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

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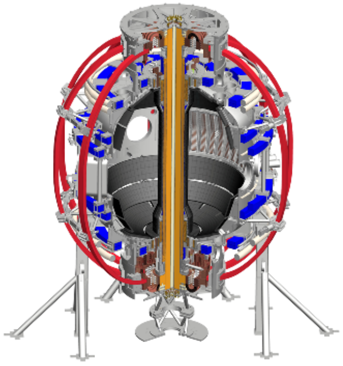
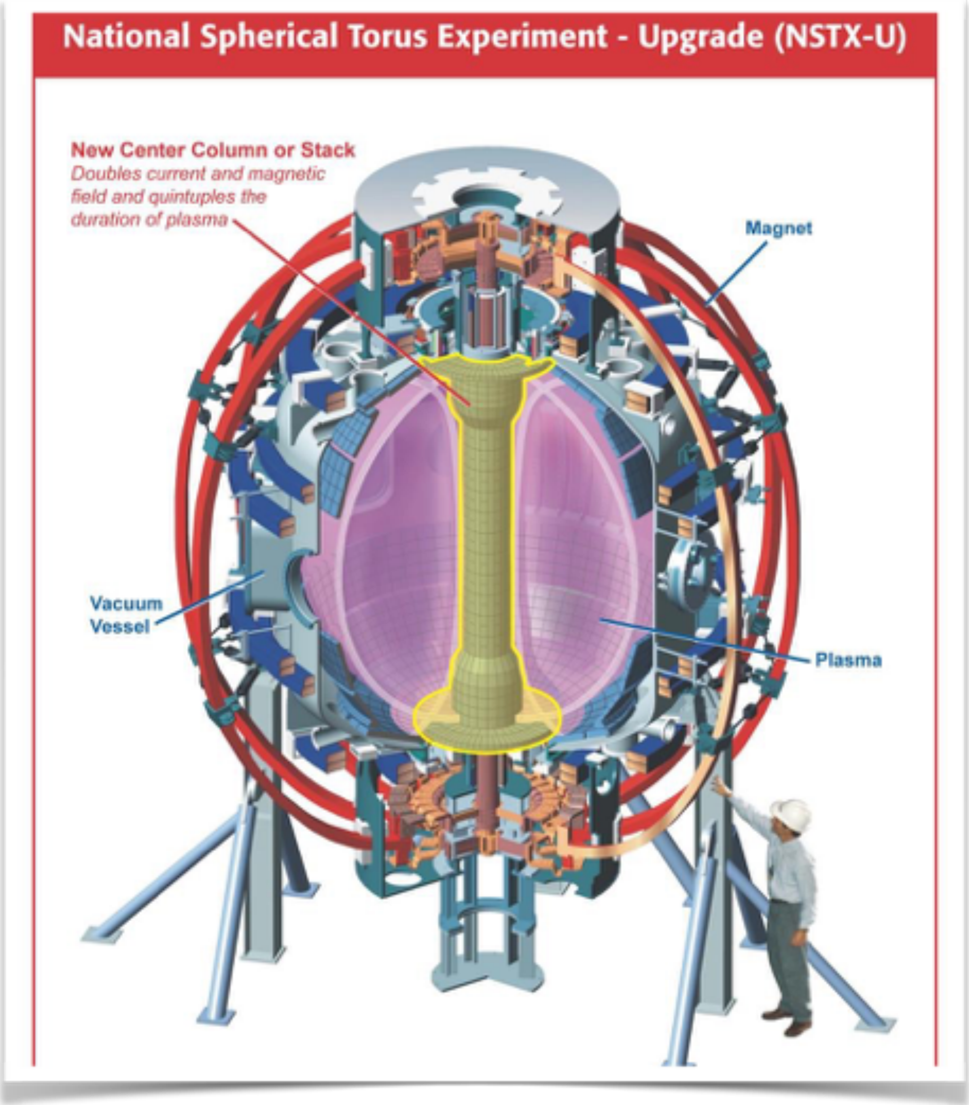


National Spherical Torus Experiment

- Low aspect ratio: R/a ~ 1.3
- High beta: β up to 40%
- Low toroidal field $B_T \leq 0.5$T
- High plasma current $I_P \leq$ 1.3MA
- Electron temperature ~ 1keV
- Density ~ 10^{19} m^{-3}
- Injection of up to 7MW of E $\leq$ 100keV neutral D beam
- Preferential electron heating (2:1)
- Low collisionality

