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

David R. Smith[1], M. W. Bongard[1], R. J. Fonck[1], W. Guttenfelder[2], G. R. McKee[1], M. J. Pueschel[3], J. A. Reusch[1], P. Terry[1], and Z. Williams[1]

[1] *U. Wisconsin-Madison*
[2] *PPPL*
[3] *U. Texas-Austin*

University of Wisconsin-Madison

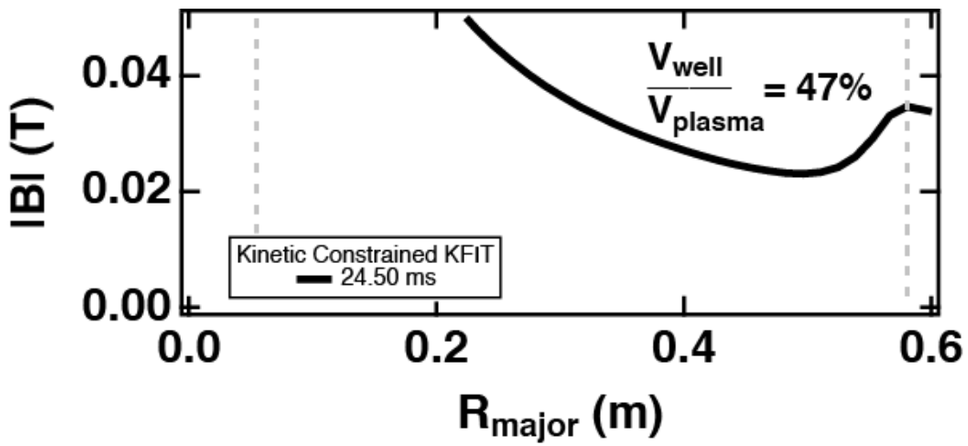
24th Joint US-EU Transport Task Force Meeting
Austin, TX
March 18-21, 2019

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].

Magnetic well from
Pegasus equilibrium reconstruction [1]



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

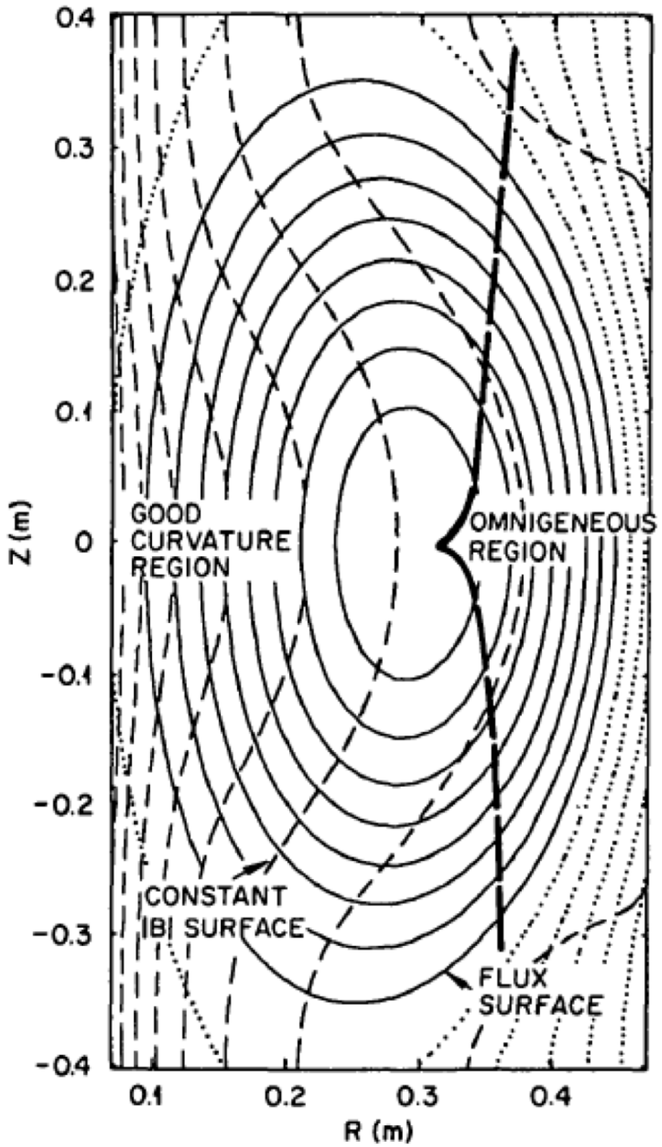
[2] F. Jenko and the GENE Development Team,
http://genecode.org/

