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PEGASUS
Toroidal Experiment

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

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Outline

- Background on 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)
  - MTMs are linearly stabilized in the outer region of the diamagnetic well
  - Additional topics: extended parallel mode structure, collisionality scaling, role of electric potential $\boldsymbol{\Phi}$, fieldline curvature
- MTM-driven transport is suppressed in the diamagnetic well
  - Points to a high-β ST regime with enhanced confinement, possibly in conjunction with β stabilization of drift waves

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 B_r is radially broad

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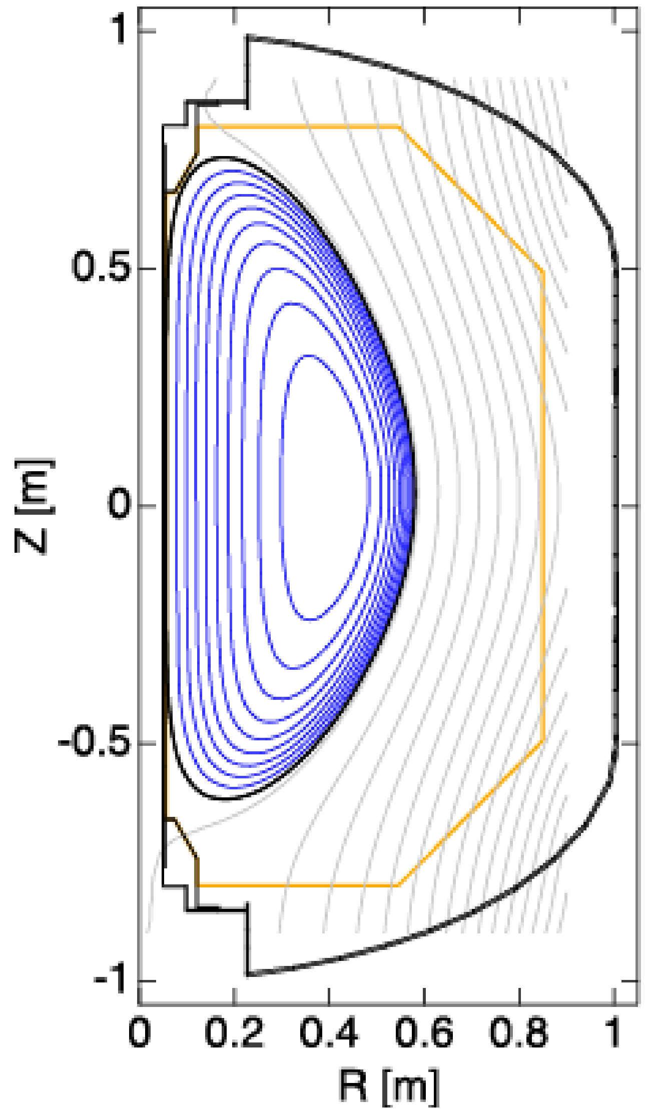
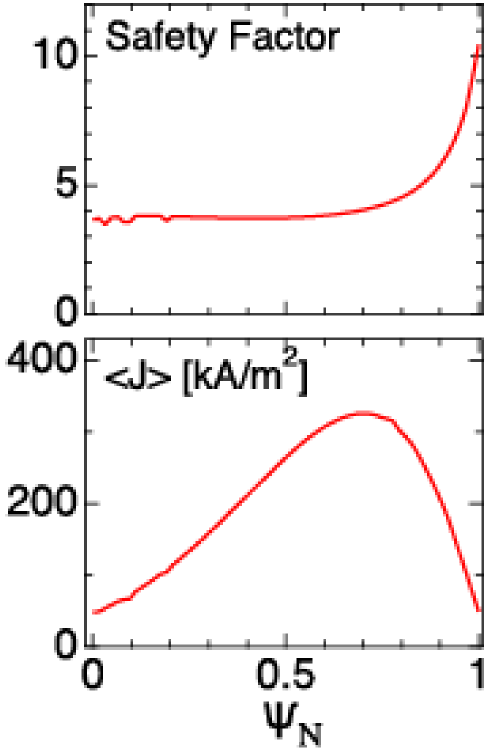
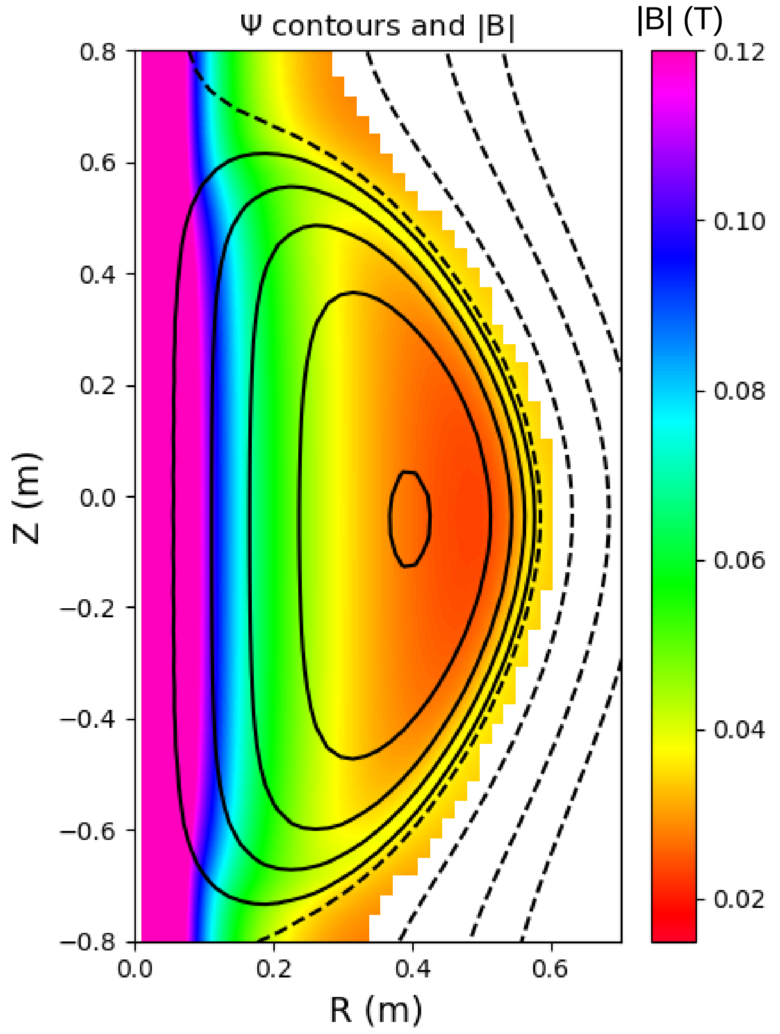
High-field-side local helicity injection (LHI) in Pegasus achieves β~100% with edge current peaking



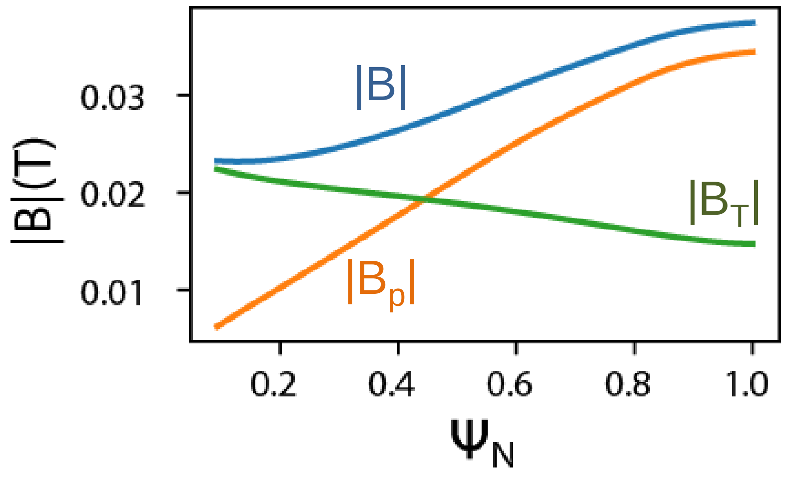


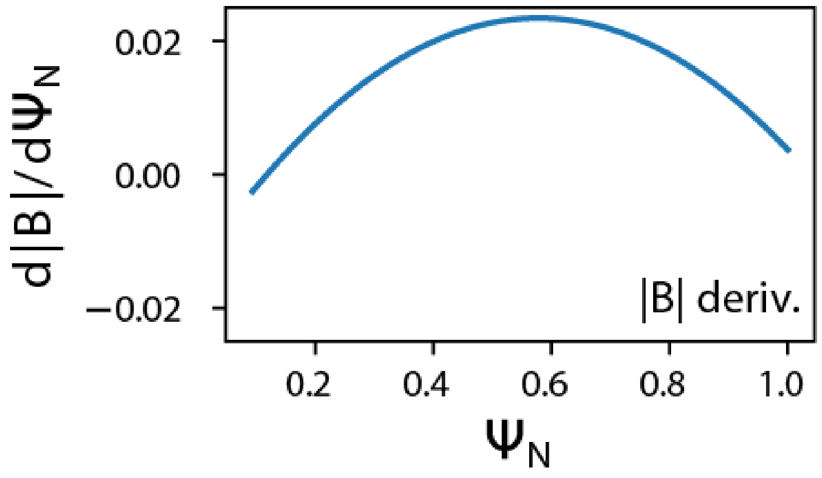
D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. thesis, 2017

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



Magnetic field on outboard midplane (|B| is not a flux function)