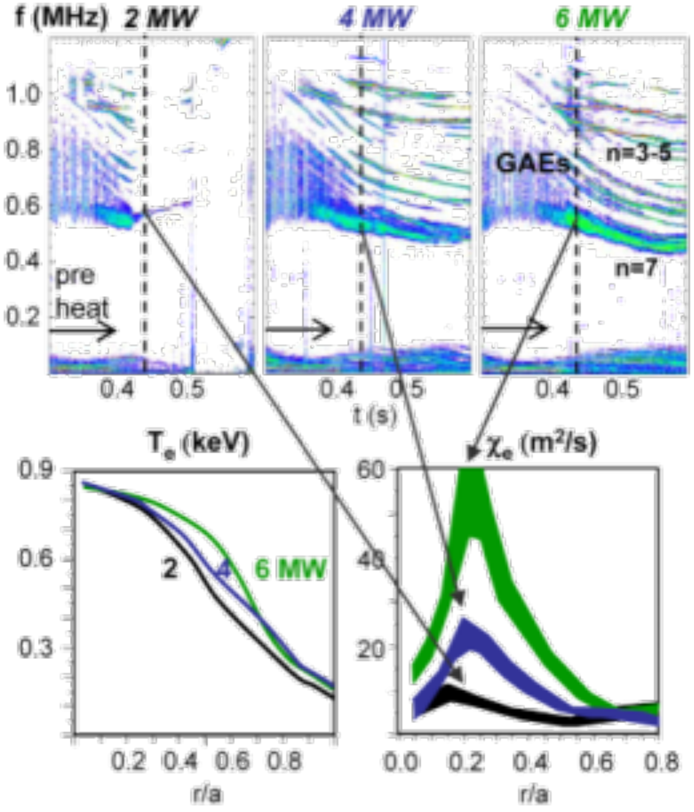


Overview

- 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 fully 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 used to investigate role of modes in anomalous electron transport, as well as understanding physics controlling the instability

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
- Proposed mechanisms
  - Resonance w/ multiple modes stochastizes e^- orbits → enhance χ_e
  - Modes channel beam energy to edge via coupling to kinetic Alfvén waves



[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]

Database extended with spectral characteristics of CAEs and GAEs

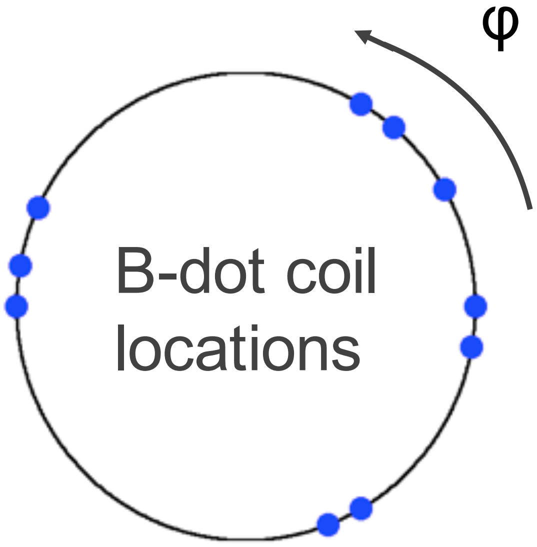
- Existing database with plasma parameters from TRANSP extended to include characteristics of CAEs and GAEs [Fredrickson 2014]
  - Database spans 195 total shots and 1051 total times
  - Majority of shots in H-mode
  - Plasma currents ranging 0.3-1.3MA, average 0.9MA
  - Plasma heated up to 6MW with maximum beam voltage 90kV
  - On-axis magnetic field from 2.7-5.3kG
  - Central electron densities from 0.9×10^{19} to 1.3×10^{20} m-3
  - Central electron temperature typically 0.8keV, ranging from 0.23 to 1.7keV

