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

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59th APS-DPP
Milwaukee, WI

26 October 2017

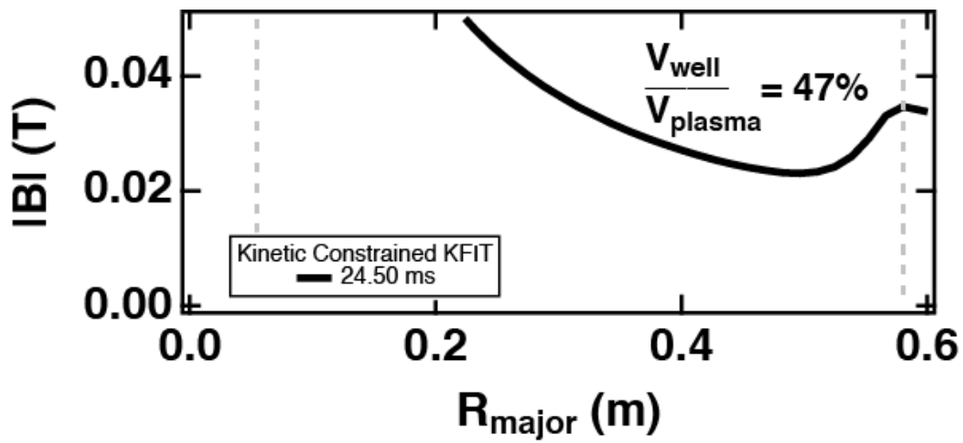


PEGASUS
Toroidal Experiment

Abstract

A local **minimum |B| region**, or "magnetic well," was recently observed in the **low-aspect-ratio 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/

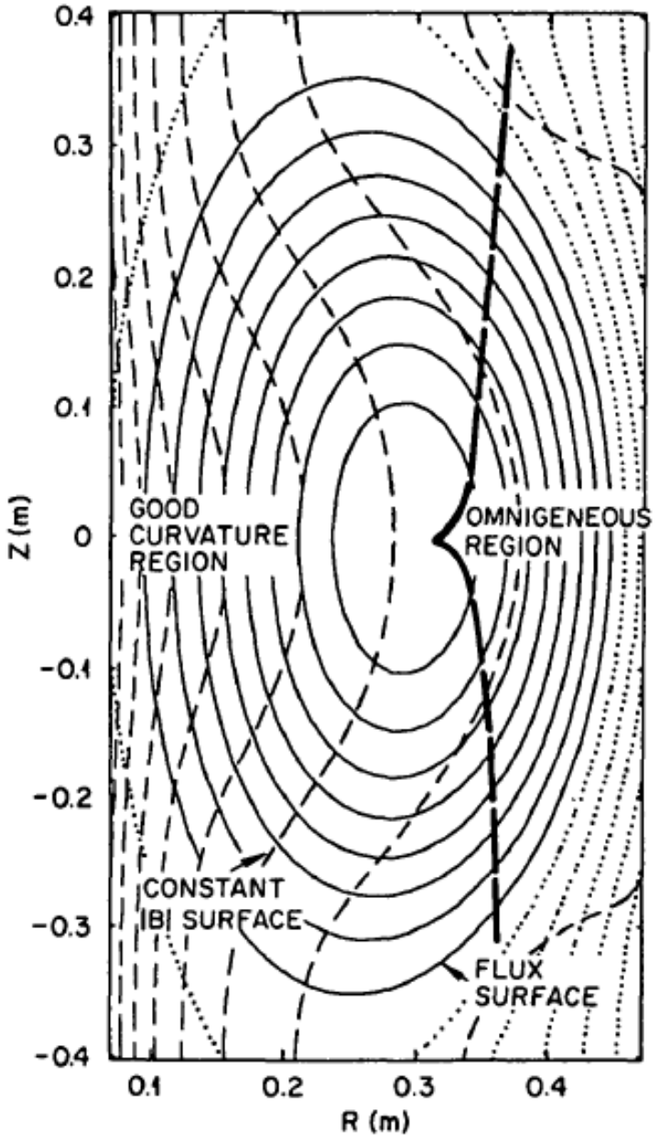
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Outline

- Background
  - Reduced neoclassical transport with ST **paramagnetism**
  - Drift wave stabilization and improved fast-ion confinement with **diamagnetic well**
- Pegasus minimum |B| regime
  - $\beta_t \approx 100\%$ operation with HFS local helicity injection
  - Diamagnetic well with net-paramagnetism
- Microstability properties of Pegasus min-|B| regime
  - GENE gyrokinetic simulations
  - Two tearing-parity modes with on- and off-midplane peaking
  - Particle, ion heat, and electron heat transport
- Discussion, plans, and summary
  - Probe measurements

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

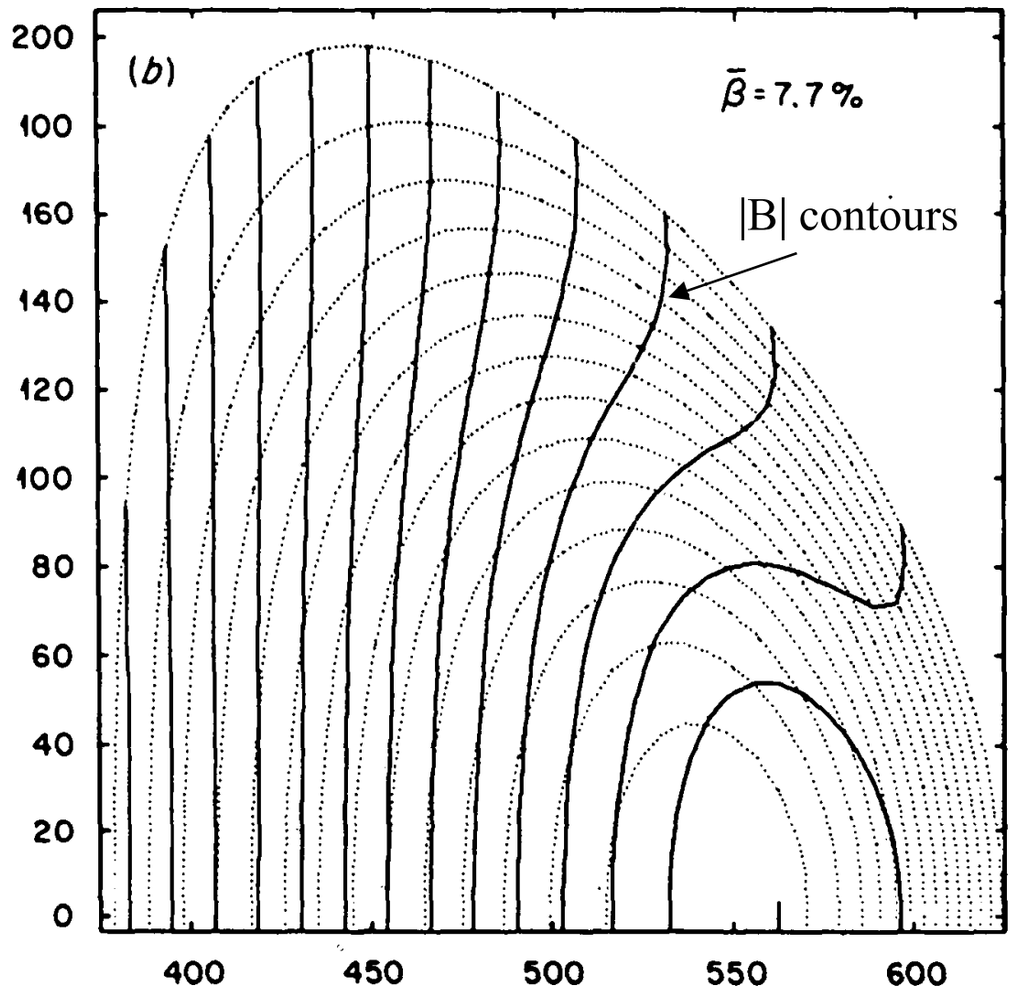


Y-K. M. Peng and D. Strickler, NF 1986

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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

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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 ∇T_i (L_T) is sufficiently large (small).