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

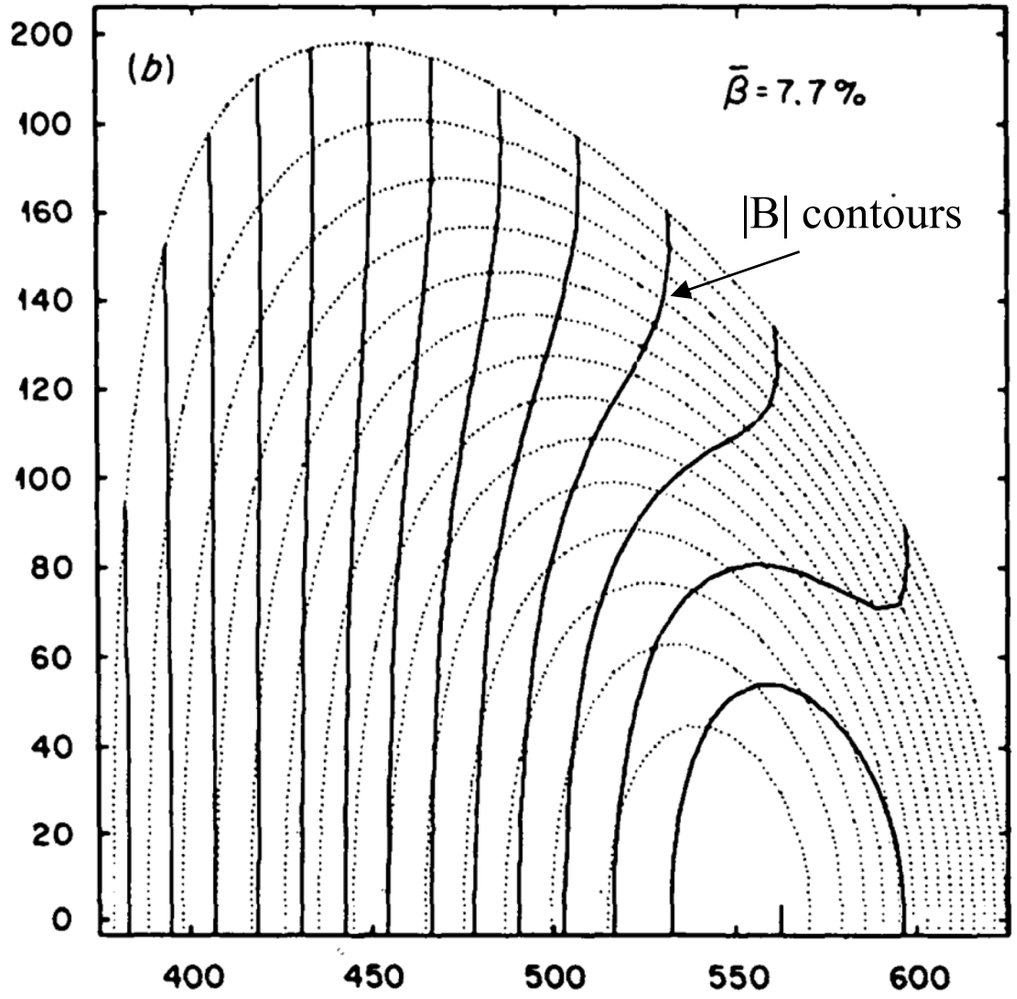


Y-K. M. Peng and D. Strickler, NF 1986

THE UNIVERSITY of WISCONSIN MADISON

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

THE UNIVERSITY of WISCONSIN MADISON

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 ITG modes are **stable**

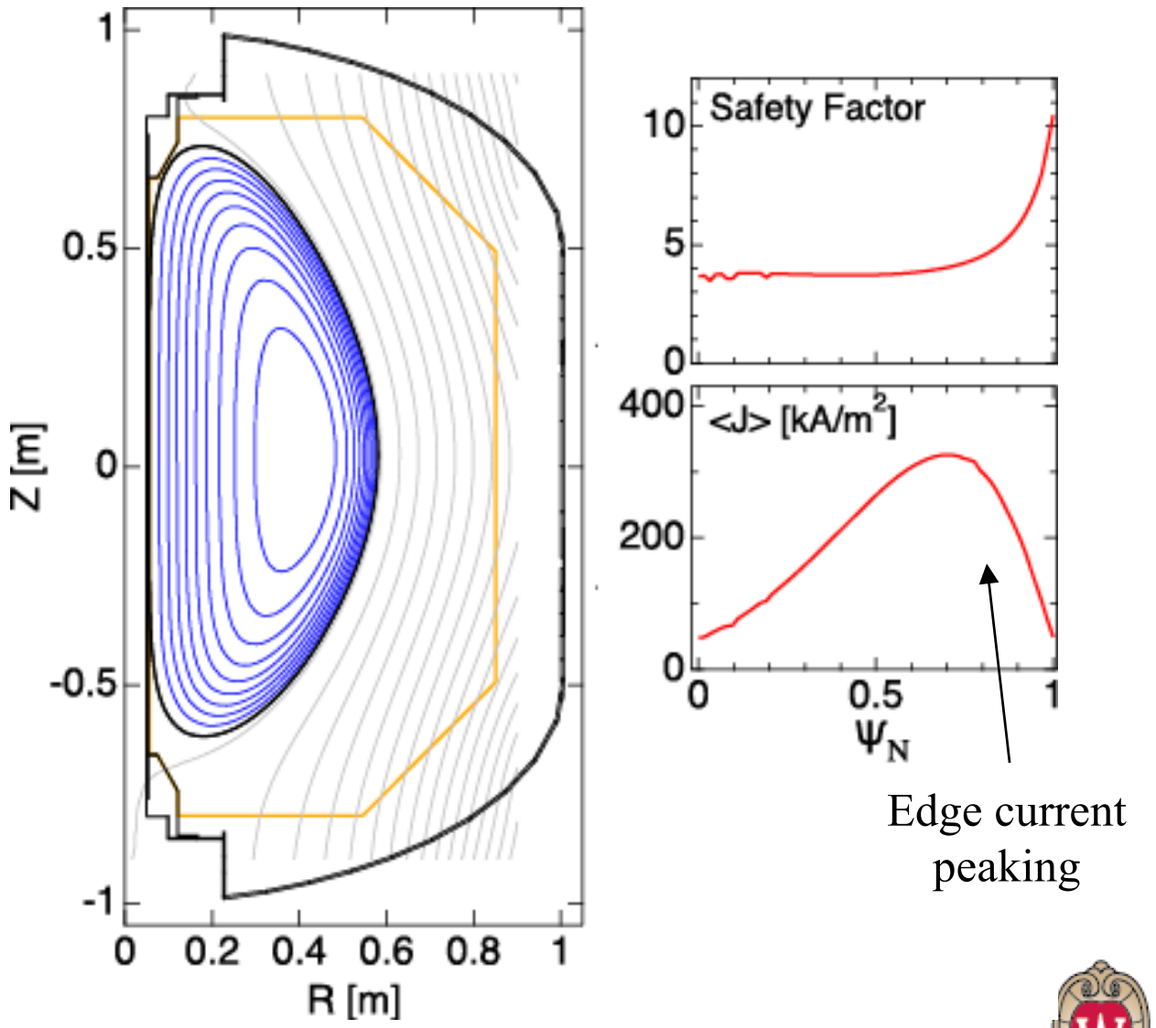
* neglect $k_\parallel$, assume $\omega \gg \omega_d$, and let $\nabla n \to 0$

THE UNIVERSITY of WISCONSIN MADISON

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

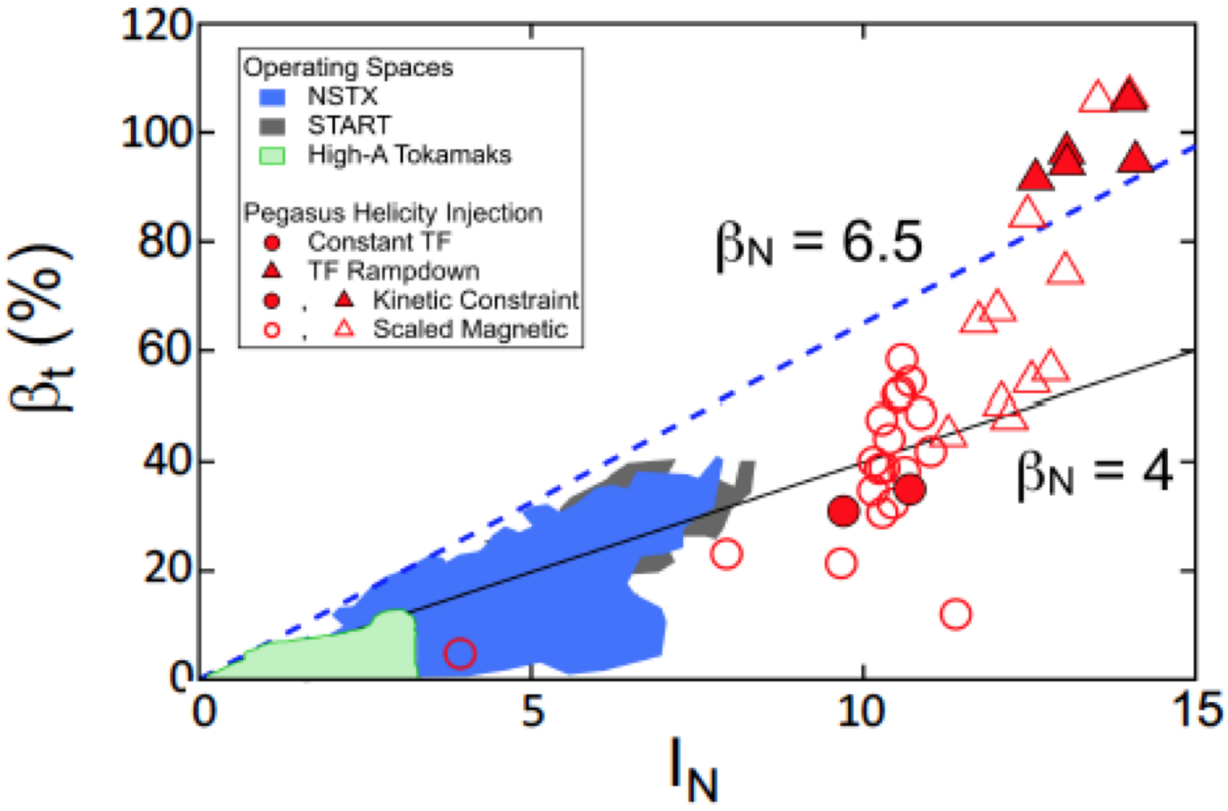
- Enhanced stability at low A (1.21) and high κ (2.6) in Pegasus
- Local helicity injection (LHI) with high field side (HFS) injectors
  - Reconnection ion heating ($T_{i0} > T_{e0}$)
  - Suppression of low-n tearing modes
  - Edge current peaking with low l_i (0.22)
- Kinetic-constrained equilibria

J. Reusch et al., PoP 25, 056101 (2018)



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

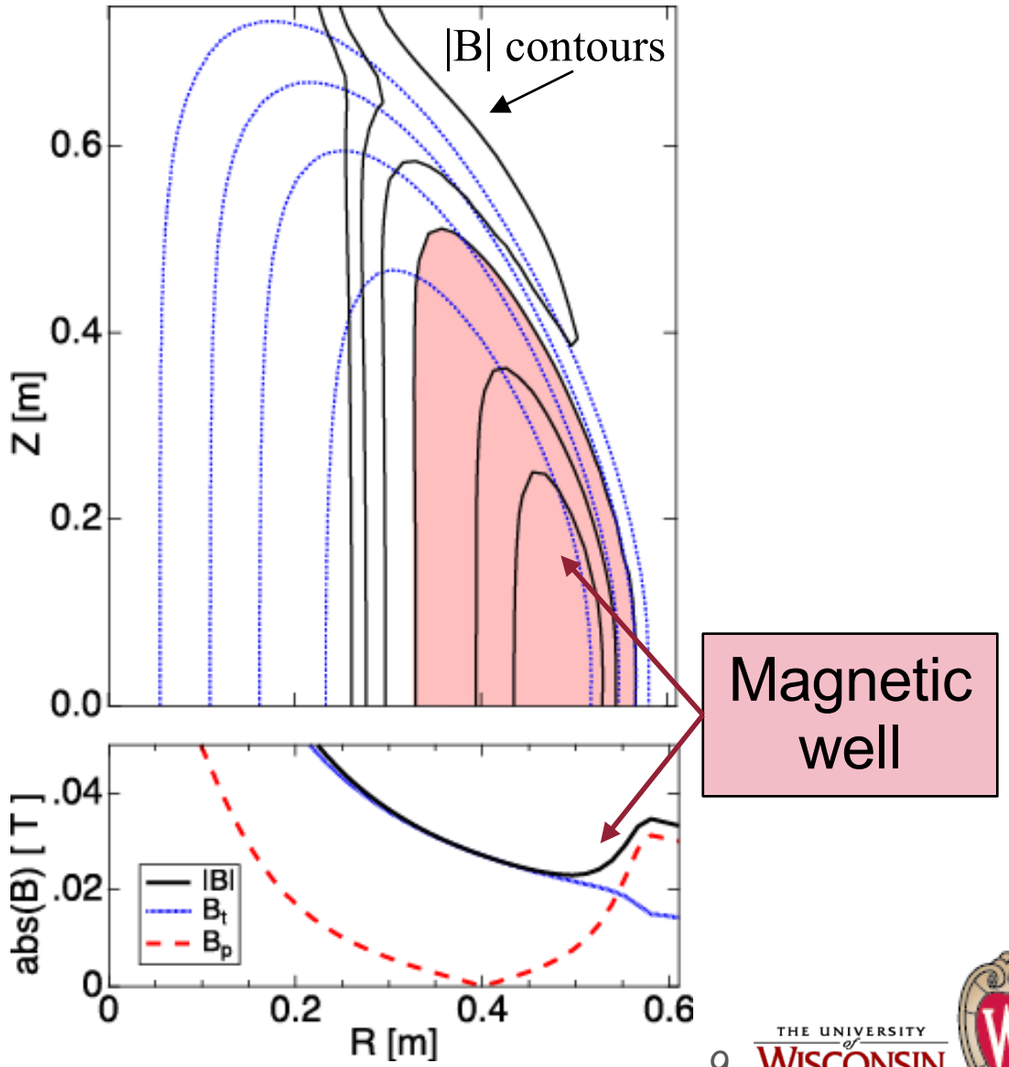
- Sykes-Troyon scaling
  - $\beta_{t,max} \propto aI_p/B_{t0}$
  - Normalized current: $I_N \equiv aI_p/B_{t0}$
  - Normalized beta: $\beta_N \equiv \beta_{t,max}/I_N$
    - Higher β_N accessible at lower A and/or higher κ
- I_{TF} ramp-down to access high I_N
  - $I_N \propto I_p/I_{TF}$