Database extended with spectral characteristics of CAEs and GAEs

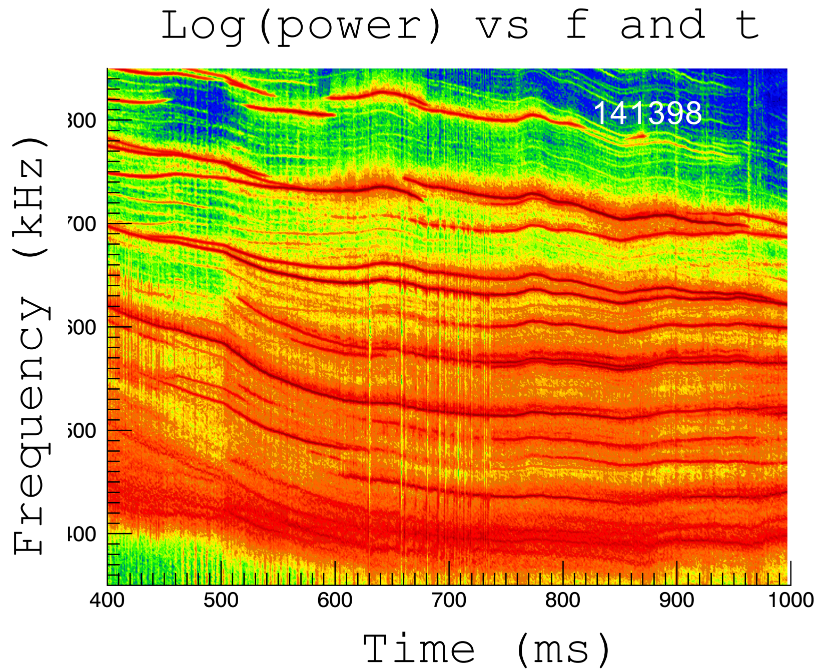
- Constructed from shots from 2010 experimental campaign on NSTX
  - Each TRANSP run divided into 50ms intervals
  - TRANSP infers transport coefficients and fast ion population from profile measurements and a model of beam deposition
  - TRANSP outputs calculated using neoclassical fast ion diffusion → neutron rate discrepancy a measure of fast ion transport
- 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

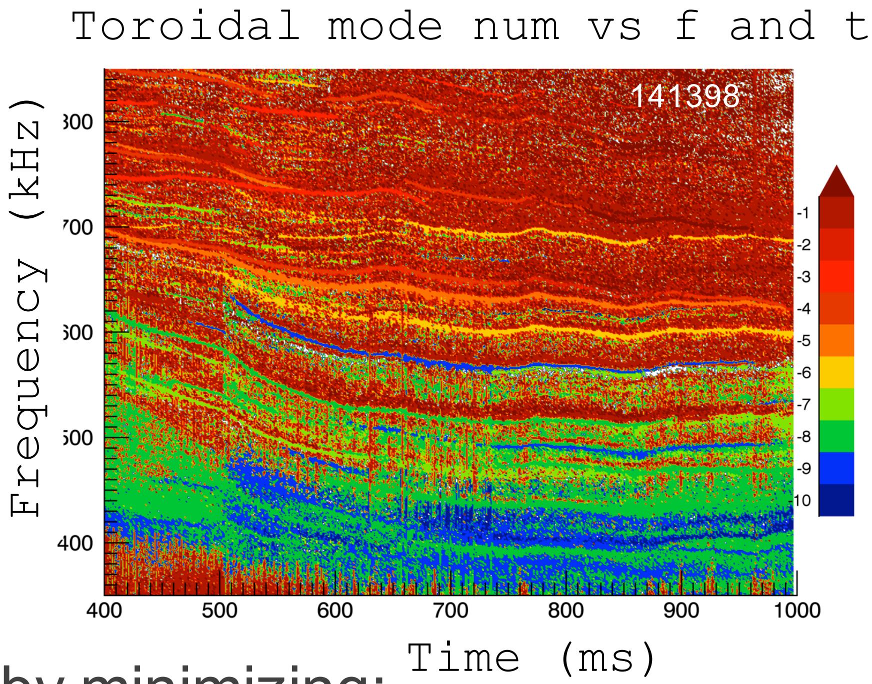
Mode activity characterized using edge B-dot array