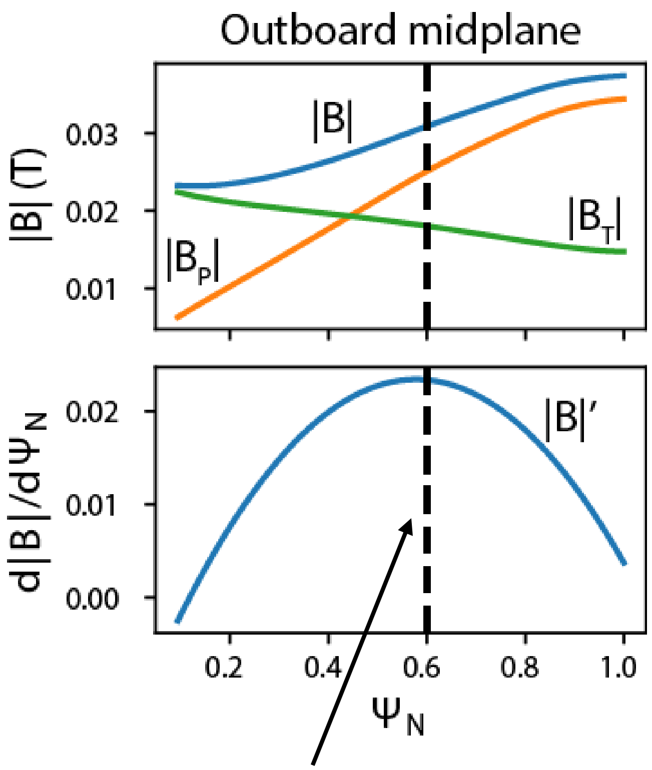




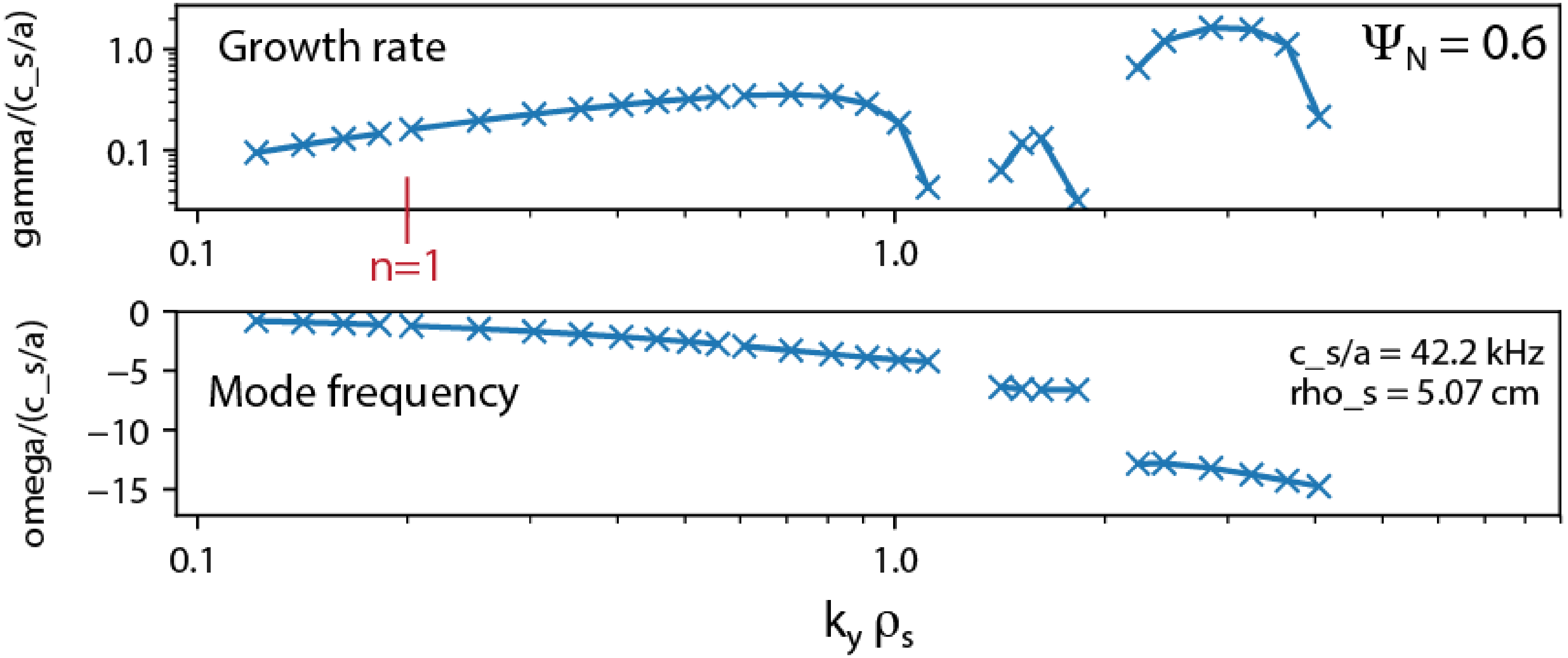
$\frac{d|B|}{d\Psi_N} > 0$ is magnetic well

STs are strongly paramagnetic (I_P enhances B_T through J approx. parallel to B at large pitch angle), but gyromotion is diamagnetic such that high β can diminish B. Peng & Strickler, NF 1986

GENE linear flux-tube calculations show unstable modes propagating in the electron diamagnetic direction



simulation location
at max ∇B reversal

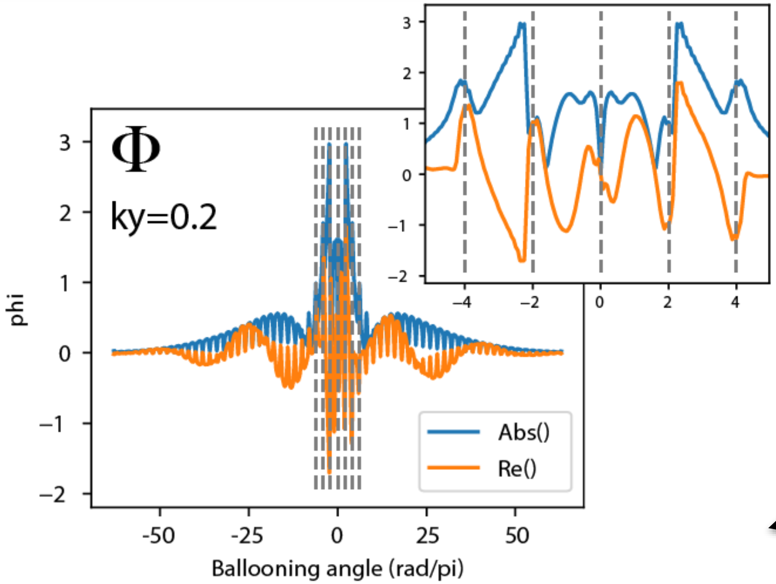


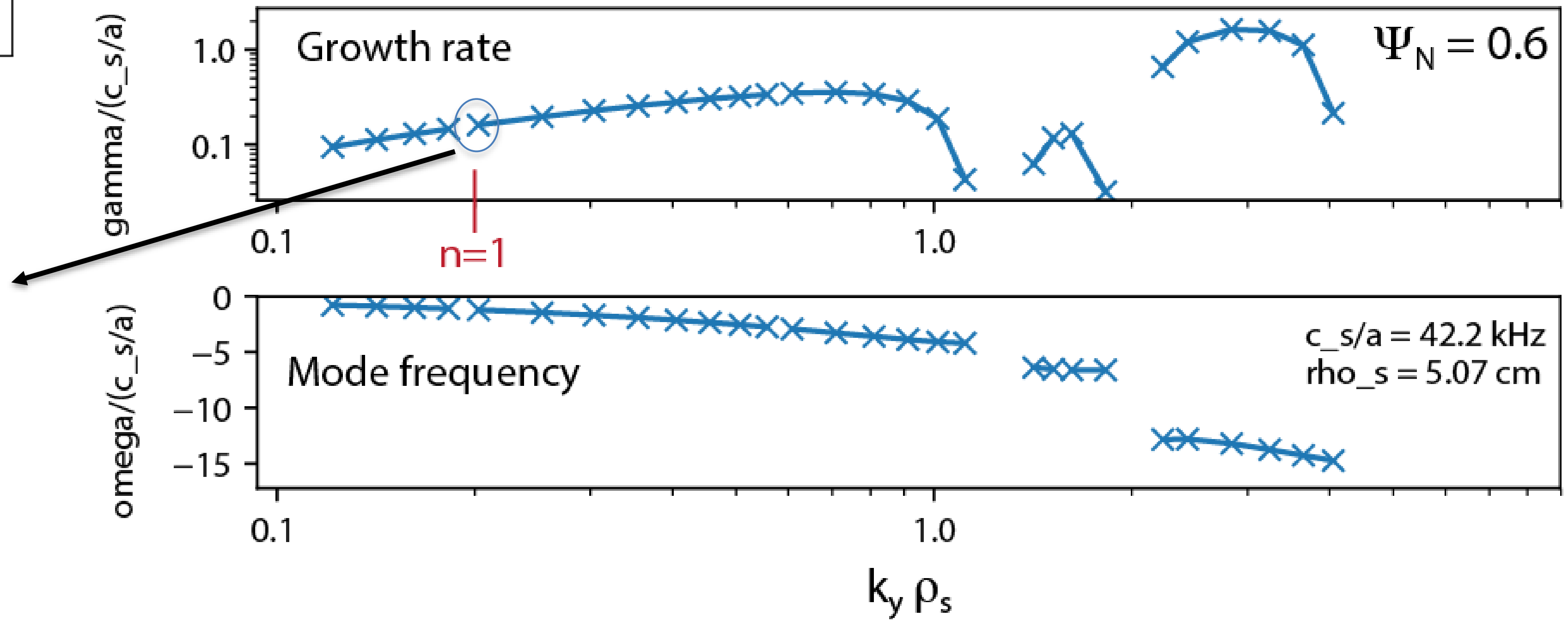
B_0 = 0.029 T
T = 0.1 keV
n = 0.55 $10^{19}/m^3$
ρ_s = 5.1 cm
$\rho^* = \rho_s/a$ = 0.2
adiabatic ions

