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UNIVERSITY OF WISCONSIN–MADISON

PEGASUS
Toroidal Experiment

Microtearing modes in the diamagnetic well of a high-β spherical torus plasma

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- We thank and acknowledge helpful discussions with R. Fonck, W. Guttenfelder, M.J. Pueschel, J. Reusch, P. Terry, and Z. Williams

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Outline

- Microtearing modes (MTMs) and electron thermal transport in STs
- MTM linear stability in a diamagnetic well at near-unity β
  - β ~ O(1) for HFS LHI operation in Pegasus
  - ∇B reversal alters magnetic drifts (∇B and curvature)
  - GENE simulations indicate MTMs are linearly stabilized in the outer region of the diamagnetic well
- Nonlinear simulations indicate MTM-driven transport is suppressed in the diamagnetic well
  - Points to an enhanced confinement regime for the ST at near-unity β

MTMs and electron thermal transport in STs

- What's special about ST transport?
  - Unlike tokamaks, ST confinement exhibits strong inverse scaling with collisionality: $t_E \propto {}^{1}/_{\nu}$
    - Inconsistent with drift waves (ITG, TEM, ETG) that are destabilized as $\nu \to 0$
    - Consistent with (classical) MTM that is stabilized as $\nu \to 0$
  - High β values in STs promote MTM destabilization
  - MTMs only produce electron thermal transport – the dominant loss mechanism in STs
    - Also, fusion α's will dominantly heat electrons
- What are MTMs?
  - Tearing parity modes with parallel current destabilized at q=m/n resonant surfaces (n,m>>1)
  - Driven by electron temperature gradient (unlike current-driven MHD tearing modes)
  - Instability onset at critical β and critical ∇T_e (or a/L_{Te})
  - Perturbed $\boldsymbol{\Phi}$ and $j_{||}$ are radially narrow; perturbed $A_{||}$ (B_r) is radially broad

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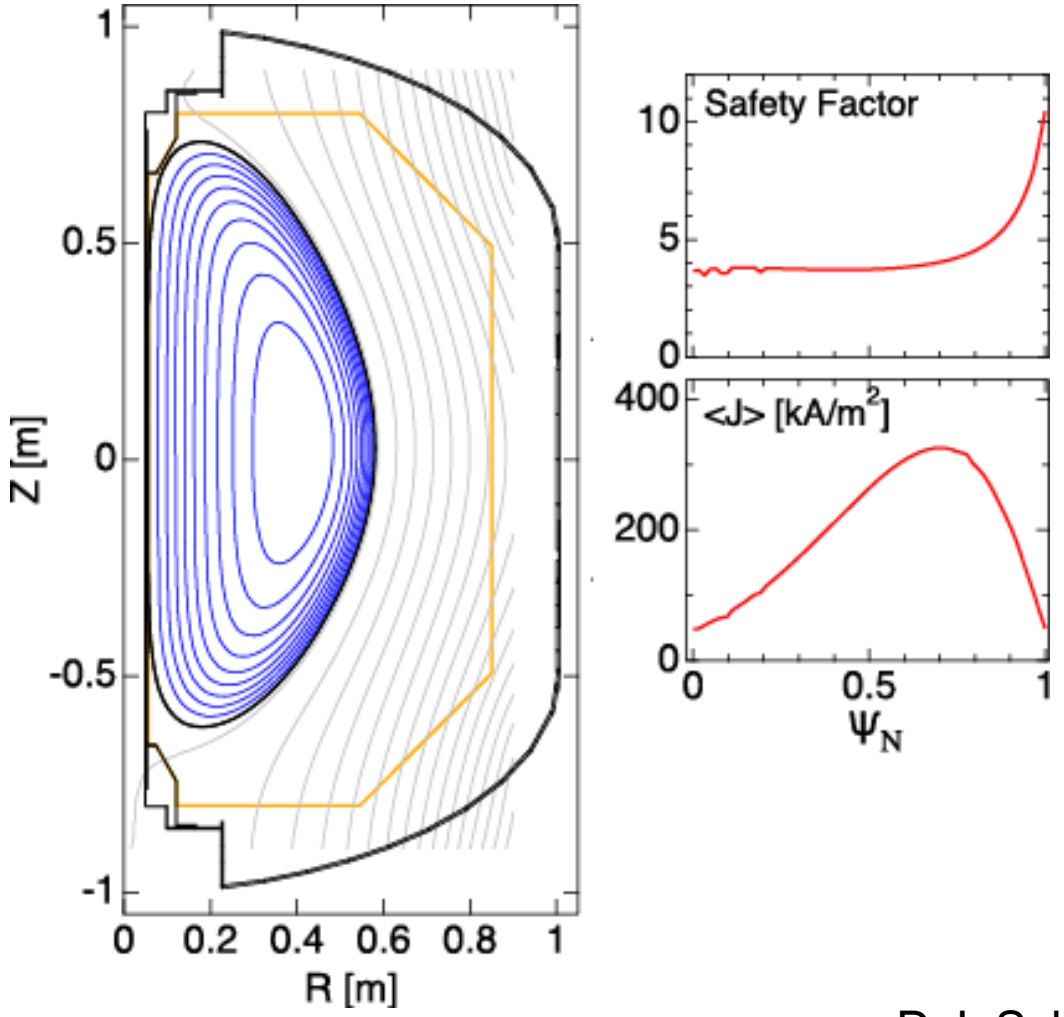
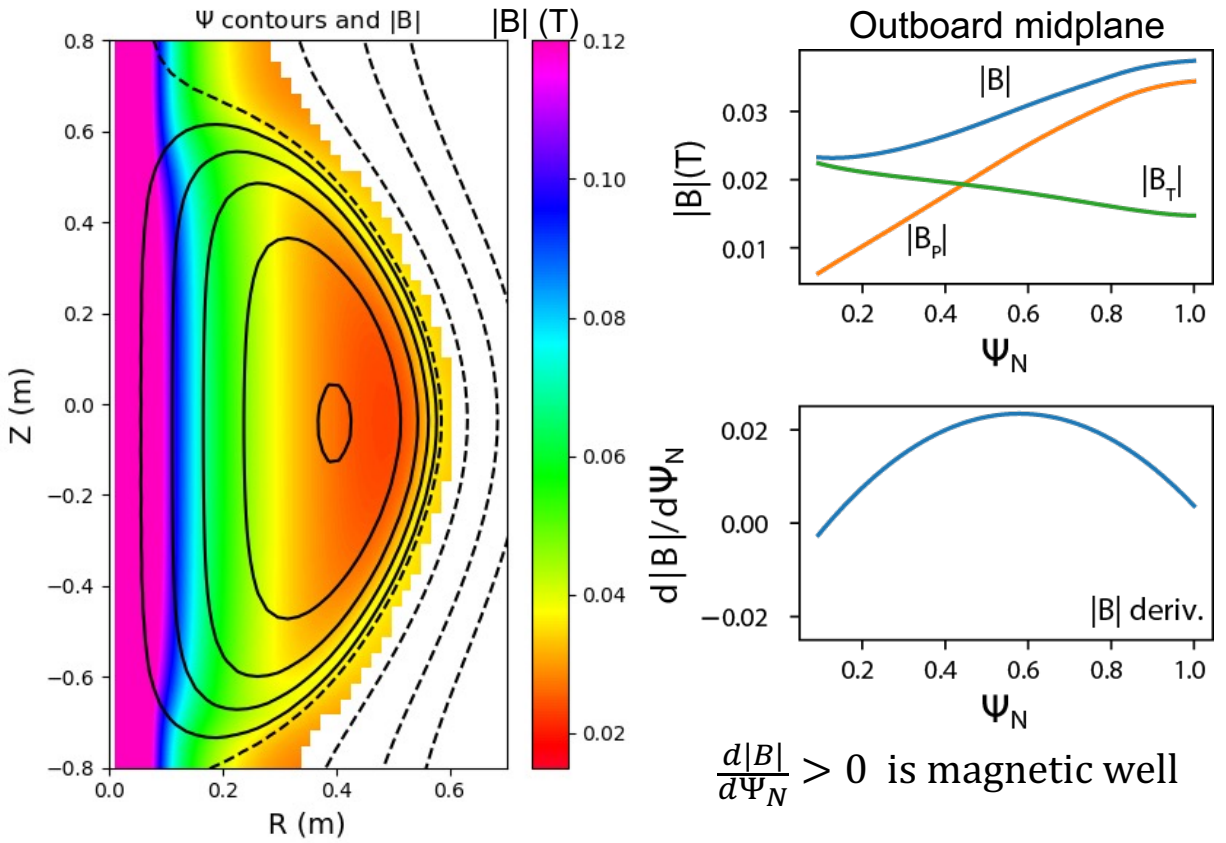
High-field-side local helicity injection (LHI) in Pegasus achieves β~100% with edge current peaking



