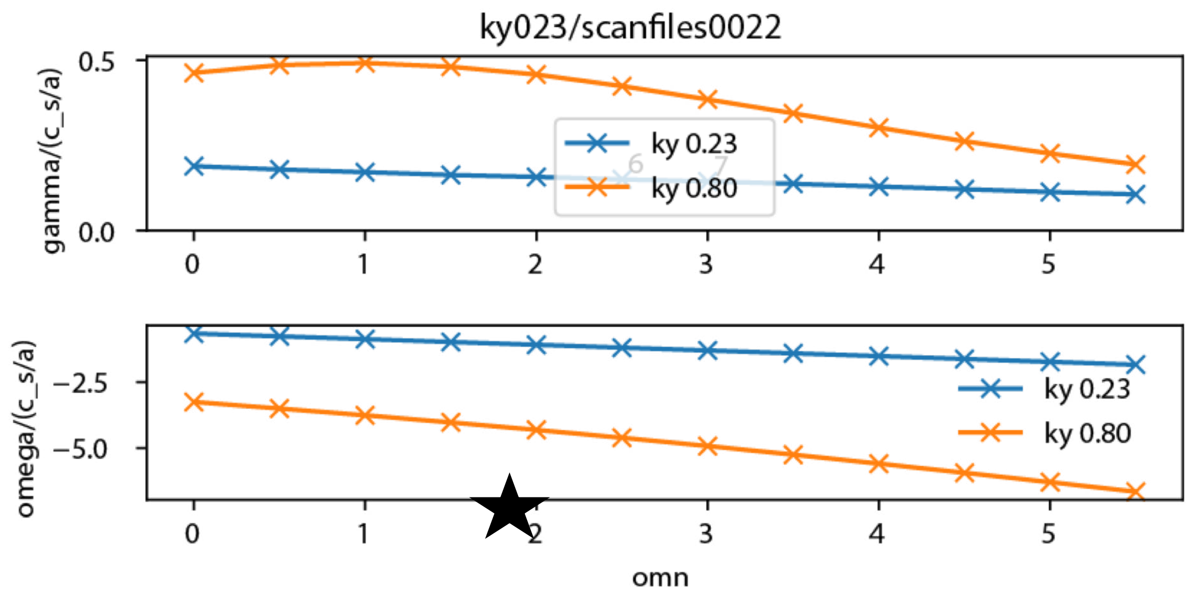
- High ky mode appears to be conventional MTM and shows critical beta ~ 3%
- Low ky mode (unconventional?) shows critical beta ~ 12%