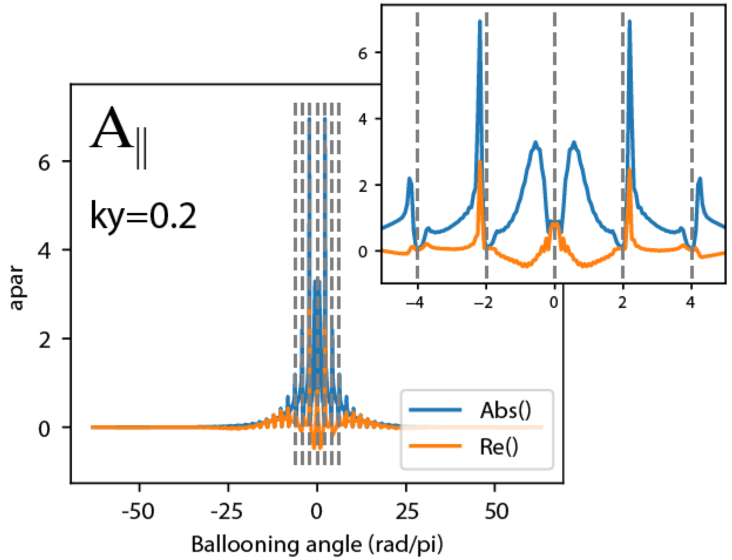
Ψ_N = 0.6
r/a = 0.786
$\varepsilon = r/R_0$ = 0.59
a/L_T = 4.4
a/L_n = 1.9

β = 27%
q = 3.5
$\hat{s}$ = 0.55
α_{MHD} = 56.6
ν^*_e = 0.14

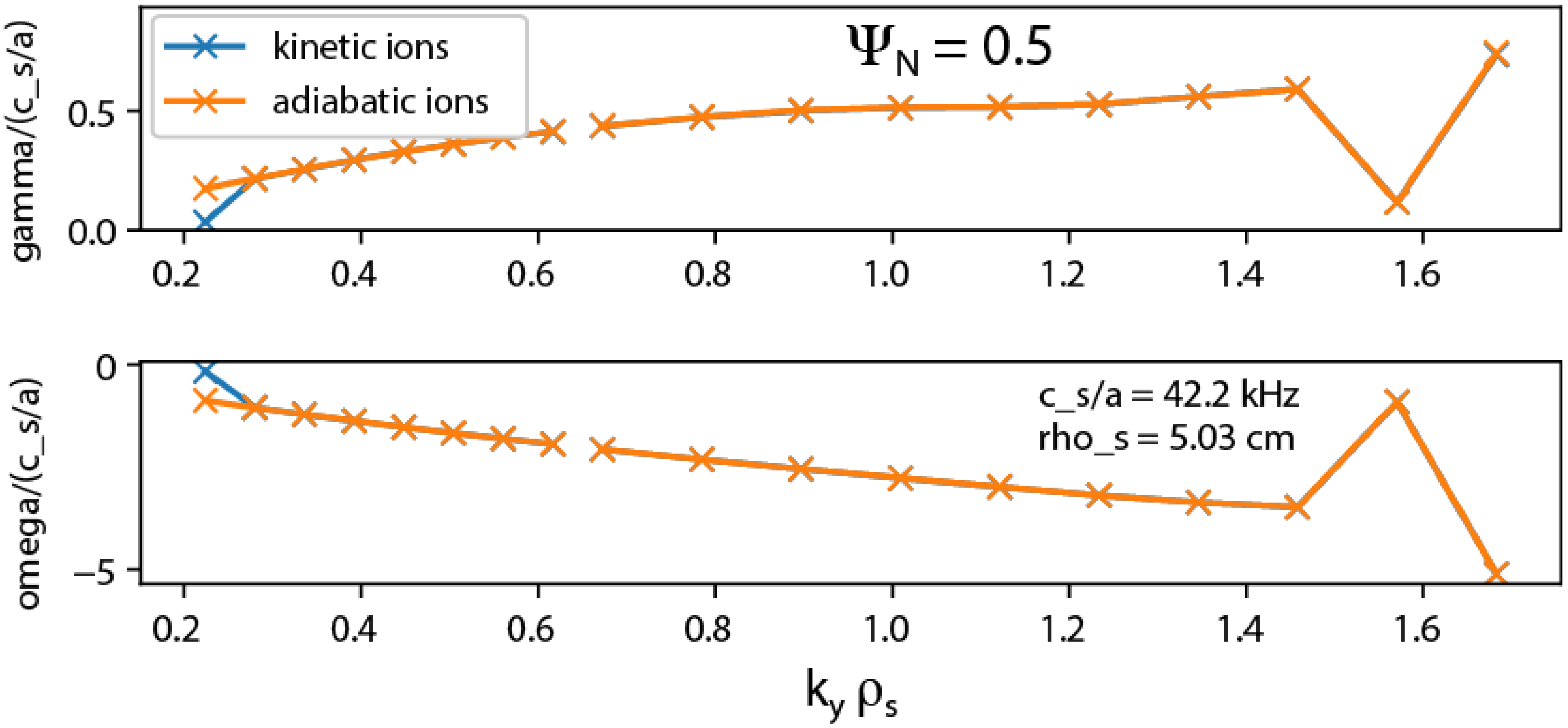
Spatially-extended, tearing parity mode structures