- 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(power) vs f and t

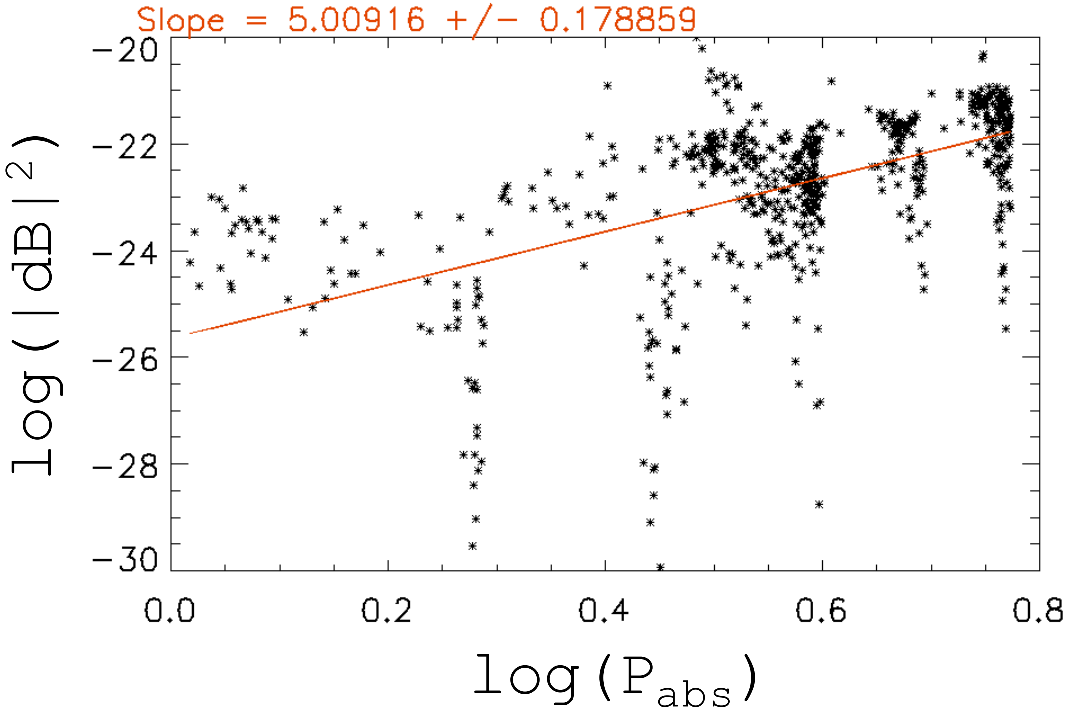

Toroidal mode num vs f and t

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

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

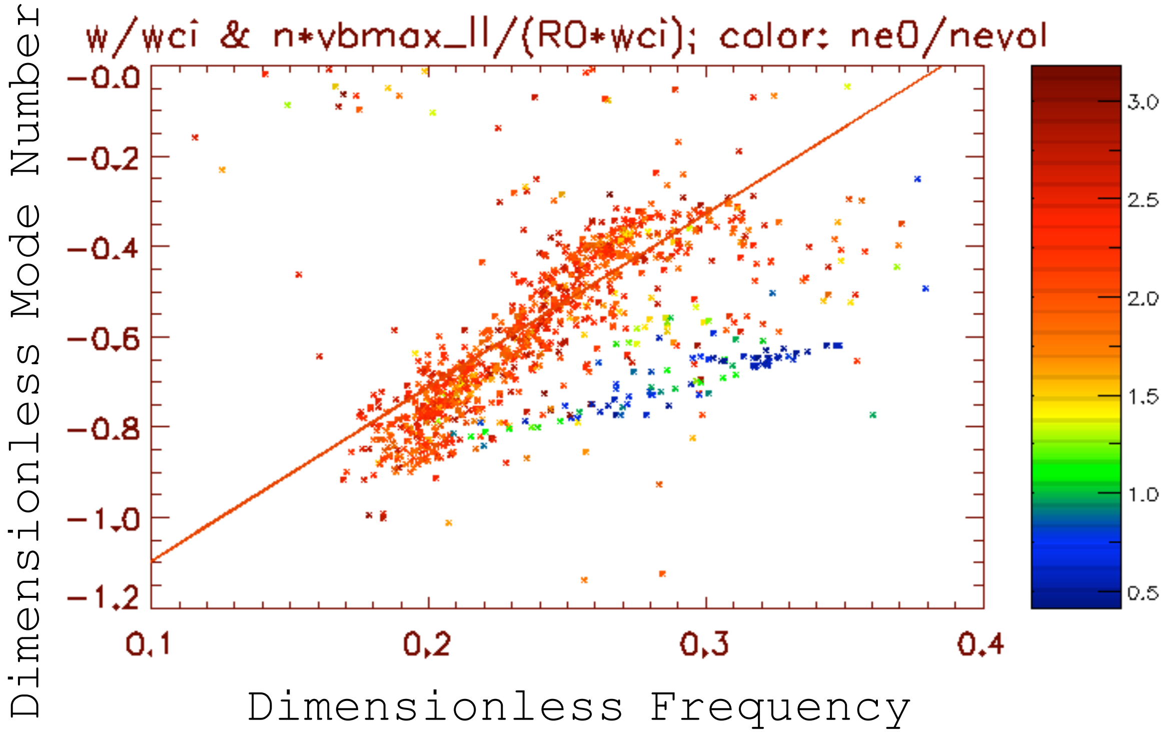
  - Low chi-square → *∂b*(*t*,*f*) dominated by single toroidal mode
- Coils are distributed toroidally with smallest coil spacing of $\varphi = 10°$ → can resolve $|n| \leq 18$ ($N_\varphi = 10$)

