NSTX

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Nonlinear three-wave interaction of fast-ion modes in the NSTX

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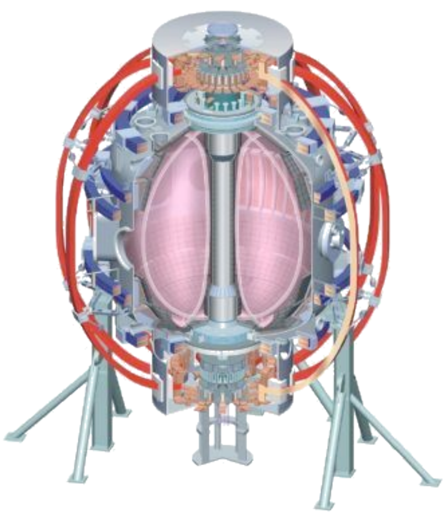

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Motivation: three-wave interaction of fast-ion modes can impact plasma performance

- Fast-ions heat fusion plasmas - must be confined
  - neutral beams in non-burning plasmas
  - fusion alphas in burning plasmas

- Fast-ion modes modify fast-ion orbits - redistribute fast-ions or degrade their confinement

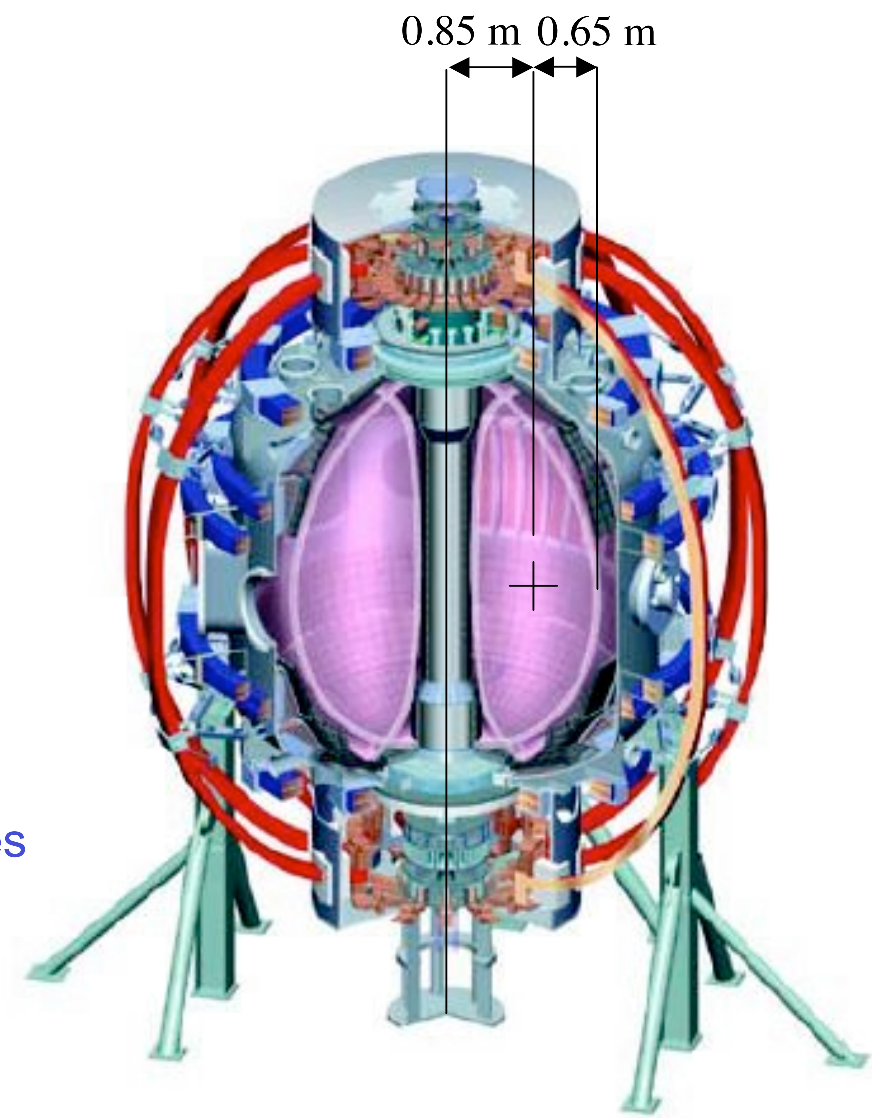
- Observed three-wave interactions *spatially concentrate mode energy* (i.e. cause “wave-packet” formation) - will *modify effect on fast-ion orbits*

