Alpha-Particle-Driven Toroidal Alfvén Eigenmodes (TAEs) in TFTR DT Plasmas

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with major contributions from

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D. Spong, R. White, S. Zweben and the TFTR team.

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Alpha Driven Instabilities Can Damage Reactor Wall and Reduce Heating Efficiency

- DT reactor requires self heating by alpha particles.
- DT experiments on TFTR and JET can benchmark theory.
- DT on TFTR with monotonic safety factor
  - no alpha instabilities with $P_{fus} \approx 10.7$ MW & $\beta_\alpha(0) \sim 0.3\%$
- TAEs observed in q(0)>1 plasmas: $\beta_\alpha(0) \sim 0.02\%$
- Implications for advanced tokamak reactor : $\langle\beta_\alpha\rangle \sim 0.5\%$

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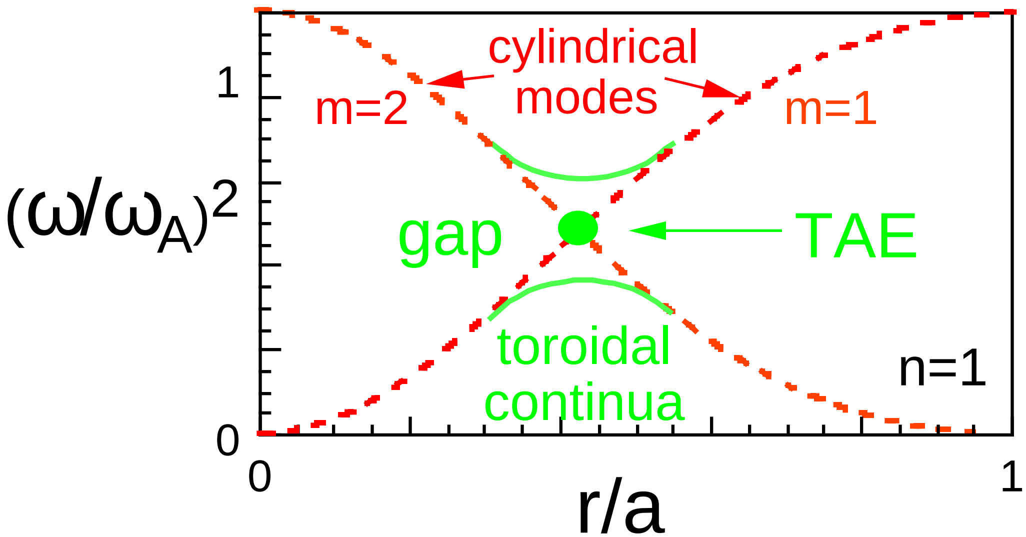
Outline

- Theoretical predictions of TAE stability confirmed on TFTR
- Reflectometer measurements map internal mode structure
- Non-linear models, alpha redistribution and loss

TOROIDICITY-INDUCED ALFVÉN EIGENMODES (TAE): WHAT ARE THEY?

- TAEs are shear Alfvén waves in a torus, where toroidicity couples m and m+1 modes to form gaps in the spectrum



$$\omega_A{}^2 = k_{||}^2 V_A{}^2$$

$$V_A = B/\sqrt{4\pi\rho} \approx V_\alpha$$

$$k_{||} = (m-nq)/Rq$$

- Wave-particle resonance can excite discrete TAE modes inside the gap in the toroidal shear Alfvén spectrum

- Gap modes are weakly damped - main damping processes are radiative, beam and thermal ion Landau damping

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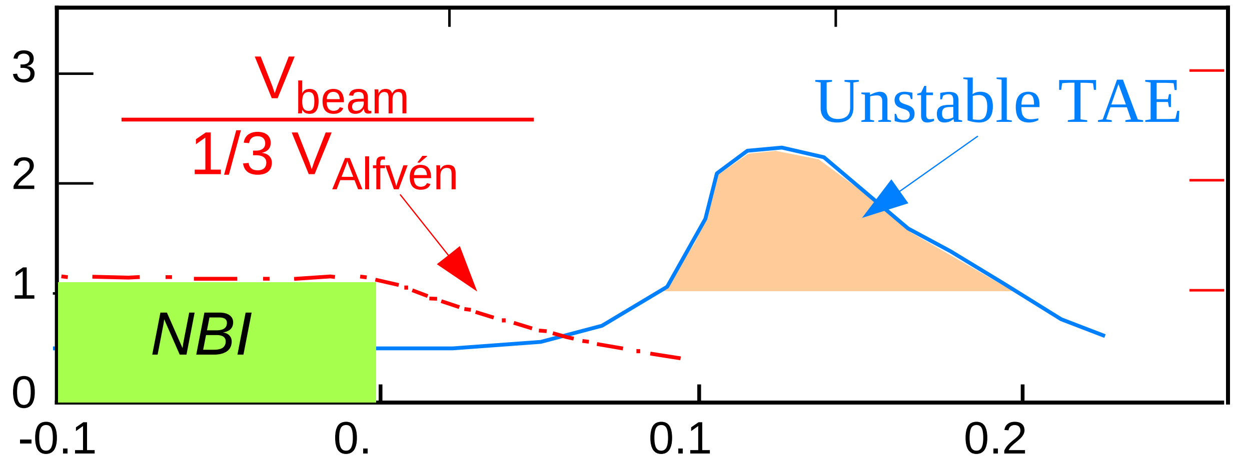
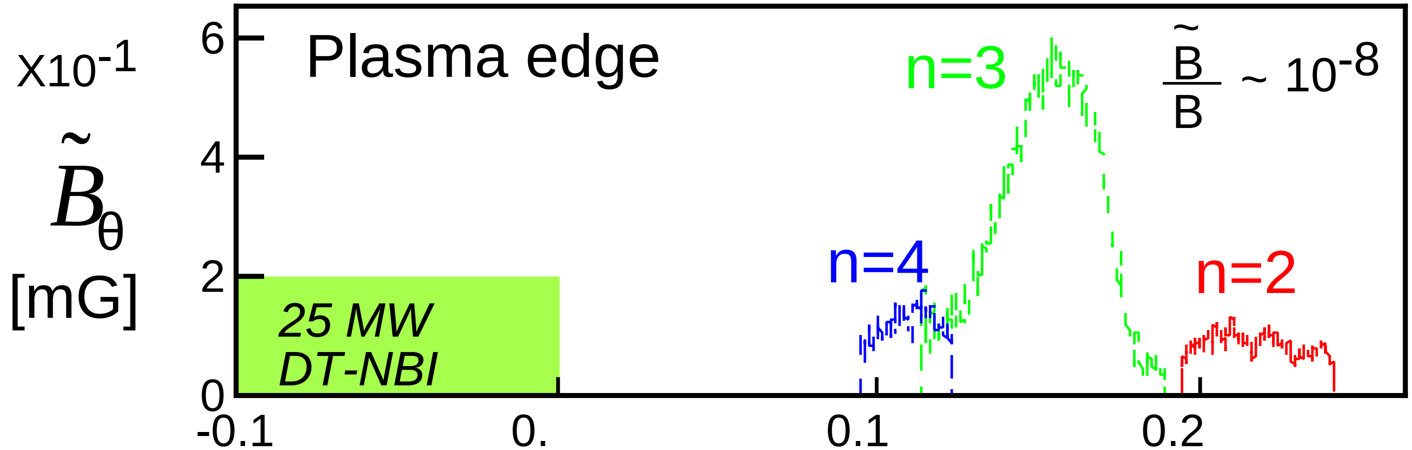
Prediction and Measurement of Alpha Driven TAEs in TFTR