Mode power increases with beam power as expected



- Correlation found between total mode power ($|\delta b|^2$) and TRANSP calculated absorbed beam power: $|\delta b| \sim P_{abs}^{2.5}$
- Roughly consistent with nonlinear simulations and analytic theory which have shown: $\delta b \sim P_b^2$ [Belova & Lestz, 2016]

High correlation of n, f suggests importance of parallel resonance condition



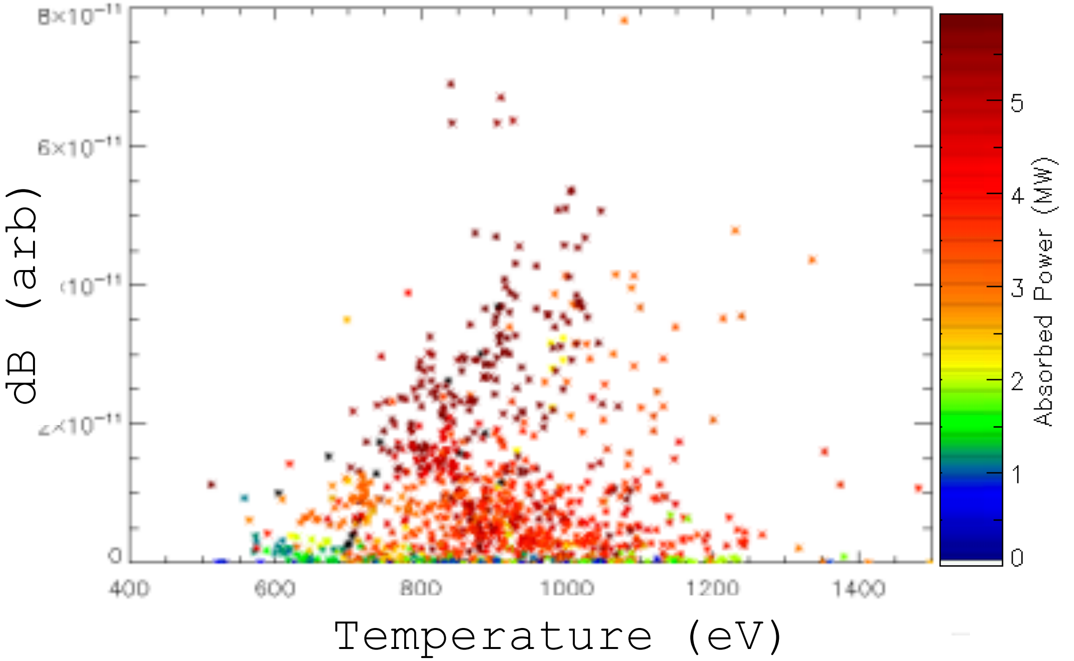
- Perform mode power (δB^2) weighted fit
- ω increases as |n| decreases
  - If k ~ n/R, expect ω to decrease as |n| decreases from dispersion relationship
  - However, slope consistent with parallel resonance condition if $k_{||}$ ~ n/R : $\omega_{ci} = \omega - k_{||}v_{b||}$
- Normalization of ω and n motivated by parallel resonance condition significantly improves correlation
  - Correlation coefficient improves from ρ = 0.52 +/- 0.05 to ρ = 0.80 +/- 0.05
- Plasmas with hollow density profiles have different relationship

Correlation improves with normalization motivated by parallel resonance condition