Density and T_e gradient scans consistent with MTM

$d(\ln T_e) / dr$



$d(\ln n) / dr$



Magnetic drifts and pressure term

∇B drift

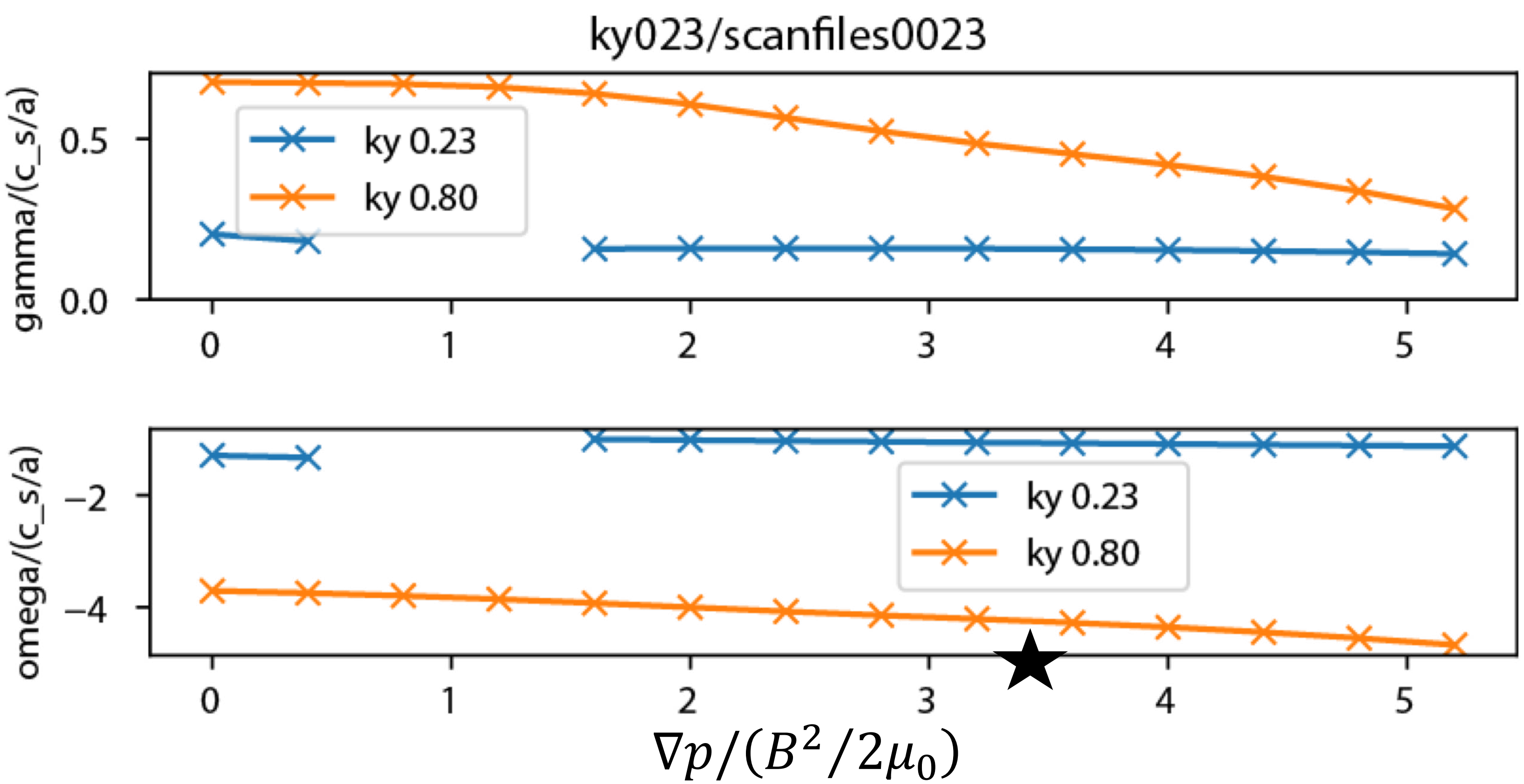
curvature drift

$$\vec{v}_D = \frac{1}{\Omega}\,\hat{b}\times\left[\left(v_{||}^2+\frac{v_\perp^2}{2}\right)\frac{\nabla B}{B}+v_{||}^2\,\frac{\nabla p}{B^2/2\mu_0}\right]$$

∇B reversal in diamagnetic well

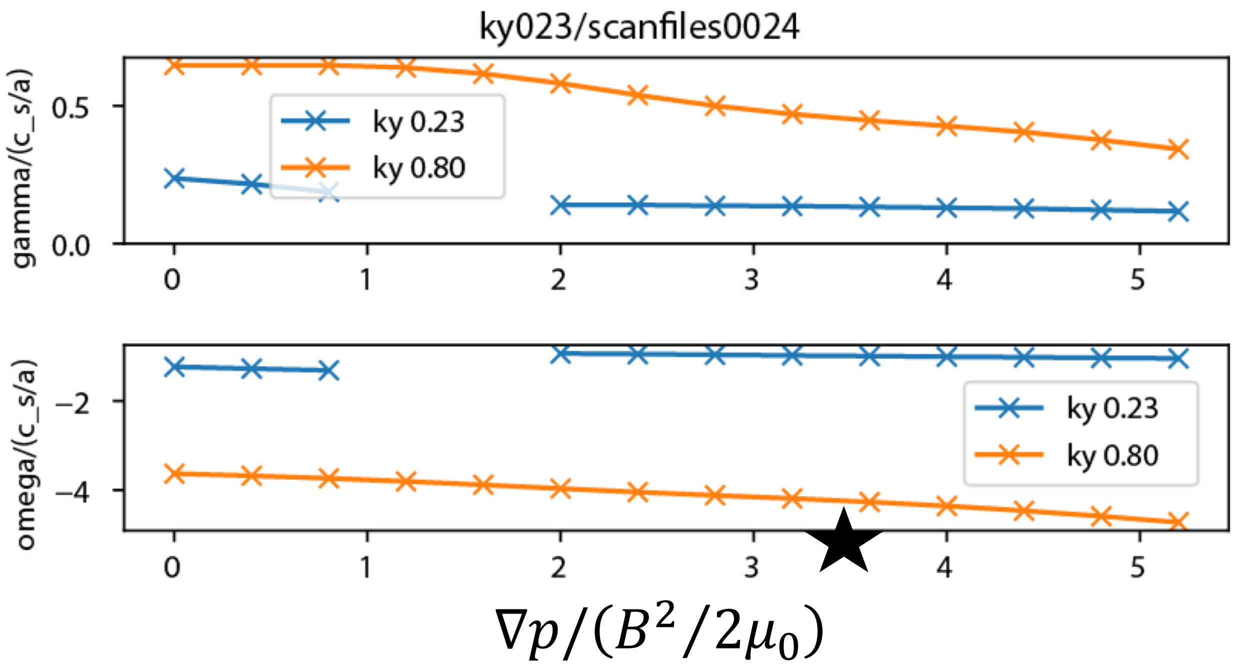
∇p negligible in low-β tokamak but important for high-β ST

