Parametric investigation of CAE/GAE instability and effect on thermal confinement in NSTX-U

Shawn Tang, UCLA
N.A. Crocker, T.A. Carter, UCLA
E.D. Fredrickson, N. N. Gorelenkov, W. Guttenfelder, PPPL

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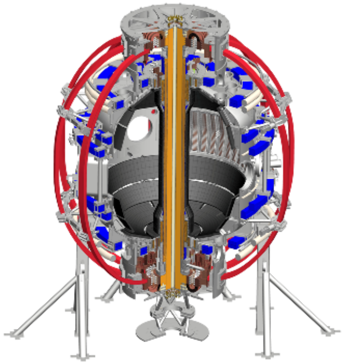
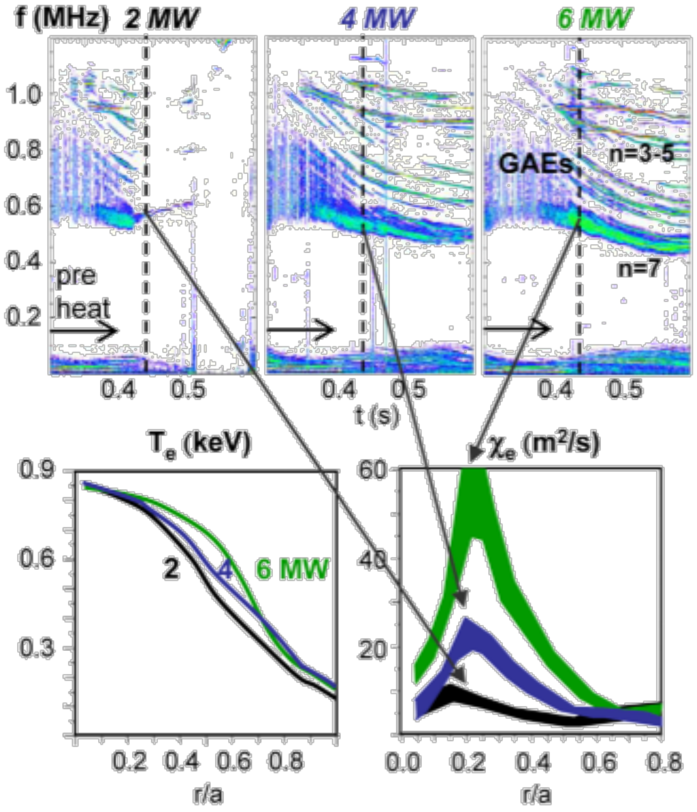


Overview

- High frequency compressional (CAE) and global (GAE) Alfvén eigenmodes are leading candidates to explain core anomalous electron heat transport with increasing toroidal field and beam power
- No validated model for predicting the spectra, structure, and amplitude of these eigenmodes
  - Motivates analysis across wide range of plasma parameters to establish scaling laws and threshold studies
- Database of shots compiled to examine correlations of mode characteristic with plasma parameters

Anomalous electron transport correlated with high frequency Alfvén activity

- Beam-heated spherical torus plasmas feature high frequency Alfvén eigenmodes (AE) (f > ~ 400 kHz): Compressional (CAE) & Global (GAE)
- CAEs & GAEs correlate with enhanced core χ_e in NSTX
- Resonant interaction of multiple modes with e^- guiding center orbits proposed to stochastize orbits, enhancing thermal transport



[D. Stutman et al., PRL 102 115002 (2009)]

CAEs and GAEs driven by Doppler-shifted cyclotron resonance with beam heating ions

- CAEs (compressional) and GAEs (global) are Alfvén eigenmodes, where approximately