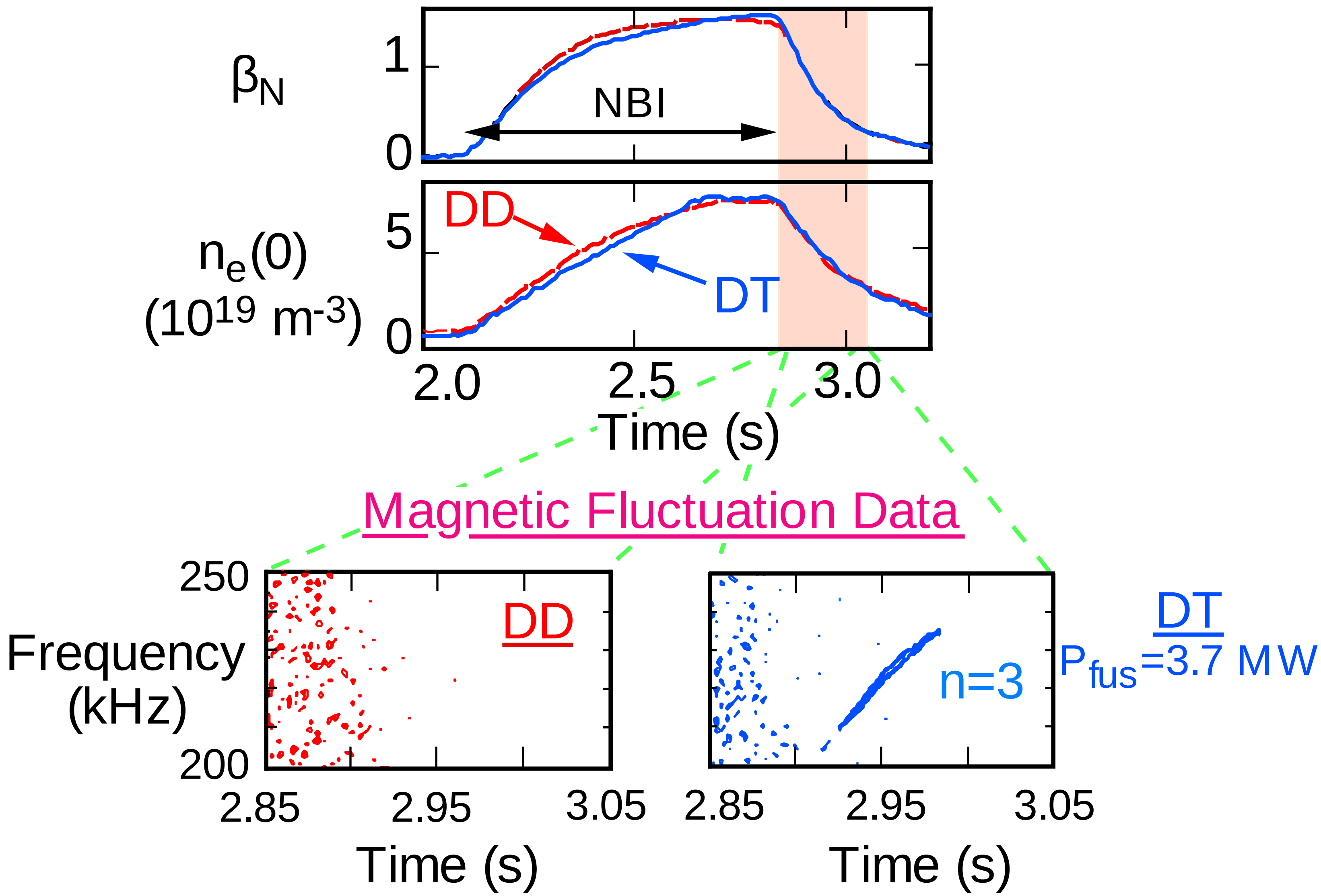
Theoretical Prediction: Fu, Spong

- Reduce magnetic shear, beam damping and raise q(0)