- Instability thought to be governed by Doppler shifted cyclotron parallel resonance condition
  - $\omega_{ci} = \omega - k_{||} v_{b||}$
  - $\omega \rightarrow \omega/\omega_{ci}$
  - $k_{tor} \rightarrow k_{tor}/(\omega_{ci}/\max(v_{b||,inj}))$, $k_{tor} = n/R$
- $k_{||}$ and destablizing $v_{b||}$ not known → k_{tor} and $\max(v_{b||,inj})$ used
- Correlation coefficient improves from $\rho = 0.52 +/- 0.05$ to $\rho = 0.80 +/- 0.05$ after normalization
- Suggests that resonance condition plays some role in governing instability

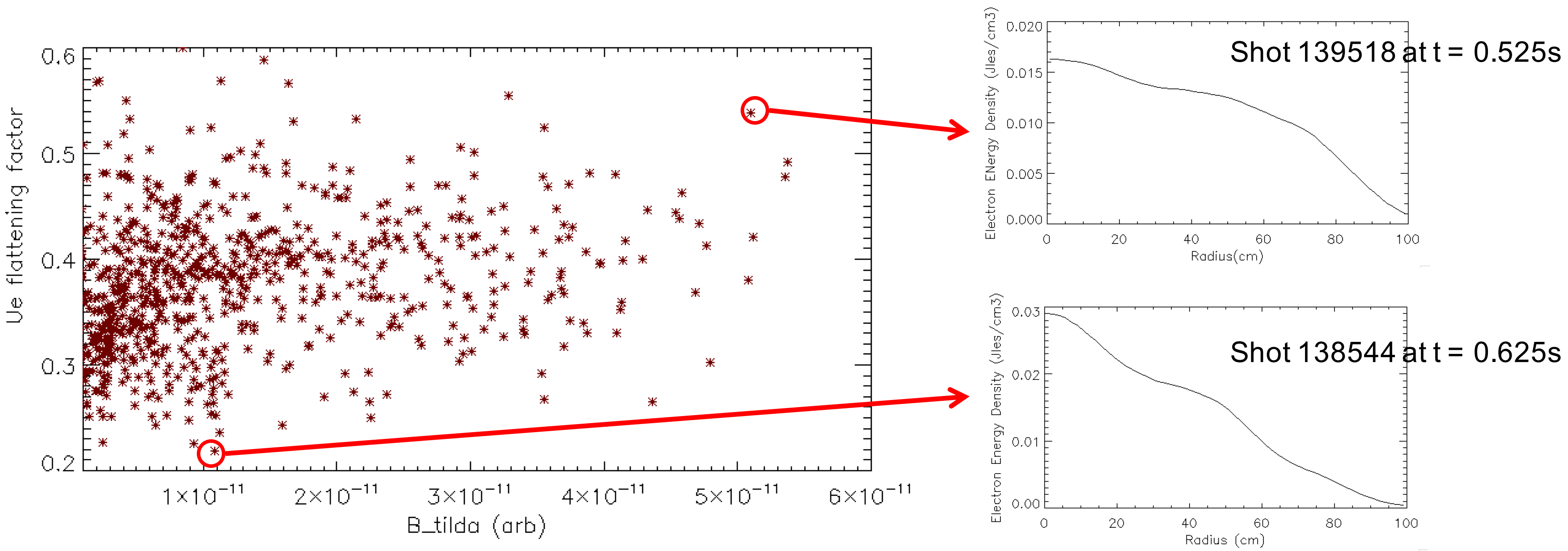
$|\delta b|^2$ correlates with T_e at high beam power

- Total mode power found to correlate with temperature at high beam power
- Further investigation required
  - Cause of correlation unknown