Mode characteristics are insensitive to ion dynamics

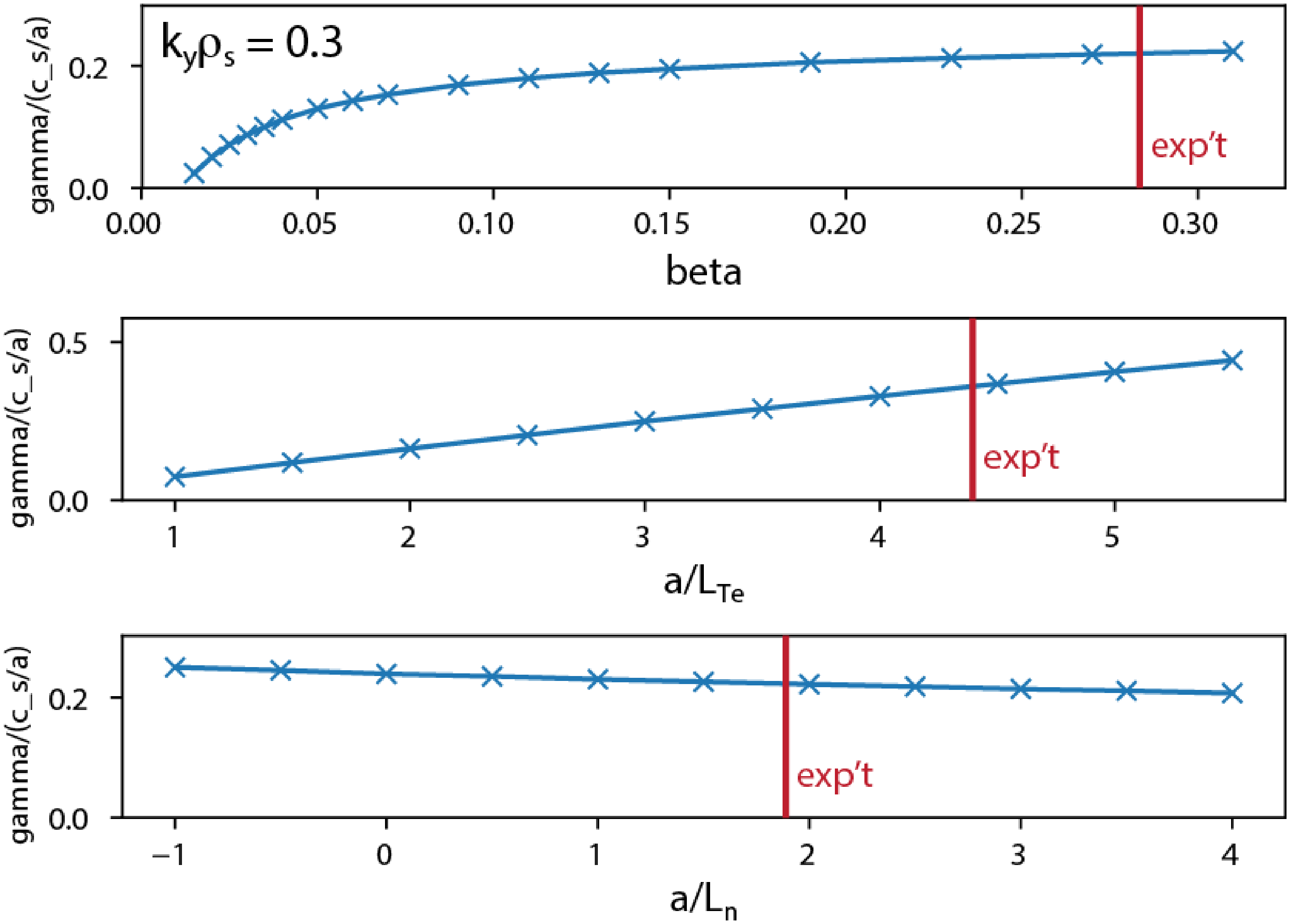


Beta and a/L_{Te} scans confirm modes are MTM

Critical β →

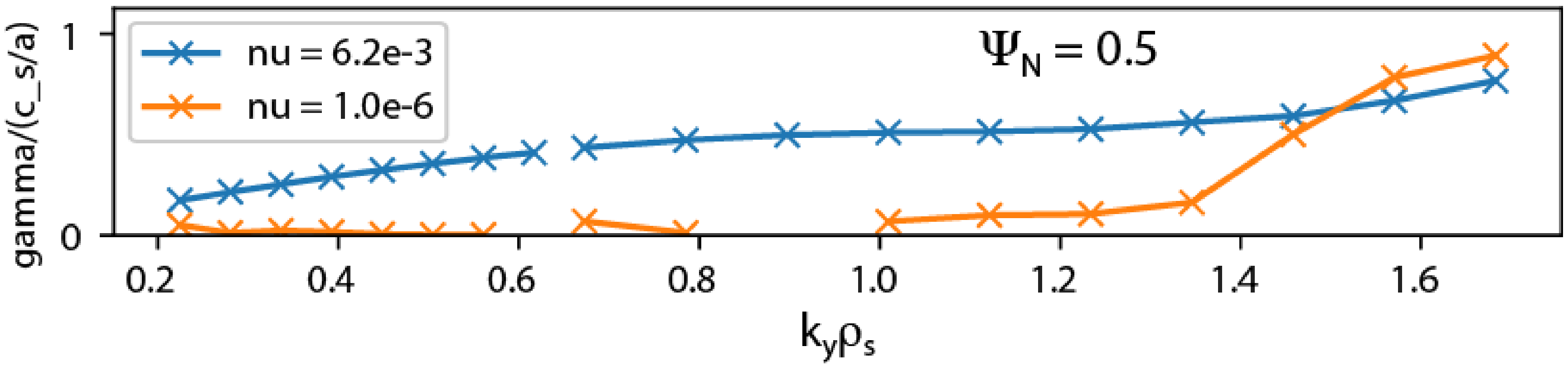
Critical a/L_{Te} →

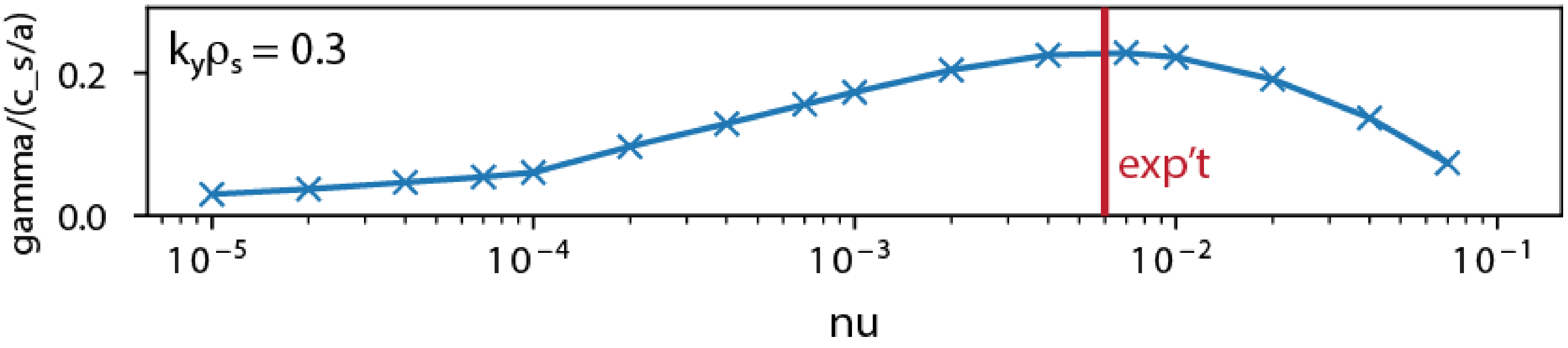
Insensitive to a/L_n →



α_{MHD} fixed in above scans

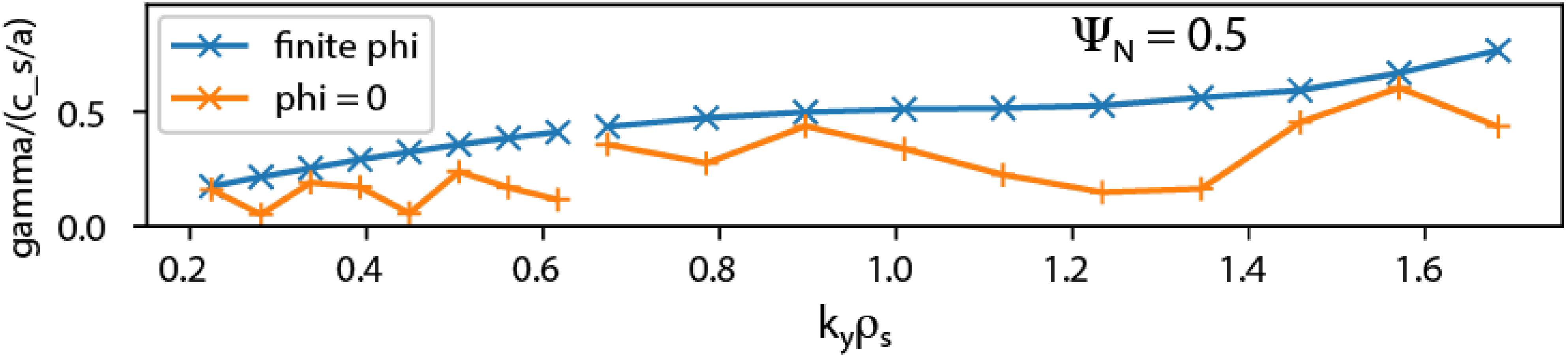
Modes are collisional MTM with stabilization at low collisionality