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

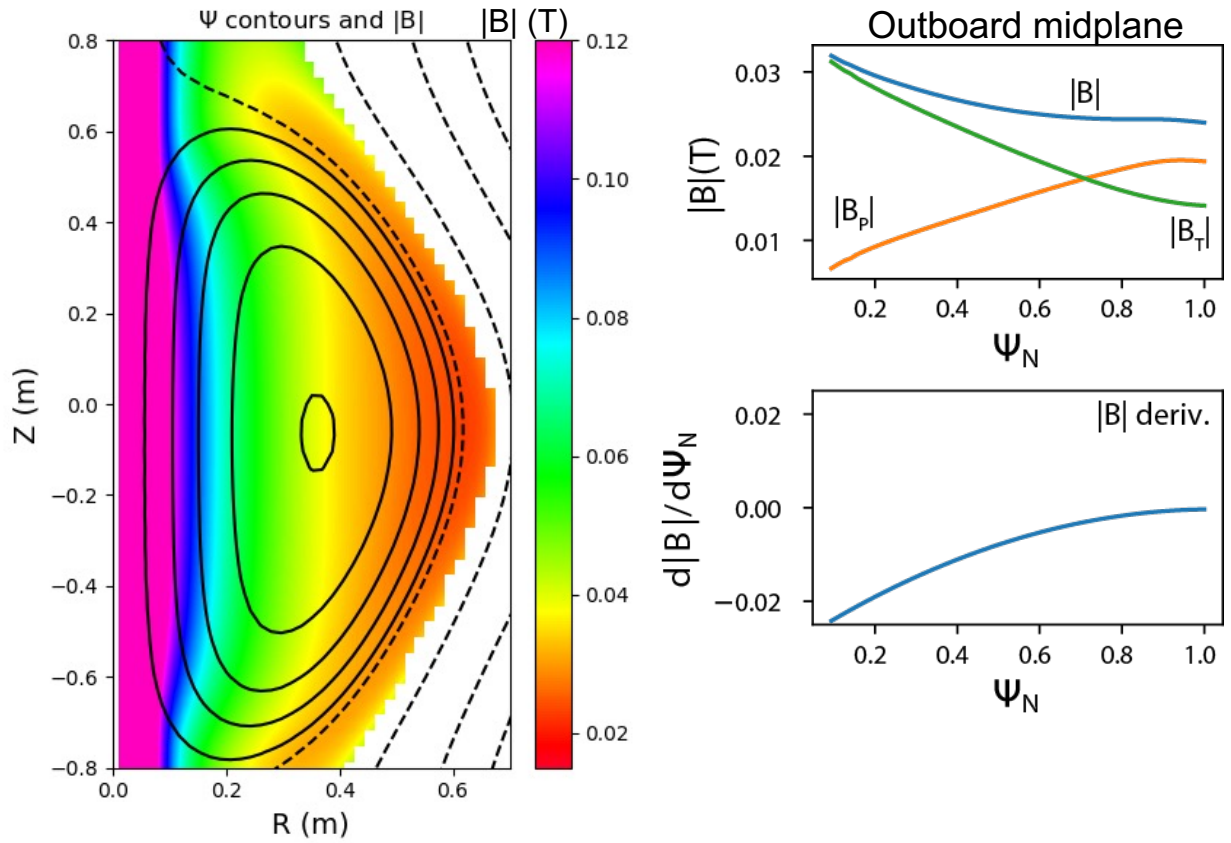
A diamagnetic well ("minimum B") is induced at high β and diminishes strong ST paramagnetism

Experimental minimum |B| configuration



$\frac{d|B|}{d\Psi_N} > 0$ is magnetic well

Similar monotonic |B| configuration



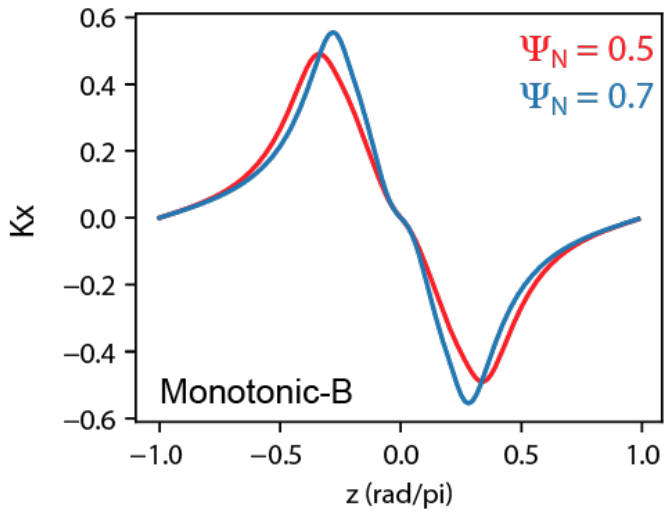
STs are strongly paramagnetic because I_P enhances B_T through J||B with large pitch angle.
However, gyromotion is diamagnetic such that high β diminishes B. (Peng & Strickler, NF 1986)

Compared to monotonic-B, the minimum-B configuration exhibits stronger inboard curvature and stronger curvature shear near midplane