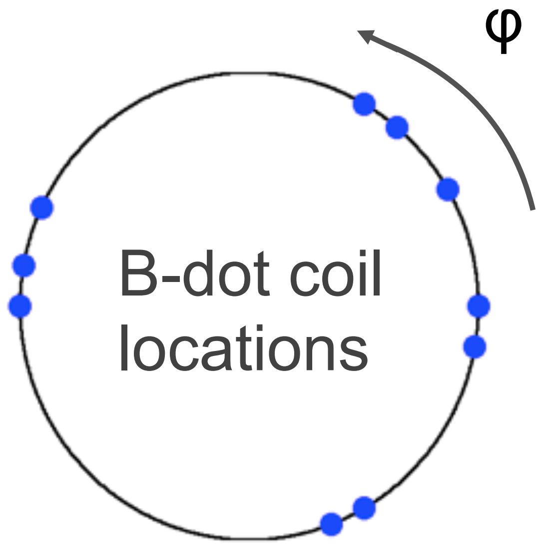
  $\omega^2 = k^2 V_A{}^2$ (CAE)

  $\omega^2 = k_{||}{}^2 V_A{}^2$ (GAE)
- For cyclotron resonance the parallel resonance condition is: $\omega - k_{||} v_{B||} = \omega_{CB}$
- The perpendicular instability condition requires finite orbit widths, e.g.:
  - CAEs: $1 < k_\perp \rho_{\perp b} < 2$
  - GAES: $2 < k_\perp \rho_{\perp b} < 4$
  - $k_\perp \rho_{\perp b}$ is stabilizing in some ranges and destabilizing in others → anisotropy important to instability

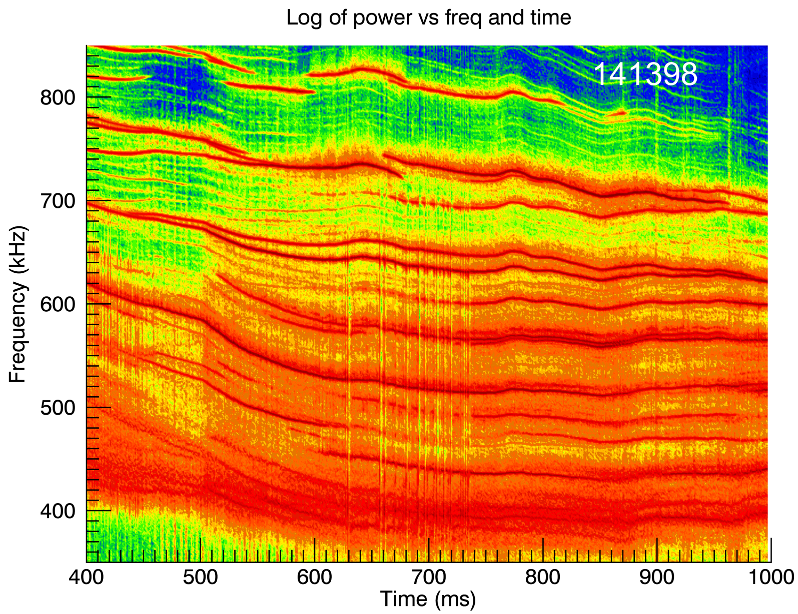
[N.N. Gorelenkov et. al., N.F. **43** (2003) 228-223]