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 and/or lower B_t

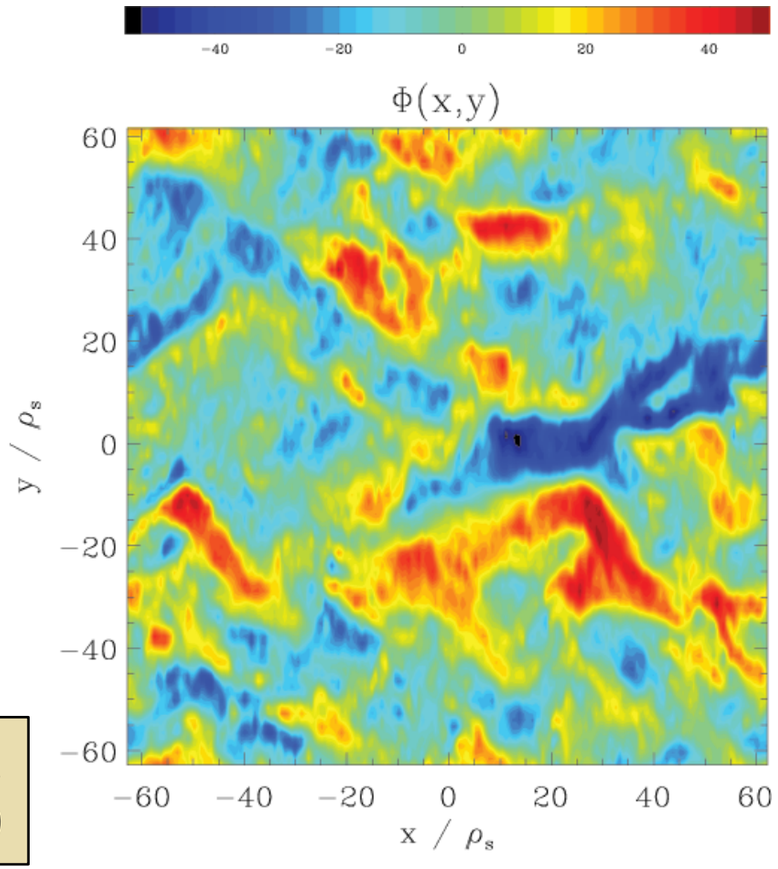


D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

Gyrokinetic simulations with *GENE*

- *GENE* evolves gyrokinetic equations in 5-dimensional phase space
  - Electromagnetic with $A_{\|}$ (and $B_{\|}$ 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

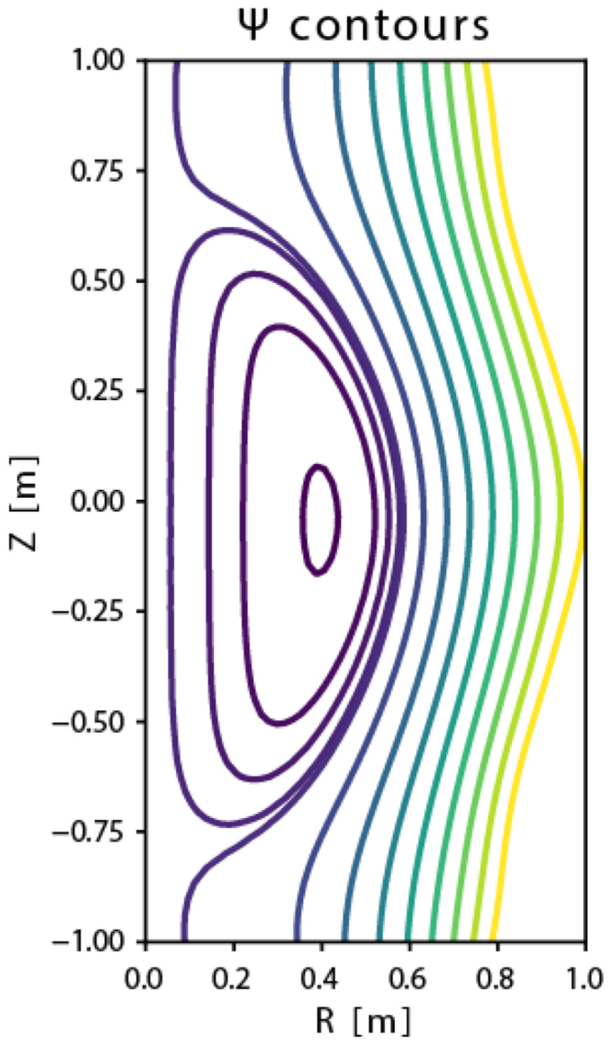


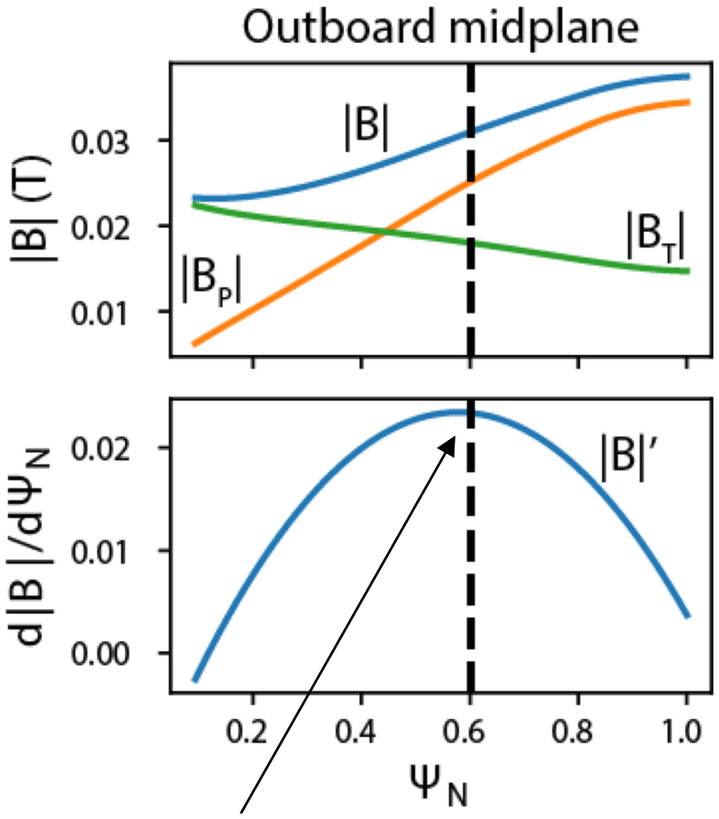
M. J. Pueschel and F. Jenko, PoP 2010

THE UNIVERSITY of WISCONSIN MADISON

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
  - $a/L_n = 1.9$
  - $a/L_{Ti} = a/L_{Te} = 4.2$
  - $T_e = T_i$



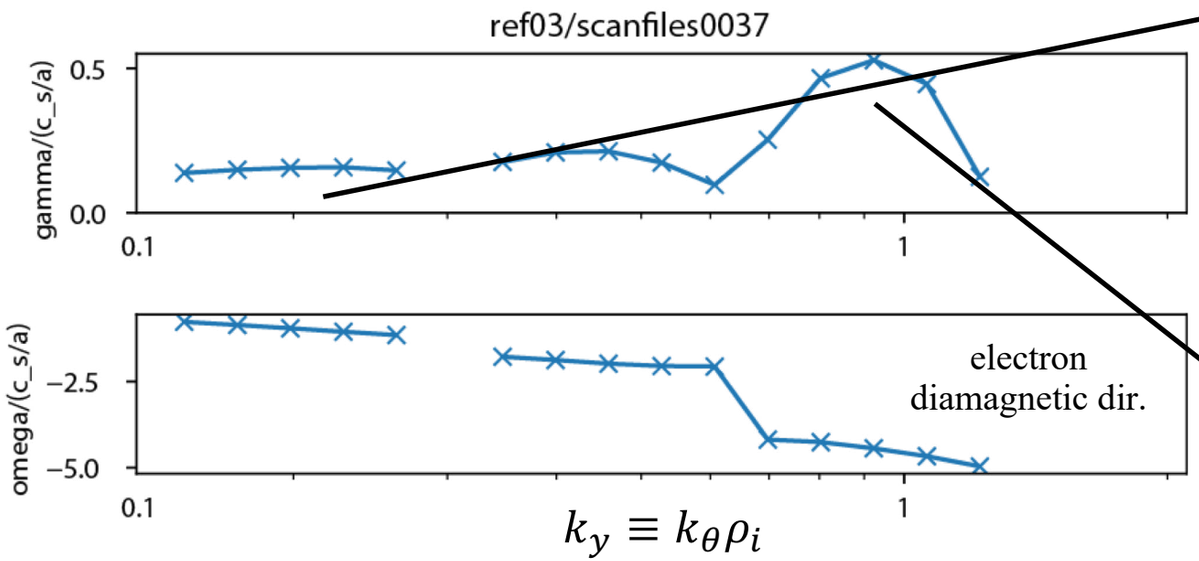


max ∇B reversal

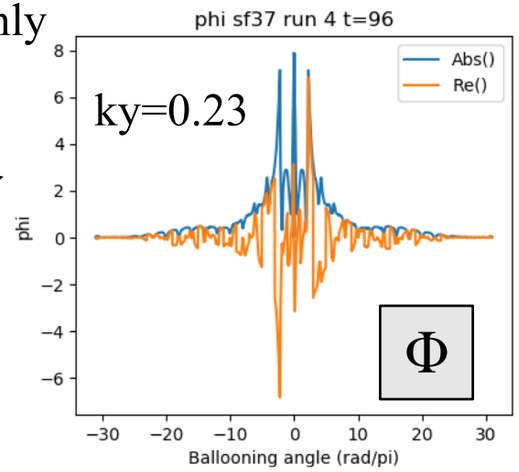
THE UNIVERSITY of WISCONSIN MADISON

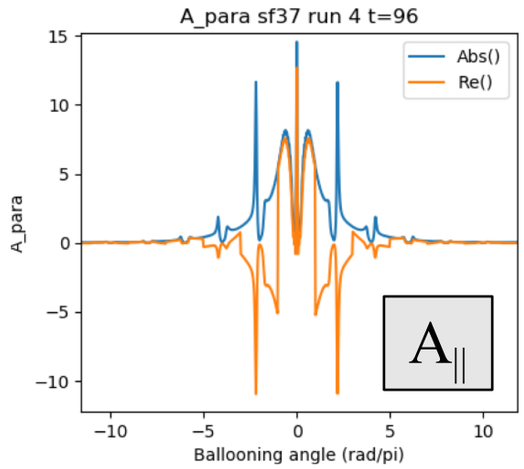
Tearing-parity electron modes in diamagnetic |B| well