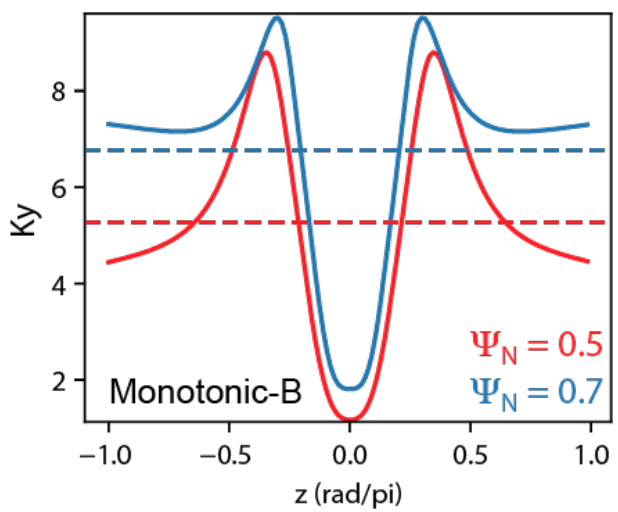
Monotonic-B

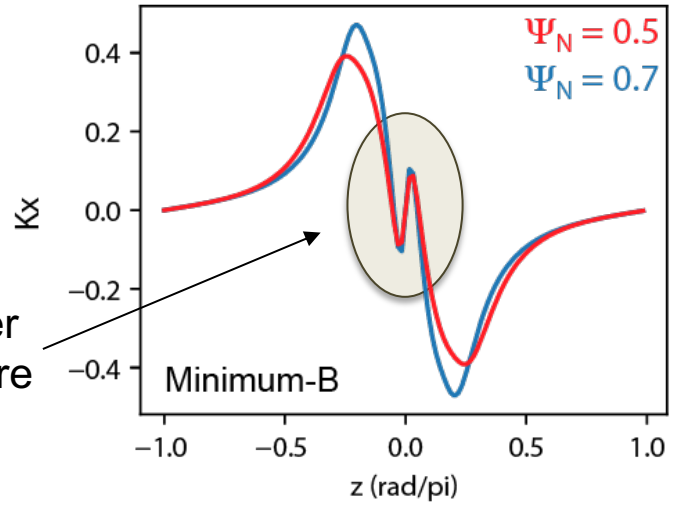
Minimum-B

Radial B curvature

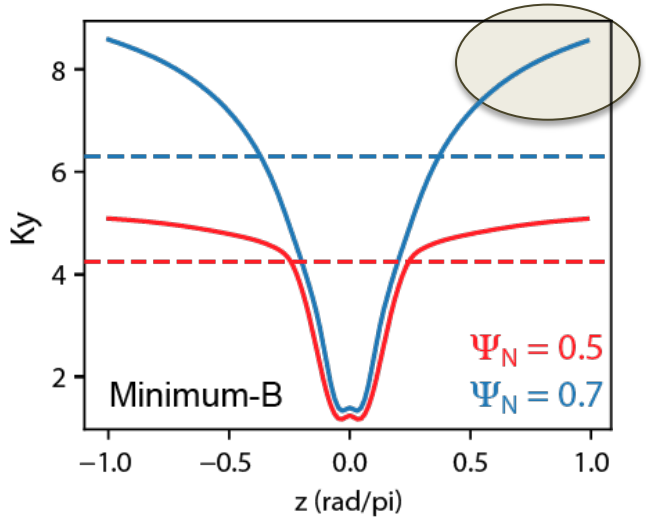


Binormal B curvature





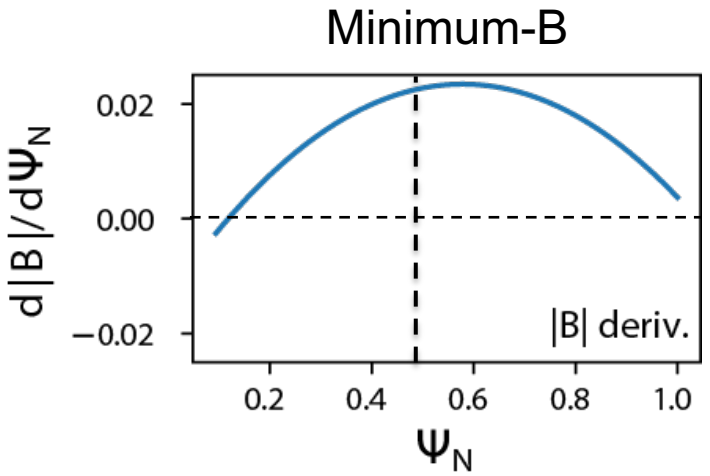
Stronger curvature shear

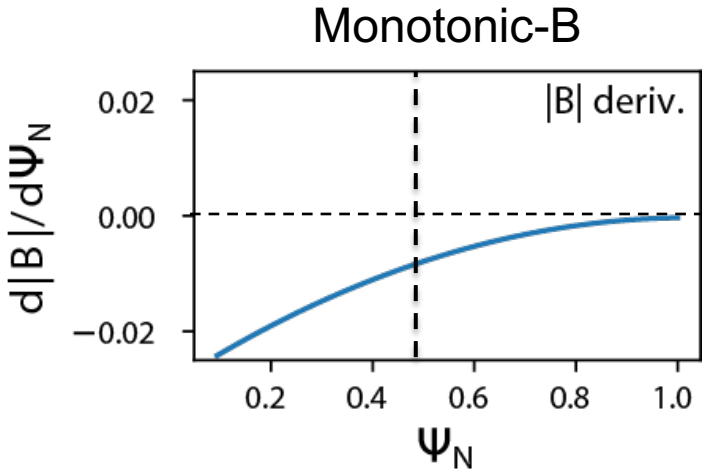


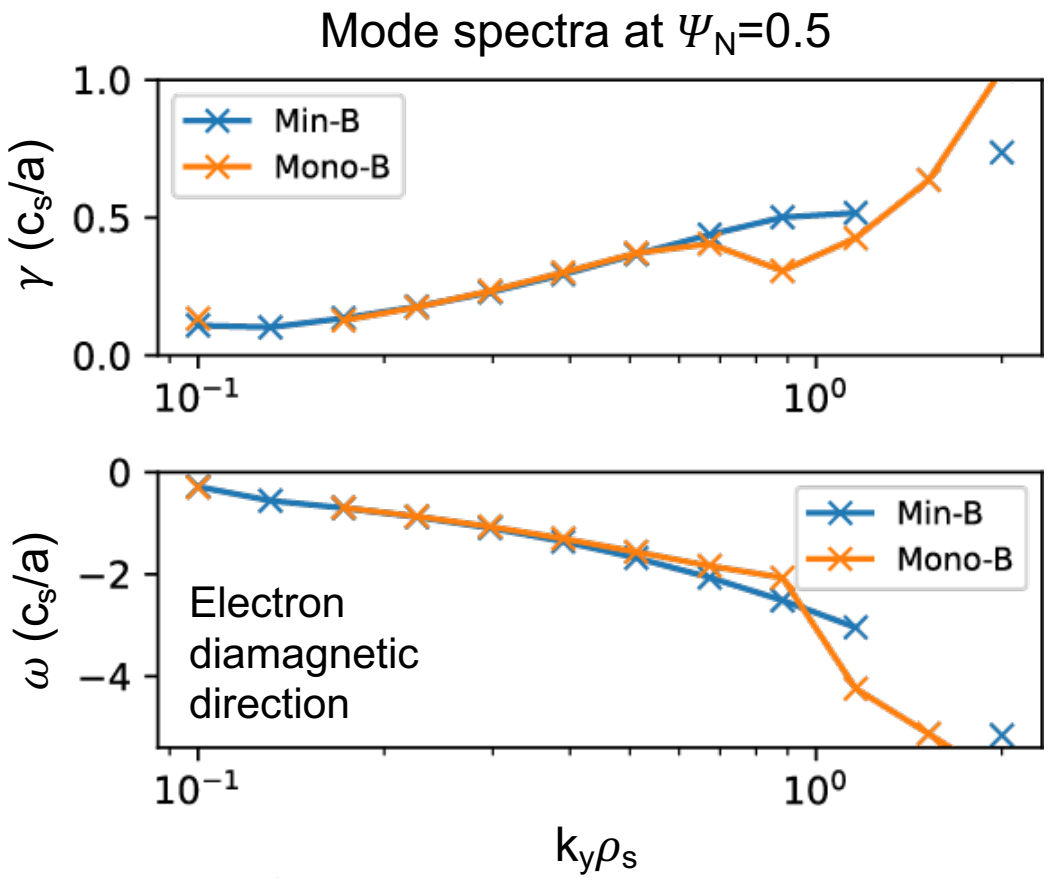
Stronger inboard curvature, though average curvature (dash) is slightly lower

How does the high-β, minimum-B ST configuration impact gyrokinetic stability and transport?

Minimum-B and monotonic-B configurations show instabilities that propagate in the electron diamagnetic direction







q = 3.5
ŝ = 0.25 min-B,
-0.5 mono-B
$\kappa, \boldsymbol{\delta}$ = 2.8, 0.5

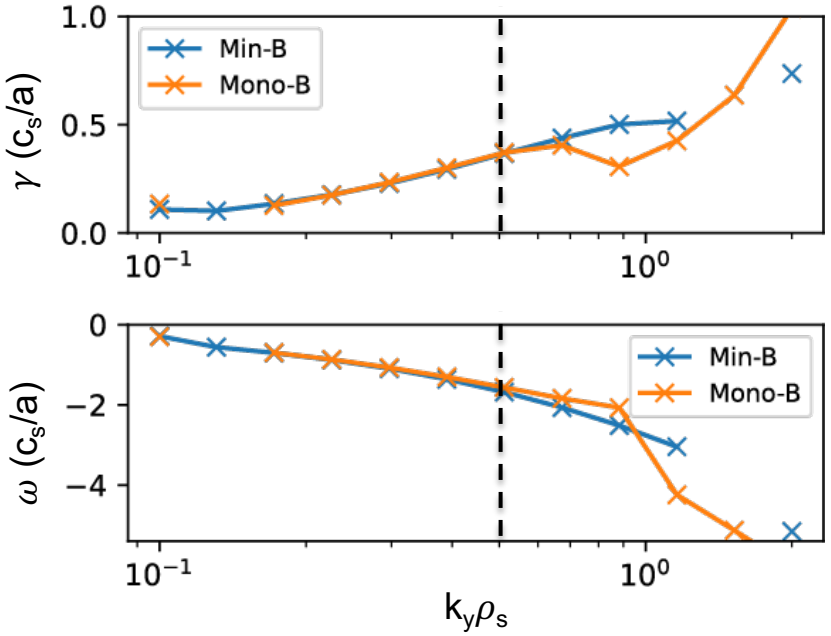
$a/L_{T\{e,i\}}$ = 2.8
a/L_n = 1.2
β_e = 30%

Linear GK simulations with GENE
F. Jenko, Comp. Phys. Comm. 125, 196 (2000)

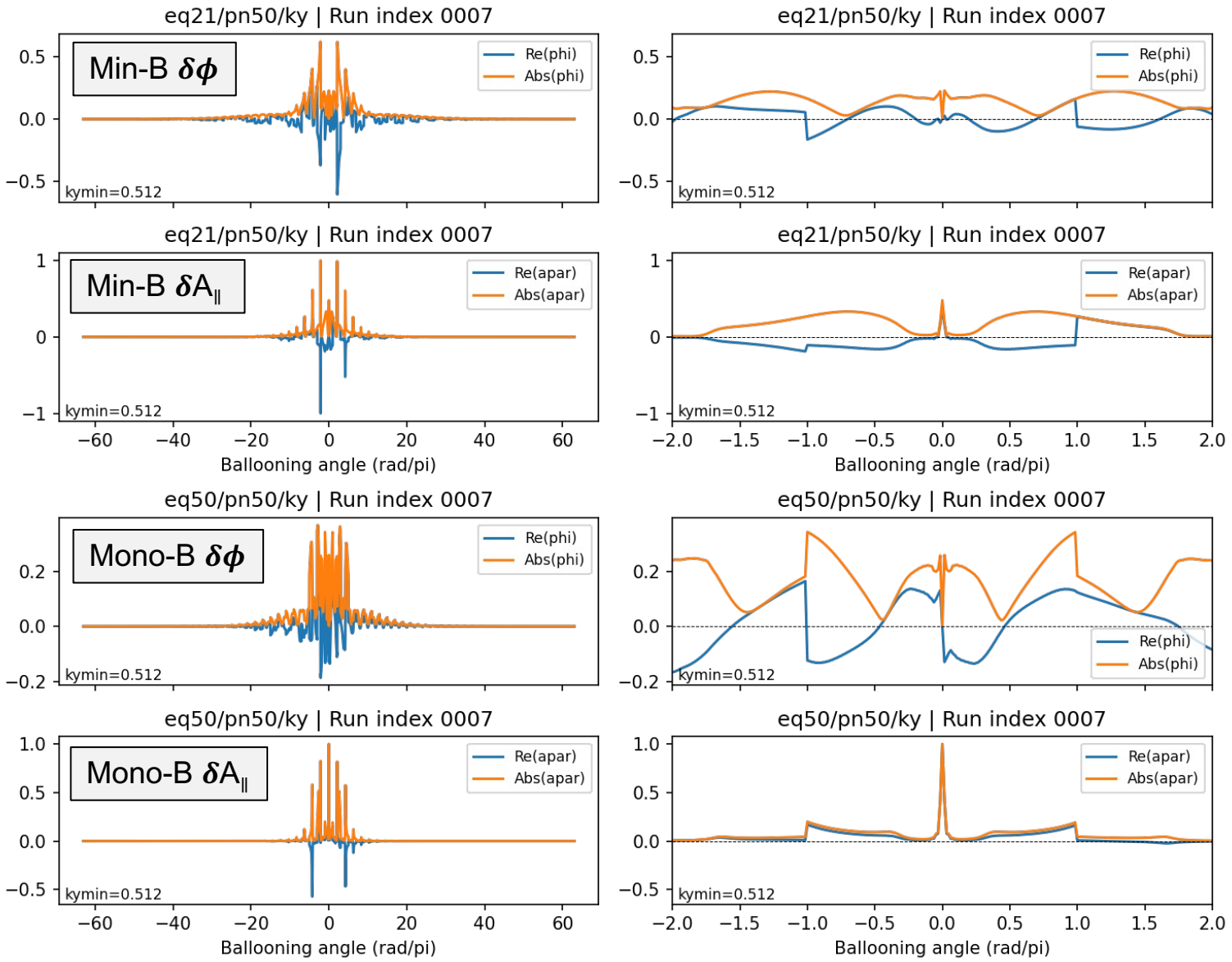
Instabilities are tearing-parity with extended parallel mode structures

$k_y\rho_s = 0.51$

Mode spectra at Ψ_N=0.5



Modes are converged in radial and parallel coordinates:
nx=64, nz=128

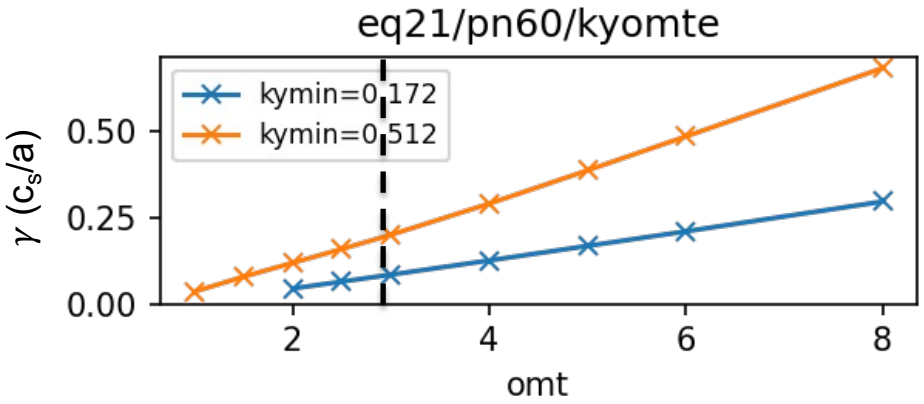


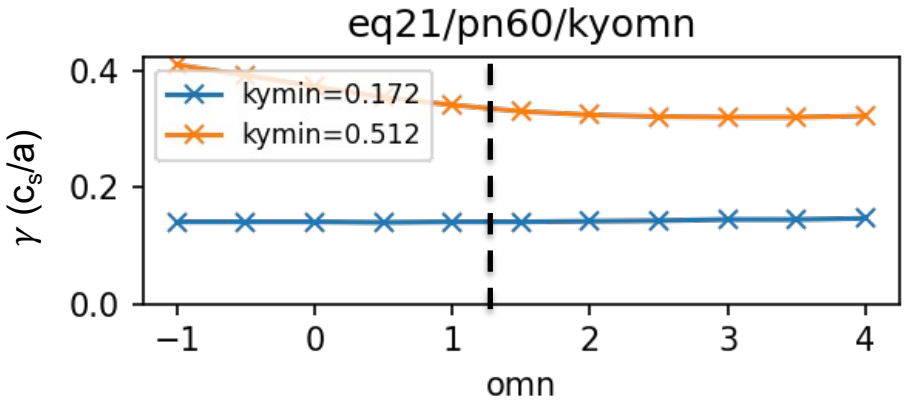
Instabilities are destabilized with a/L_{Te} and insensitive to a/L_n, consistent with MTMs