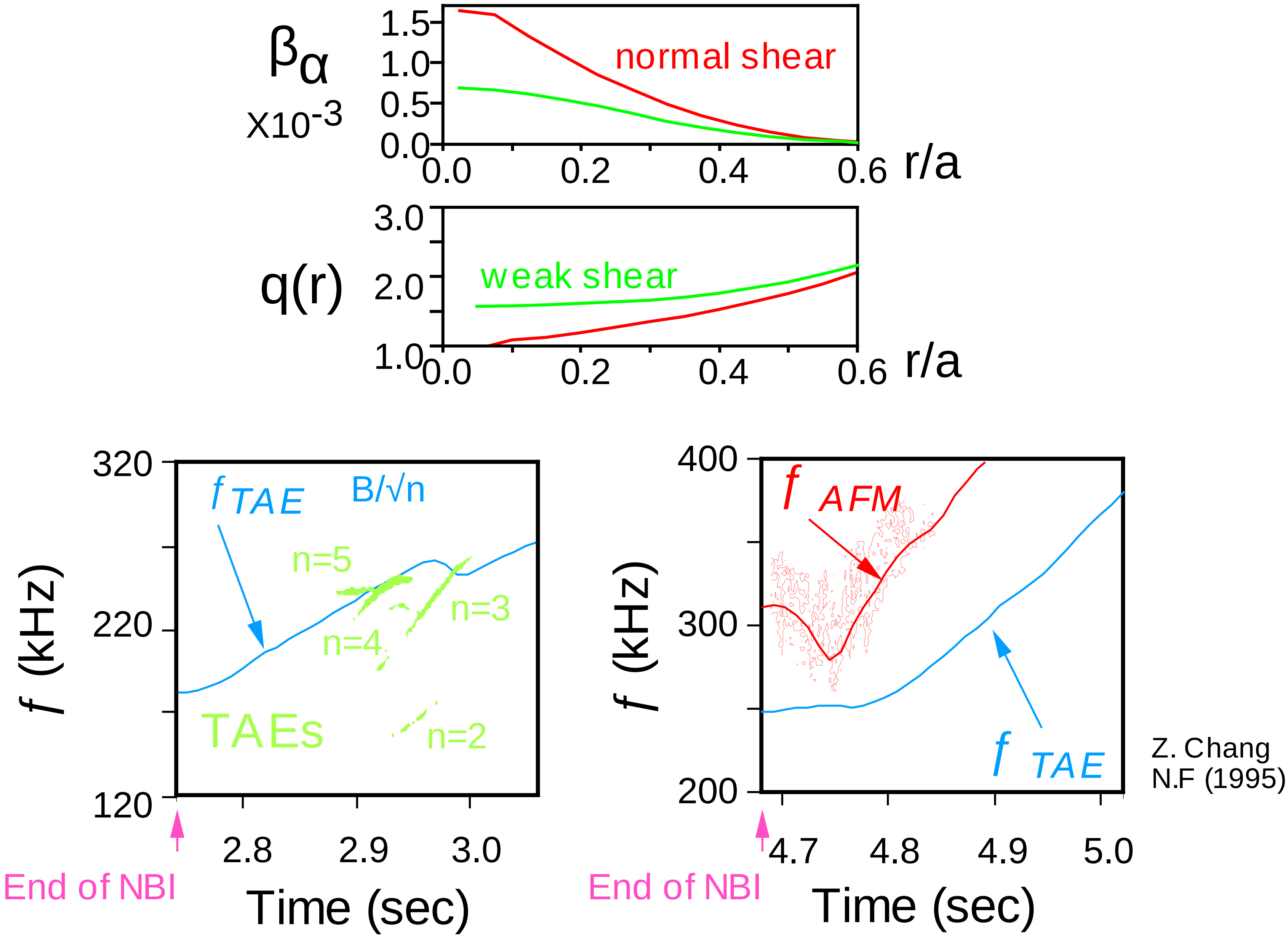


Modes only Seen In DT Plasmas

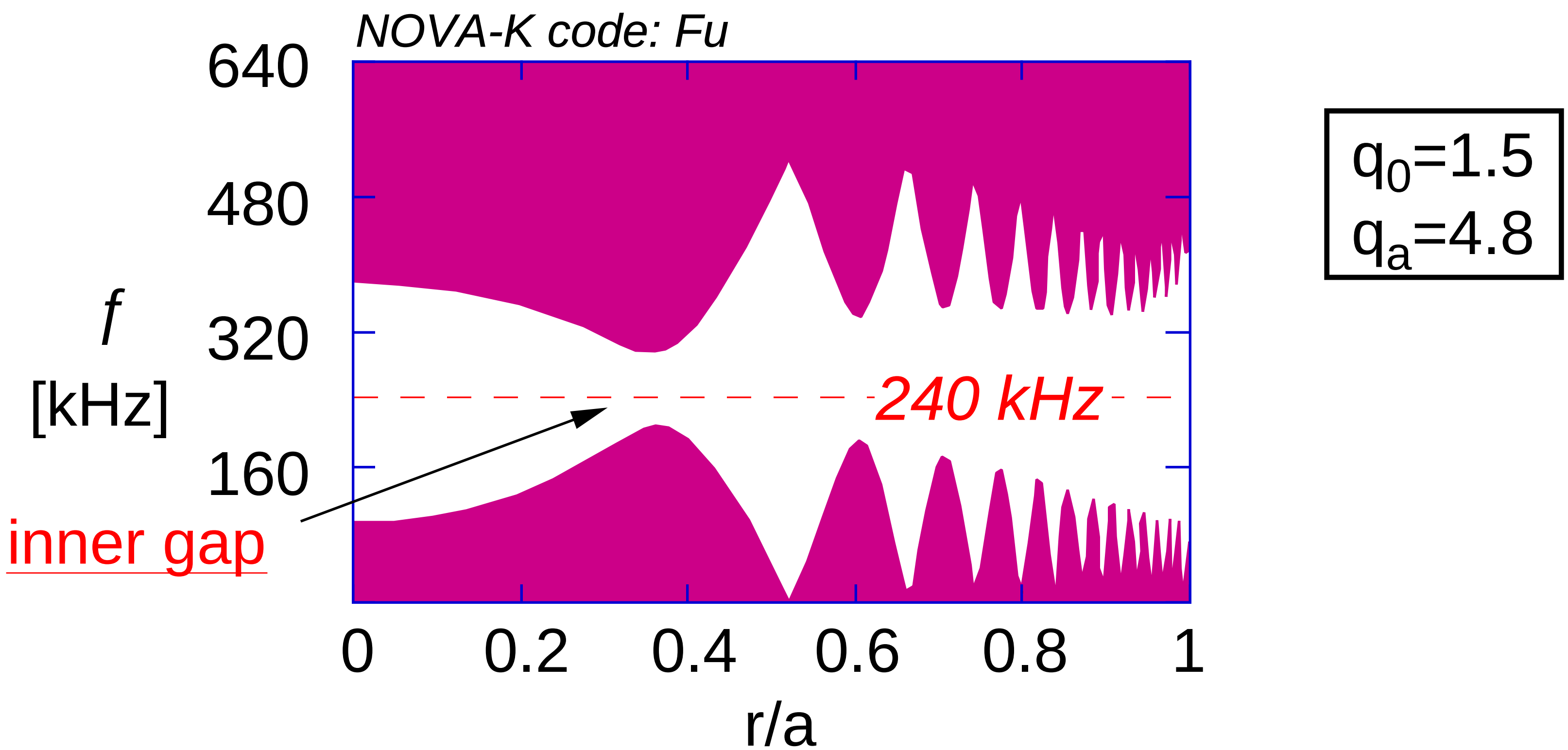


- Modes only seen after DT beams turn off.

NEW MODES SEEN ONLY IN WEAK SHEAR DT PLASMAS: q(0)>1

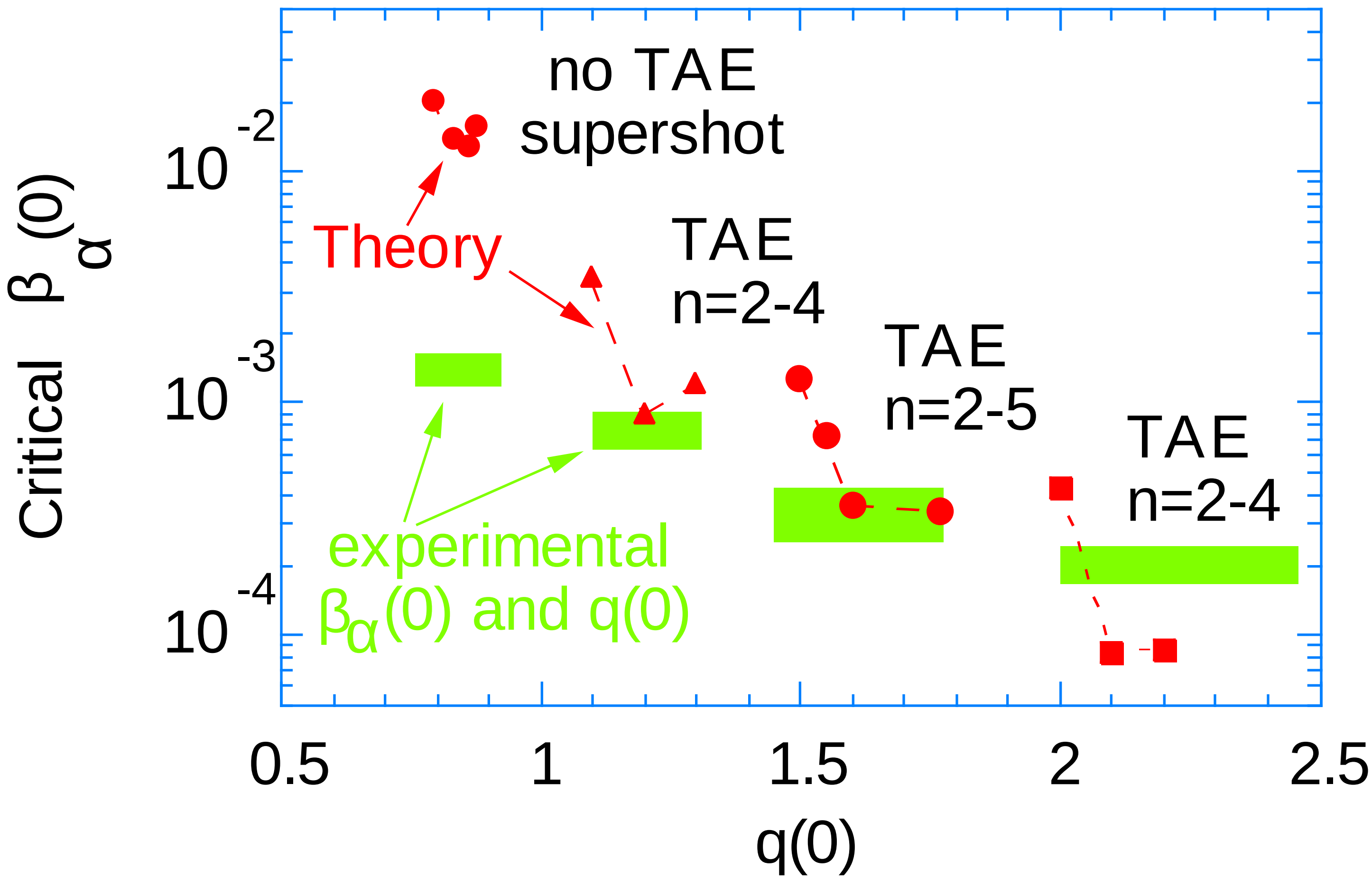


N=4 Frequency Lies Inside Toroidicity Induced Gap in Alfvén Spectrum



- Theory predicts alpha driven TAEs localized to inside gap
- Center frequency of gap varies weakly with radius

CALCULATED CRITICAL β_α DECREASES WITH INCREASING q(0)



- Low shear and high q(0) are destabilizing.

NOVA-K : Guoyong Fu

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Detailed Internal Measurements are Required for Making Furthur Progress in Understanding TAEs : Why?

- Theory predicts core localized modes in weak magnetic shear region, similar to reactors.
  ==> important to confirm core localization

- Need to understand non-linear dynamics of mode saturation and alpha loss.
  ==> Reflectometry, PCX, lost alpha detectors.