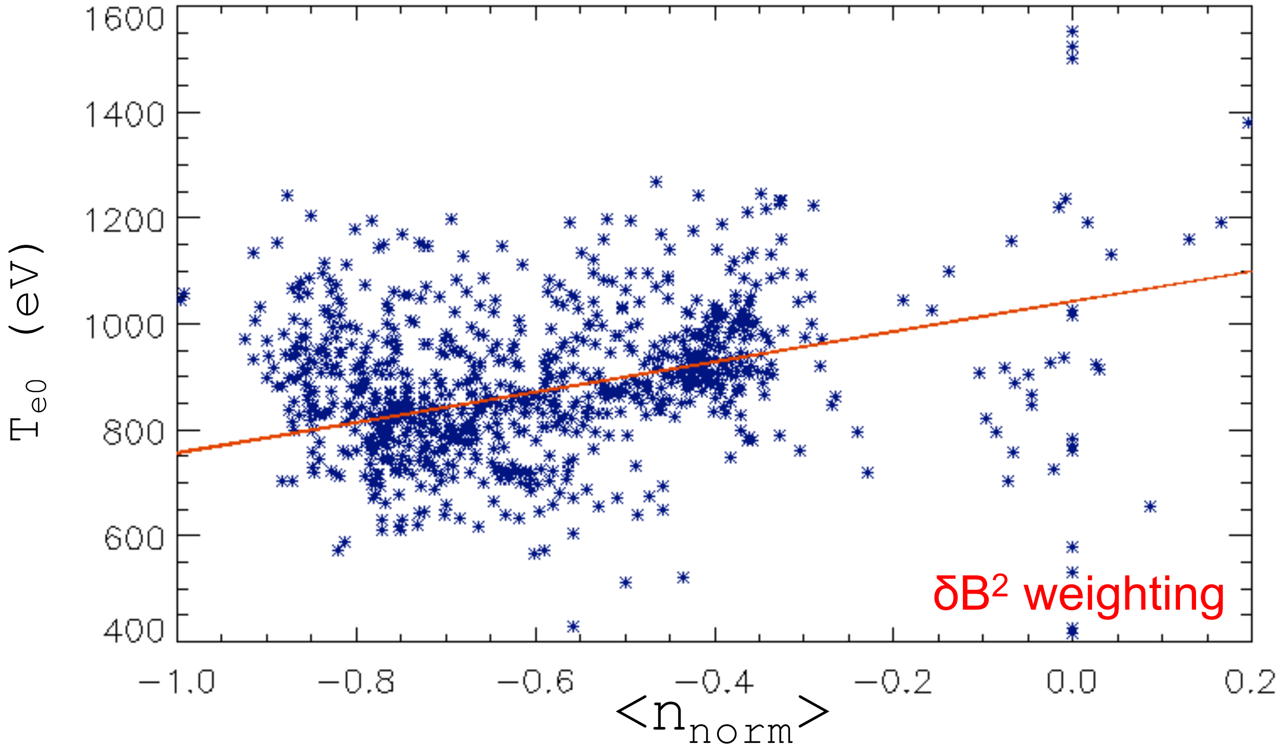
- T_e may be important for its role in Landau damping and anisotropy of beam ion distribution

Electron energy density profile flattens with increased mode power



- U_e flattening factor approximated by volume averaged electron energy density (U_e) over peak U_e: $\dfrac{\langle U_e\rangle}{U_e(0)}$
- Correlation consistent with theory of anomalous electron transport by CAE/GAEs
  - TRANSP calculations assumed no anomalous fast ion diffusion
- Further analysis needed to explore implications of this result

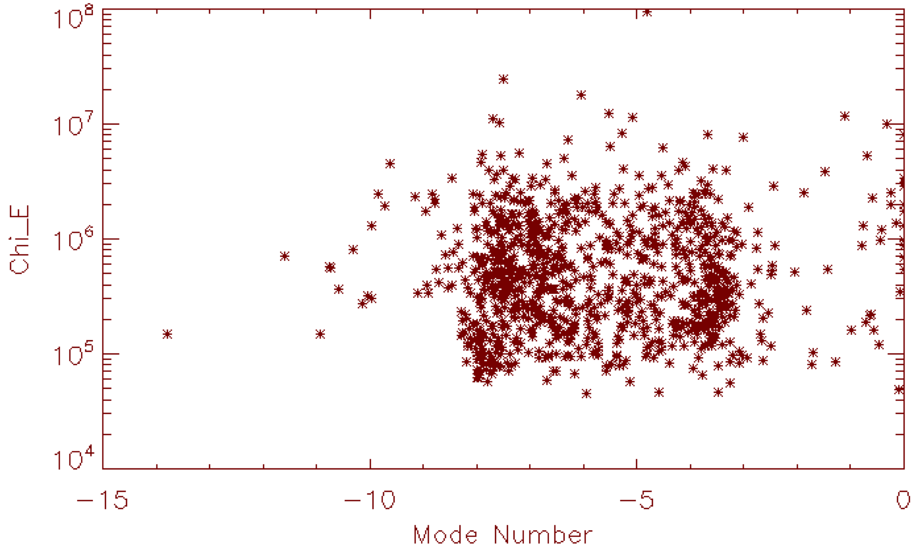
T_{e0} correlates with both $\langle f_{norm} \rangle$, $\langle n_{norm} \rangle$