a/L_{Te} scan

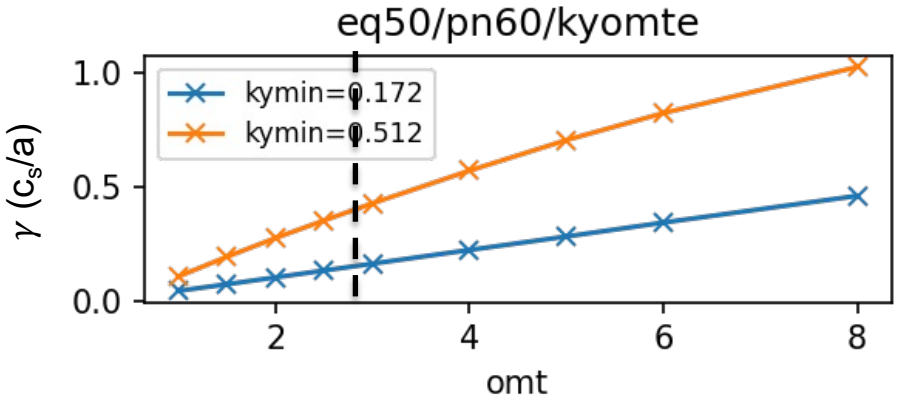
a/L_n scan

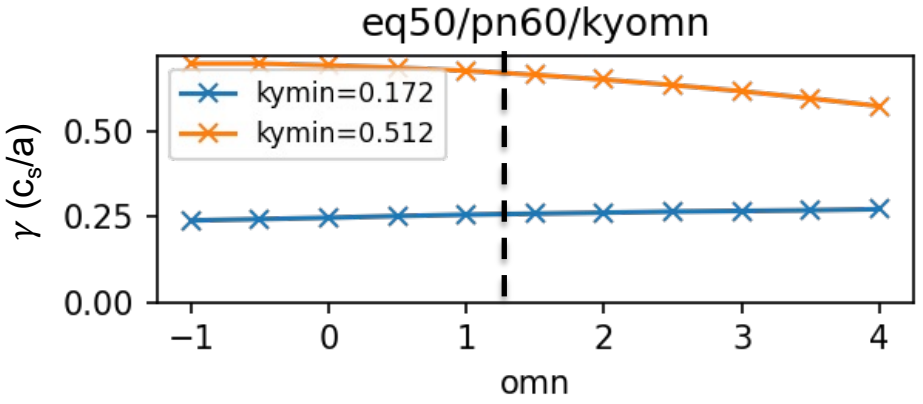
Minimum-B





Monotonic-B





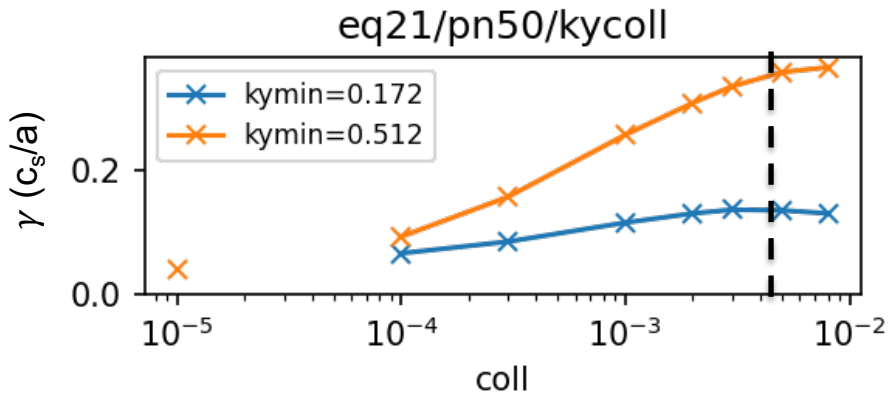
Dashed = baseline value

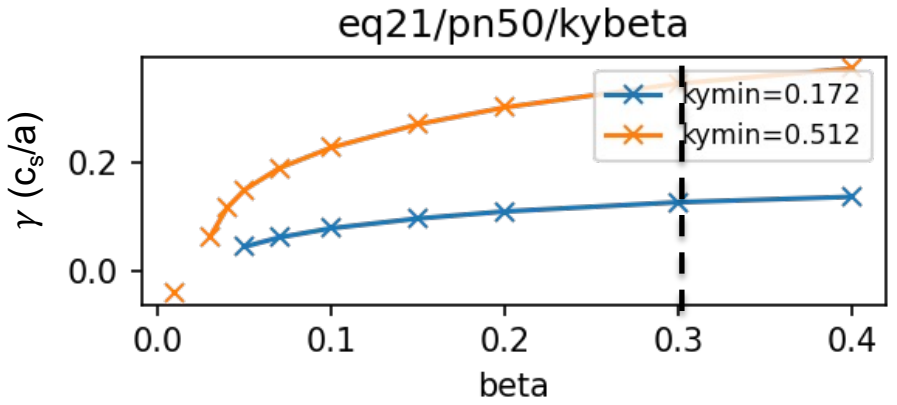
Instabilities are collisional and exhibit critical β_e, consistent with MTMs