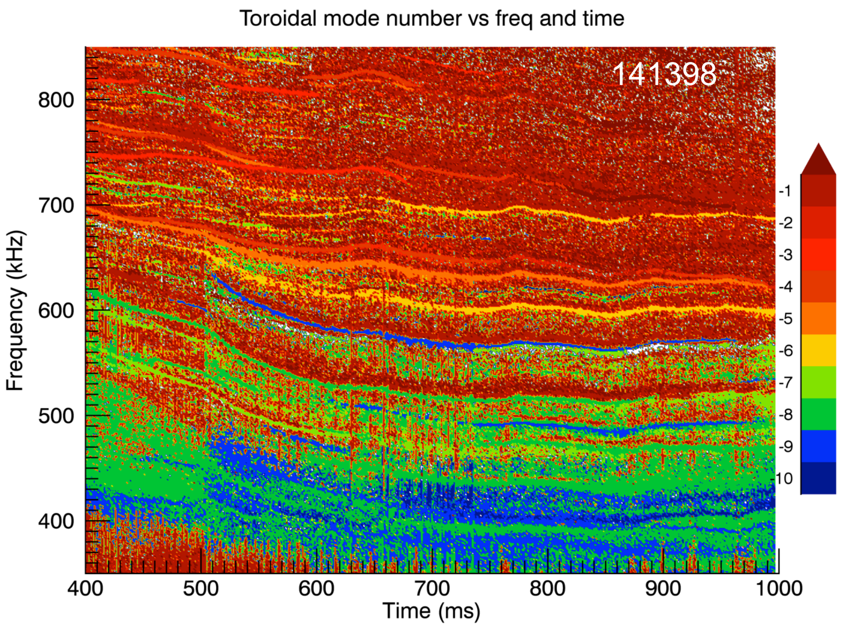
Mode activity characterized using edge B-dot array

- δb measured by a toroidally distributed array of poloidal magnetic field sensing coils (Mirnov coils)
  - 10 coils
- Statistical analysis yields frequency, mode number, and amplitude
- Use a rule of thumb of f > 200kHz to look for modes



Modes identified by testing quality of fit to single toroidal mode number


Log of power vs freq and time


Toroidal mode number vs freq and time

- Find the best fit *n* for each *t, f* by minimizing:

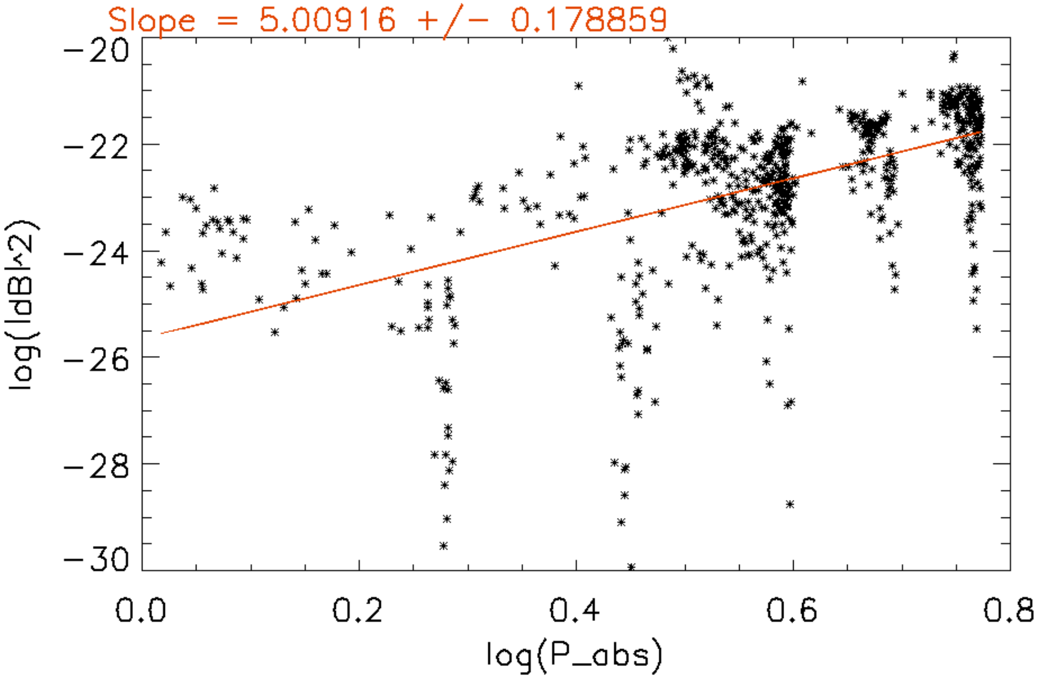
$$\chi^2 \equiv 1 - \left|\sum_{\forall\phi} \delta b e^{-in\phi}\right|^2 \Big/ \left(N_\phi \sum_{\forall\phi} |\delta b|^2\right)$$