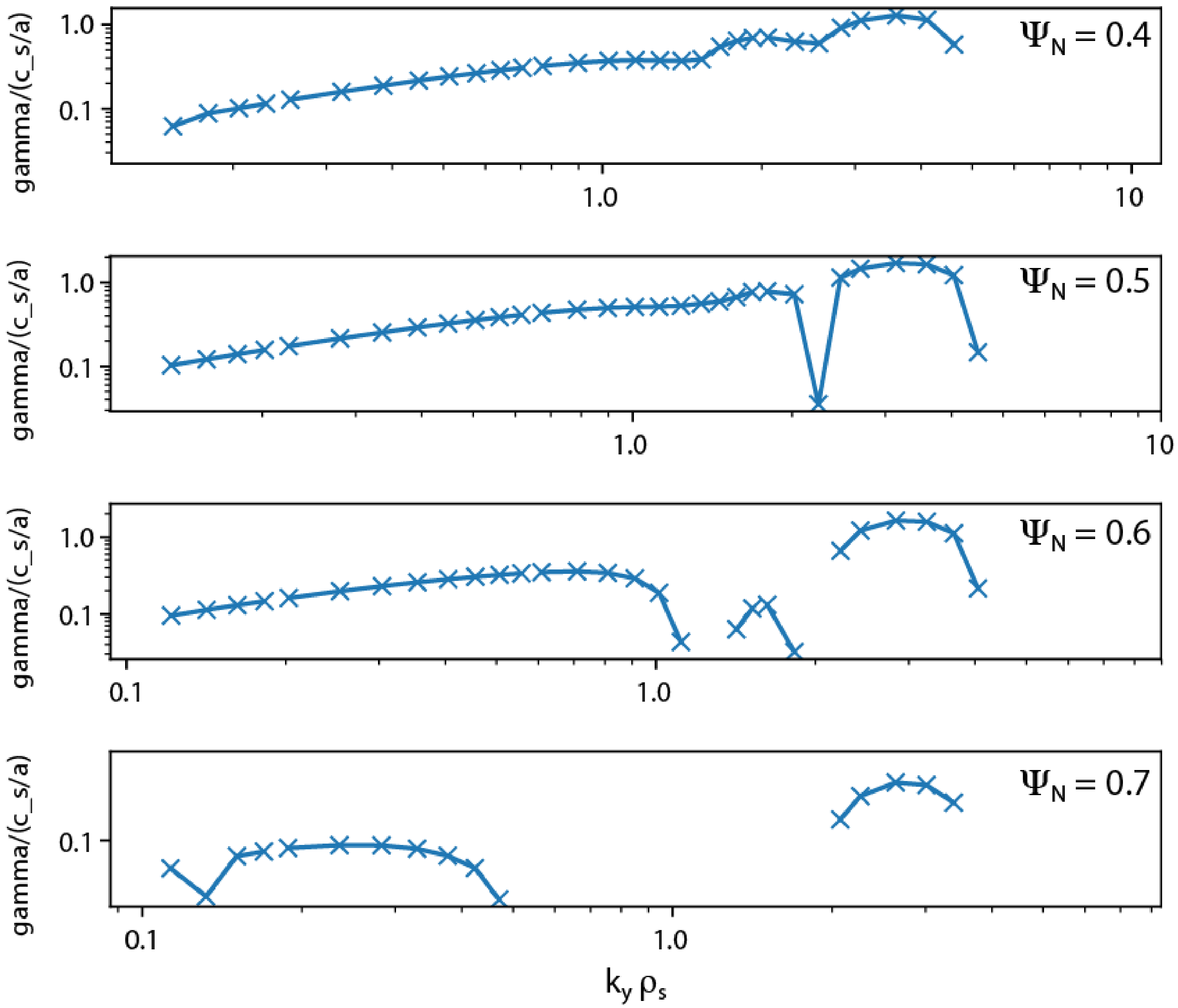


High collisionality inhibits formation of island current layer

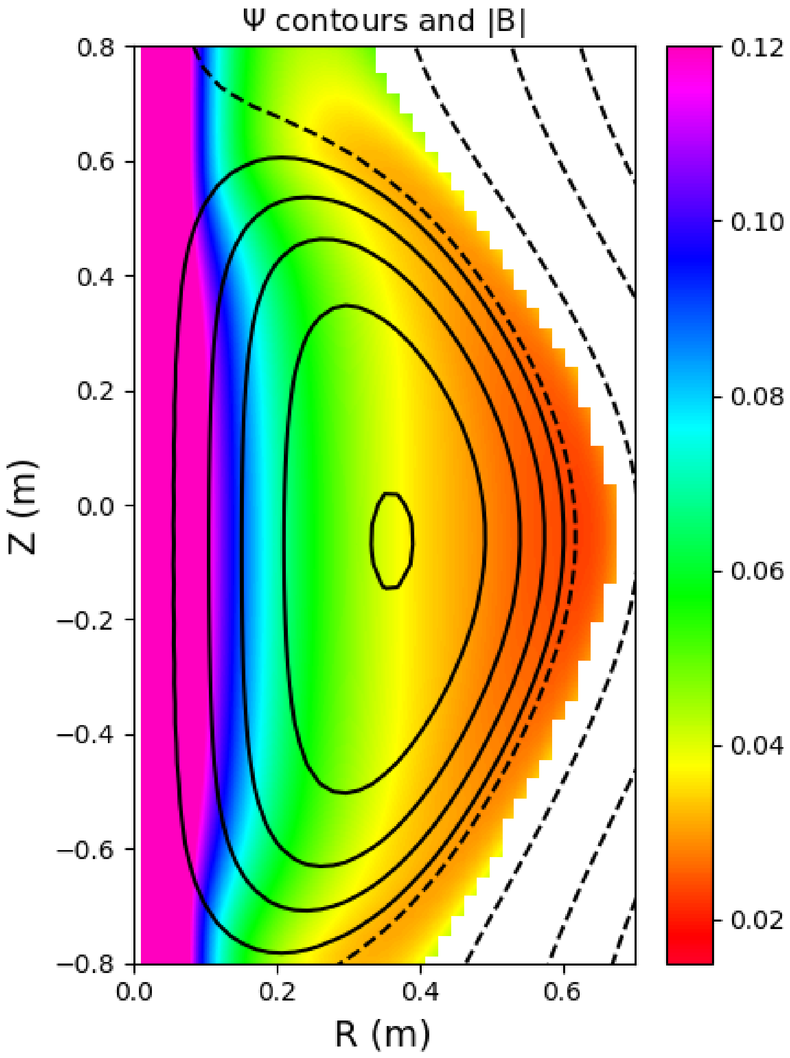
Finite phi required for robust MTM instability



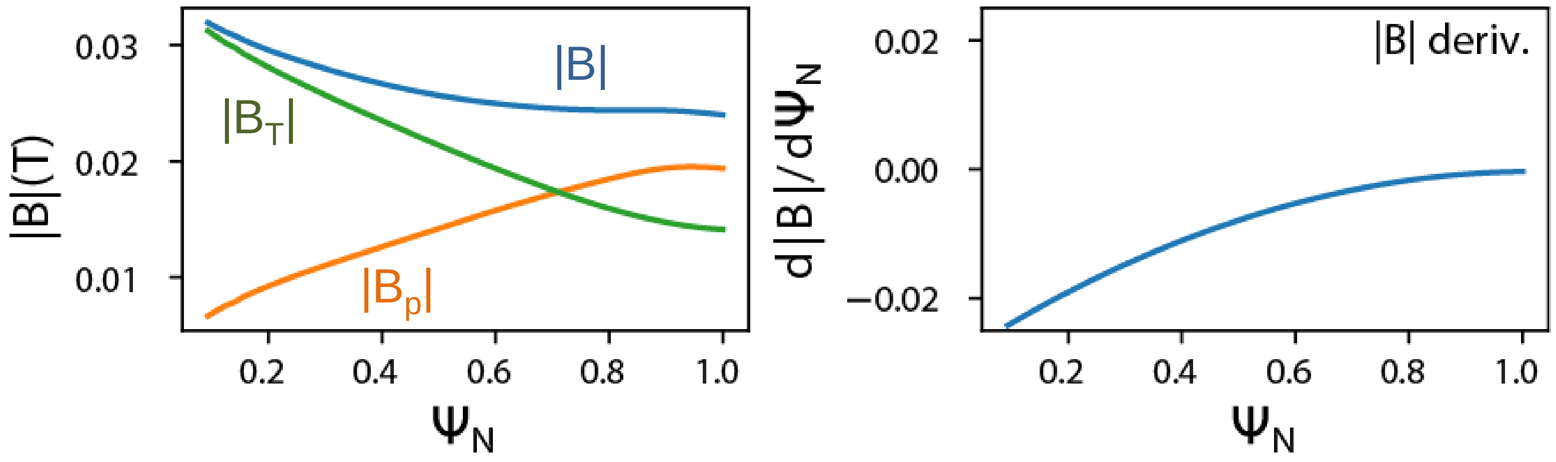
Broadband MTM instability in core; weakened in edge



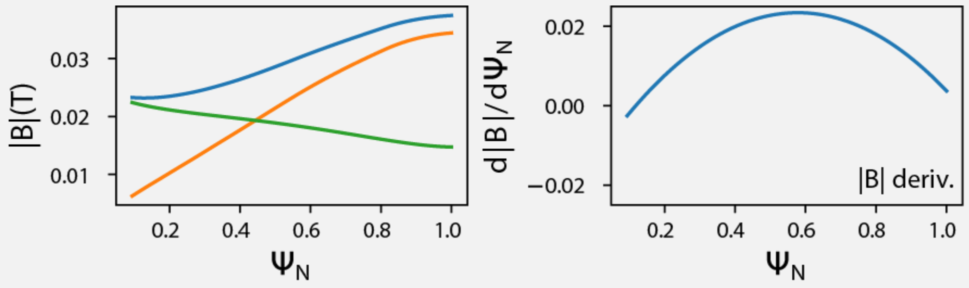
Monotonic |B| equilibrium for comparison