Collisionality scan

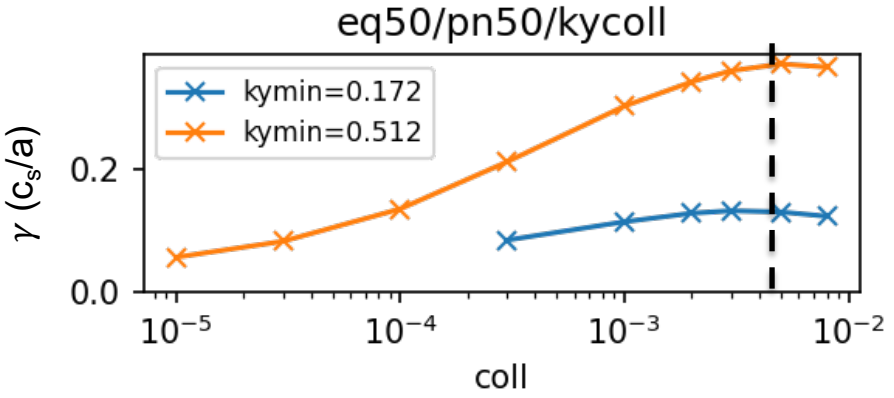
Beta scan

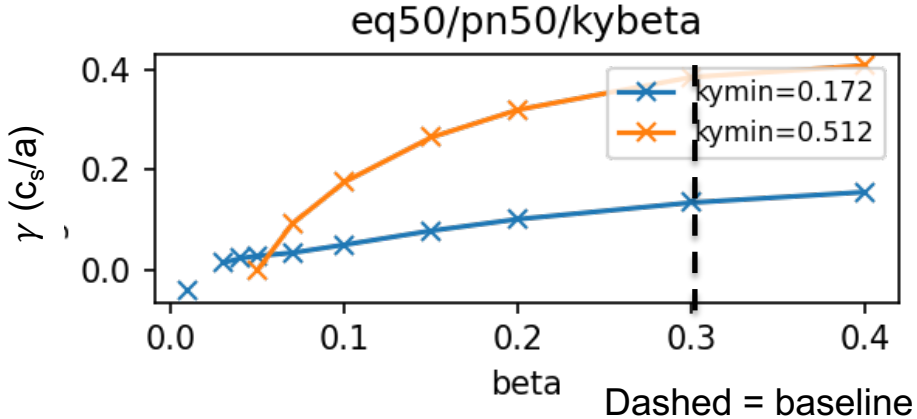
Minimum-B





Monotonic-B

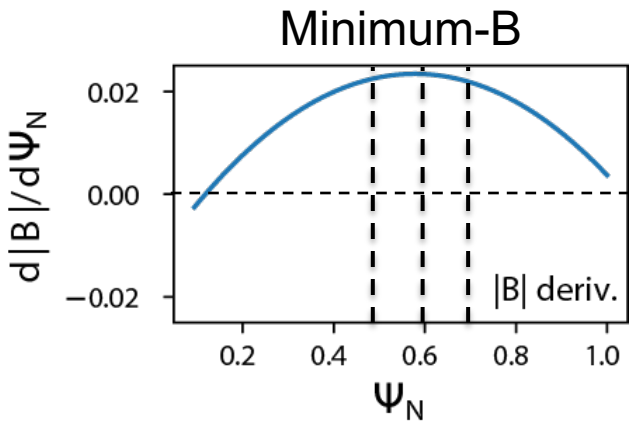


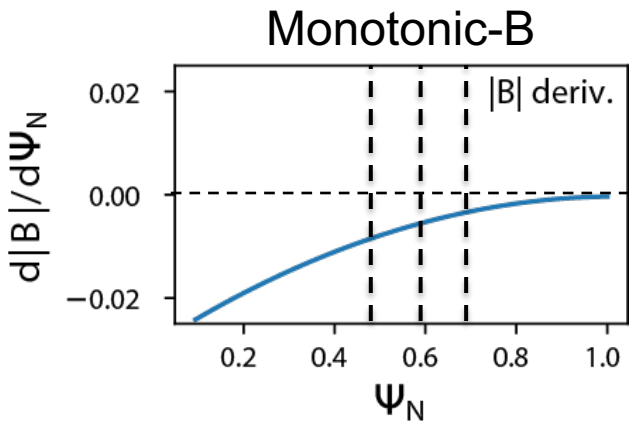


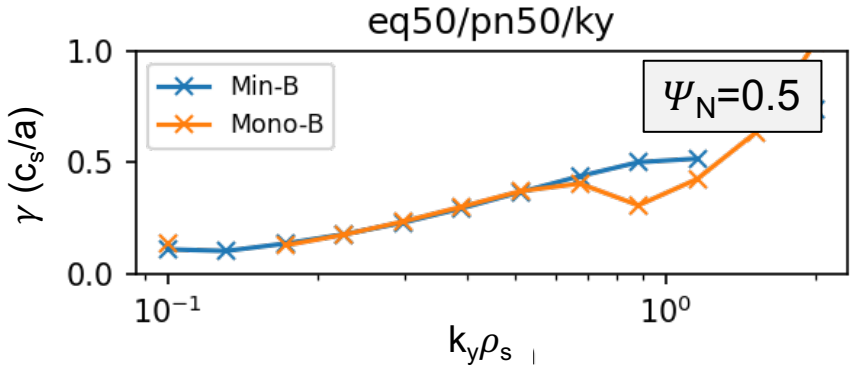
Dashed = baseline value

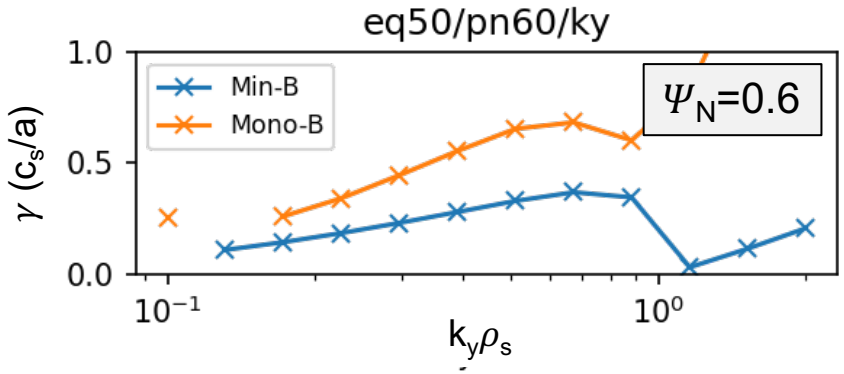
Also, instabilities persist with adiabatic ions and instabilities require finite $\delta\phi$.

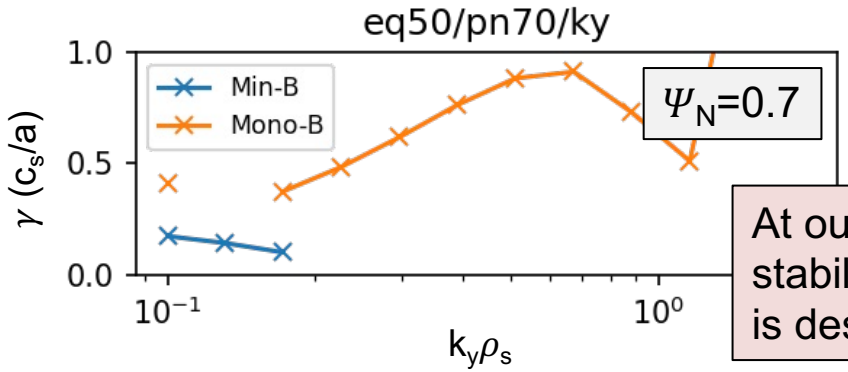
At outer radii, modes are stabilized in minimum-B configuration and destabilized in monotonic-B configuration





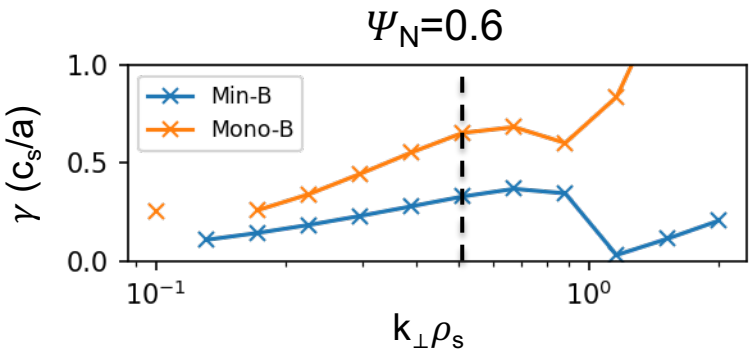




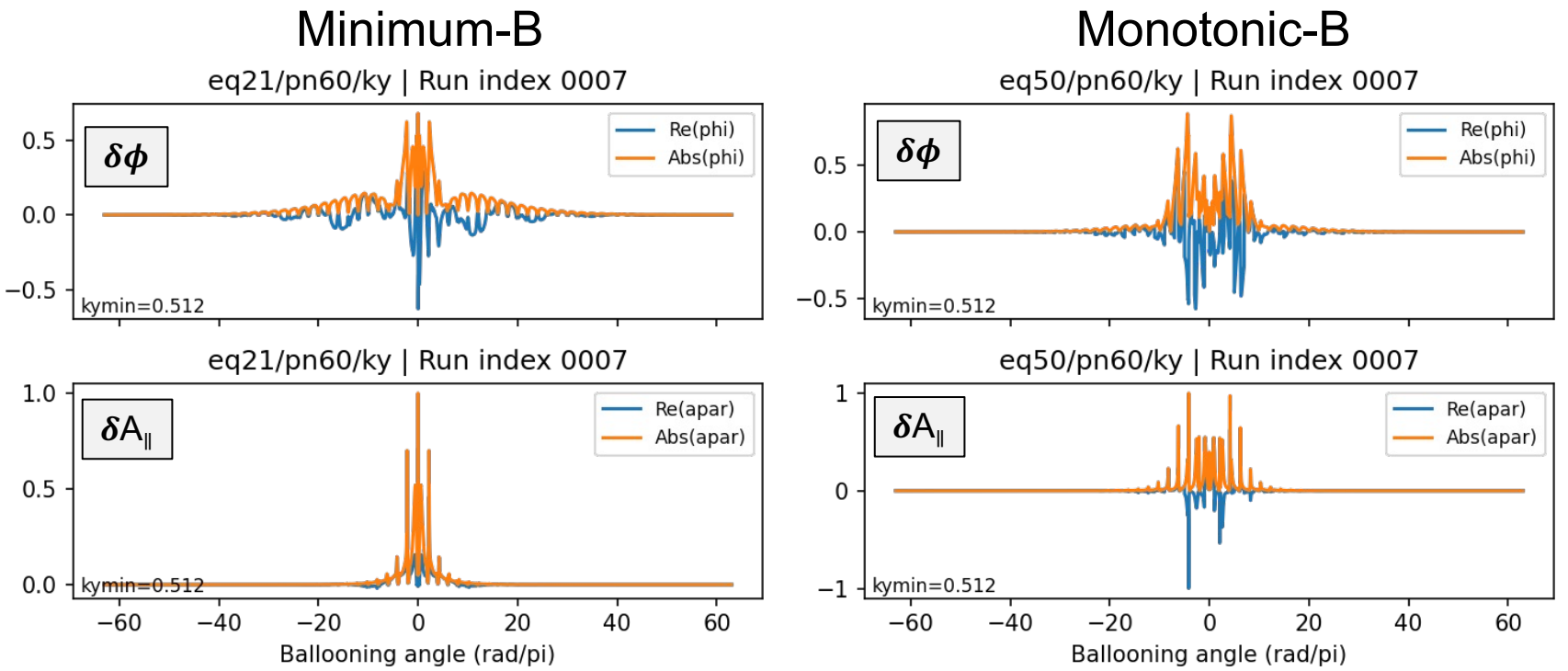


At outer radii, minimum-B is stabilizing, and monotonic-B is destabilizing

The parallel mode structure is narrower for modes stabilized in the minimum-B configuration



$k_y \rho_s$ = 0.51



Partially stabilized modes in the minimum-B configuration show narrower mode structures

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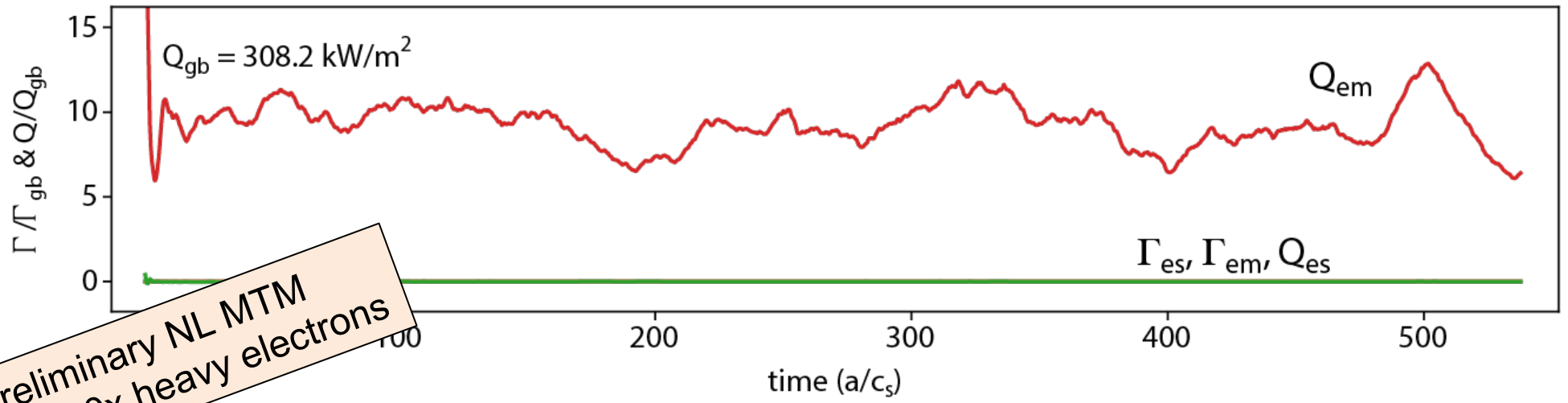
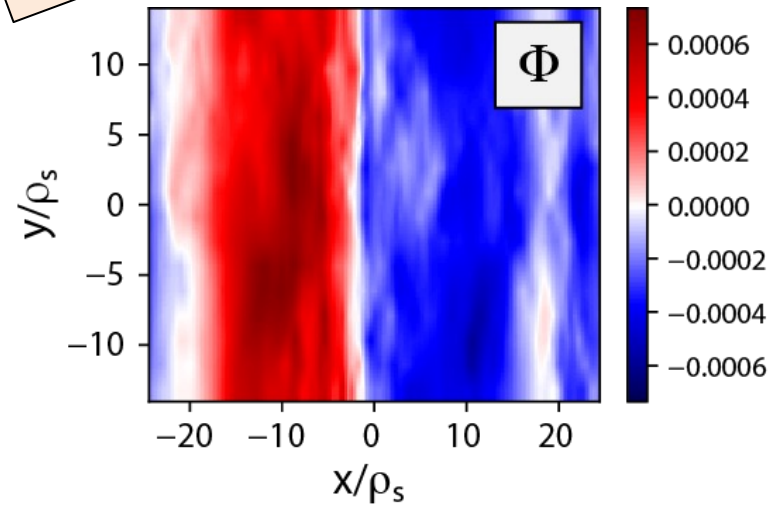
Nonlinear simulations of minimum-B regime show MTM turbulence with radially narrow $j_{||}$ structures and radially extended $A_{||}$ structures