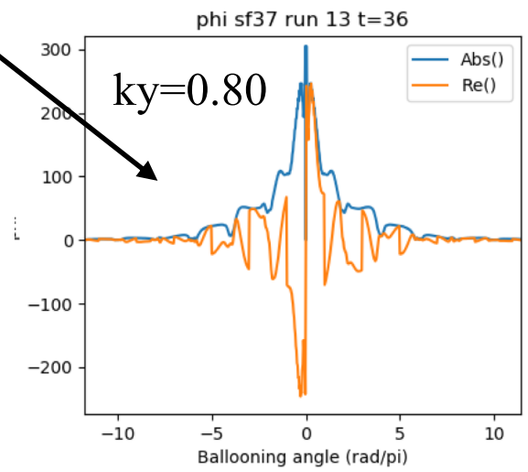
Low ky mode structure is highly extended along fieldline

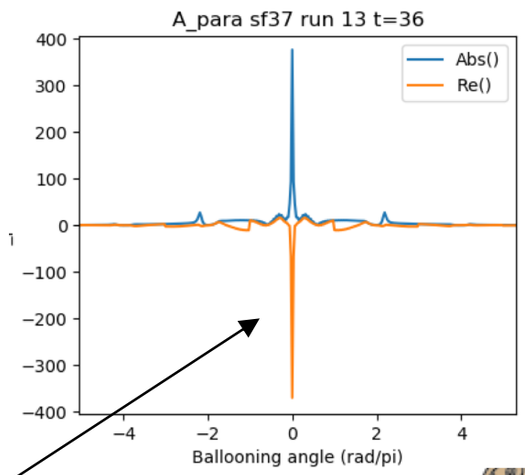


c_s/a = 265 kHz
ρ_i = 5.1 cm



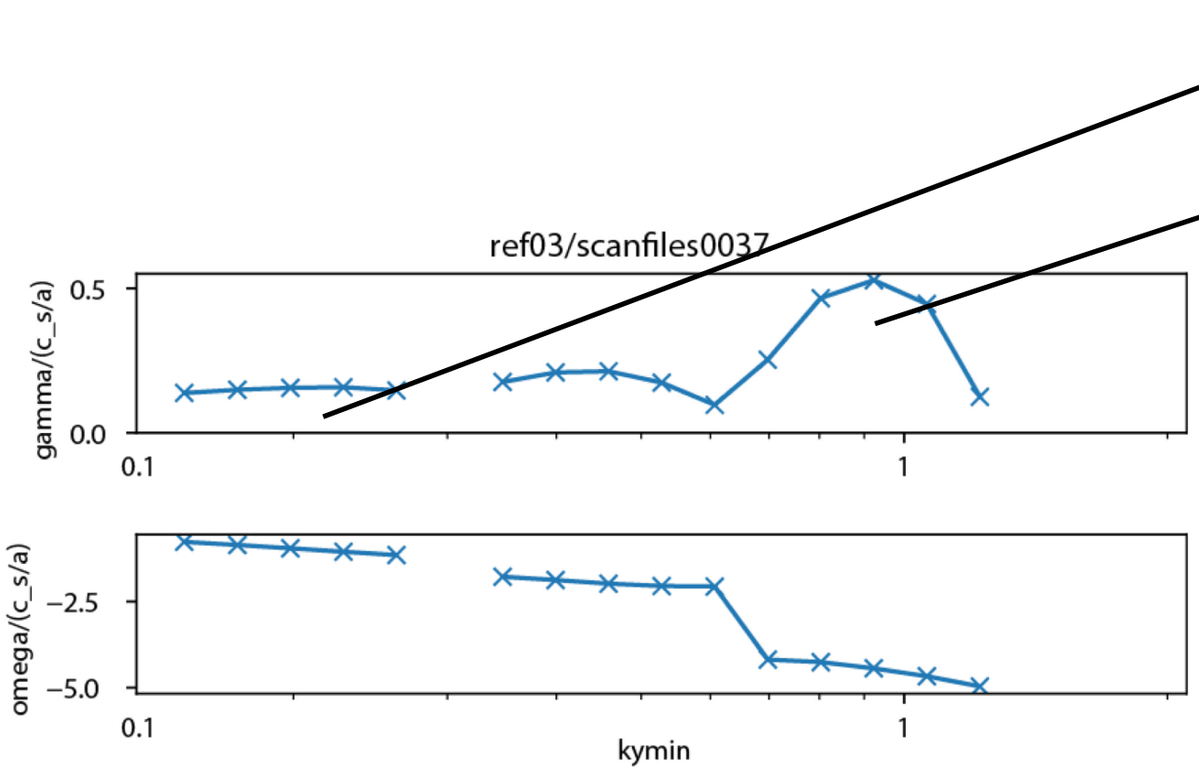


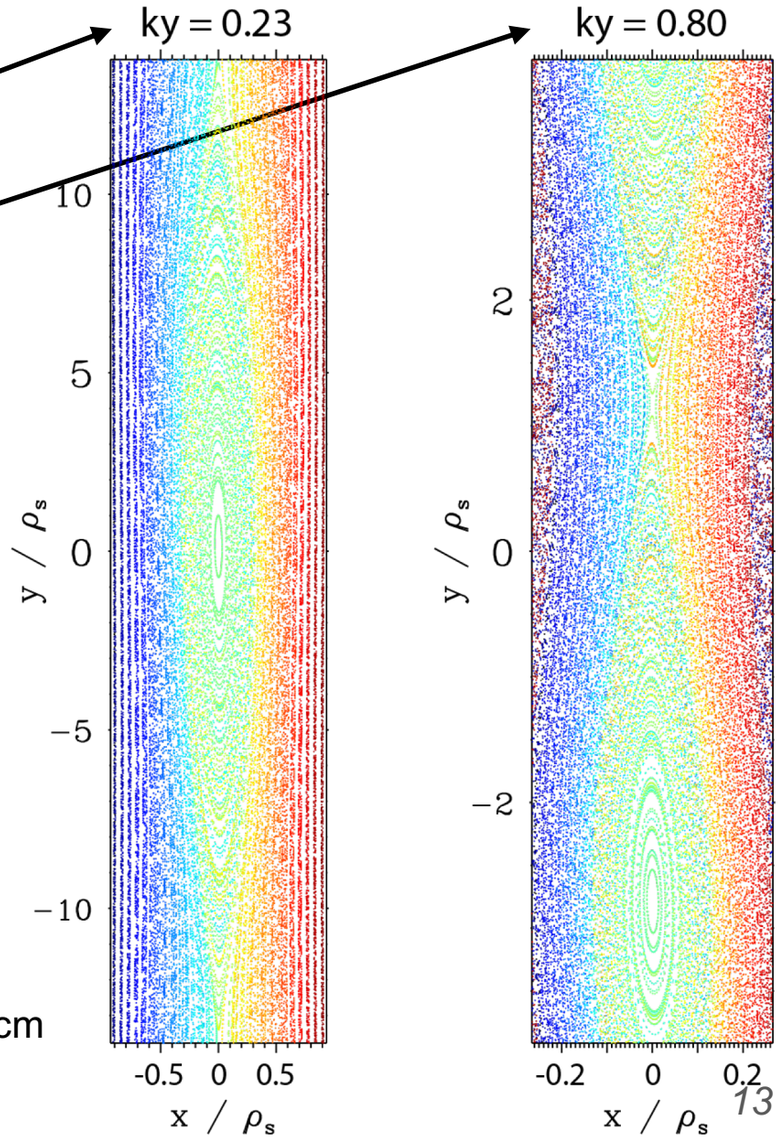




High ky mode structure looks like a "conventional" MTM

Poincare plots show magnetic islands for low-k and high-k modes



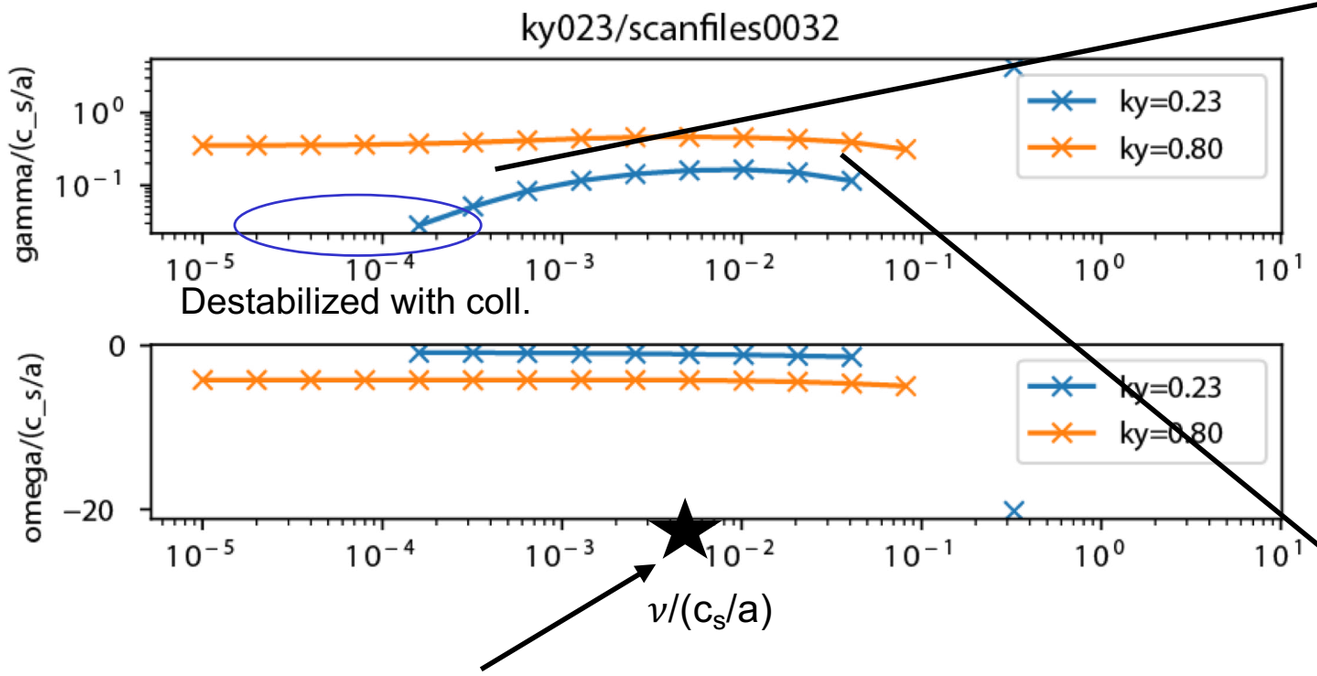


Poincare plots of perturbed B

ρ_s = 5.1 cm

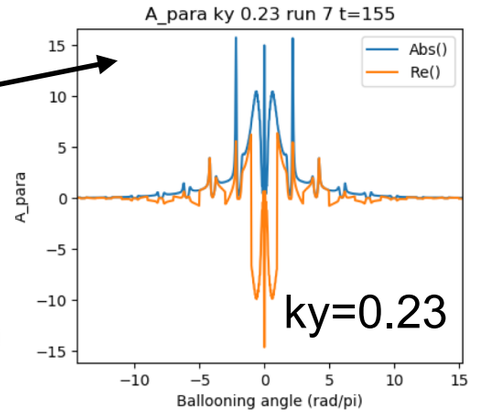
THE UNIVERSITY of WISCONSIN MADISON

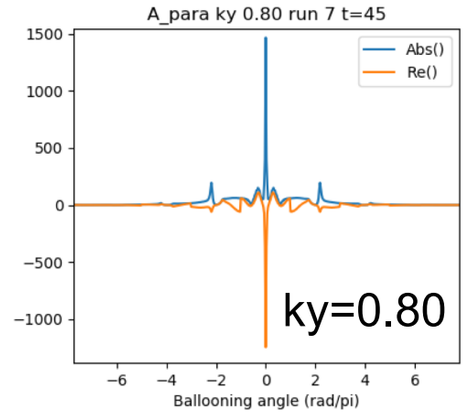