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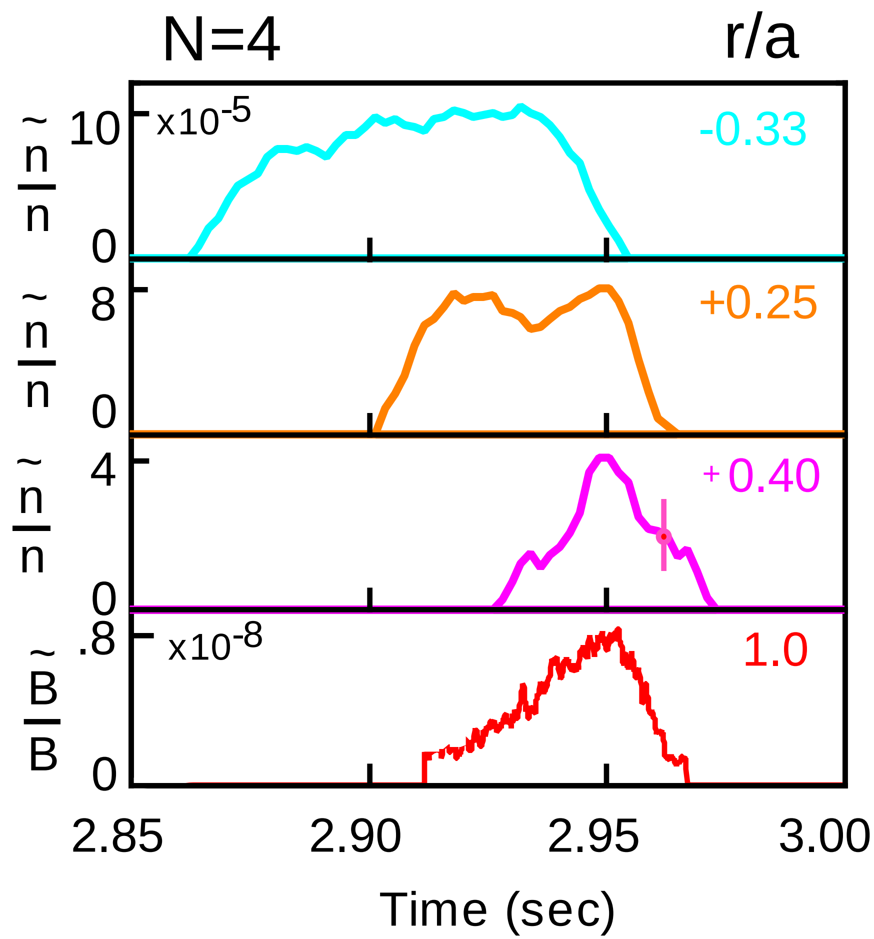
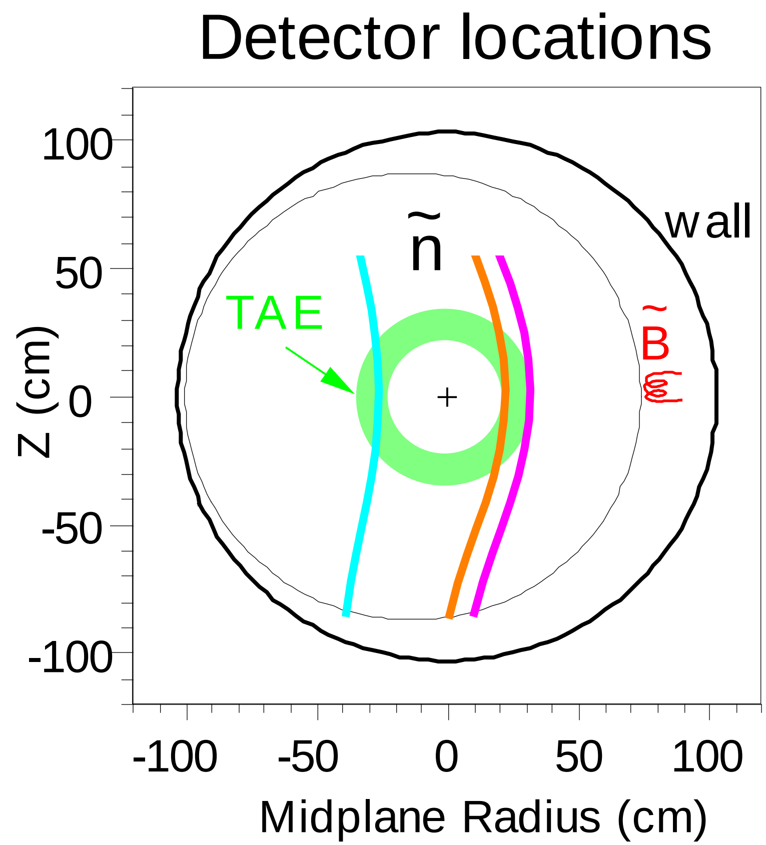
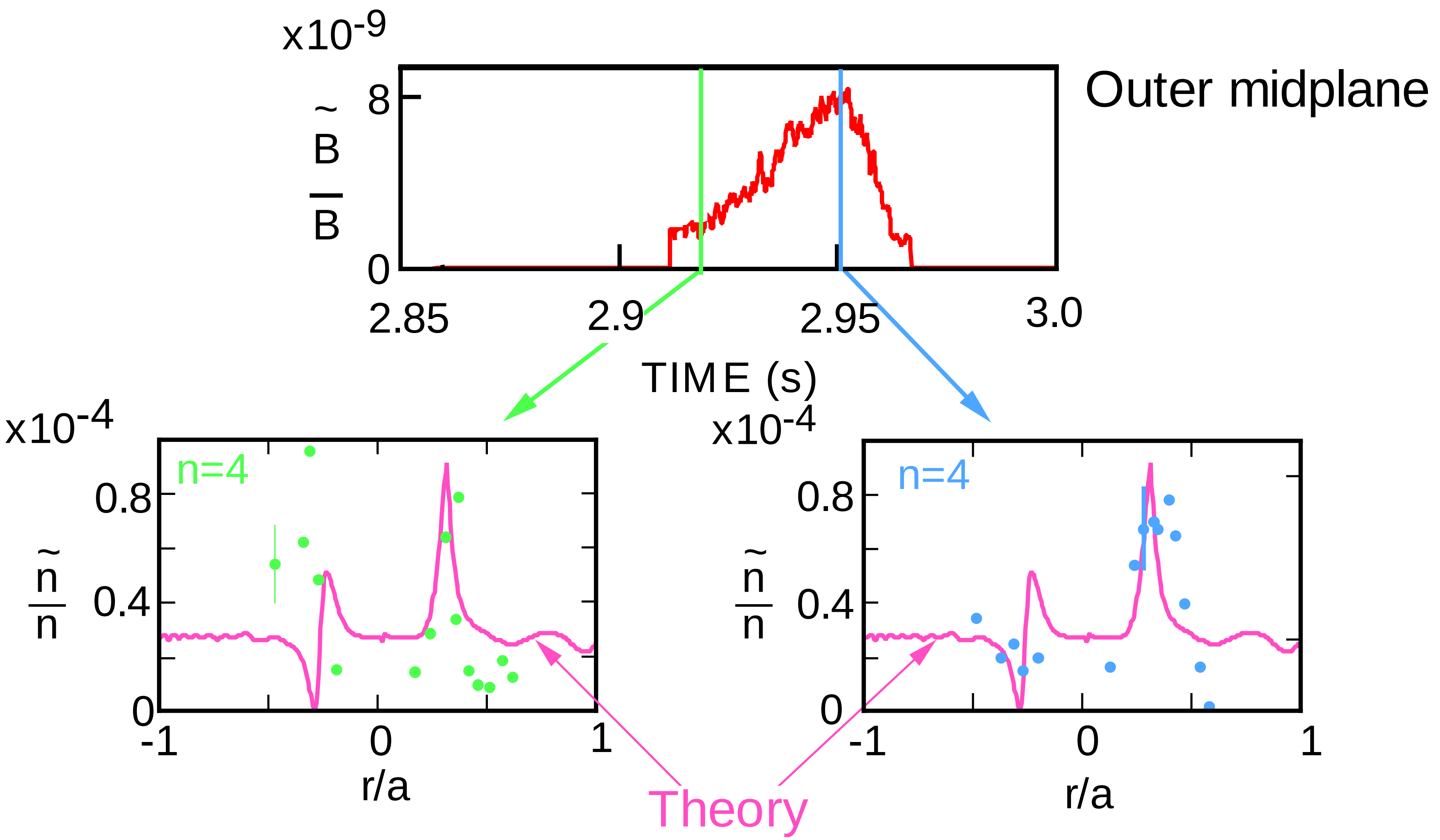
X-Mode Reflectometer Measures Evolving Mode Structure