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

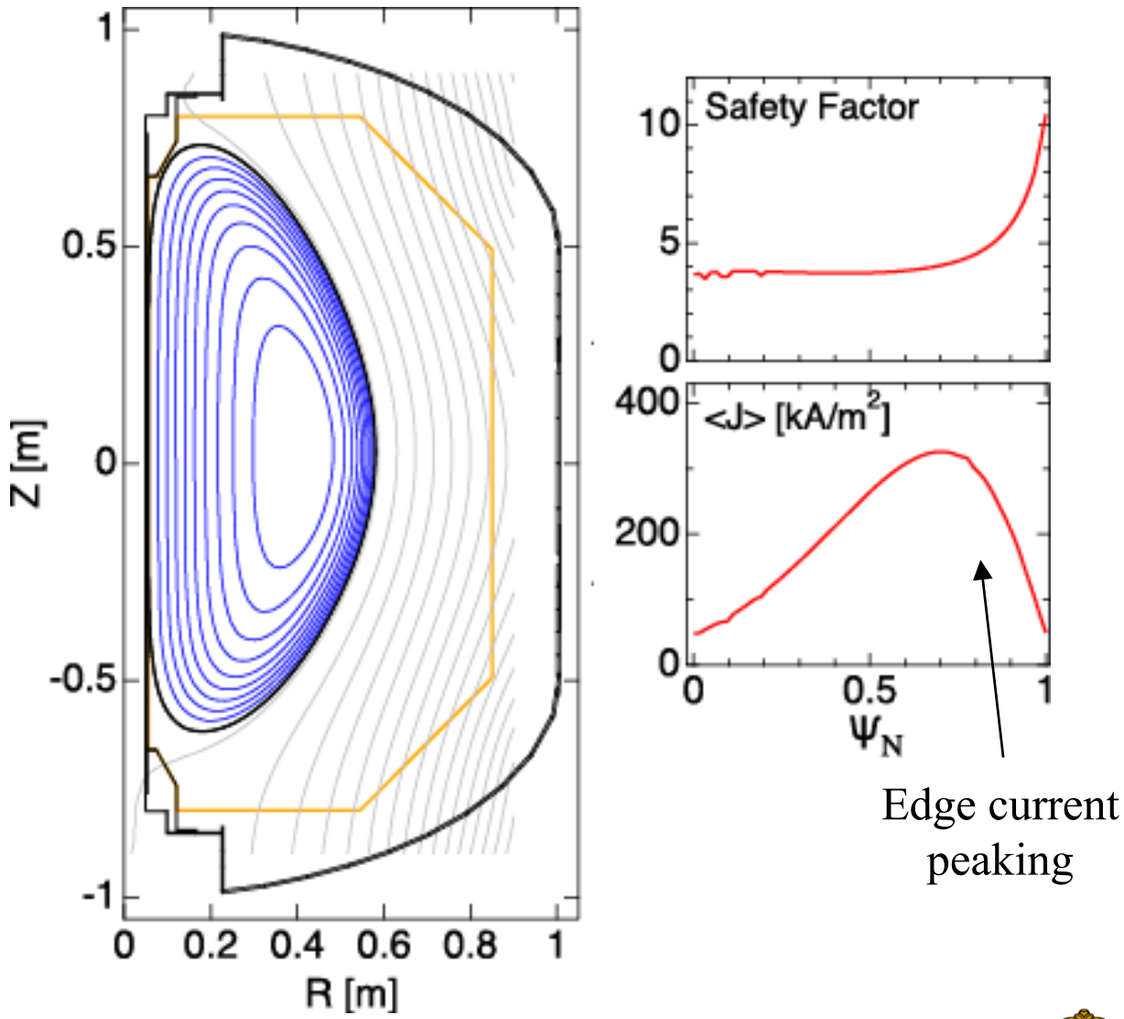
* neglect $k_\parallel$, assume $\omega \gg \omega_d$, and let $\nabla n \to 0$

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

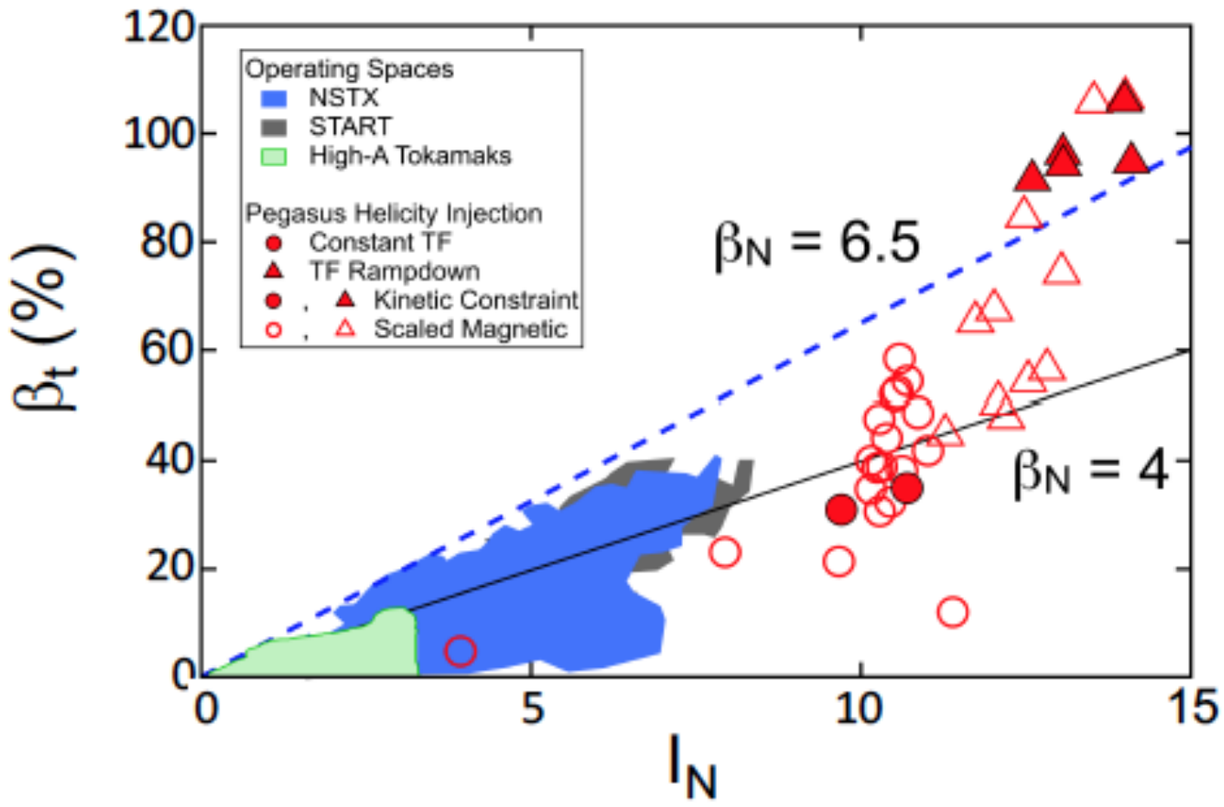
- Enhanced stability at low A (1.21) and high κ (2.6) in Pegasus
- Local helicity injection (LHI) with high field side (HFS) injectors
  - Reconnection ion heating ($T_{i0} > T_{e0}$)
  - Suppression of low-m tearing modes
  - Edge current peaking with low l_i (0.22)
- Kinetic-constrained equilibria