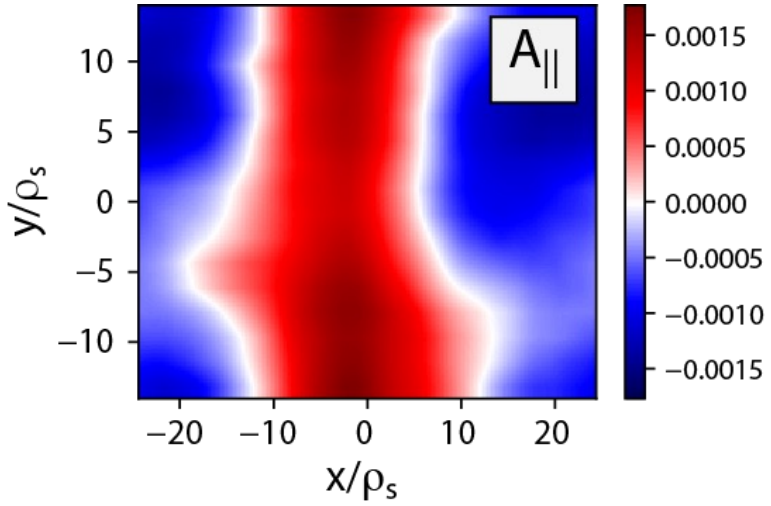


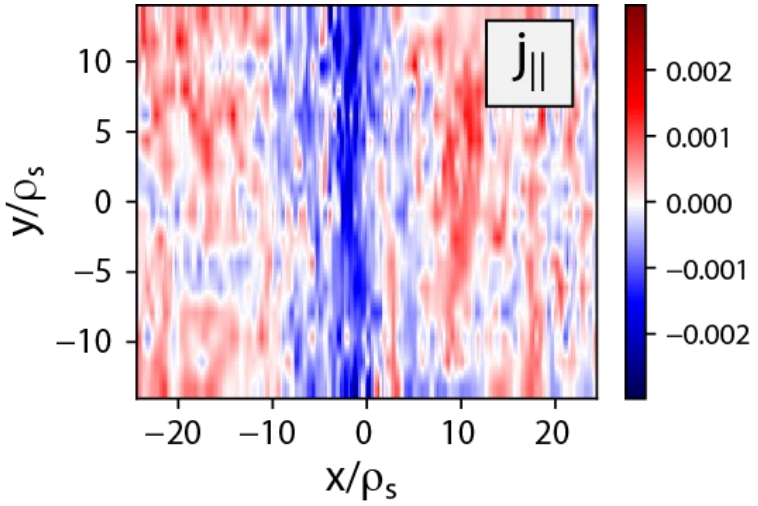
Preliminary NL MTM with 10x heavy electrons

Min-B @ Ψ_N=0.5
adiabatic ions
nx = 256
ny = 16
nz = 128
$nv_{||}$ = 32
$nv_{\perp}$ = 8

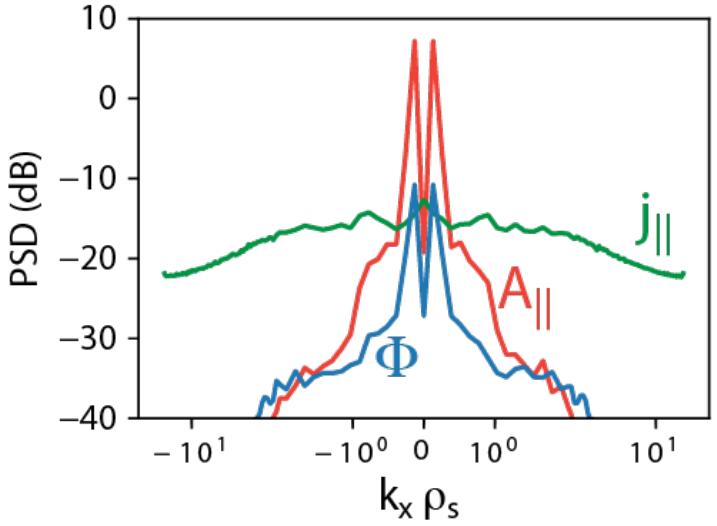
2,200 node-hours on Cori Haswell

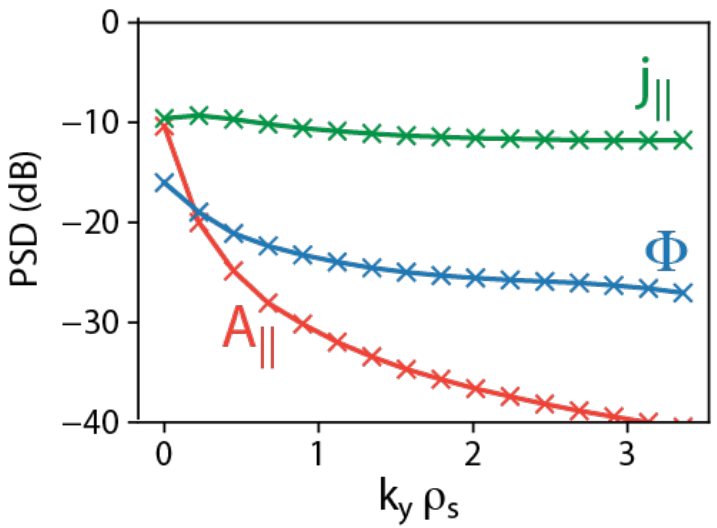


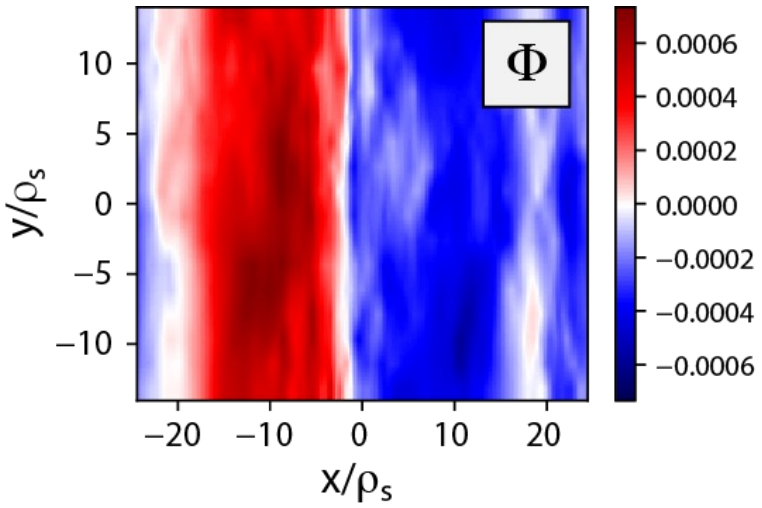


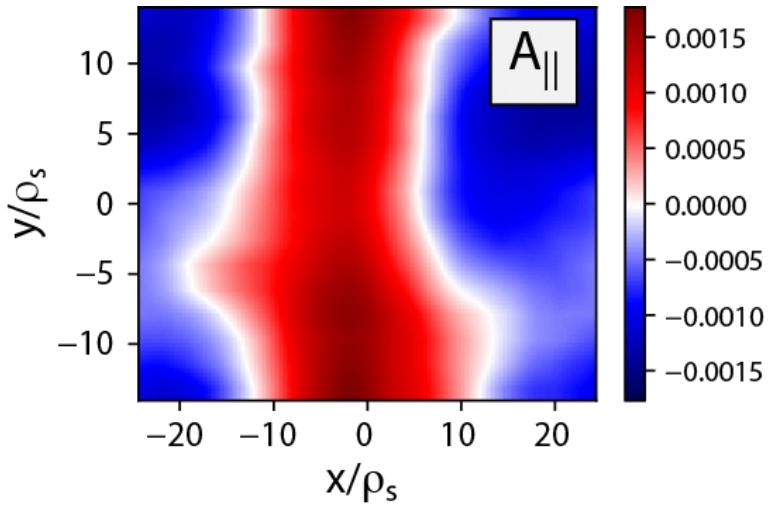


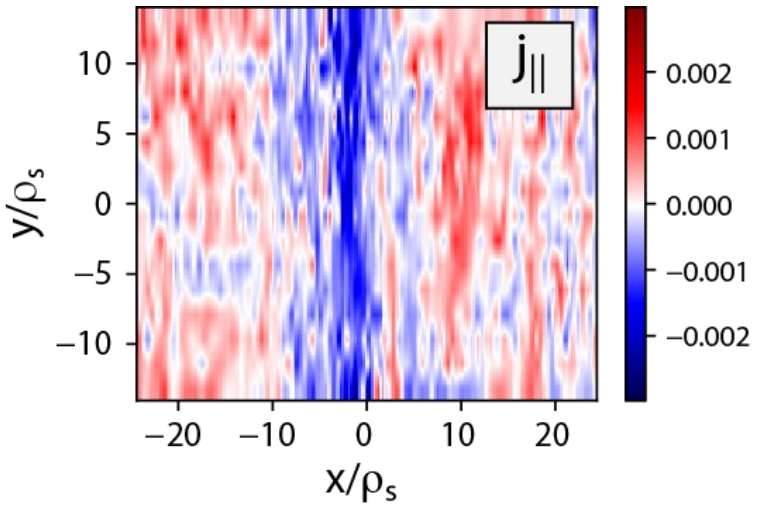
Nonlinear simulations of minimum-B regime show MTM turbulence with radially narrow $j_{||}$ and Φ structures and radially extended $A_{||}$ structures