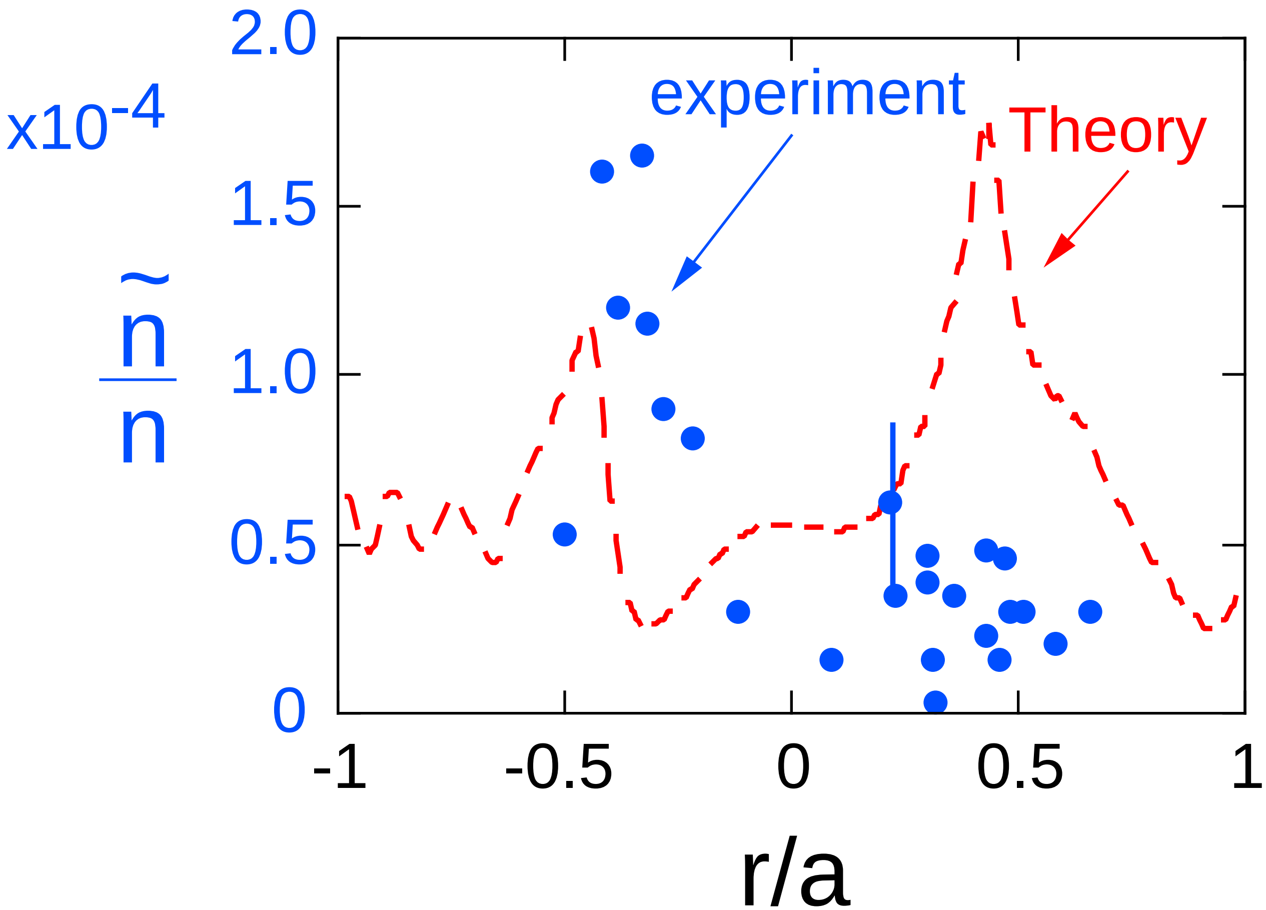
- Mode appears to moves out radially vs. time
- Edge $\tilde{B}$ is not a good indicator of internal mode amplitude