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



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

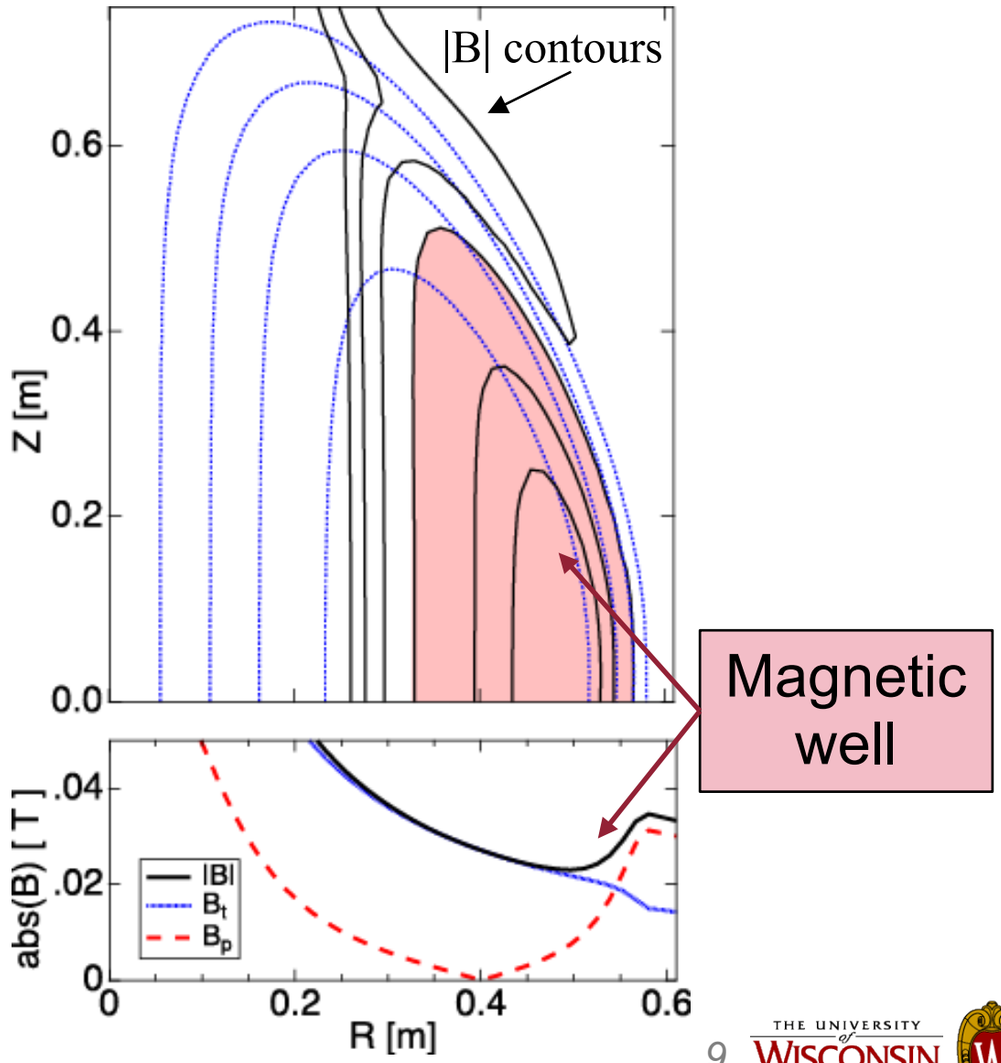
- Sykes-Troyon scaling
  - $\beta_{t,max} \propto aI_p/B_{t0}$
  - Normalized current: $I_N \equiv aI_p/B_{t0}$
  - Normalized beta: $\beta_N \equiv \beta_{t,max}/I_N$
    - Higher β_N accessible at lower A and/or higher κ
- I_{TF} ramp-down to access high I_N
  - $I_N \propto I_p/I_{TF}$



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

Diamagnetic well with net-paramagnetism in Pegasus

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

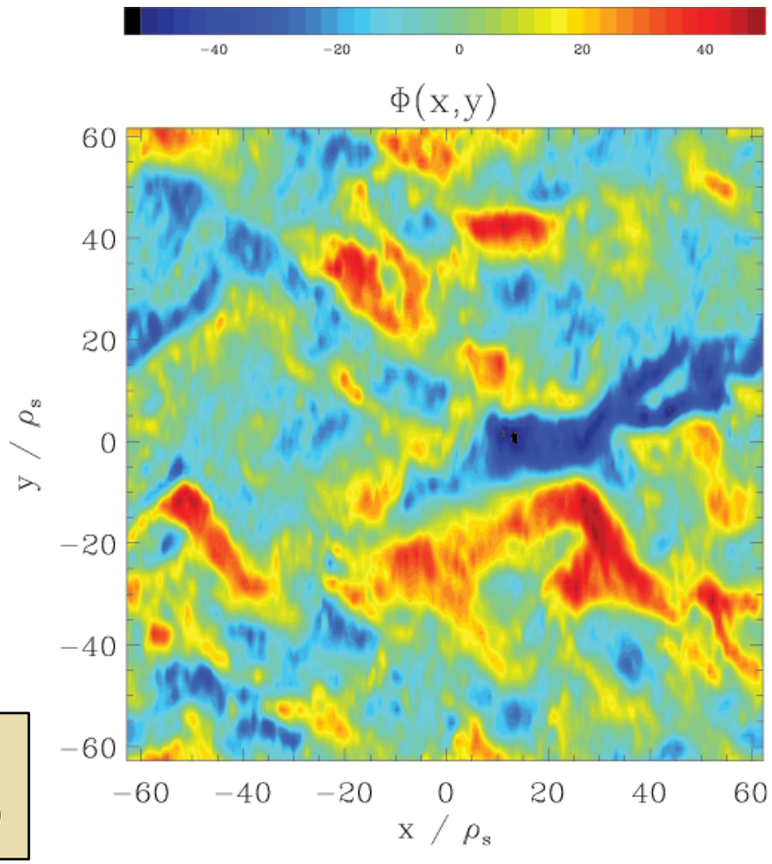


D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

Gyrokinetic simulations with *GENE*

- *GENE* evolves gyrokinetic equations in 5-dimensional phase space
  - Electromagnetic with $A_\parallel$ and/or $B_\parallel$
  - Local flux tube or nonlocal 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