Low k_y mode is insensitive to ∇p in magnetic drift

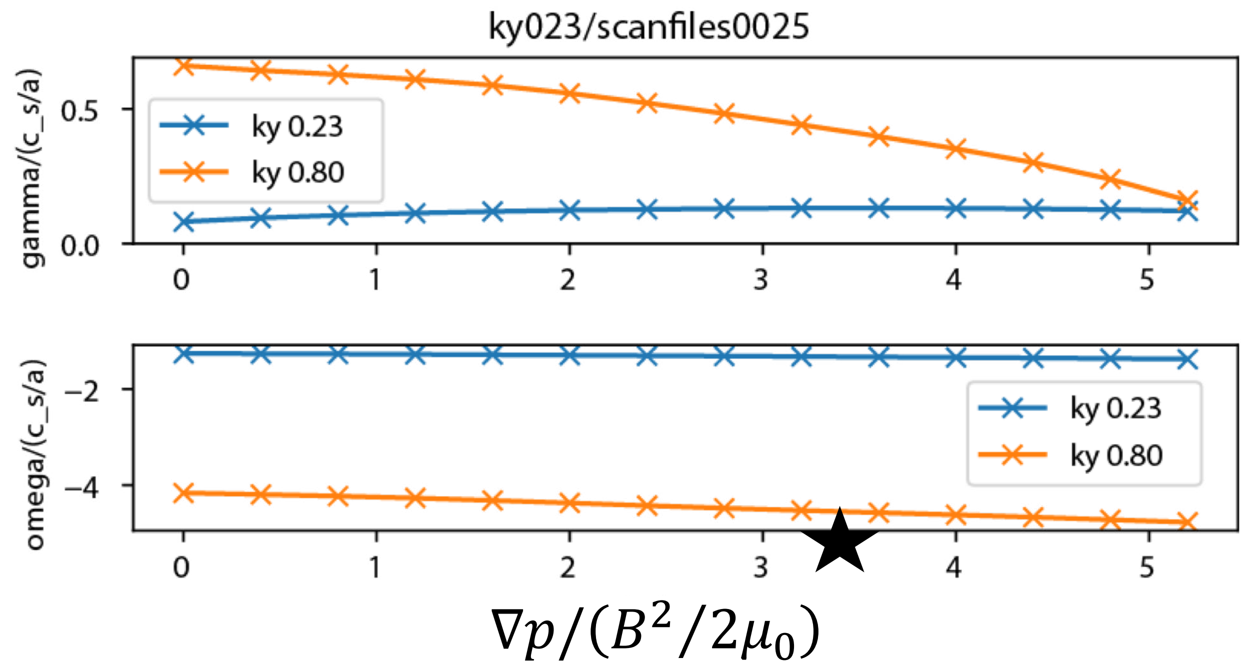


Low k_y mode remains insensitive to ∇p in magnetic drift at high and low collisionality