N=4 Mode Becomes More Ballooning with Time



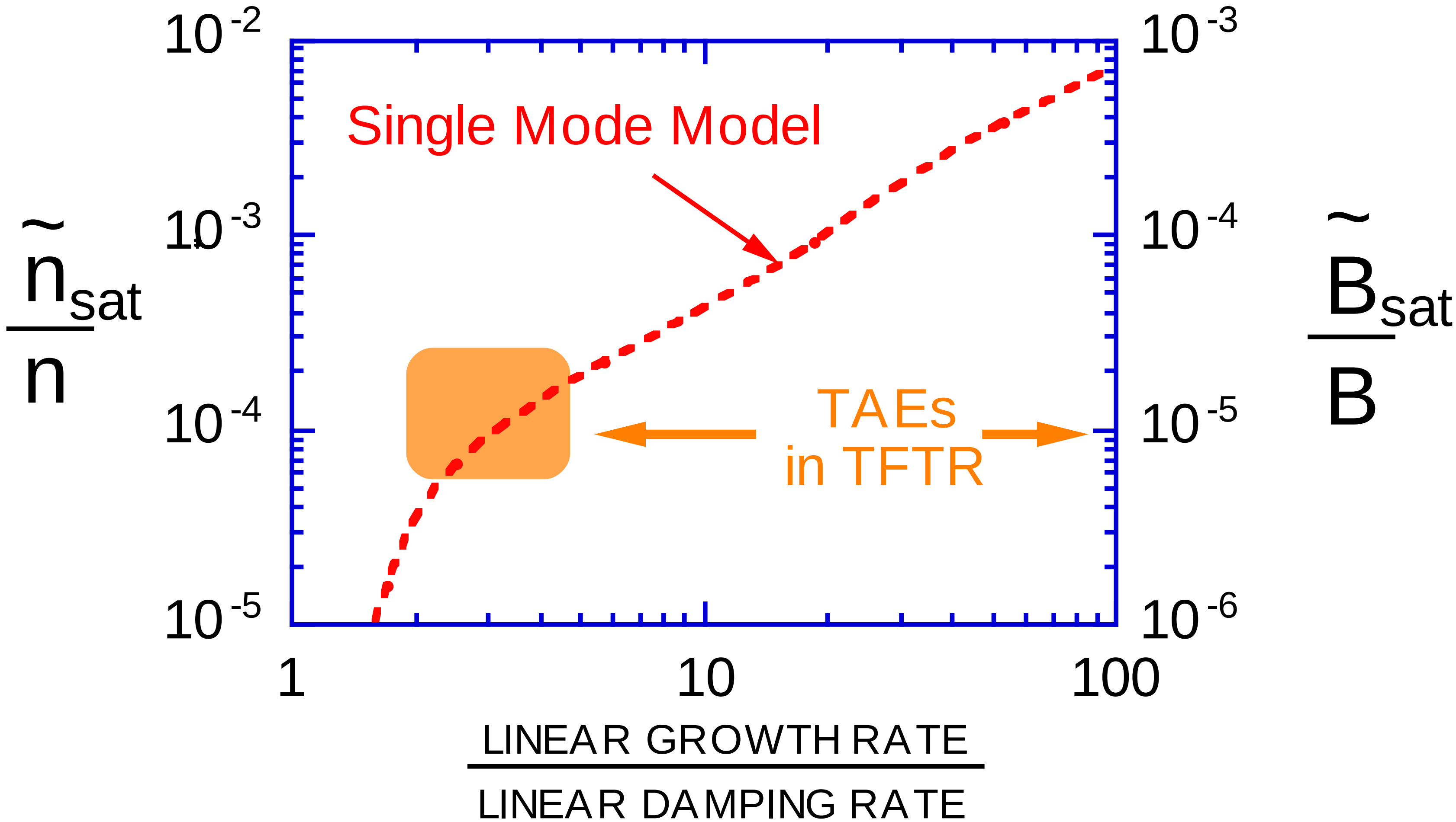
- Mode location in good agreement with theory
- $\tilde{B}/B \sim 10^{-5}$

N=2 Mode is Core Localized and Anti-Ballooning



- Frequency ~30% below TAE frequency
- Theory predicts anti-ballooning modes are stable.

SATURATED AMPLITUDE ROUGHLY CONSISTENT WITH NONLINEAR MODEL



- Saturated amplitude is sensitive to source rate of resonant alpha particles.