  - Low chi-square → $\partial b(t,f)$ dominated by single toroidal mode
- Coils are distributed toroidally with smallest coil spacing of $\varphi = 10°$ → can resolve $|n| \leq 18$ ($N_\varphi = 10$)

Database extended with spectral characteristics of CAEs and GAEs

- Existing database with plasma parameters from TRANSP extended to include characteristics of CAEs and GAEs [Fredrickson 2014]
  - Database spans 195 total shots and 1051 total times
- Frequency, mode power, and toroidal mode number calculated for each 50ms interval
  - Divide into 1ms records and FFT
  - Keep points (t,f) that are a good fit to single toroidal mode number ($\chi^2 < 0.5$)
  - Power weight ($|\delta B|^2$) average f, n
- Investigate whether these modes play a role in anomalous electron transport, as well as understanding physics controlling the instability

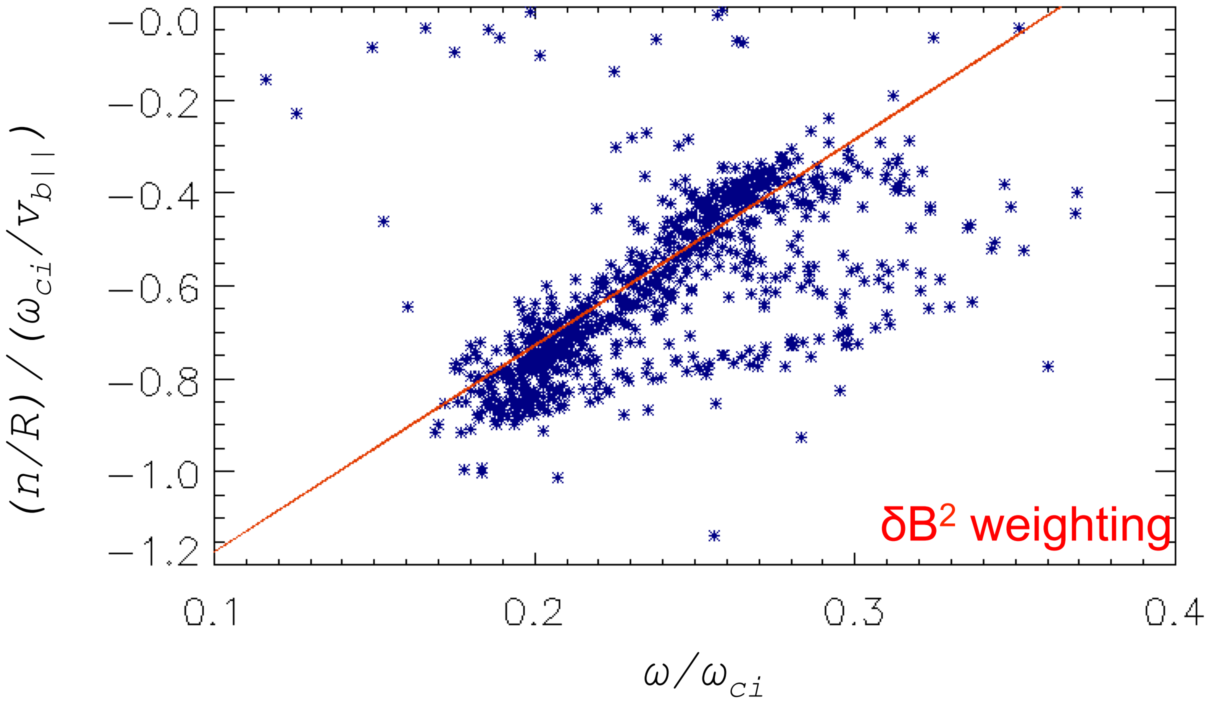
Beam power correlates with mode power



- Correlation found between total mode power (|δb|^2) and TRANSP calculated absorbed beam power
- Power law found $|\delta b| \sim P_{abs}^{2.5}$
- Roughly consistent with nonlinear simulations and analytic theory which have shown: $\delta b \sim P_b^2$