low coll = 2E-3



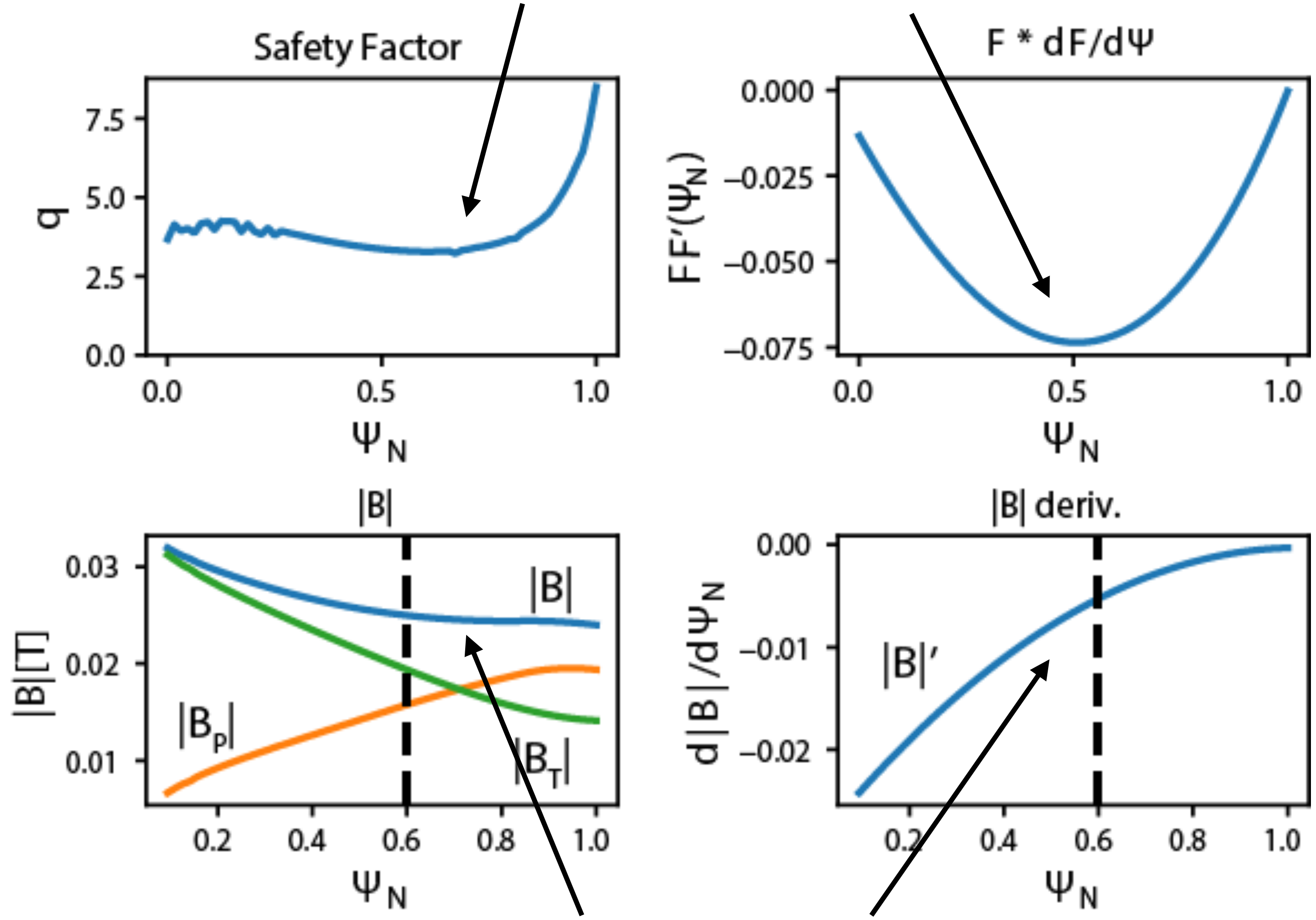
high coll = 3E-2



exp't coll = 4.6E-3

Monotonic |B| equilibrium for comparison to |B| well

Slight RS and less edge current