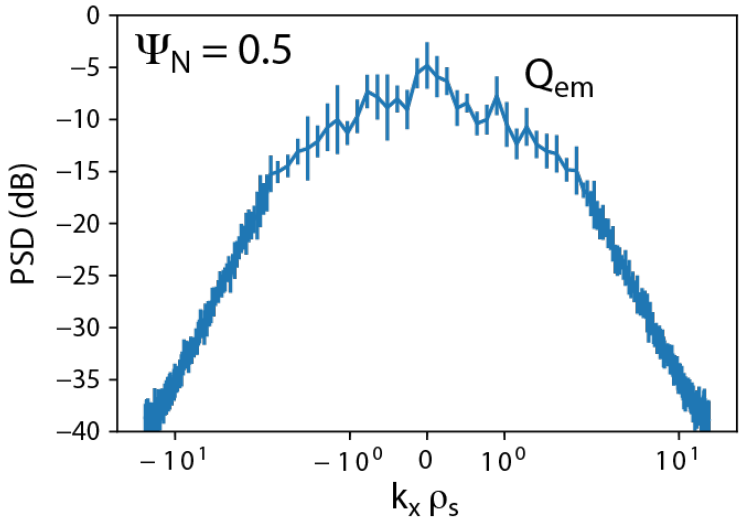


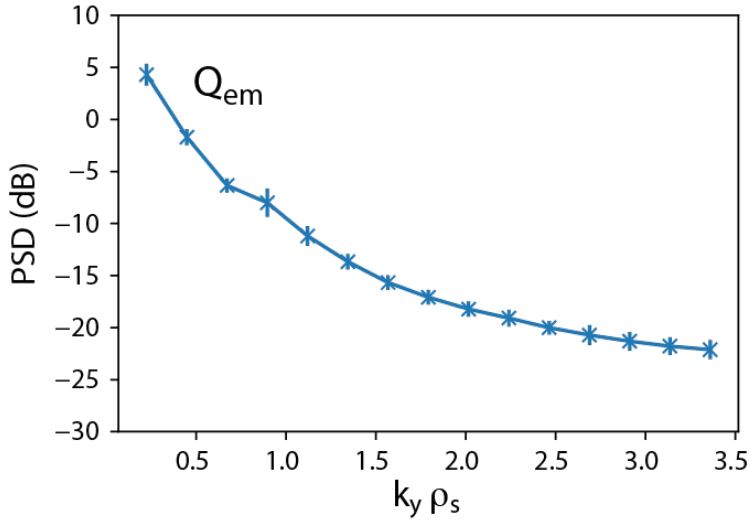


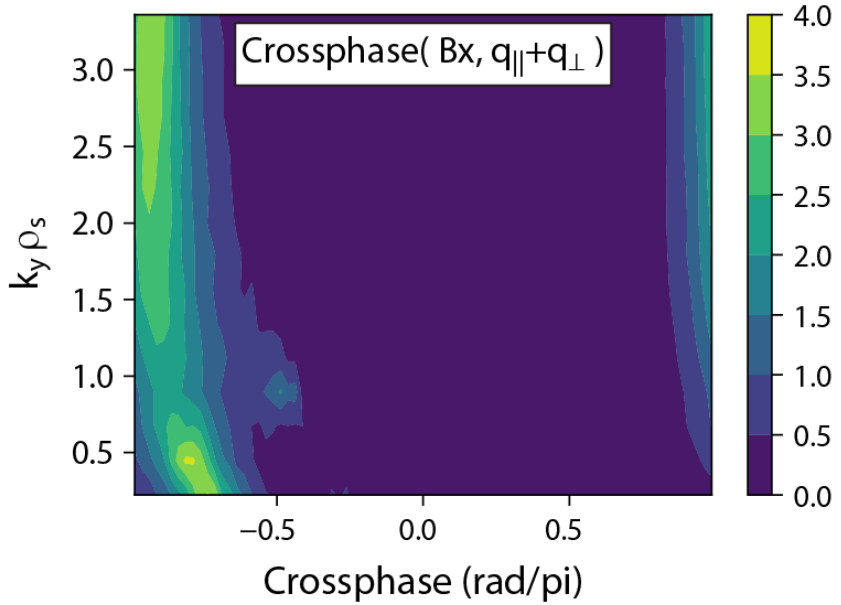




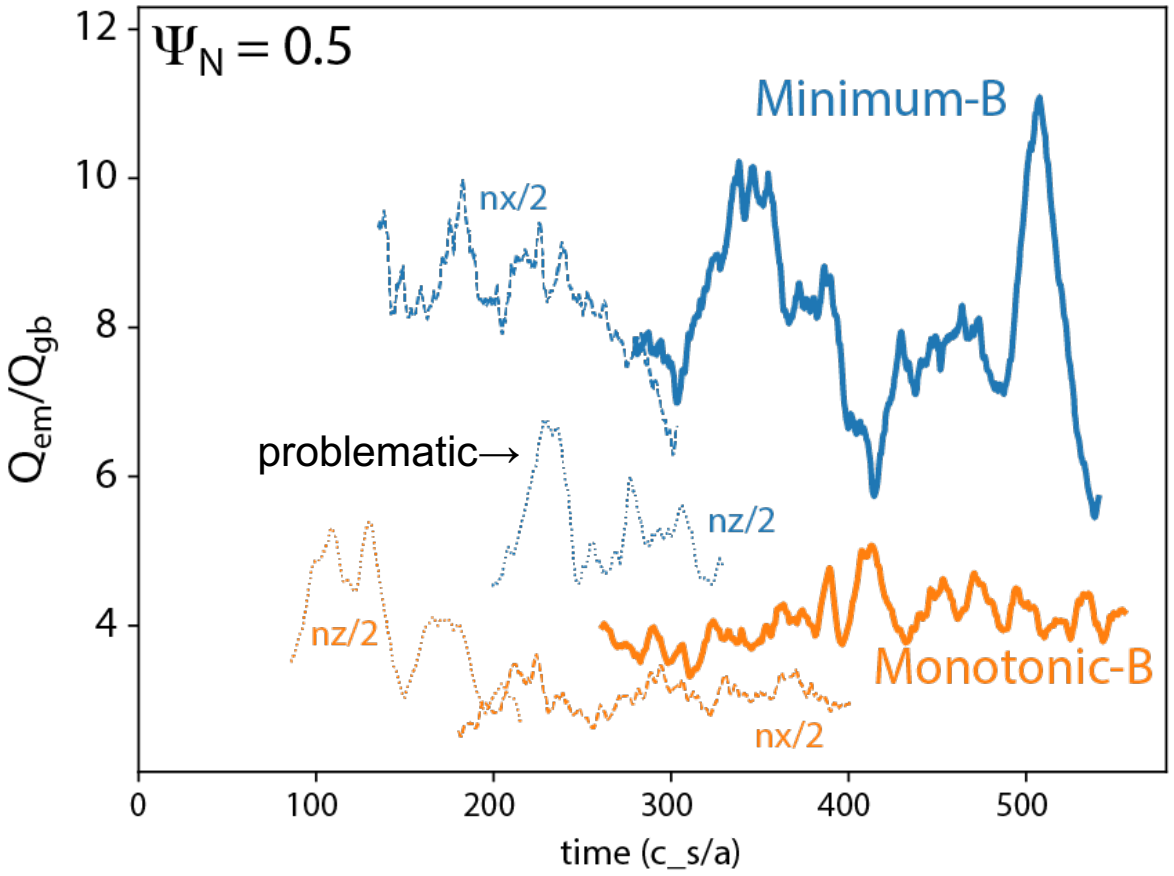
Flux spectra show dominant contribution from low-k_y magnetic fluctuations