[Belova & Lestz, 2016]

Toroidal mode number and frequency highly correlated

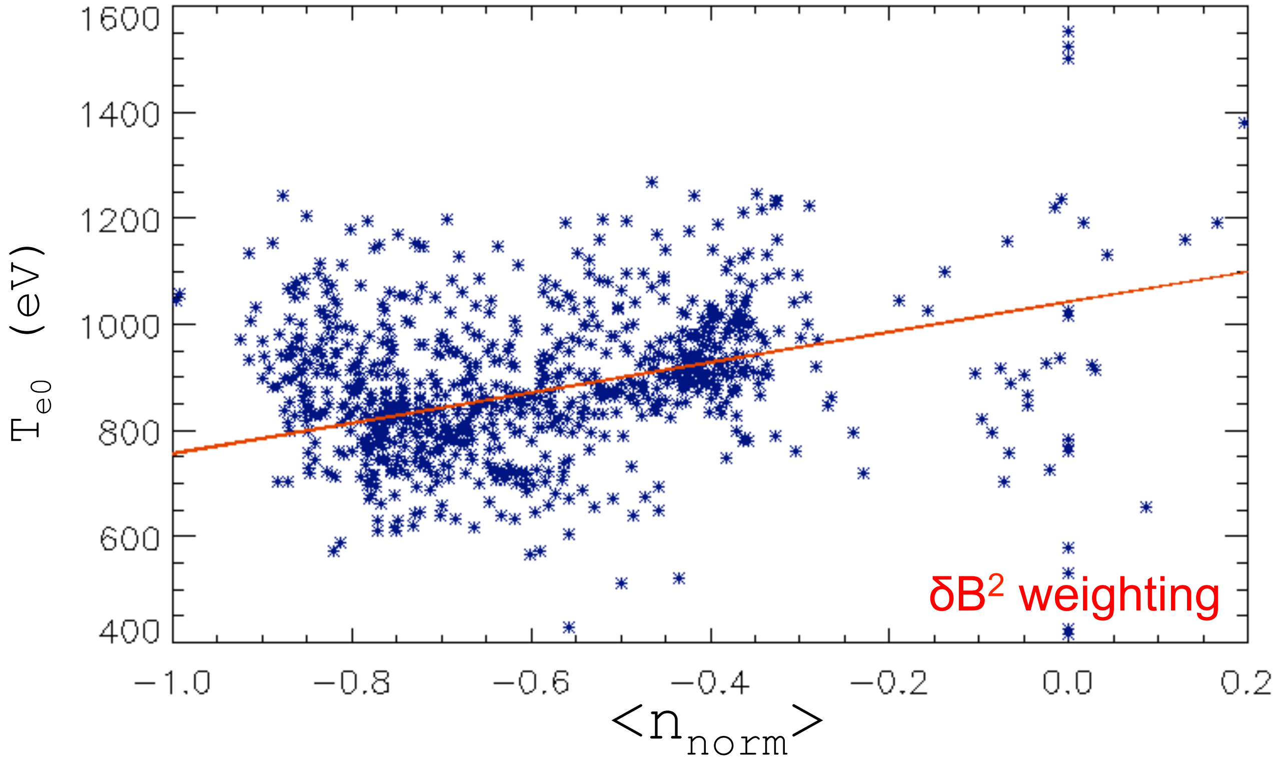


- Normalize *ω* and n as:
  - $\omega \rightarrow \omega/\omega_{ci}$
  - $k_{tor} \rightarrow k_{tor}/(\omega_{ci}/\max(v_{b||,inj}))$, $k_{tor} = n/R$
  - Motivated by parallel resonance condition
- Perform mode power (δB^2) weighted fit