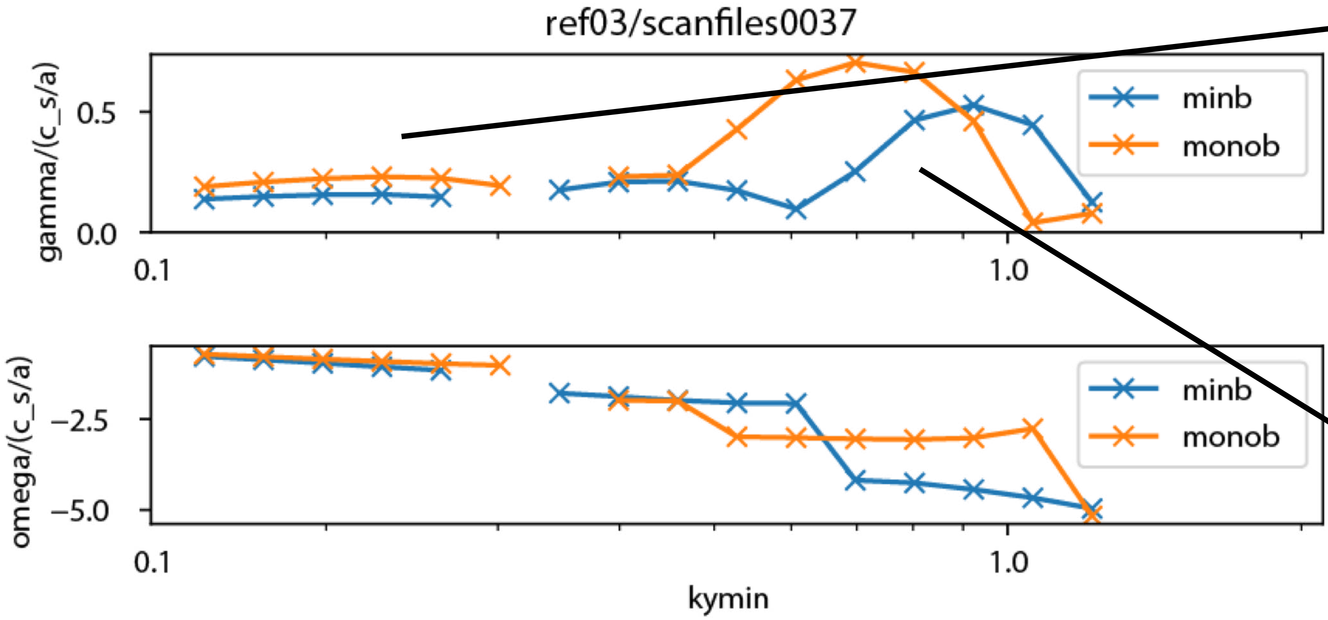


Monotonic |B| and |B|′<0

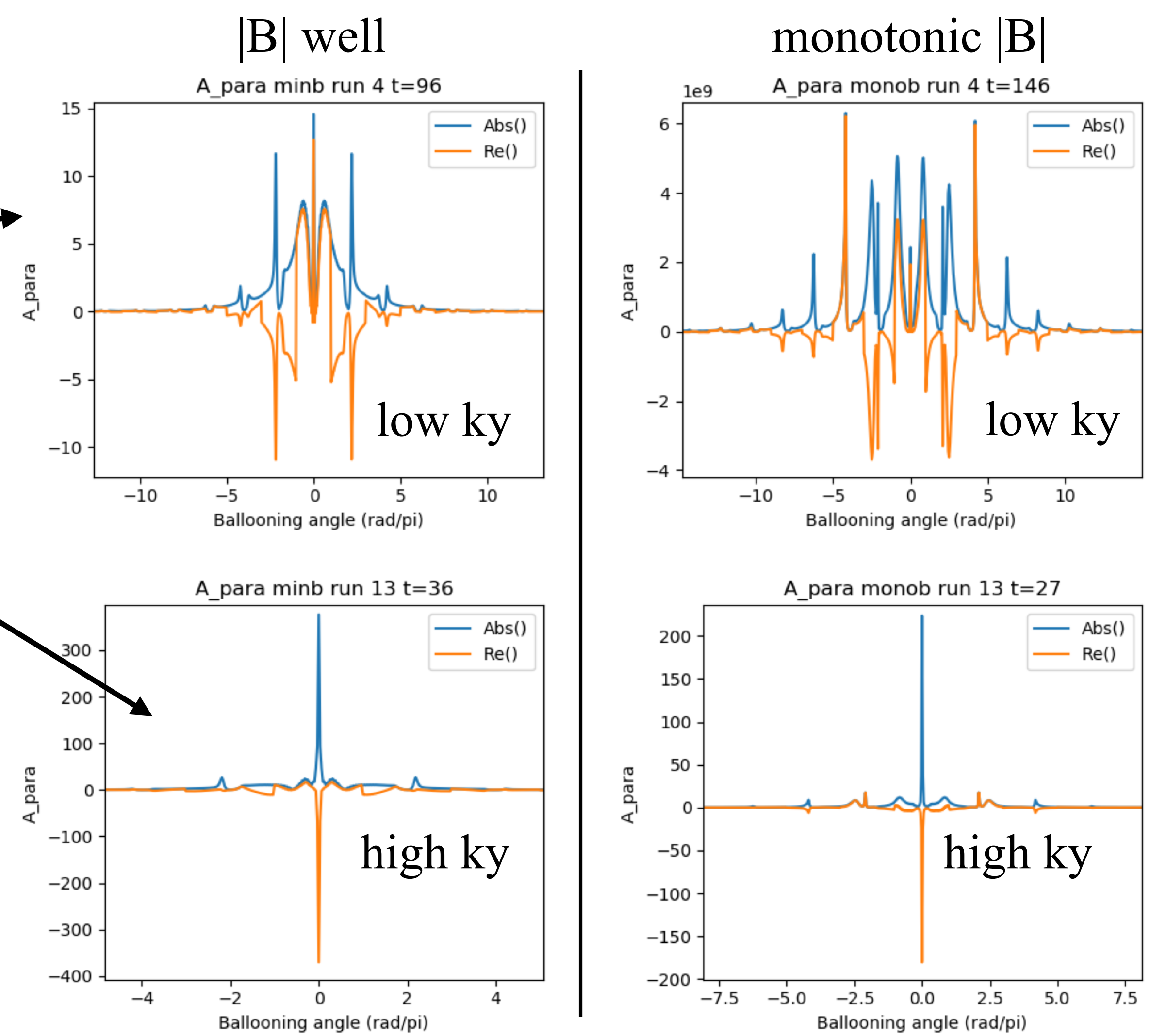
Compare to pgs 7 & 11

Instabilities are modestly stabilized