Magnetic field on outboard midplane

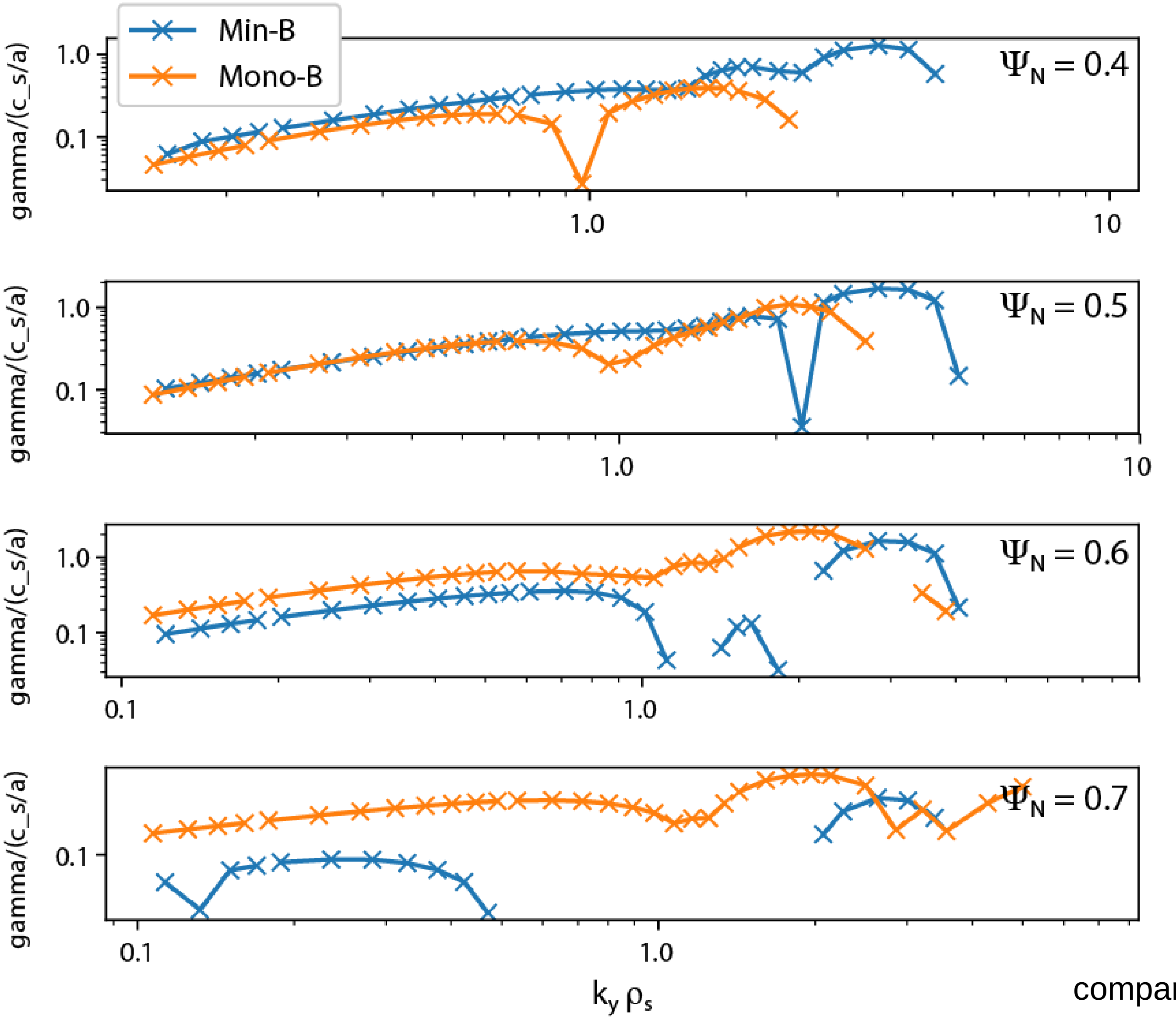


$$\frac{d|B|}{d\Psi_N} < 0 \text{ everywhere} \rightarrow \text{ no mag. well}$$



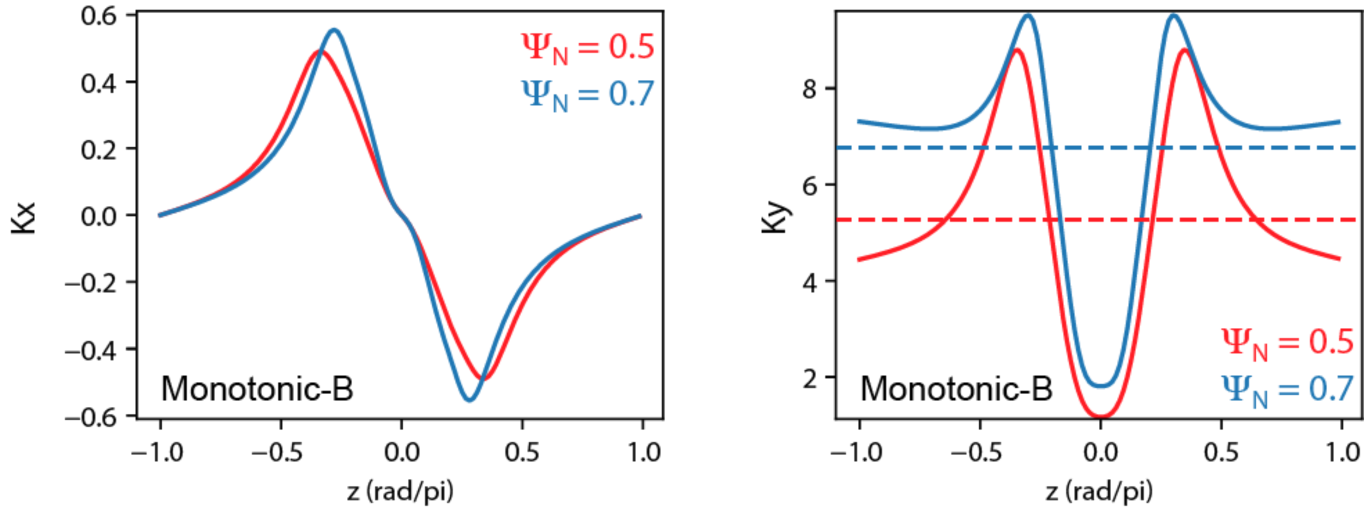
Minimum-B for comparison (see pg. 6)

Minimum-B configuration is stabilizing for MTMs at outer radii

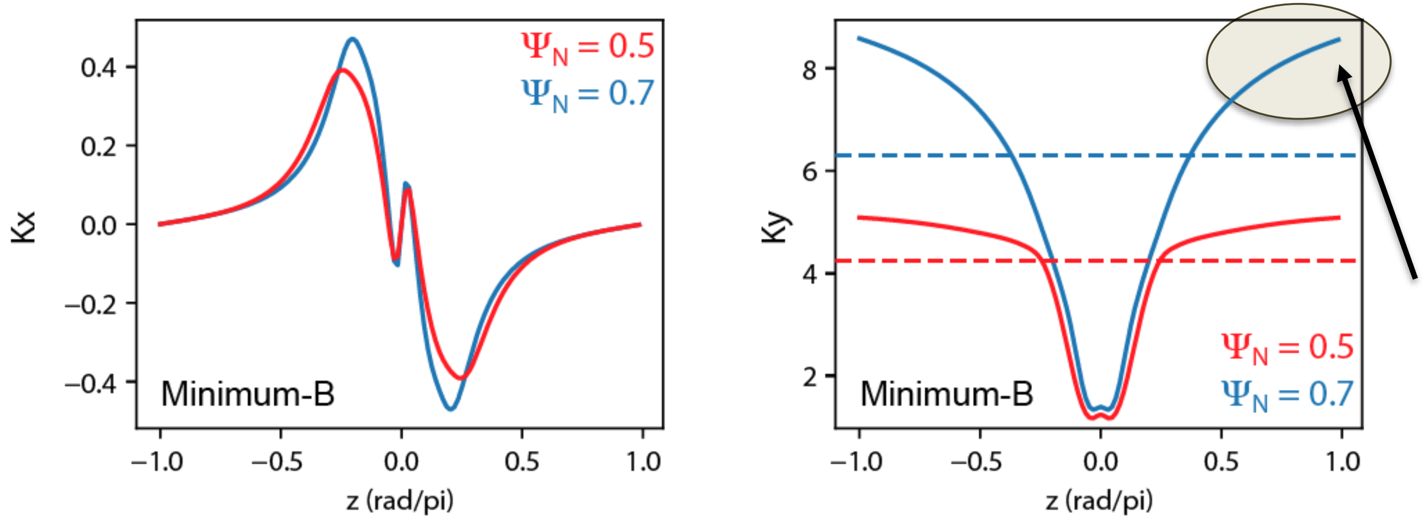


compare with pg. 13

Minimum-B configuration exhibits stronger curvature on the inboard side of outer flux surfaces



Monotonic-B



Minimum-B

Extended region of stronger curvature on inboard side of outer flux surfaces.
Is this stronger curvature responsible for the observed MTM suppression?

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Preliminary NL MTM with 10x heavy electrons

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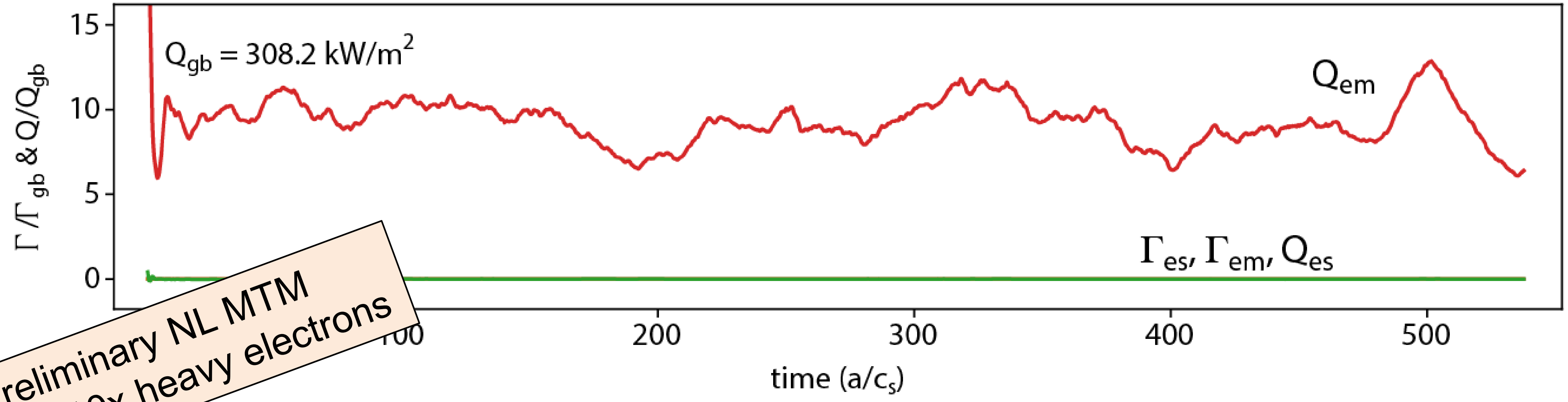
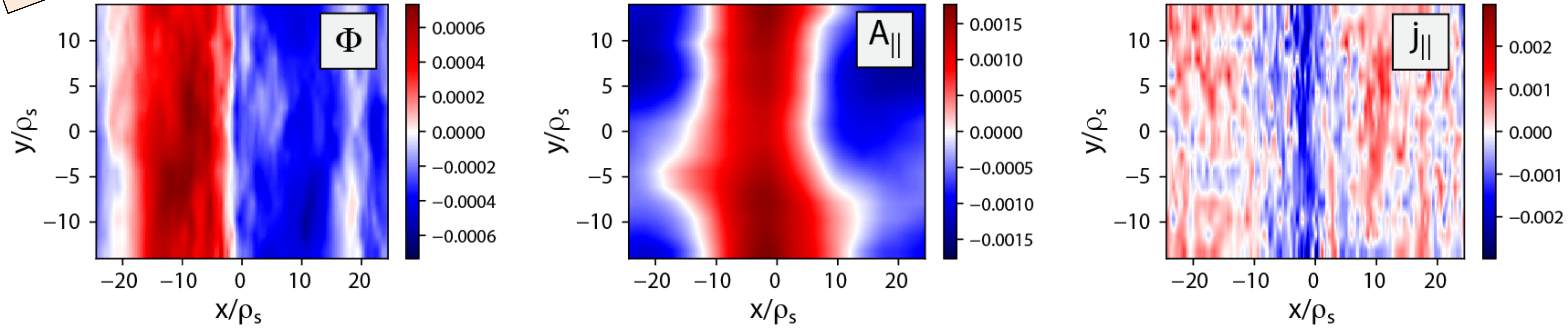
Nonlinear simulations of minimum-B regime show MTM turbulence with radially narrow $j_{||}$ structures and radially extended $A_{||}$ structures