Low ky mode is collisional MTM; High ky mode is collisionless MTM



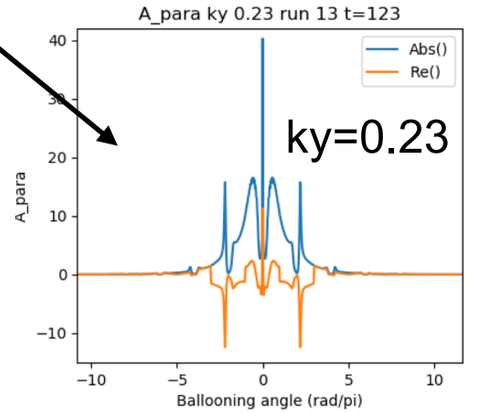
exp't value $\nu/(c_s/a)$ = 4.6e-3
$(\nu_i^* = 0.07)$

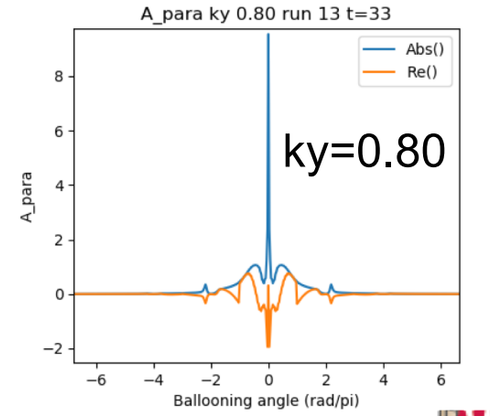
$A_{||}$ mode structures at low $\nu/(c_s/a)$ ~ 6e-4



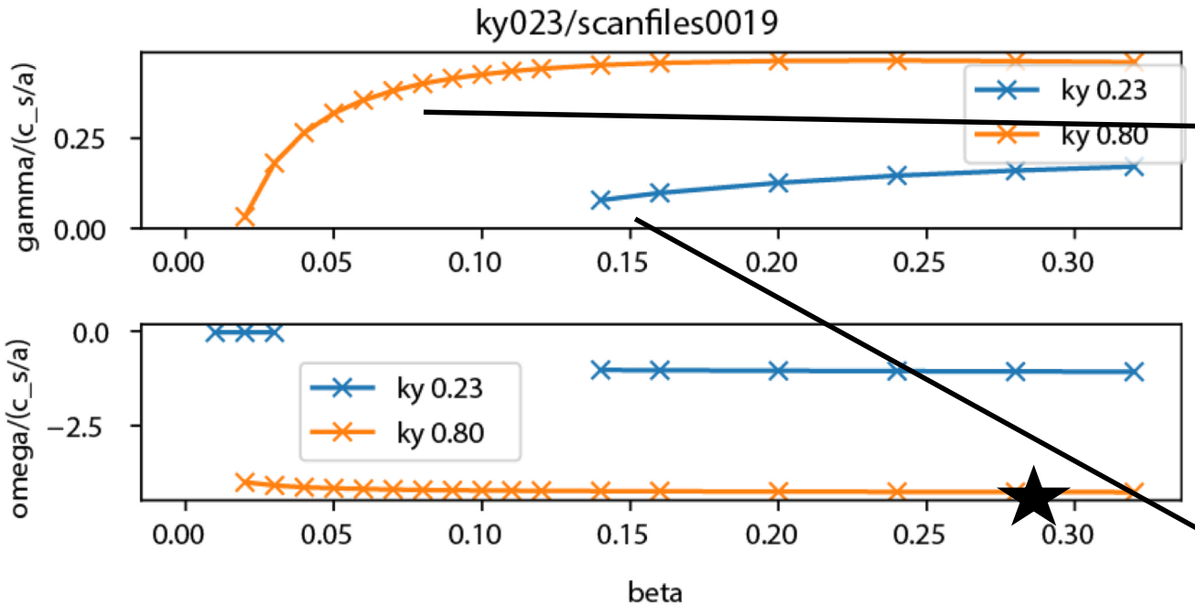


$A_{||}$ mode structures at high $\nu/(c_s/a)$ ~ 4e-2

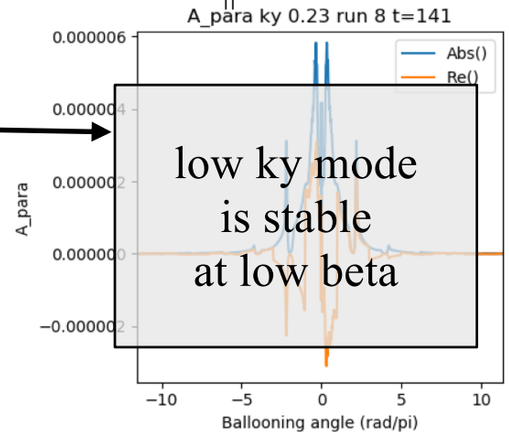


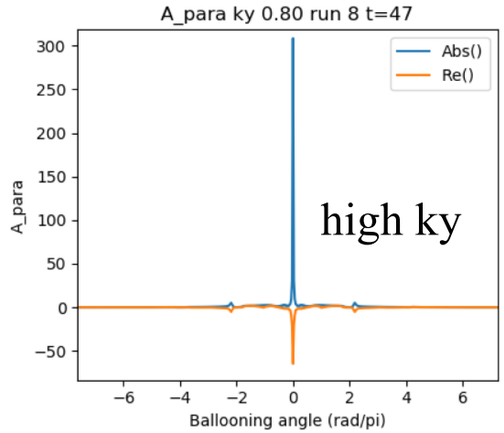


Low-k and high-k modes show distinct critical betas

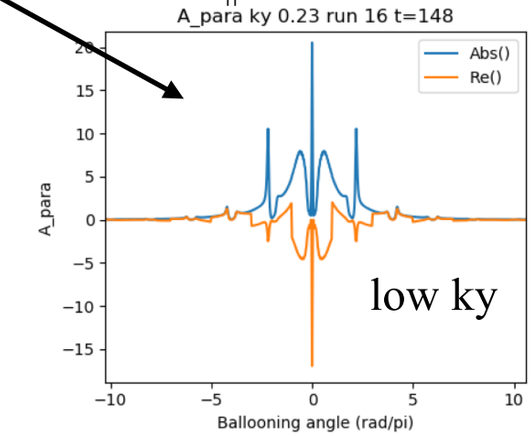


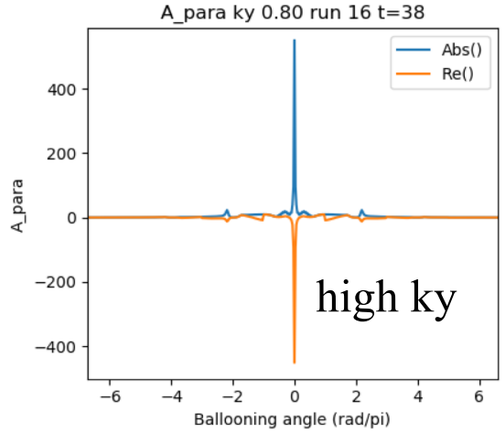
$A_{||}$ mode structures at low beta ~ 6%