with |B| well relative to monotonic |B|

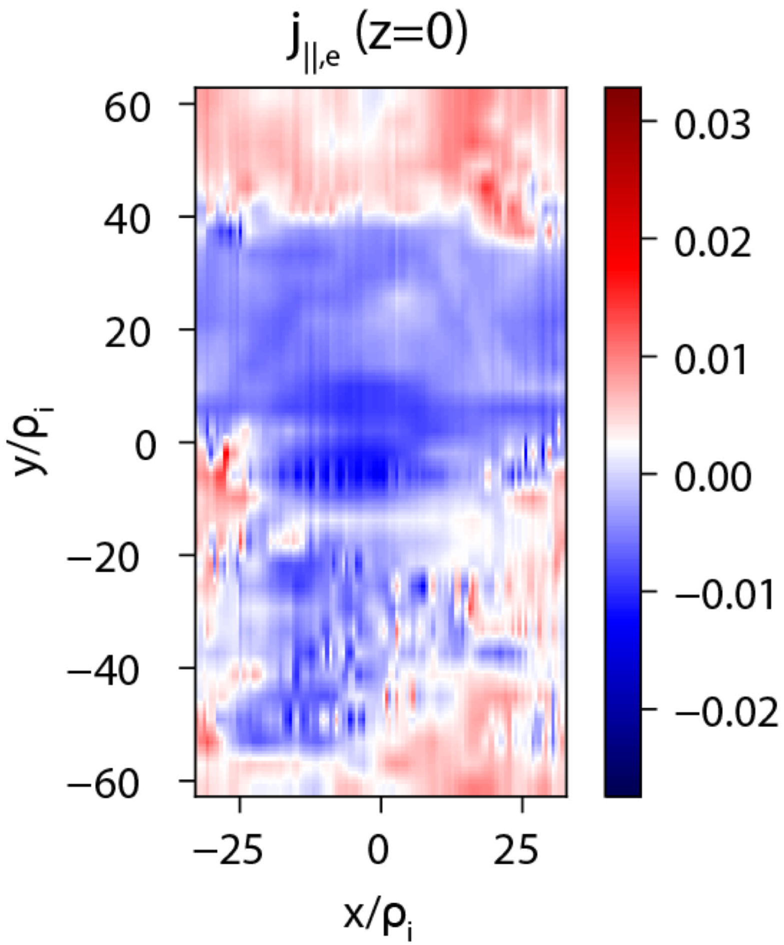
High k_y modes shift to higher k_y in |B| well, but parallel mode structures are largely preserved