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



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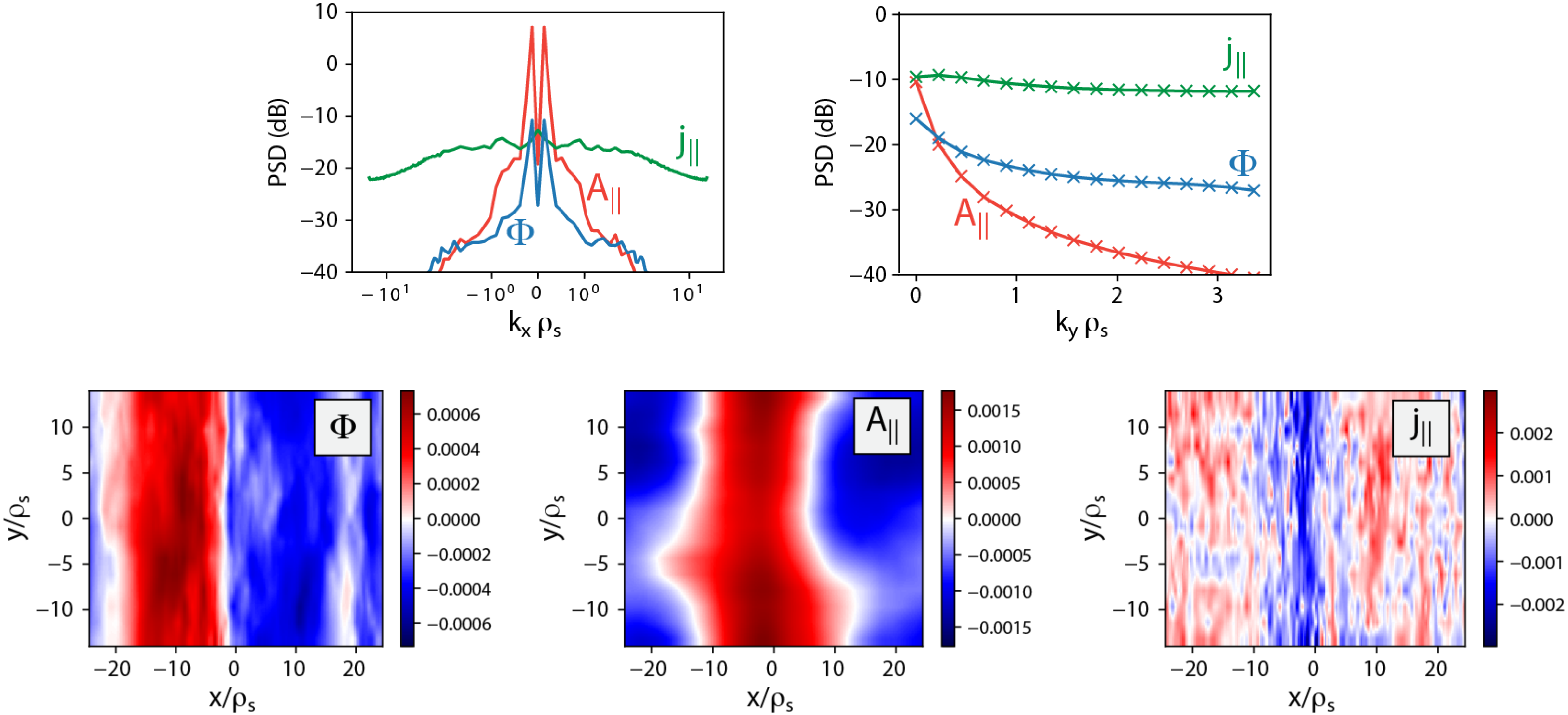
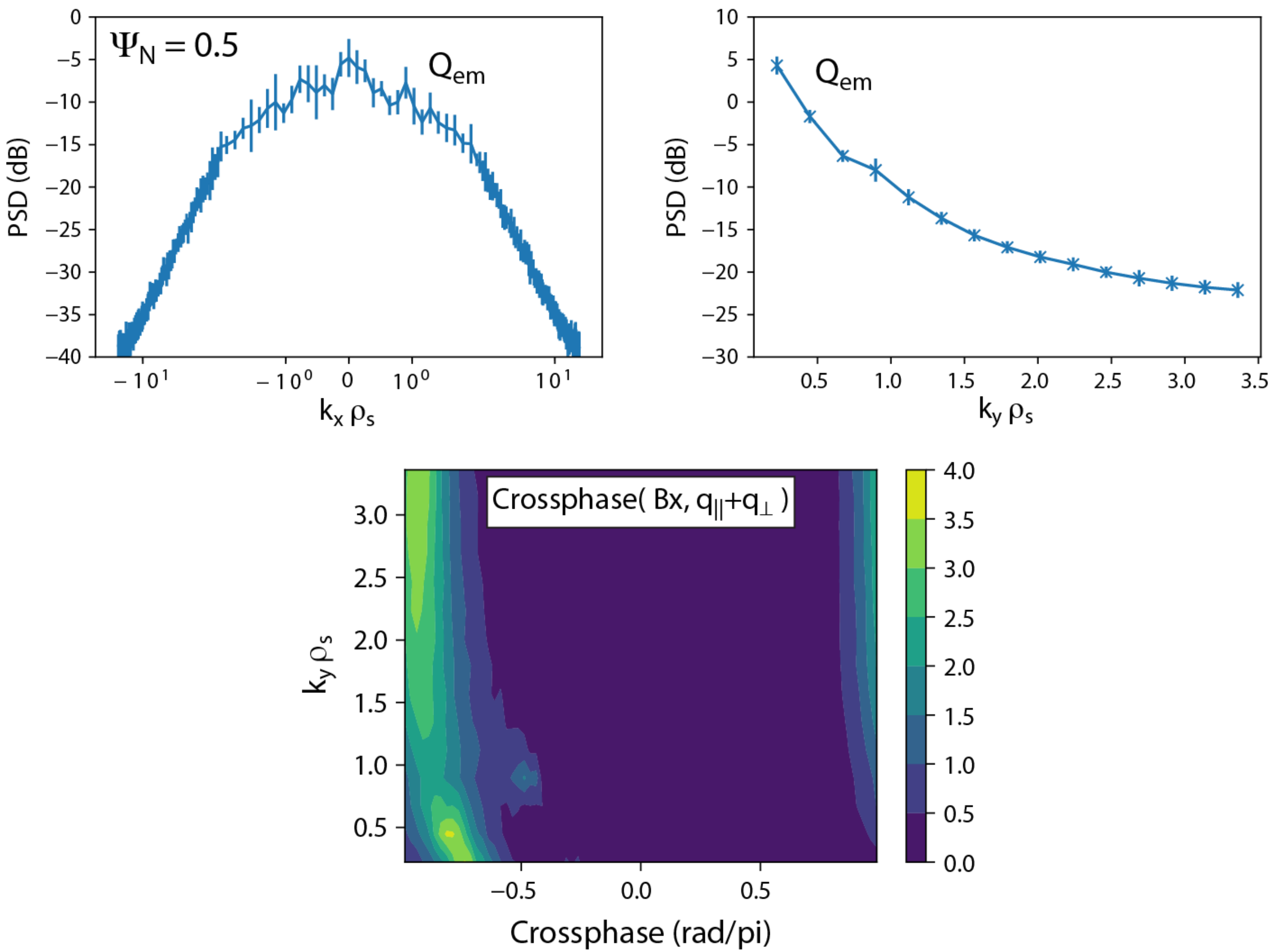
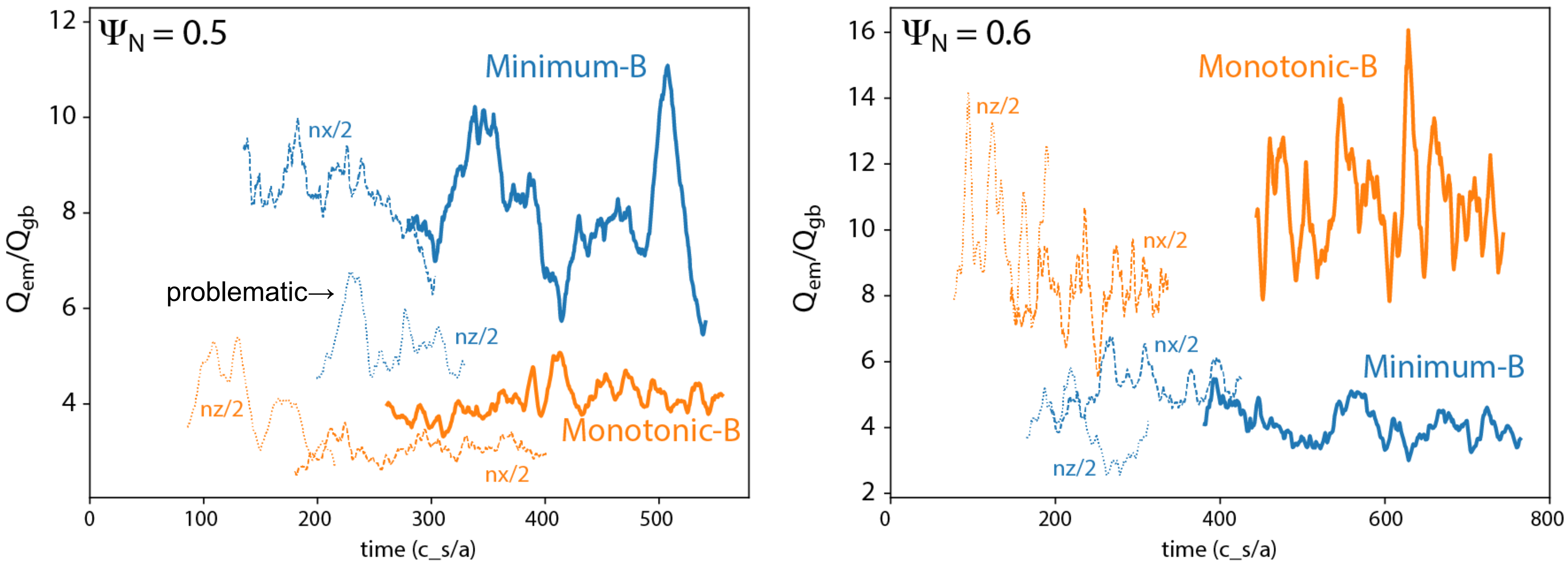