Correlation improves with normalization motivated by parallel resonance condition

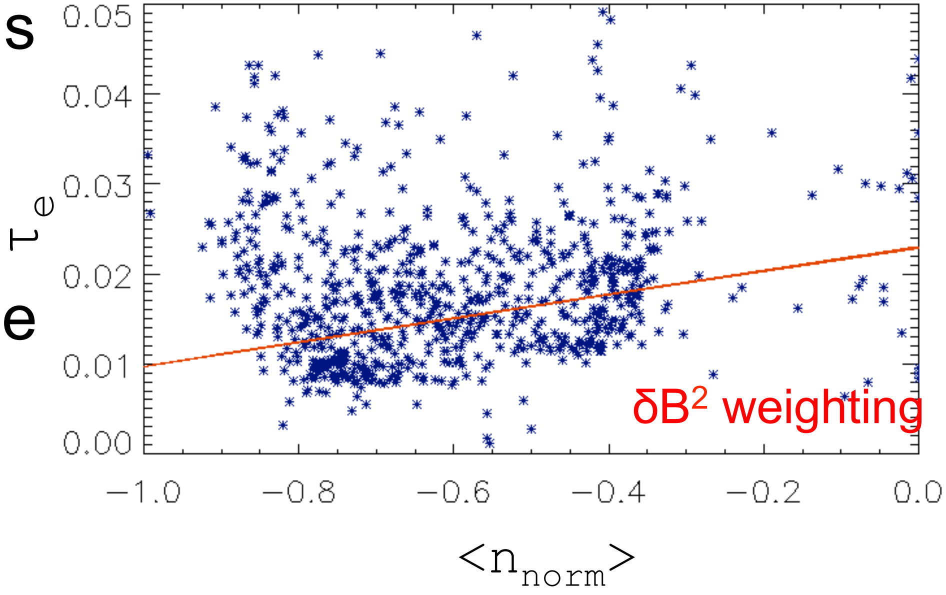
- Instability thought to be governed by Doppler shifted cyclotron parallel resonance condition
  - $\omega_{ci} = \omega - k_{||} v_{b||}$
- $k_{||}$ and destablizing $v_{b||}$ not known → k_{tor} and $\max(v_{b||,inj})$ used
- Correlation coefficient improves from $\rho = 0.52$ +/- 0.05 to $\rho = 0.85$ +/- 0.05
  - ρ calculated using dB^2 weighted
- Suggests that resonance condition plays some role in governing instability

T_{e0} correlates with both $<f_{norm}>$, $<n_{norm}>$



- T_{e0} correlates with both $<f_{norm}>$ and $<n_{norm}>$ with statistical significance, with $\rho = 0.32 \pm 0.05$ and $\rho = 0.45 \pm 0.05$ respectively
- $<f_{norm}>$,$<n_{norm}>$ control T_{e0}?

min(τ_e) in core correlates with $<f_{norm}>$,$<n_{norm}>$



- χ_e ideal indicator of anomalous transport but very noisy
  - Connects to Stutman PRL 2009
- Electron energy confinement time $\tau_e(\rho)$ integrated, low noise
  - Median smoothing to eliminate outliers
  - take minimum value between $\rho = 0.1$ and $\rho = 0.5$
- Correlation of $<f_{norm}>$, $<n_{norm}>$ with τ_e gives $\rho = 0.296 \pm 0.05$, 0.302 ± 0.05 respectively
- Modeling assume classical fast ion diffusivity → τ_e controlled by anomalous fast ion transport?
- Some f, n more effective at orbit stochastization?

Future Work

- Implementing step-wise multiple linear regression to better understanding of parameters controlling transport
- Extending research to DIII-D through experiment currently in planning
  - Complementary control of injection angle allowing for exploration of parallel resonance condition and perpendicular instability condition