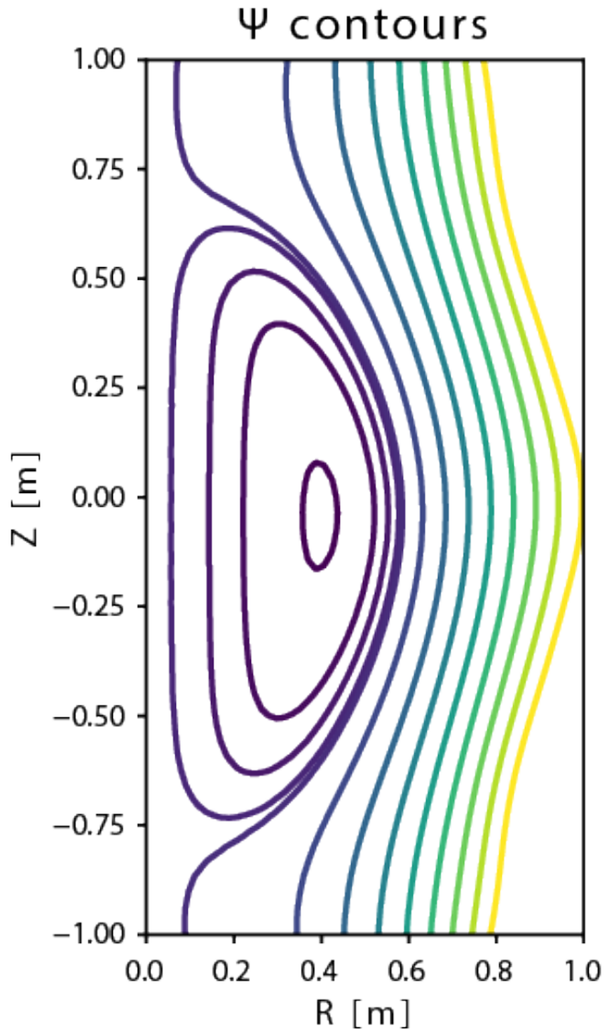


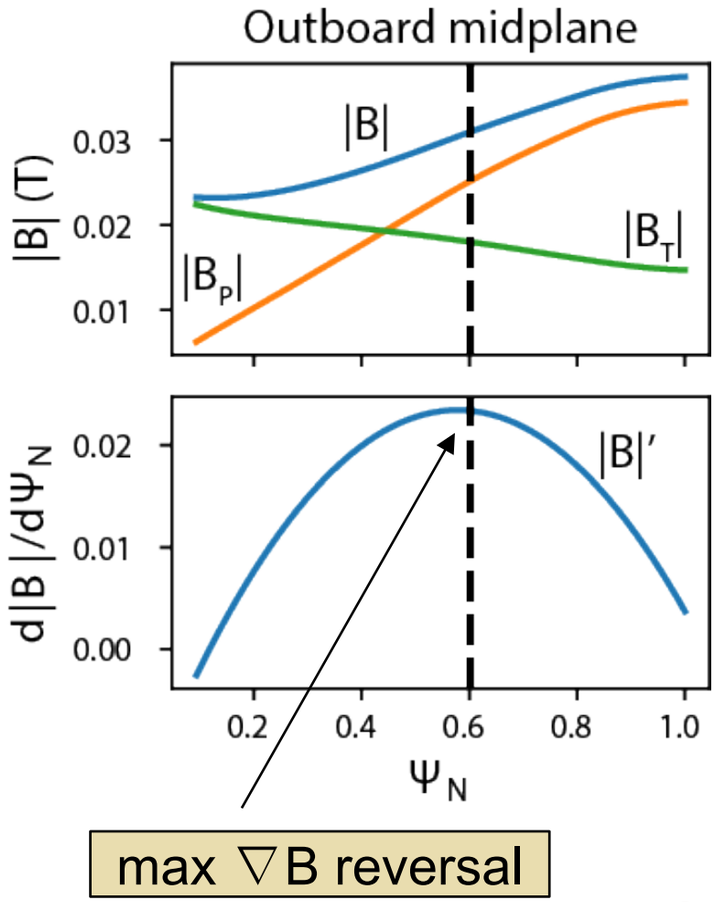
M. J. Pueschel and F. Jenko, PoP 2010

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Simulation parameters for Pegasus min-|B| regime

- Flux tube
  - $\Psi_N = 0.6$ @ max ∇B reversal
  - $q = 3.5$ and $\hat{s} = 0.55$
- Physics model
  - ϕ and $A_{||}$
  - $m_e/m_d =$ **1/100** (heavy electrons)
  - $\nu_i^* = 0.07$
  - $\beta_e = 27\%$
- Species' profiles
  - $a/L_n = a/L_{Ti} = a/L_{Te} = 3.15$
  - $T_e = T_i$

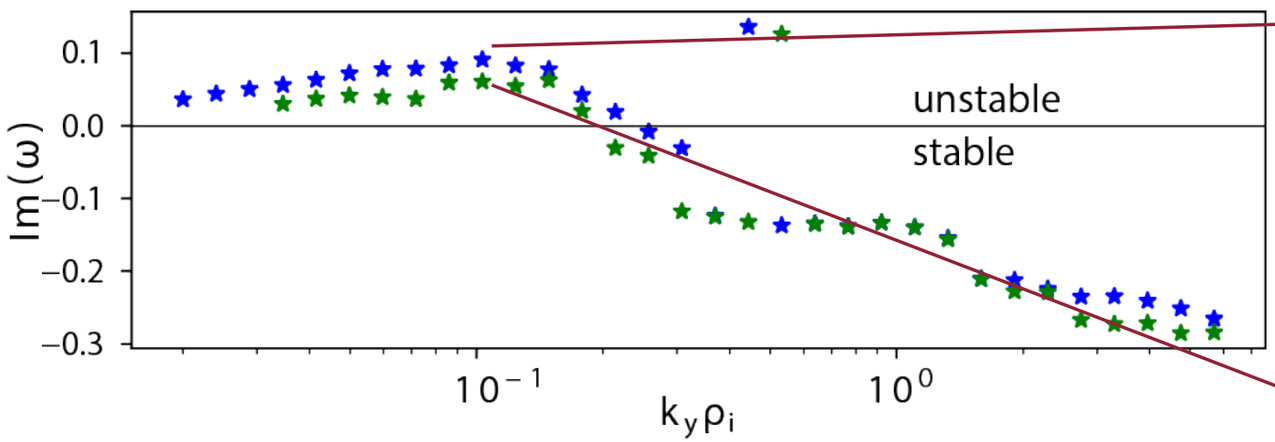


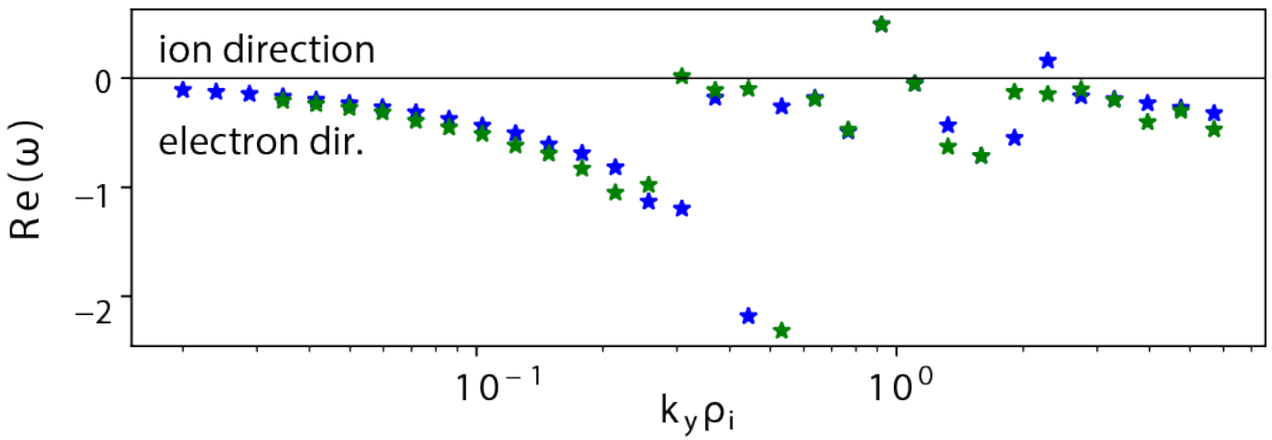


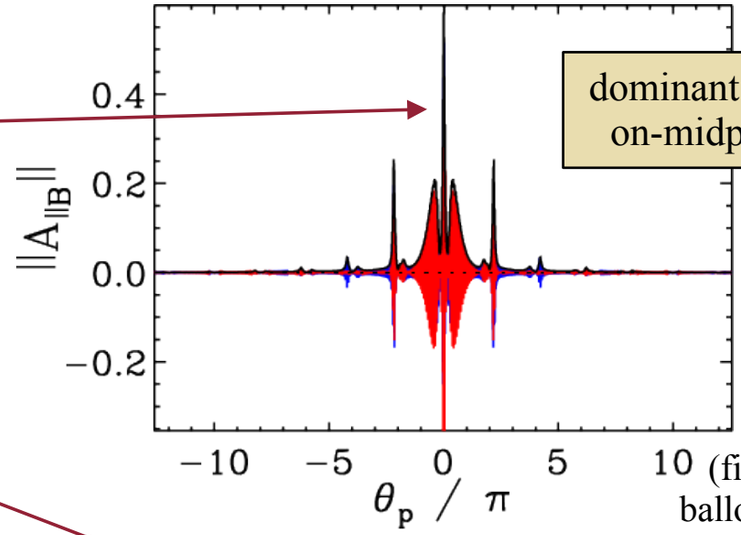
max ∇B reversal

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Linear eigenvalue solver indicates tearing-parity electron modes at $k_y\rho_i \sim 0.1$