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



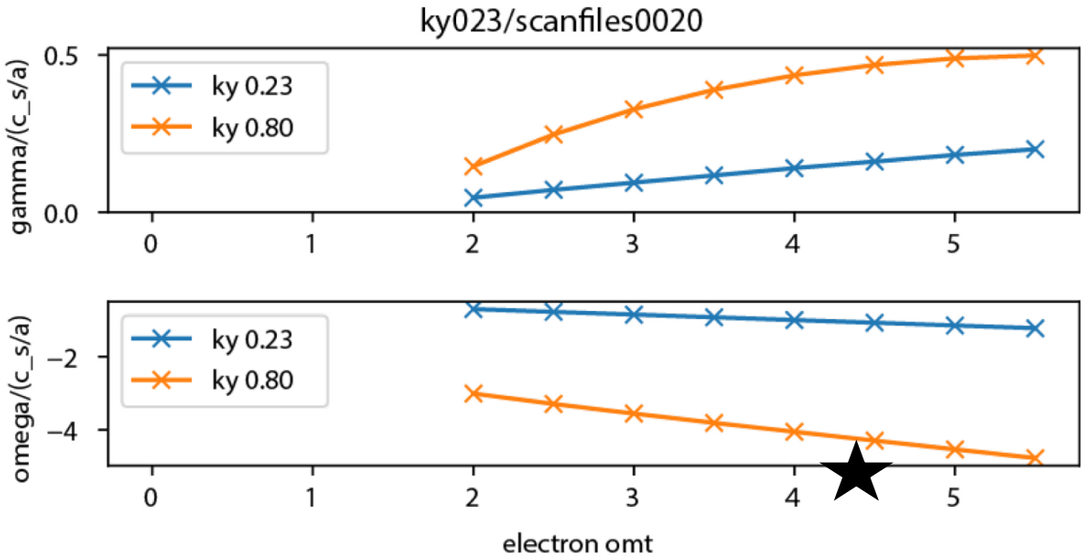


- High ky mode appears to be conventional MTM and shows critical beta ~ 3%
- Low ky mode shows critical beta ~ 12%
- beta = electron beta w/ B_T @ flux surface center