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

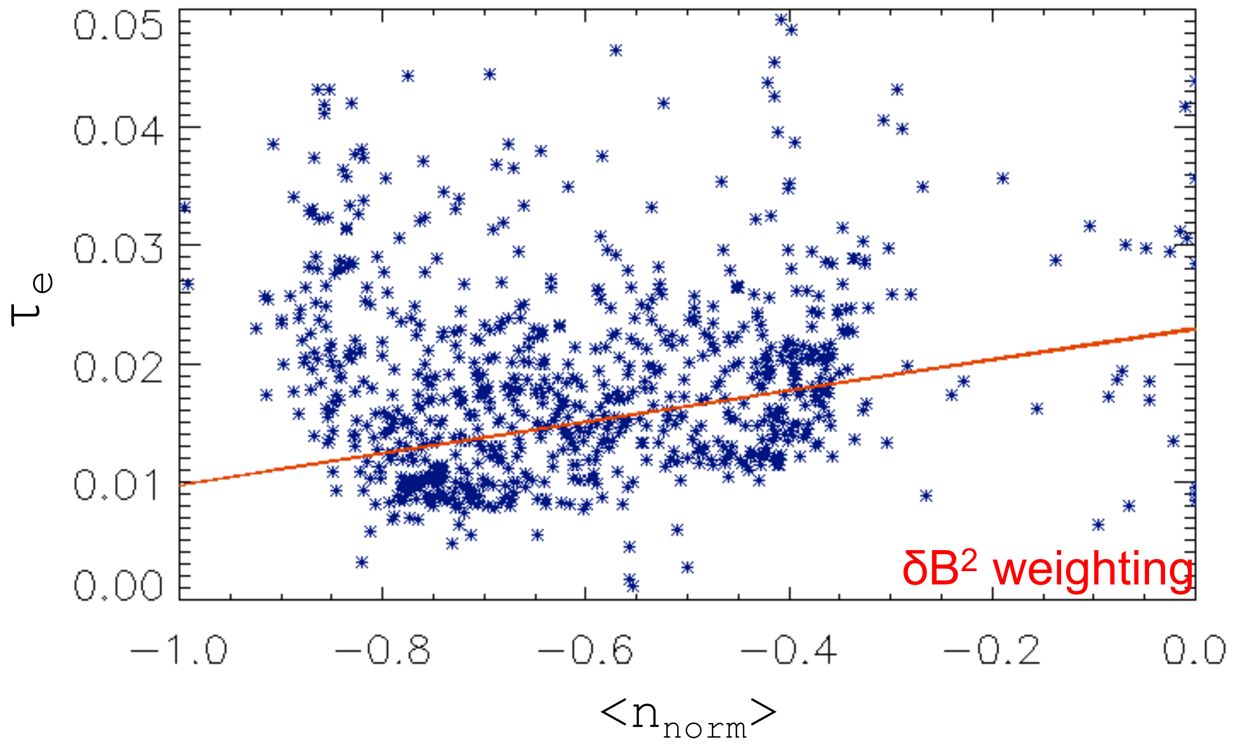
Electron energy confinement time in core correlates with $\langle f_{norm} \rangle, \langle n_{norm} \rangle$

- χ_e ideal indicator of anomalous transport but very noisy
  - Connects well to Stutman PRL 2009
  - Grad Te goes to zero in areas of interest



- Electron energy confinement time $\tau_e(\rho)$ is lower noise
  - Modeled as a function of radius, and is an integrated measure of confinement
  - Median smoothing over time to eliminate outliers
  - take minimum value in deep core between $\rho = 0.1$ and $\rho = 0.5$

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



- Correlation of $<f_{norm}>$, $<n_{norm}>$ with τ_e gives $\rho = 0.296 \pm 0.05, 0.302 \pm 0.05$ respectively
- Modeling assume classical fast ion diffusivity → τ_e controlled by anomalous fast ion transport?
- Some f, n more effective at orbit stochastization?

Conclusions

- Beam power correlates with mode power
- Toroidal mode number correlates highly with frequency
  - Correlation improves with normalization motivated by parallel resonance condition
- dB scales with Te at high beam power
- Electron energy density profile flattens with increased mode power
- Central temperature correlates with frequency and mode number
- Electron confinement time correlates with frequency and mode number

Future Work

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