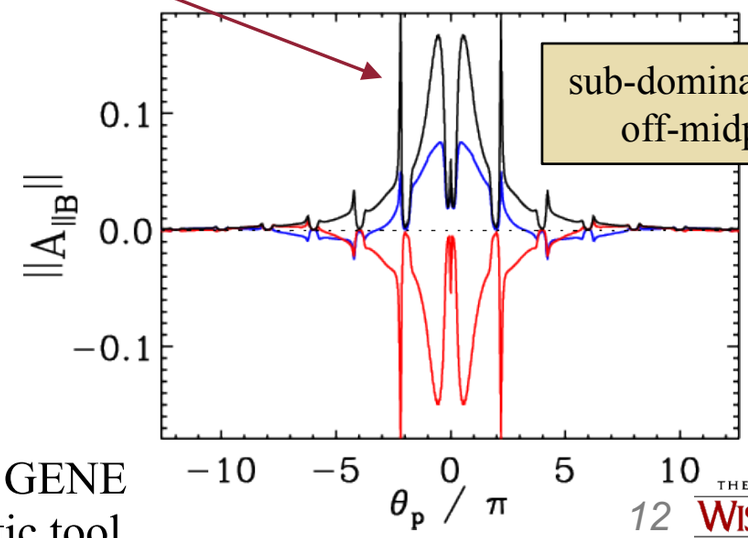






dominant mode with on-midplane peak

(field-aligned ballooning angle)

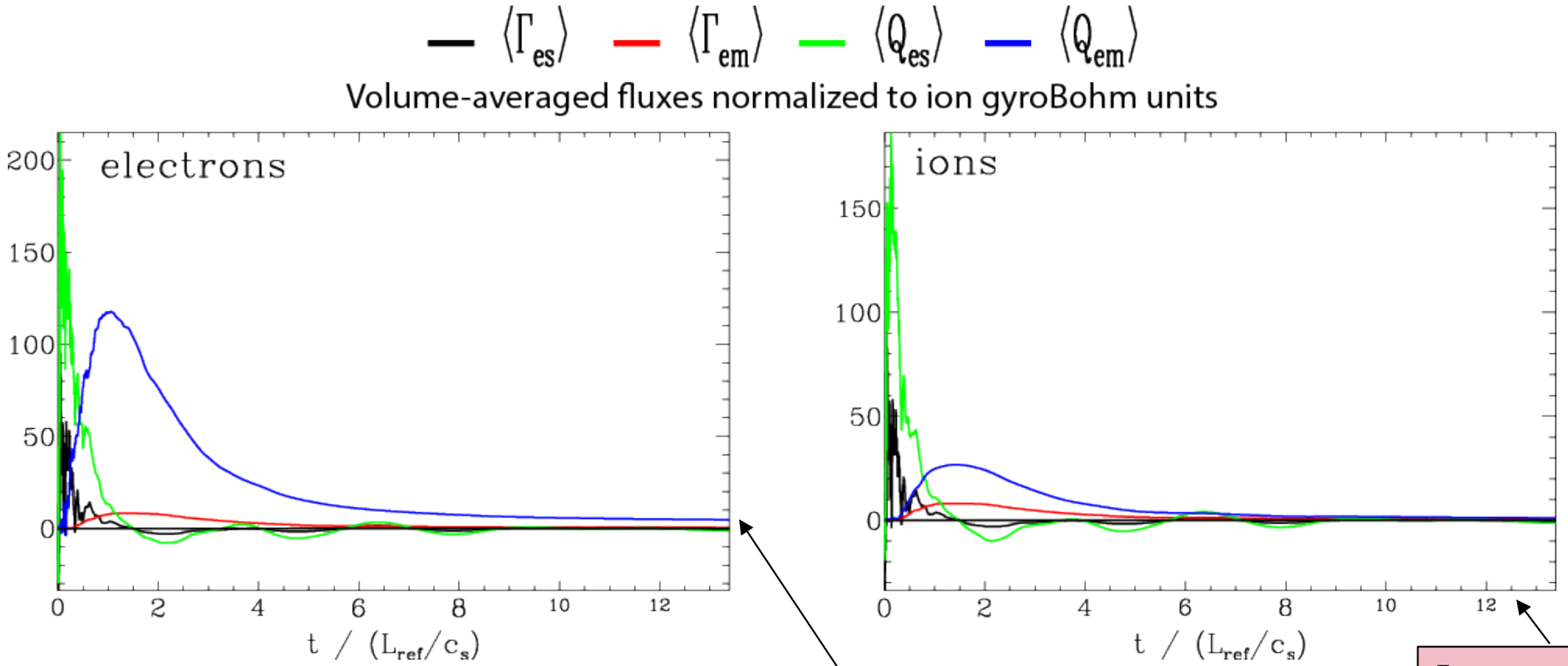


sub-dominant mode with off-midplane peak

Plots by GENE diagnostic tool

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Preliminary nonlinear simulations indicate dominant electron electromagnetic heat flux