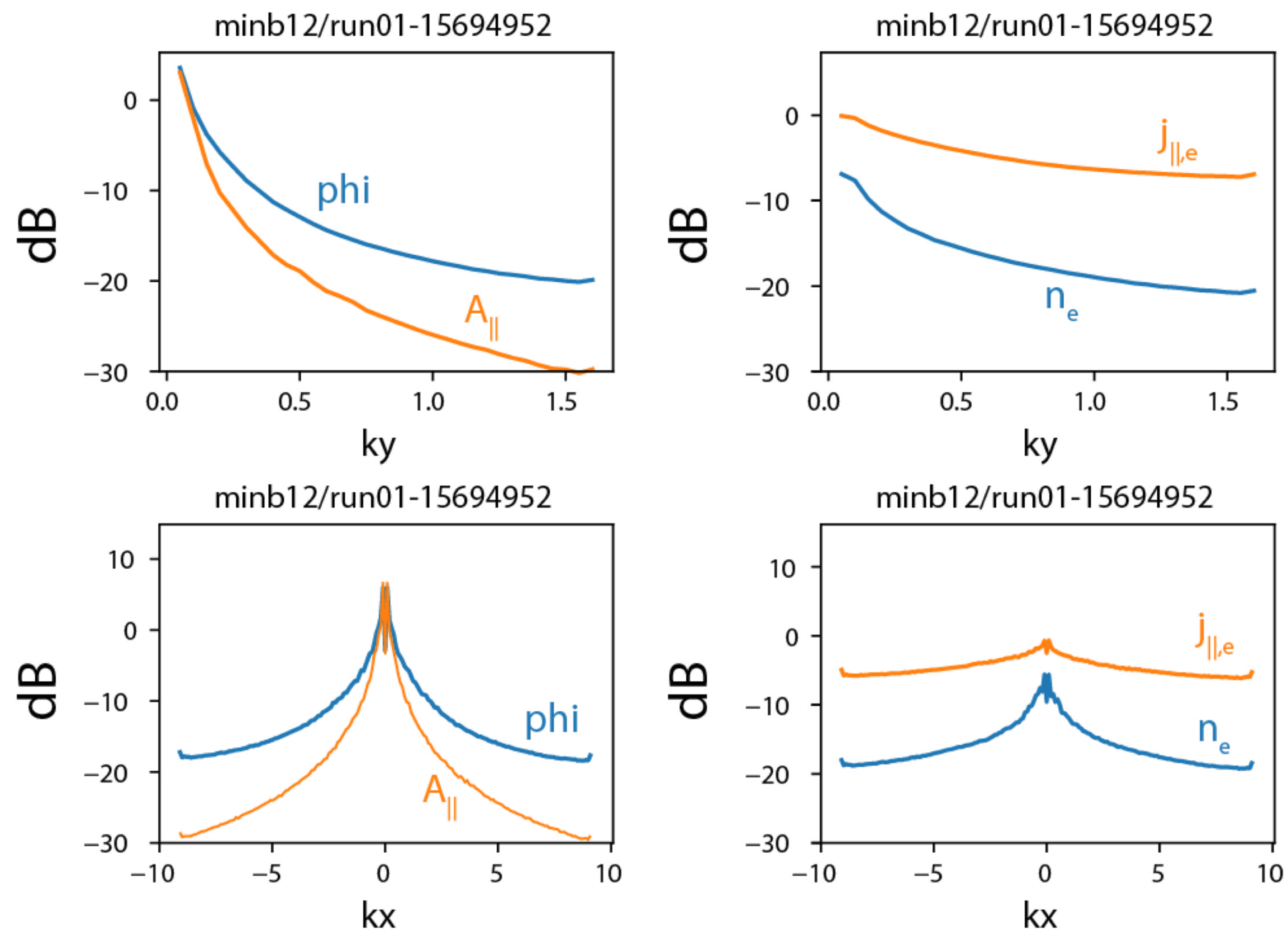


$A_{||}$ mode structures



Initial nonlinear simulation shows dominant electron EM heat transport and radially narrow, poloidally elongated $j_{||,e}$ structures





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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
- Tearing parity instabilities at k_y ~ 0.1-1.2 in Pegasus diamagnetic well
  - High k_y modes appear to be conventional microtearing mode
  - Low k_y modes are not conventional microtearing modes
    - Extended $A_{||}$ mode structure
    - Collisionless with high $\beta_{crit} \approx 12\%$
    - Insensitive to ∇p in magnetic drift
    - Initial nonlinear simulation shows dominant electron EM heat transport and radially narrow, poloidally elongated $j_{||,e}$ structures