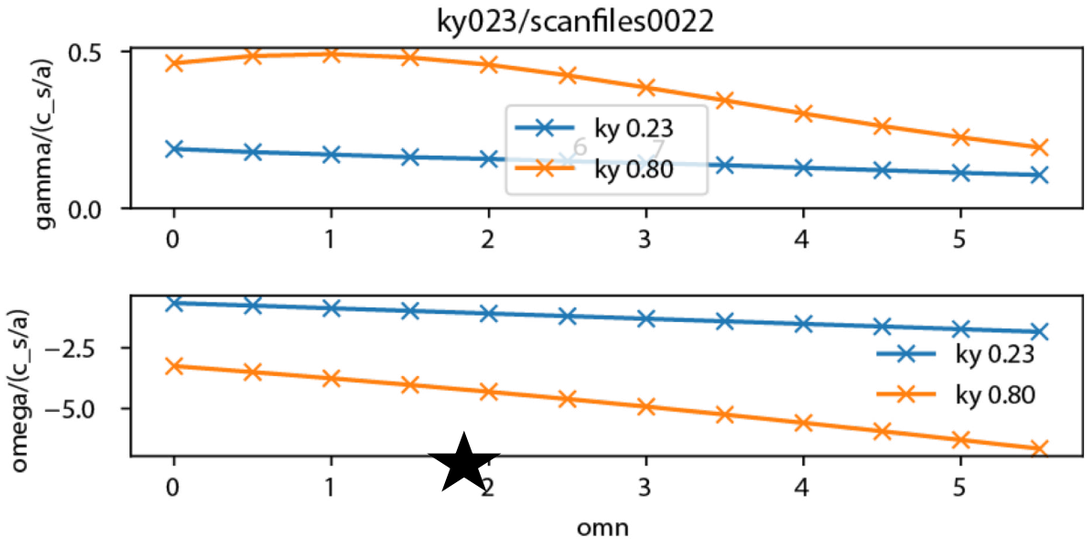
THE UNIVERSITY of WISCONSIN MADISON

Density and T_e gradient scans consistent with MTM

$d(\ln T_e) / dr$



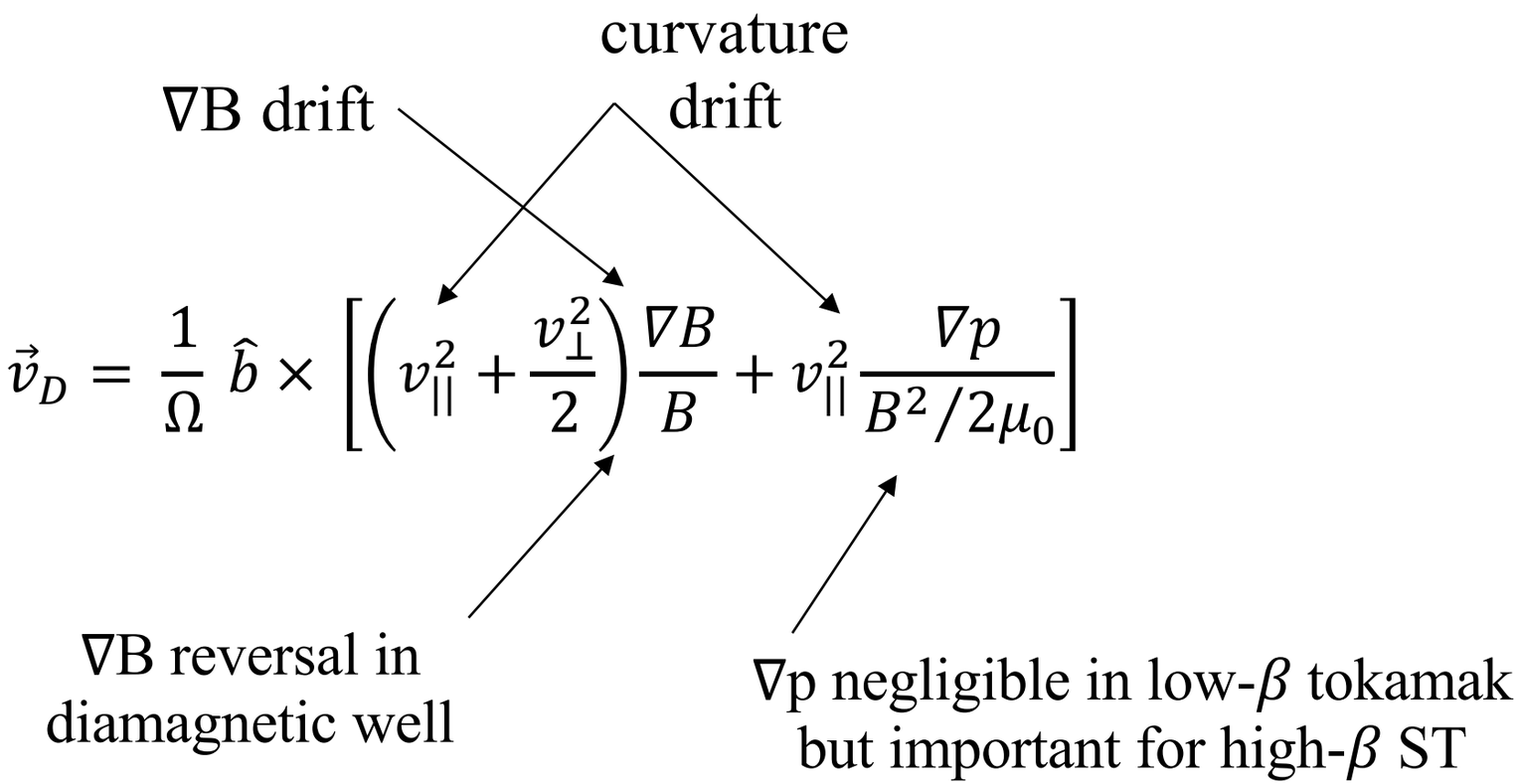
$d(\ln n) / dr$



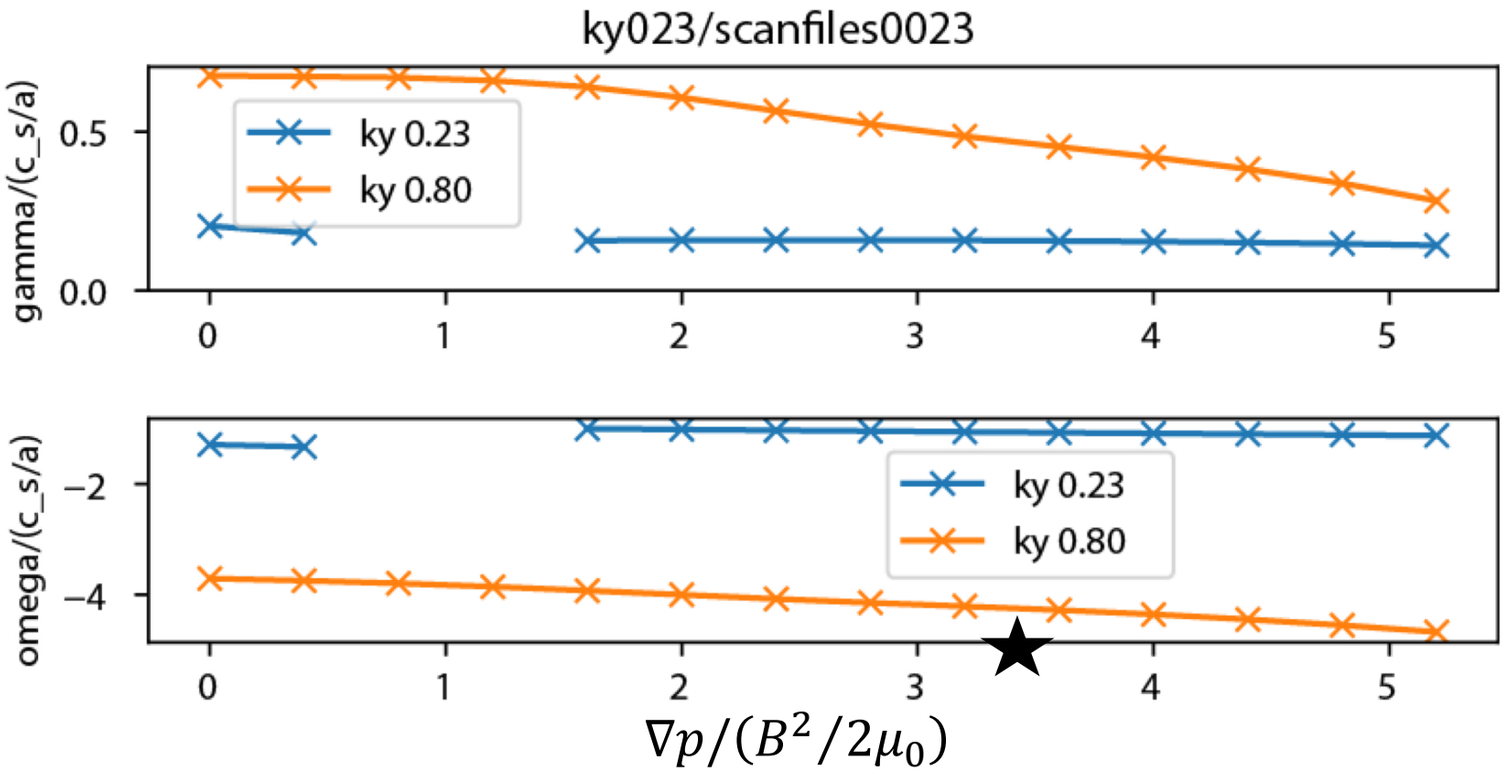
Growth rates increase with T_e gradient

THE UNIVERSITY of WISCONSIN MADISON

Magnetic drifts and pressure term

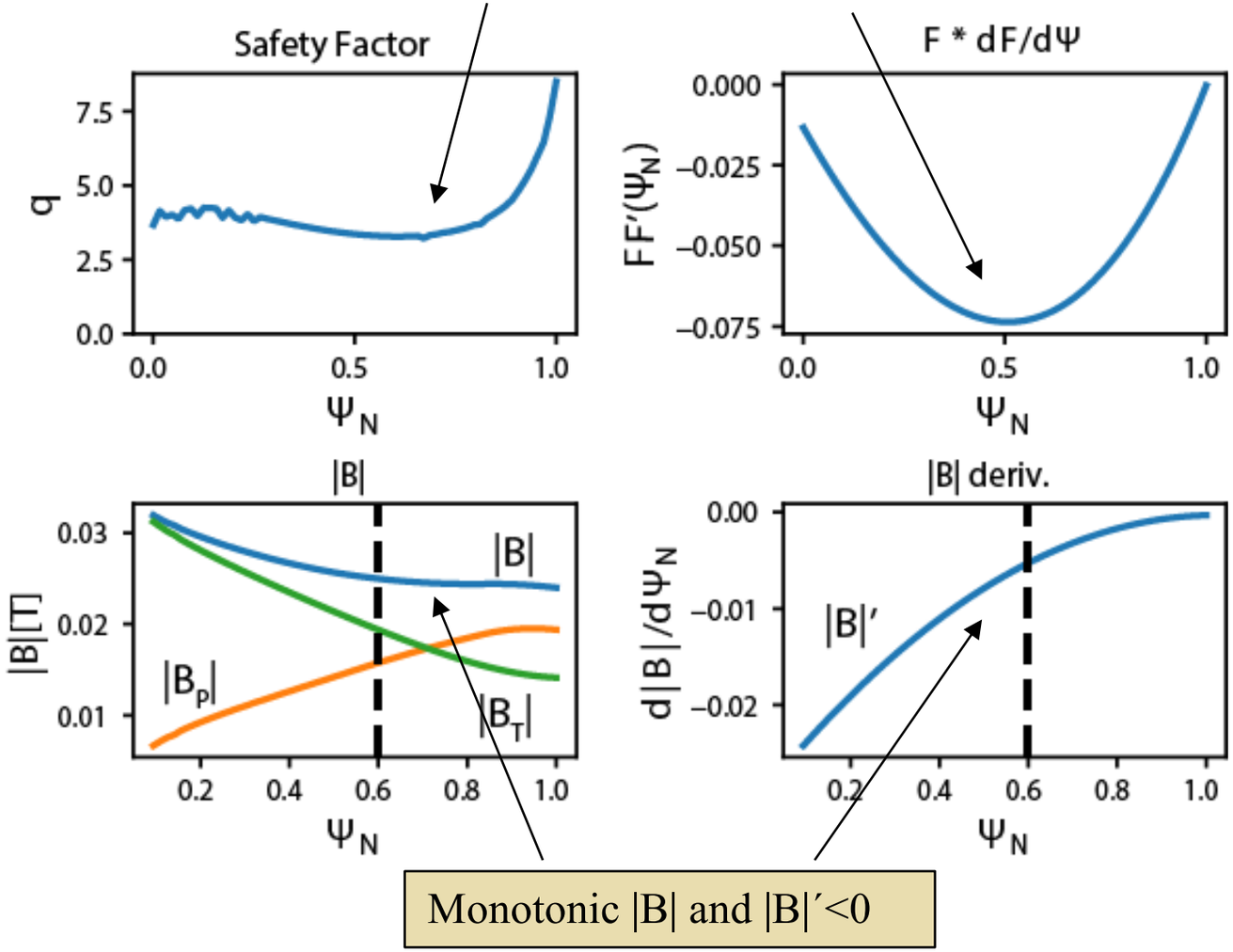


Low k_y mode is insensitive to ∇p in magnetic drift



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

Slight RS and less edge current

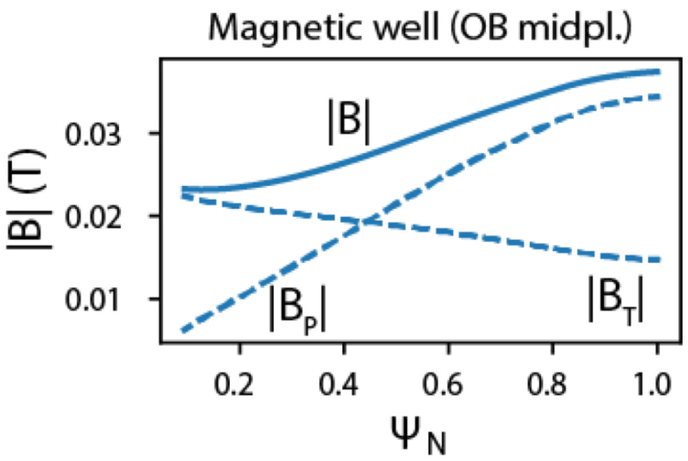


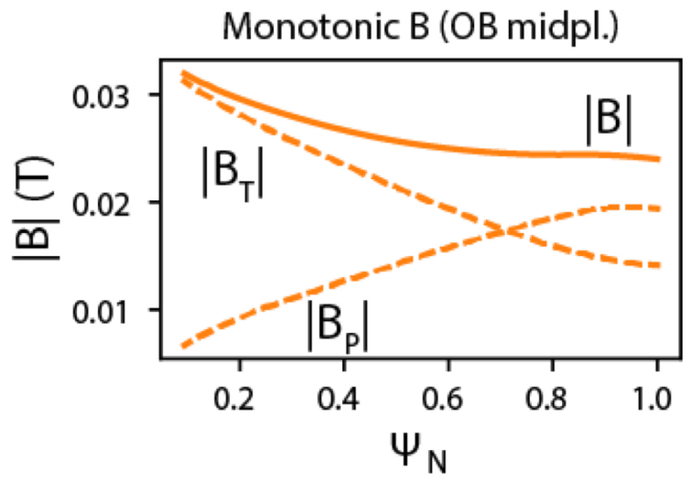
Monotonic |B| and |B|′<0

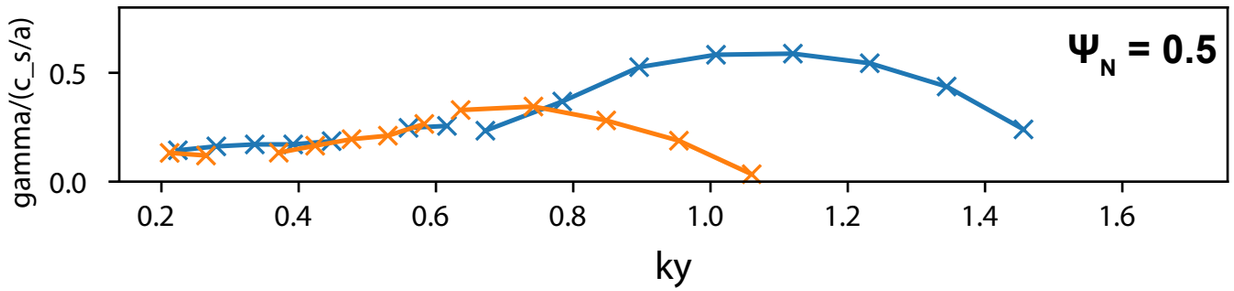
Compare to pgs 7 & 11

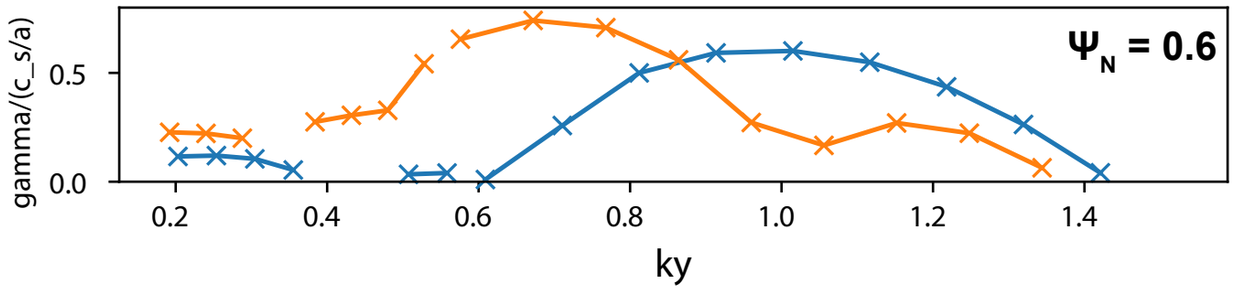
THE UNIVERSITY of WISCONSIN MADISON

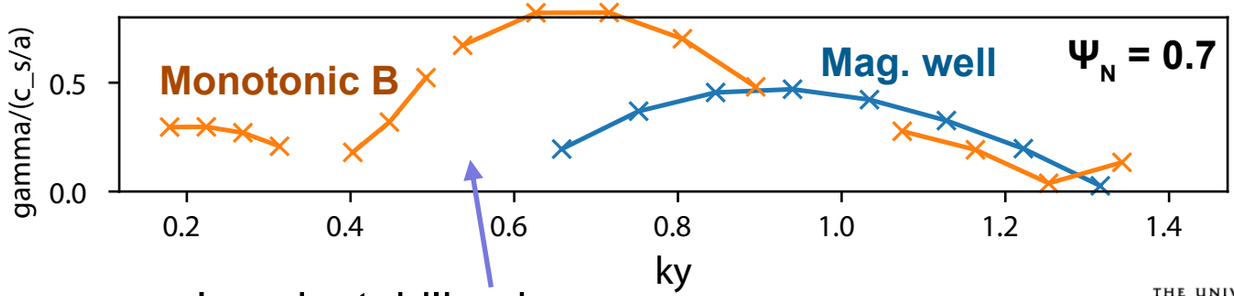
The magnetic well configuration is stabilizing for low-k MTMs in the outer plasma







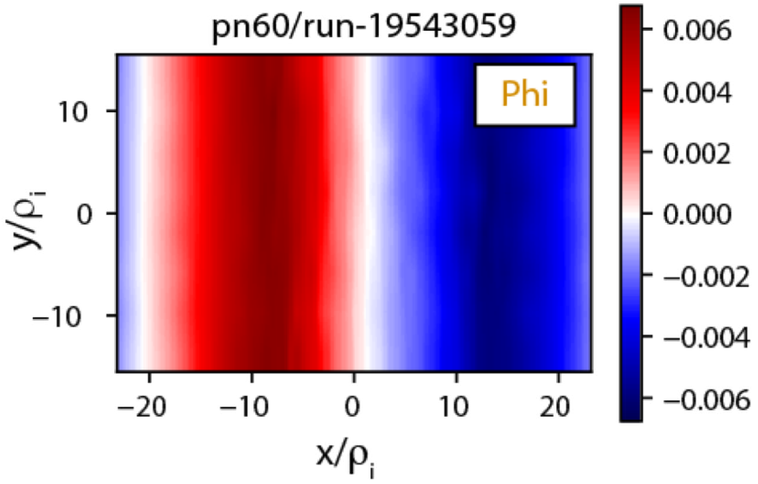


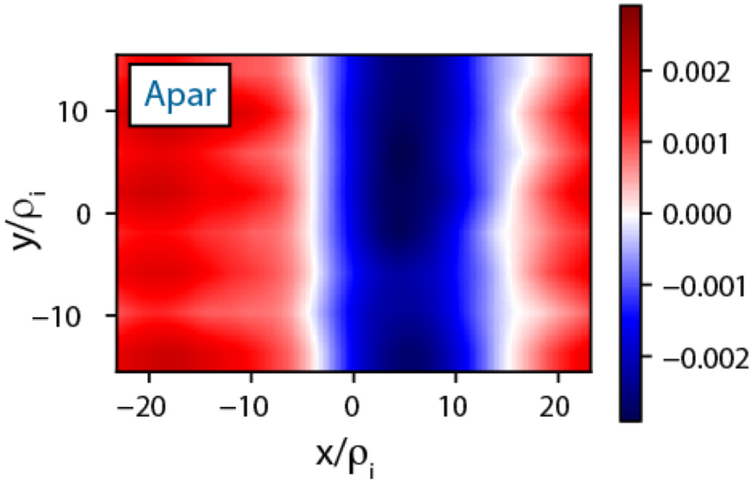