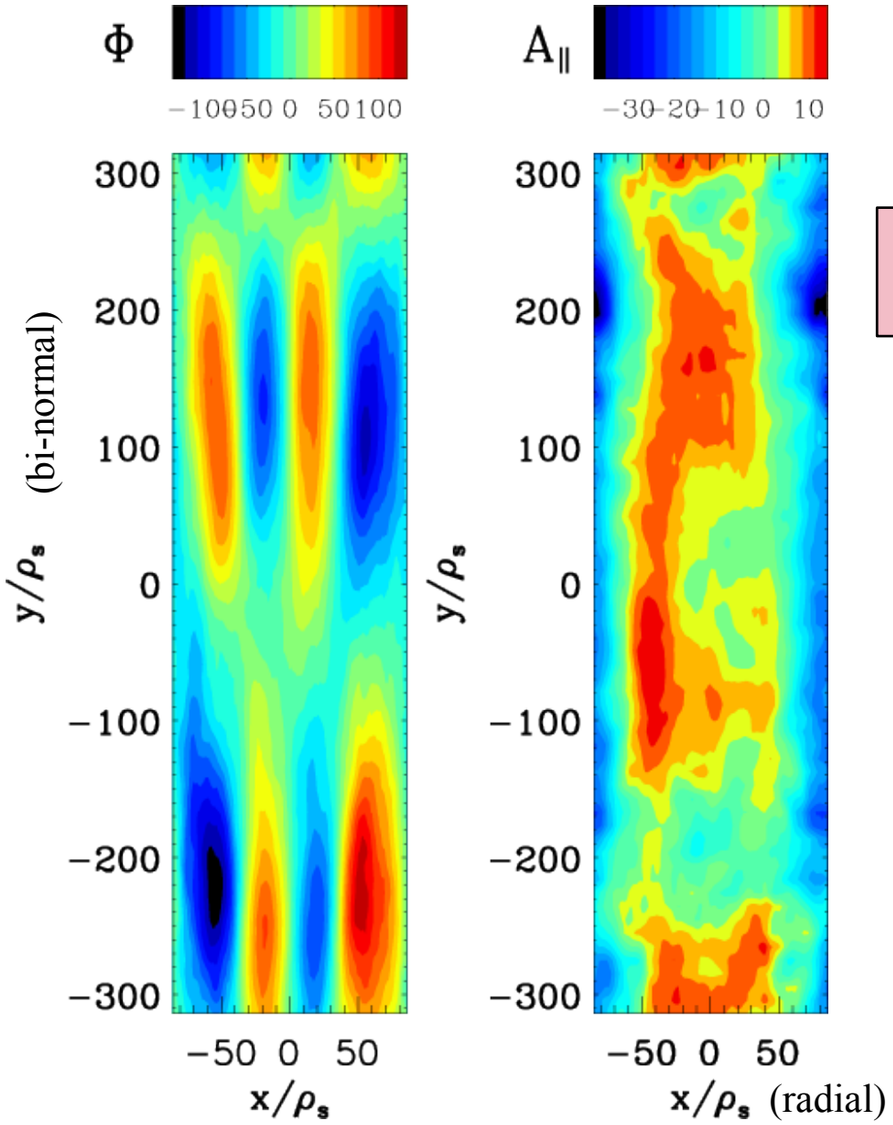
Plots by GENE diagnostic tool

Large saturation value for electromagnetic component of electron heat flux $\approx \mathcal{O}(10 \times Q_{i,gB})$

Longer run needed

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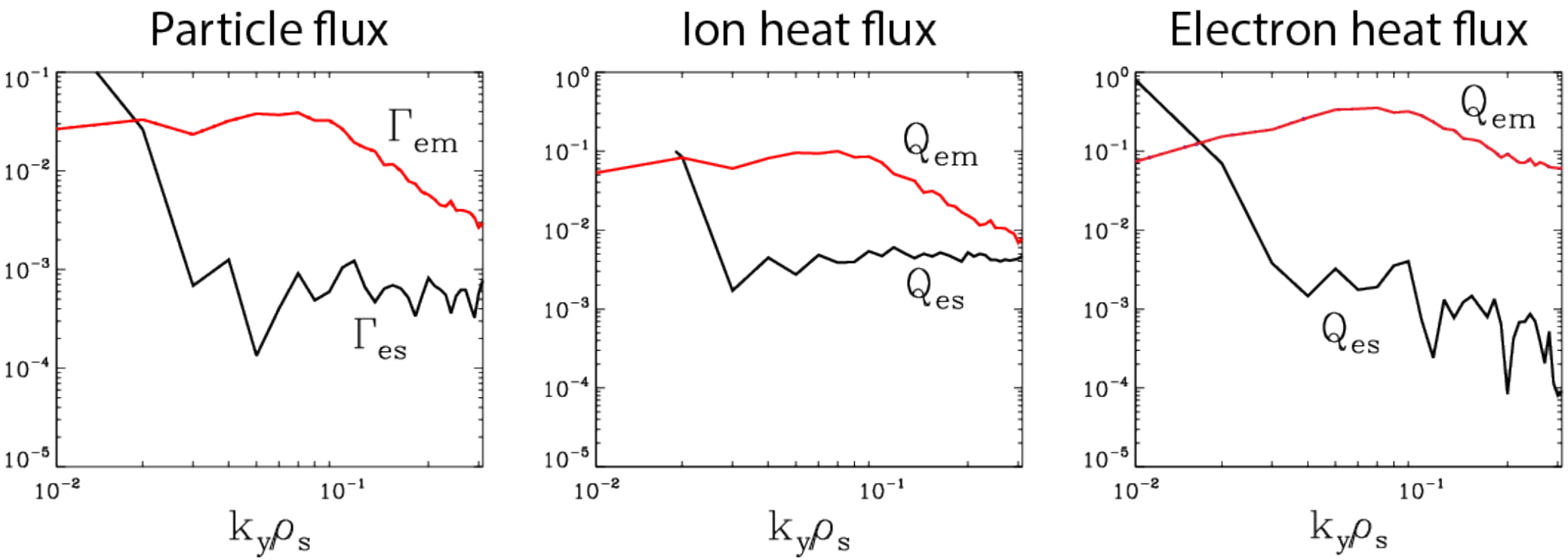
Contour plots show microtearing-like eddies in ϕ with narrow Δx and extended Δy



$Lx = 171\rho_i$ and $\Delta x/\rho_i = 0.67$
$Ly = 628\rho_i$ and $k_y\rho_i = 0.01\text{-}0.32$
likely insufficient res.

Plots by GENE diagnostic tool

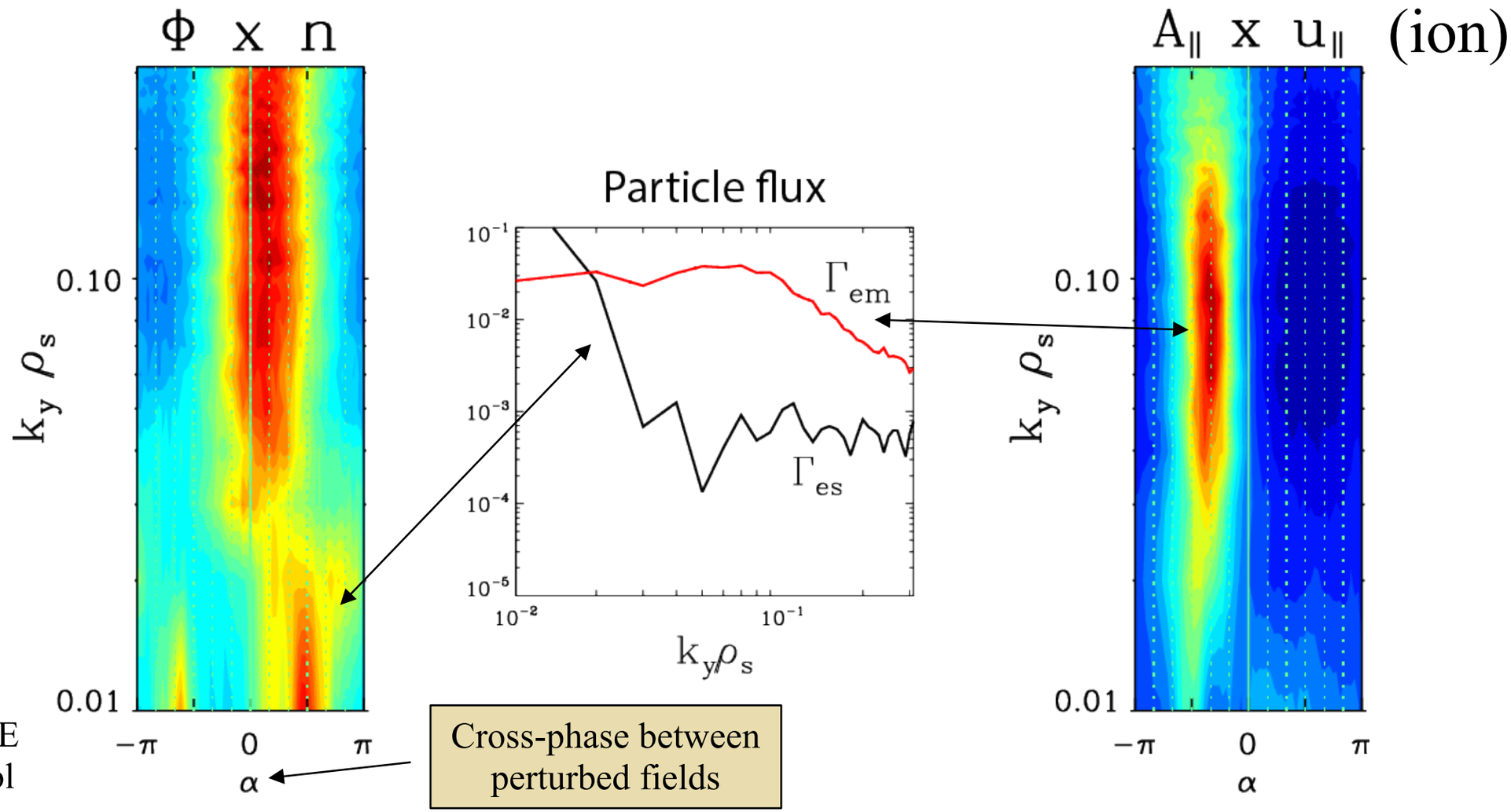
Particle and heat flux spectra show strong electromagnetic components at $k_y\rho_i \sim 0.1$