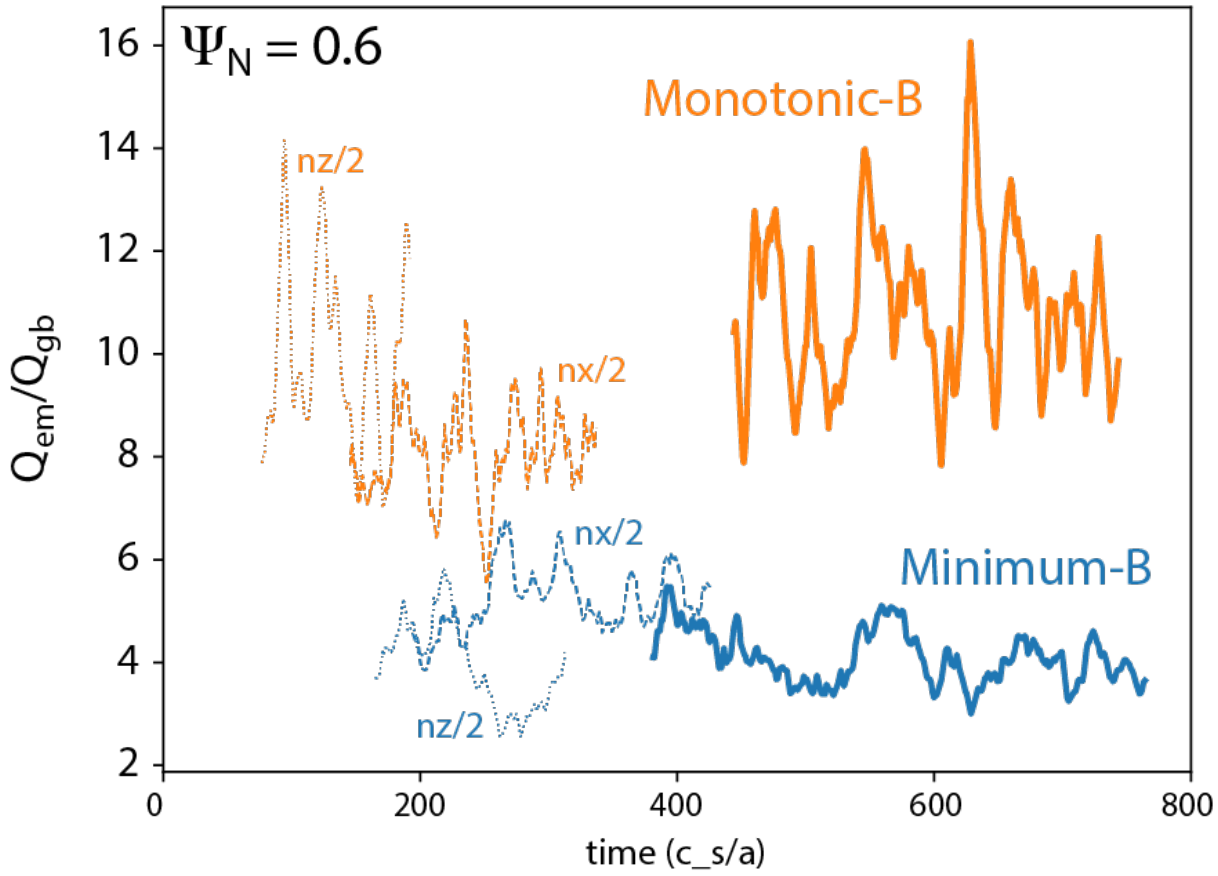




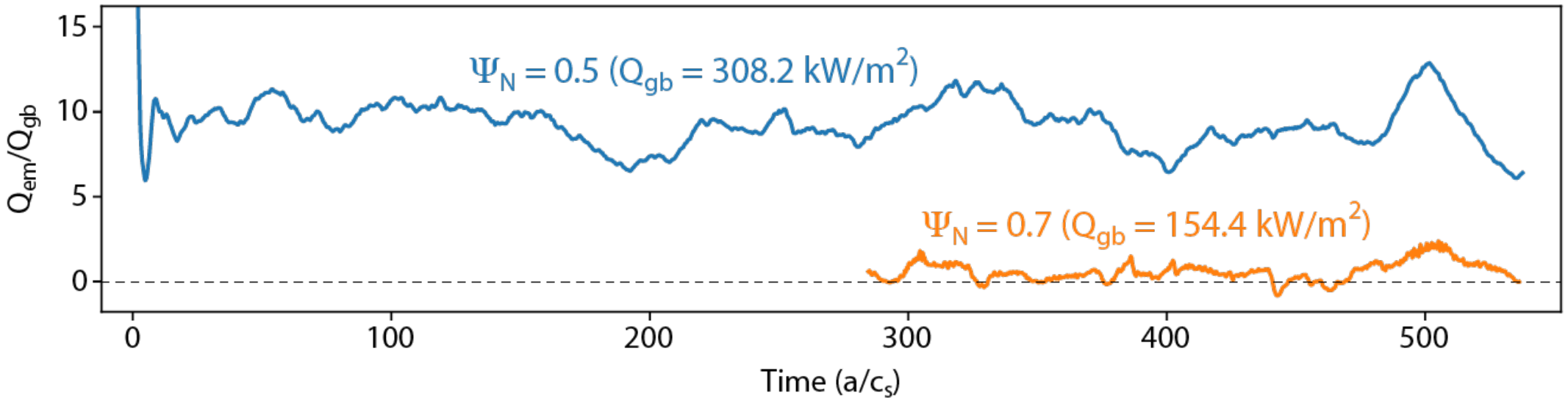


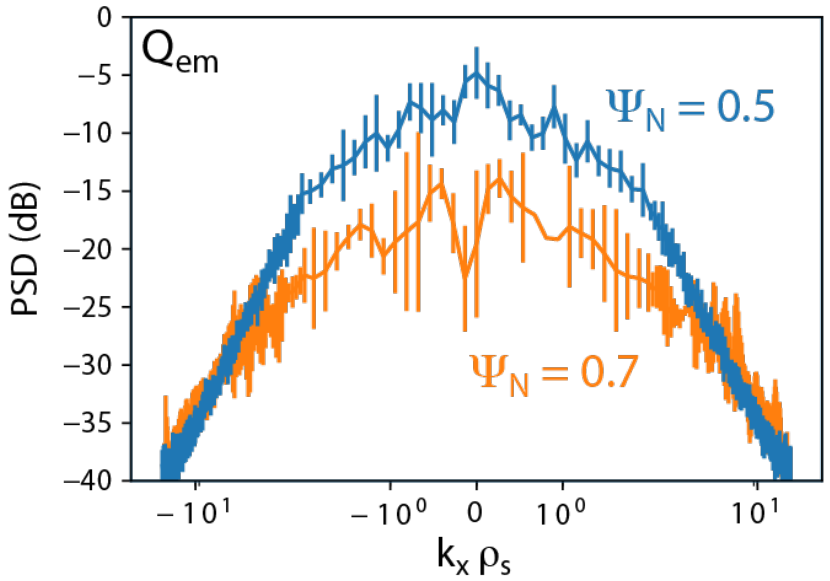
Nonlinear simulations with heavy electrons are largely converged with respect to coarser grids

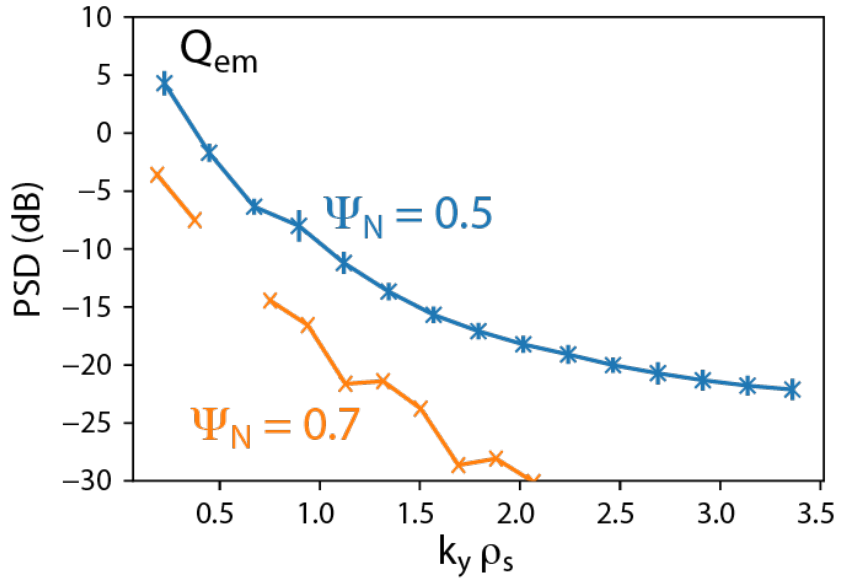




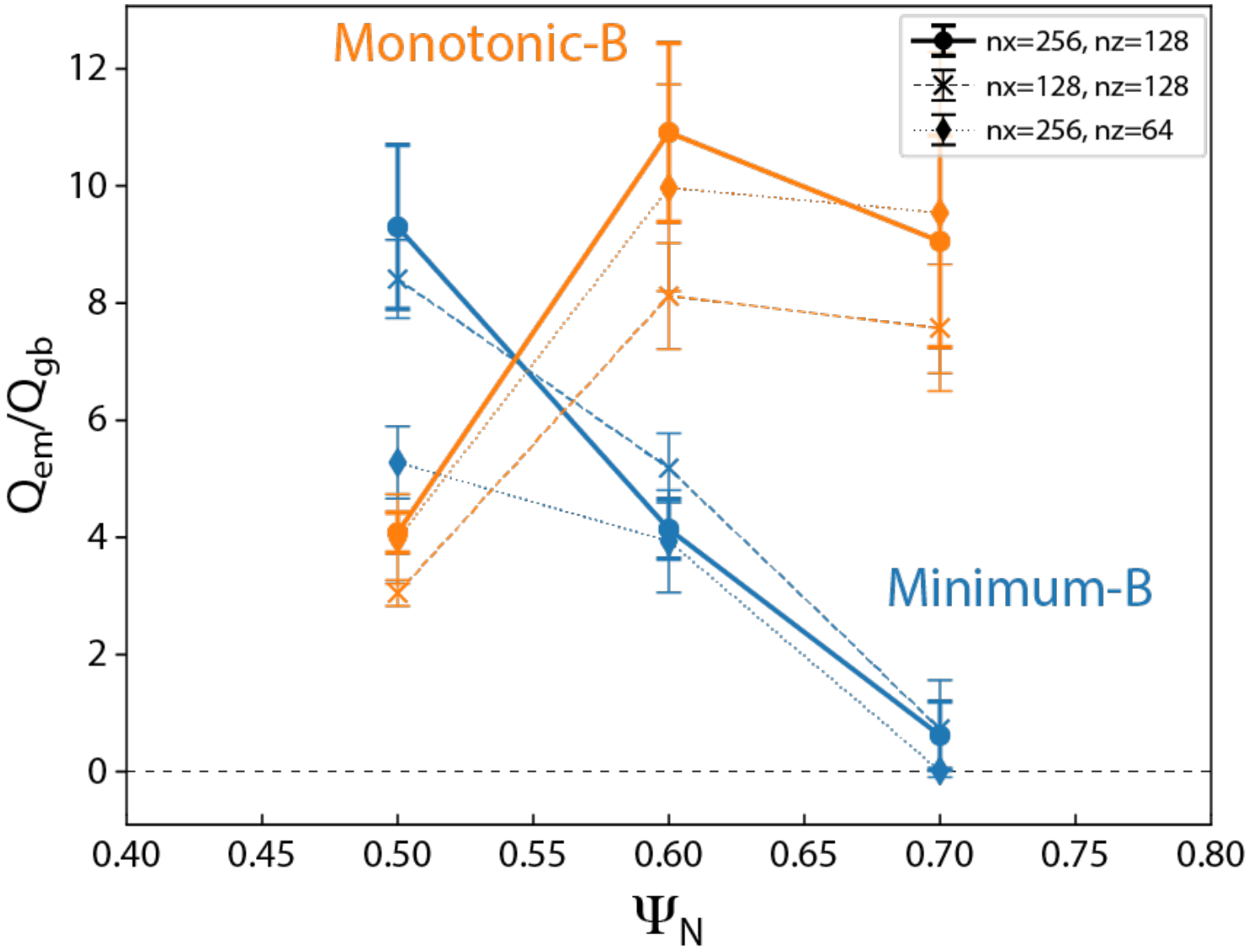
MTM transport with heavy electrons in the minimum-B configuration decreases at outer radii







The minimum-B configuration shows reduced MTM transport with heavy electrons near the edge where monotonic-B MTM transport is high



Reduced MTM transport in the minimum-B configuration points to a high-β ST regime with enhanced confinement

Summary of results

- Collisional MTMs with extended parallel mode structures are unstable in the high-β ST
  - $\Psi_N \approx 0.4\text{-}0.8$ and $k_y\rho_s \approx 0.1\text{-}3$
- MTMs at outer radii are stabilized in a minimum-B configuration (diamagnetic well), but remain unstable in a monotonic-B configuration
- Similarly, MTM transport with heavy electrons decreases at outer radii in the minimum-B configuration, but the transport increases at outer radii in the monotonic-B configuration
  - Suggests the high-β diamagnetic well offers a favorable confinement regime with MTM suppression, possibly in conjunction with full drift-wave suppression