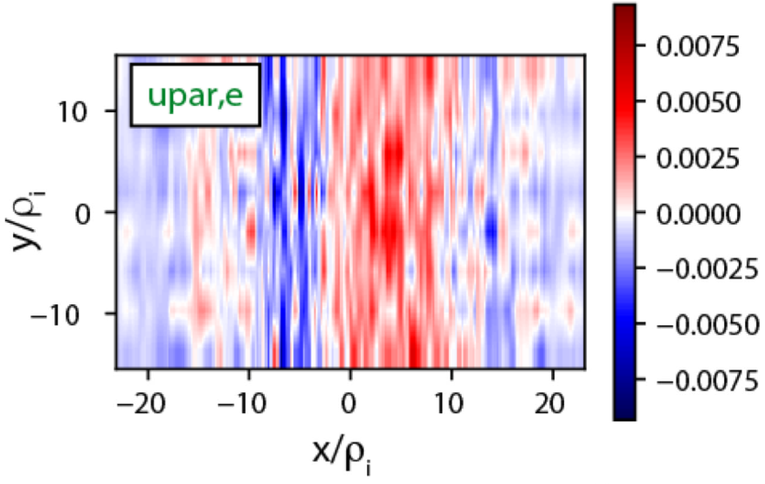
Low-k stabilized

THE UNIVERSITY of WISCONSIN MADISON

Nonlinear simulation (work-in-progress) shows dominant electron EM heat transport and radially narrow, poloidally elongated $u_{||,e}$ structures

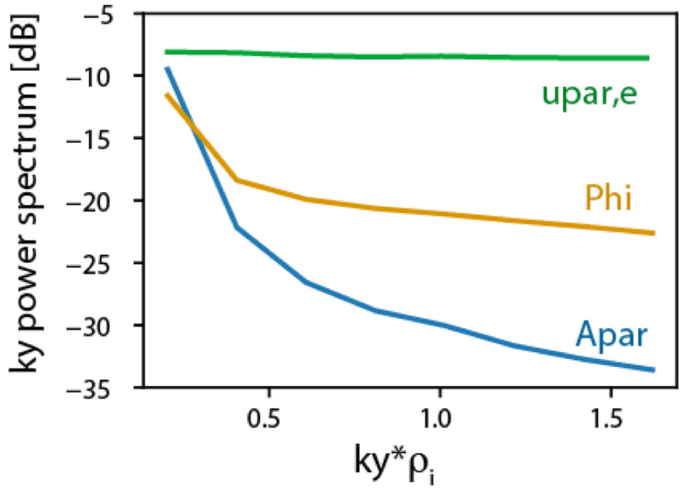


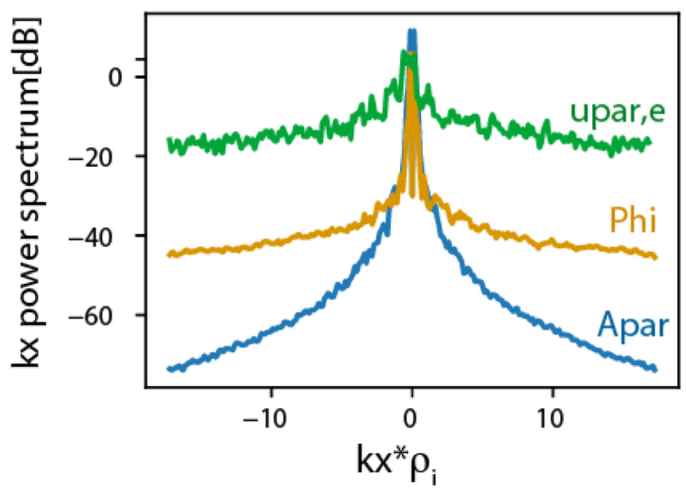




$\rho_i = 5.1$ cm

$t = 1208\ a/c_s$





THE UNIVERSITY of WISCONSIN MADISON

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
- Microtearing instabilities at k_y ~ 0.2-1.5 in Pegasus diamagnetic well
  - High k_y microtearing modes
    - Narrow $A_{||}$ mode structure
    - Collisionless with $\beta_{crit} \approx 3\%$
  - Low k_y microtearing modes
    - Extended $A_{||}$ mode structure
    - High $\beta_{crit} \approx 12\%$ and stabilized at low collisionality
    - Stabilized in monotonic-B configuration
  - Initial nonlinear simulation shows dominant electron EM heat transport and radially narrow, poloidally elongated $j_{||,e}$ structures

THE UNIVERSITY of WISCONSIN MADISON