Plots by GENE diagnostic tool

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Particle flux due to low-k electrostatic component and ion magnetic flutter

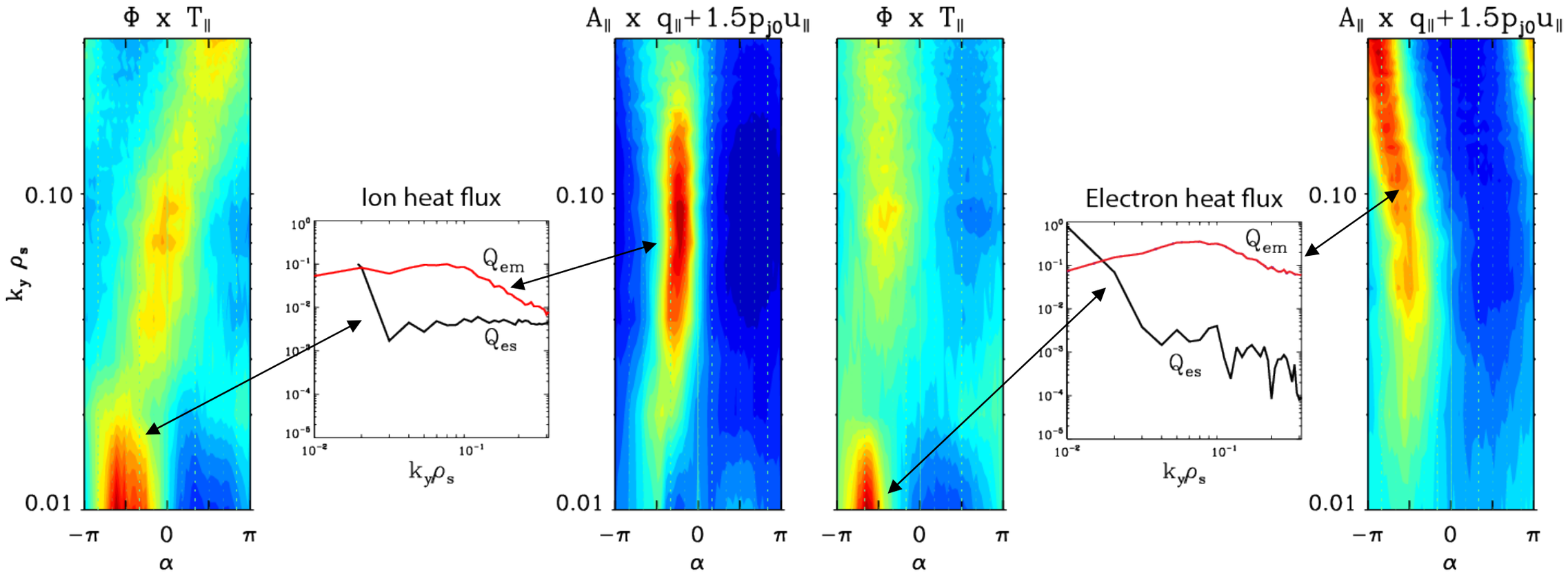


Plots by GENE diagnostic tool

Cross-phase between perturbed fields

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Cross-phase and heat flux spectra indicate two modes are active



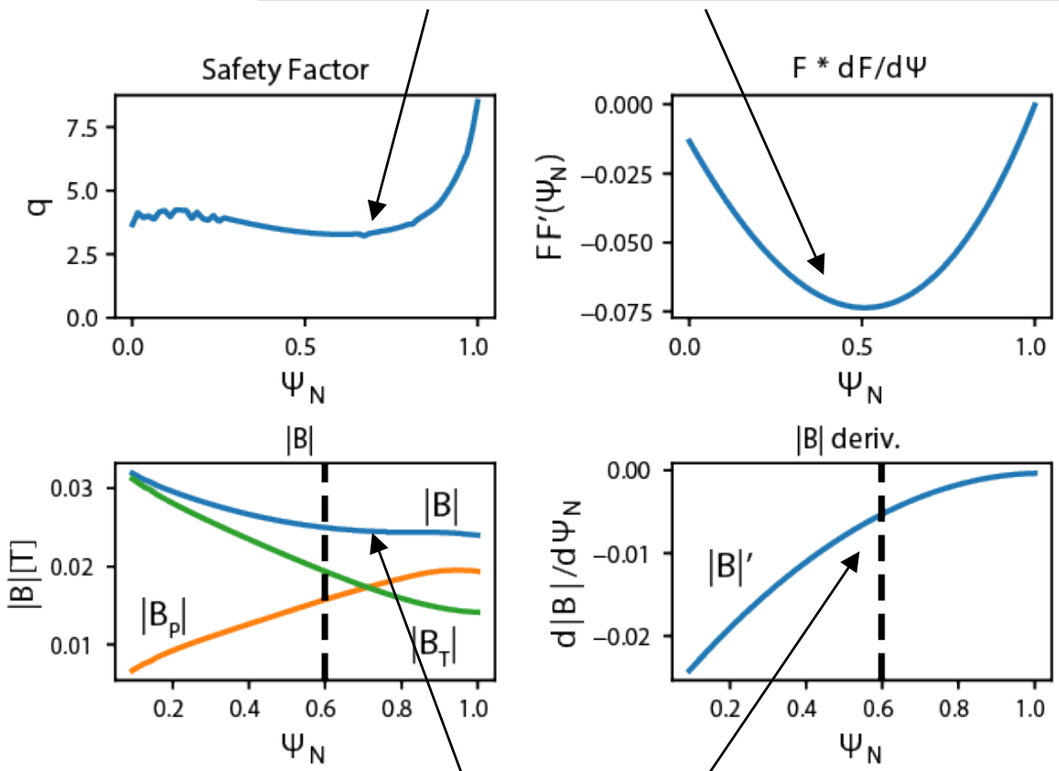
Linear eigensolver (pg. 12) and nonlinear cross-phase spectra point to **two instabilities**

- Both tearing parity and propagate in electron direction
- One mode generates particle and ion heat flux; the other mode generates electron heat flux