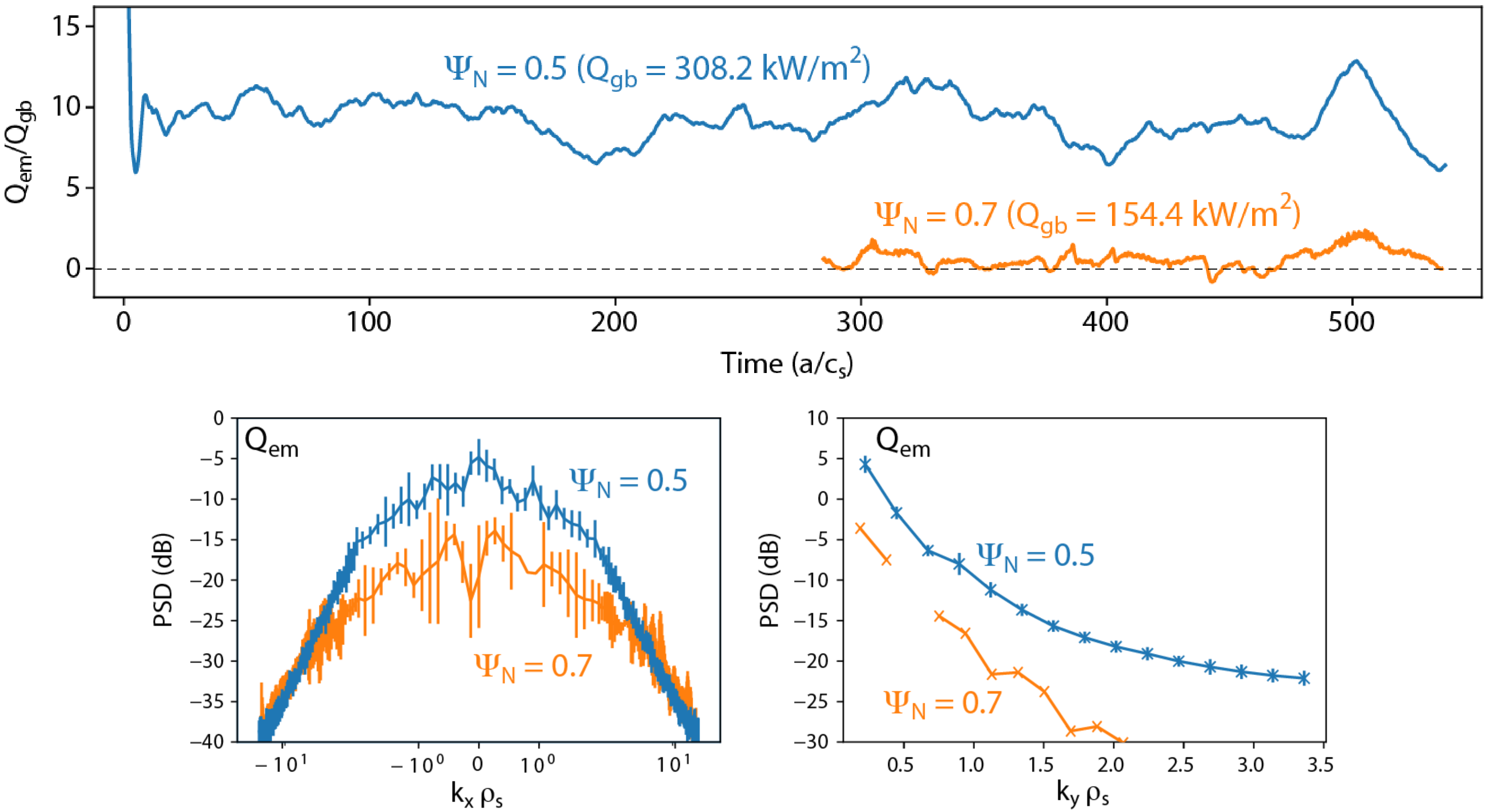
Flux spectra show dominant contribution from low-k_y magnetic fluctuations



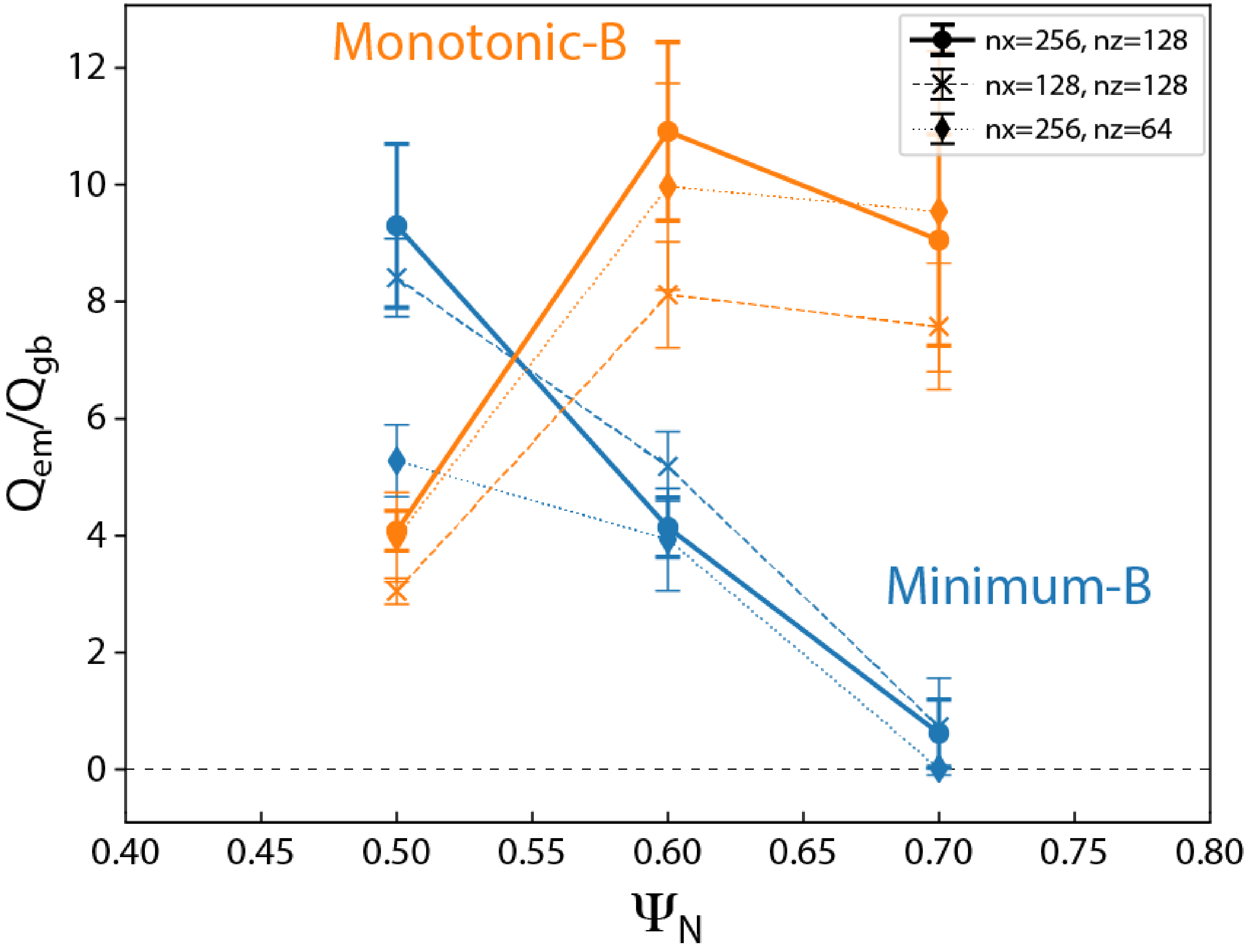
Nonlinear simulations with heavy electrons are largely converged with respect to coarser grids



MTM transport with heavy electrons in the minimum-B configuration decreases approaching the edge



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 (10x) falls 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