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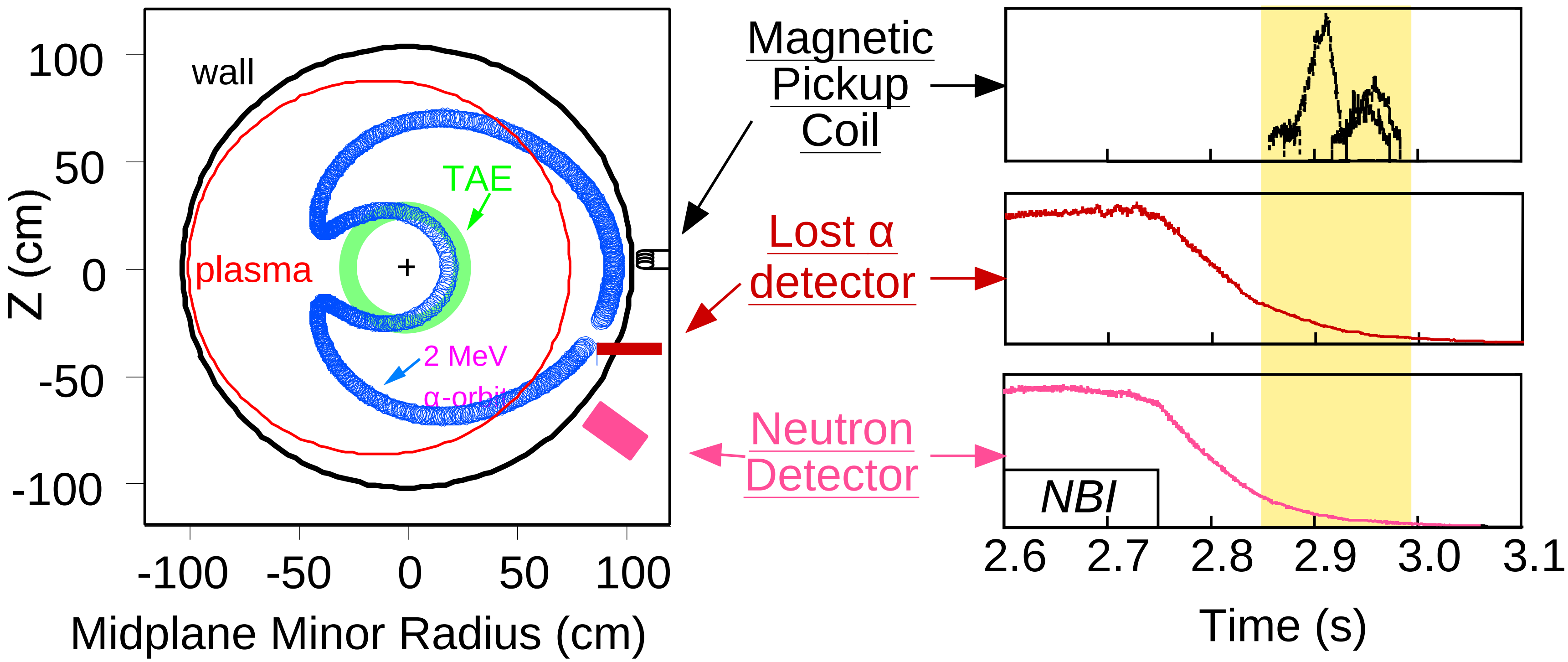
No Observed Increase in Alpha Loss During TAE



- 2 MeV trapped alphas intersect mode location and lost alpha probe
- Loss expected near trapped passing boundary

Darrow, Zweben

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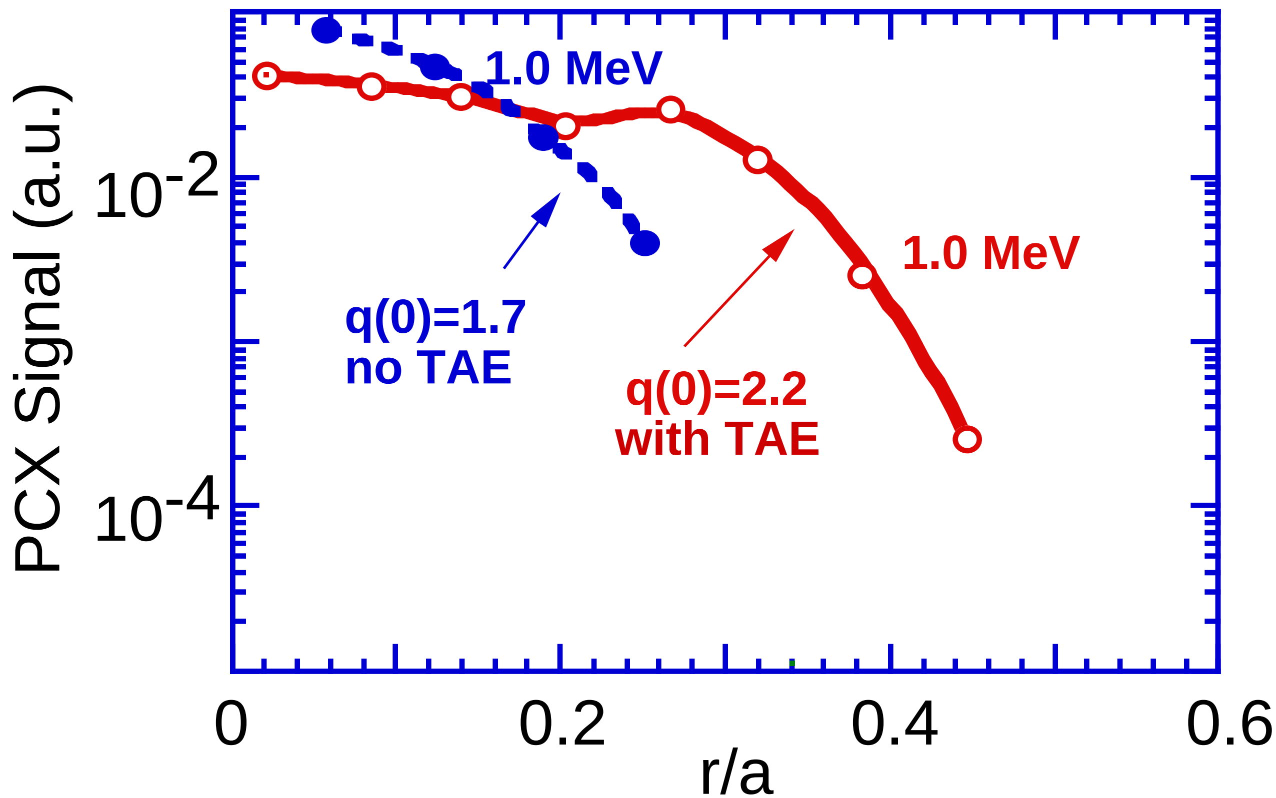
Central Broadening of Deepy Trapped Alpha Particles Observed in Presence of TAE



- Redistribution observed in presence of weak TAEs with $\tilde{B}/B \sim 10^{-5}$
- Ripple loss also depends on q(0)

SUMMARY

- Experimental results on TFTR show alpha-driven-TAE instability occured as predicted by theory
- Reflectometer measurements confirms core localization
- Observed low saturation levels roughly consistent with non-linear model
- Possibility of internal alpha redistribution but no alpha loss

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Implications and Future Directions

- Observation of TAEs in weak shear q(0)>1 plasmas of concern for advanced tokamak concepts.
- Similar Alfvén modes observed in STs (START) and stellarators (W7-AS)
- ITER like plasmas will have many high-n modes instead of a few low-n modes
- Need more internal measurements of energetic particles and mode structure to test nonlinear models.