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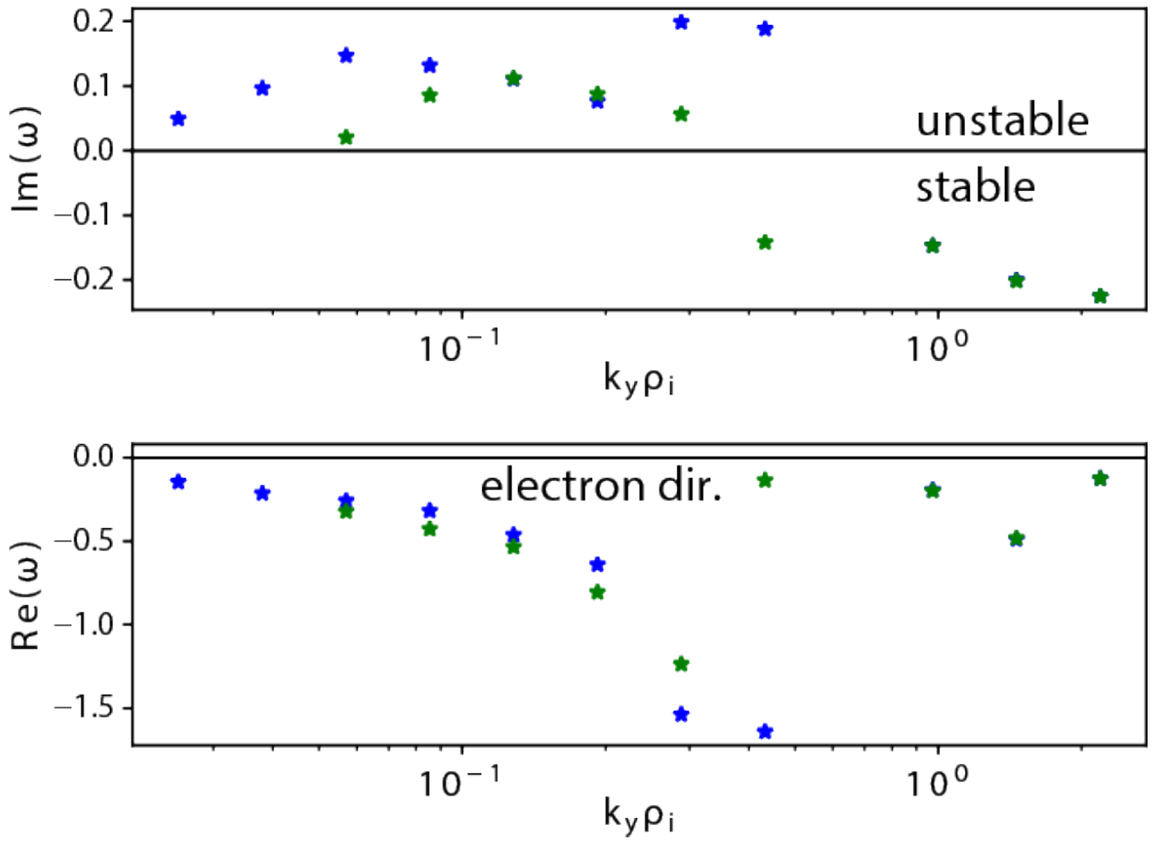
Modified equilibrium with monotonic |B| shows larger growth rates

Slight RS and less edge current (cf. pg. 7)



Monotonic |B| and |B|′< 0 (cf. pg. 11)

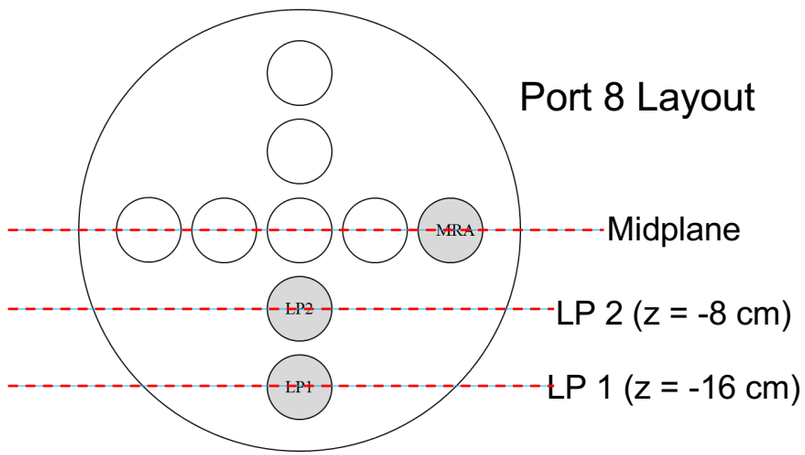
Larger growth rates for unstable electron modes (cf. pg. 12)

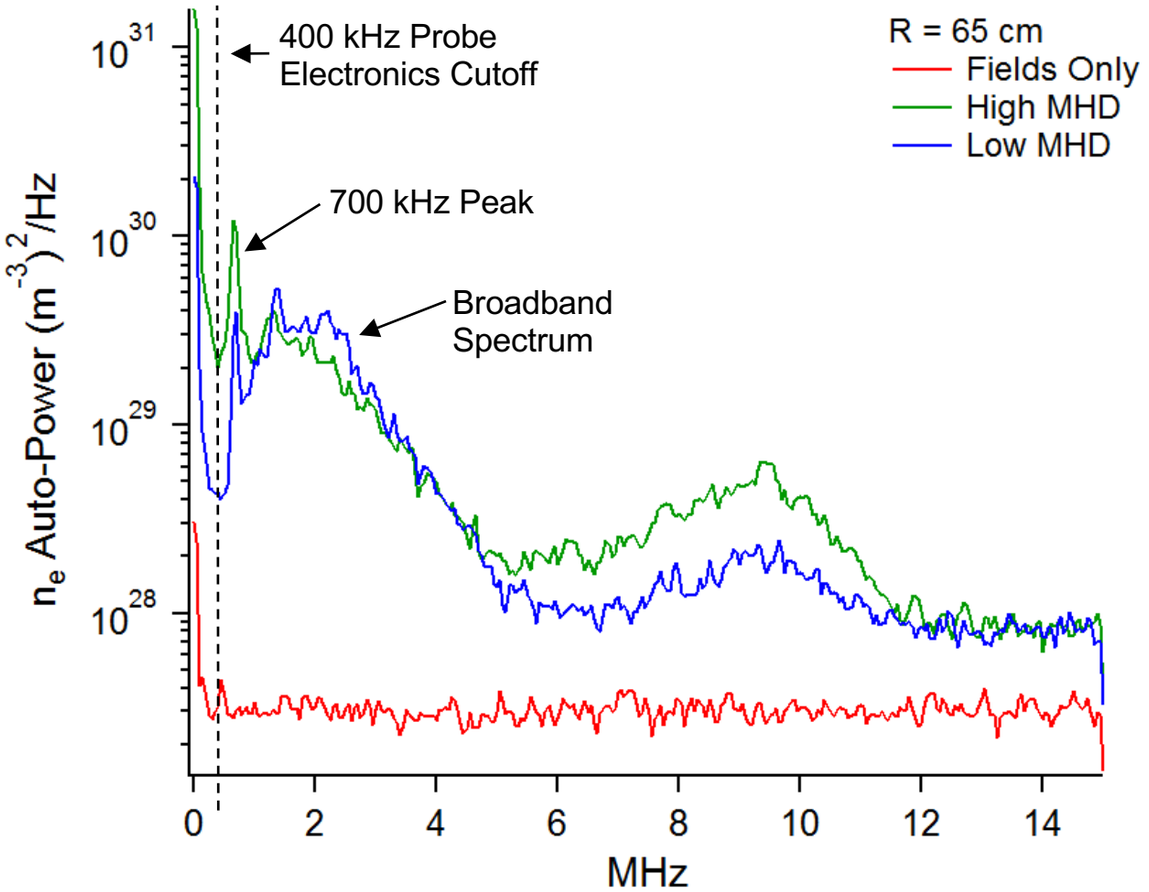


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Discussion and plans

- Assess spectra, correlations, and mode structure of electric and magnetic fluctuations with probes
  - Core access
  - Configure for field-aligned or off-midplane measurements





A. Rhodes et al, UP11.00091

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Summary

- ST paramagnetism and diamagnetic wells provide mechanisms for improved confinement
  - Drift wave stabilization with ∇B reversal
- 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; D.J. Schlossberg, Ph.D. Thesis 2017
- *GENE* gyrokinetic simulations at min-|B| region identify two tearing-parity modes at $k_y\rho_i \sim 0.1$
  - Tearing-parity modes linked to particle, ion, and electron heat flux
  - Subdominant mode with off-midplane peak

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