Summary of Results

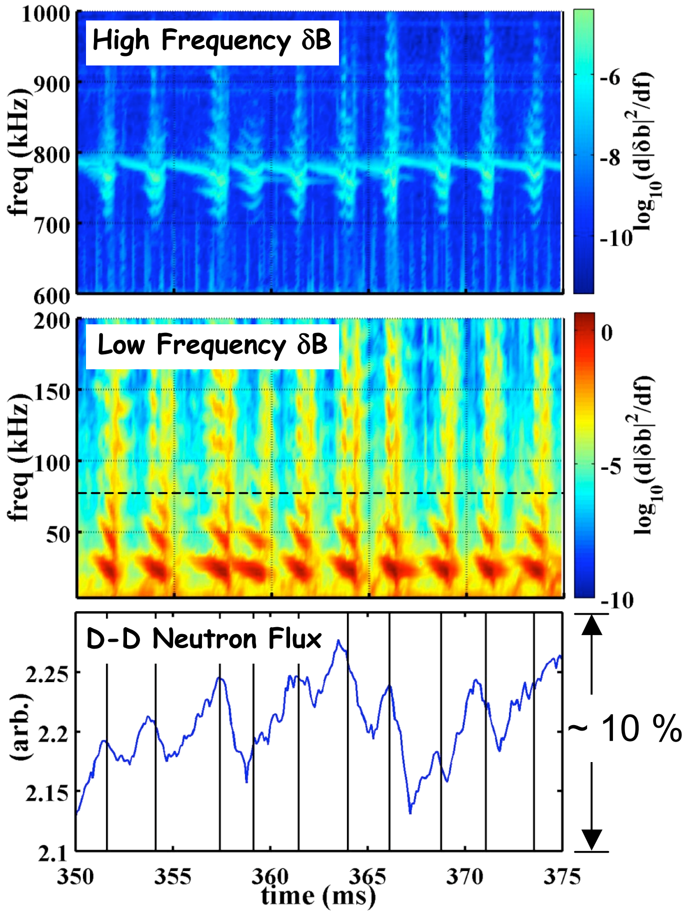
- Bursts of fast-ion driven modes observed - correlated with fast-ion loss
  - Compressional Alfvén eigenmodes (CAE) - high frequency (*f*) and wave number (*n*)
  - Toroidicity-induced Alfvén eigenmodes (TAE) - intermediate *f* and *n*
  - Energetic Particle Modes (EPM) - low *f* and *n*
- Three-wave interactions identified across all scales: EPM—TAE, EPM—CAE and TAE—CAE
  - Mode triplets identified satisfying *f* and *n* matching conditions
  - High bicoherence confirms interactions
- Universal effect observed: wave-packet formation
  - lower *f* modes spatially concentrate energy of higher *f* modes

NSTX makes high temperature, high density toroidal plasmas

- B_{TOR} = 0.44 T, I_p = 0.8 MA
- 2 MW Neutral beam heating
  - Two 1 MW beams, 65 keV Deuterium
- $n_{e0} \sim 3.85\text{x}10^{19}$ m^{-3}
- $T_{e0} \sim 1.7$ keV
- $\beta = P_{thermal}/P_{magnetic} \sim 10$ %
- $V_A \sim 1.1 \times 10^6$ m/s
- $V_{fast}/V_A \sim 2.3$
  - Fast-ion can excite Alfvén eigenmodes



Fast-ion driven modes in neutral beam heated plasmas cause fast-ion loss



- Bursts of modes detected globally:
  - edge magnetic sensors
  - core reflectometry (density fluctuations)
- Multiple mode types observed:
  - 0.6 – 1 MHz: CAEs
  - 75 – 200 kHz: TAEs
  - 0 – 75 kHz: EPMs
- Modes cause fast-ion loss or redistribution
  - large drops in neutrons flux accompany bursts
  - neutrons primarily from fast-ion fusion reactions

Three-wave interactions lead to high "bicoherence" for wave triplets

- Three-wave interactions occur when a wave is driven by a quadratic nonlinearity. For example:

quadratic nonlinearity

$$d^2\Psi/dt^2 - v^2 d^2\Psi/dx^2 + \Lambda\Psi^2 = 0$$

- Nonlinearity drives sum and beat waves:

$$\Psi = A_1\sin(\omega_1 t - k_1 x) + A_2\sin(\omega_2 t - k_2 x)$$
$$+ \underbrace{A_{1+2}\sin([\omega_1+\omega_2]t - [k_1+k_2]x)}_{\text{sum wave}} + \underbrace{A_{1-2}\sin([\omega_1-\omega_2]t - [k_1-k_2]x)}_{\text{beat wave}}$$

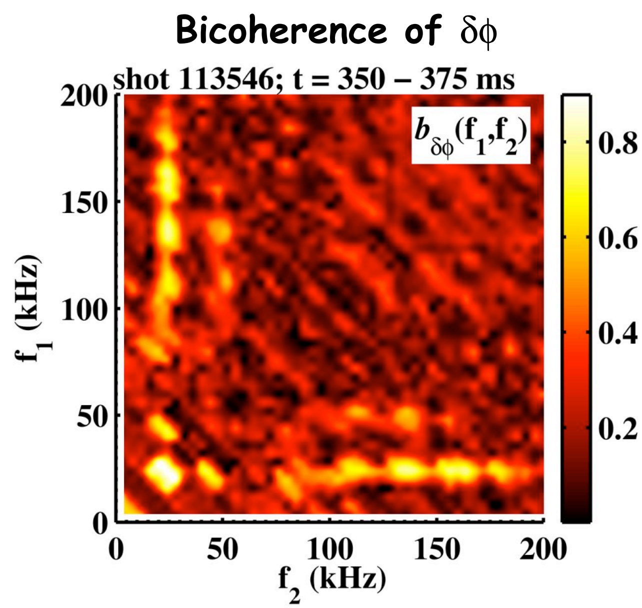
- Sum and beat waves have high value of bicoherence:

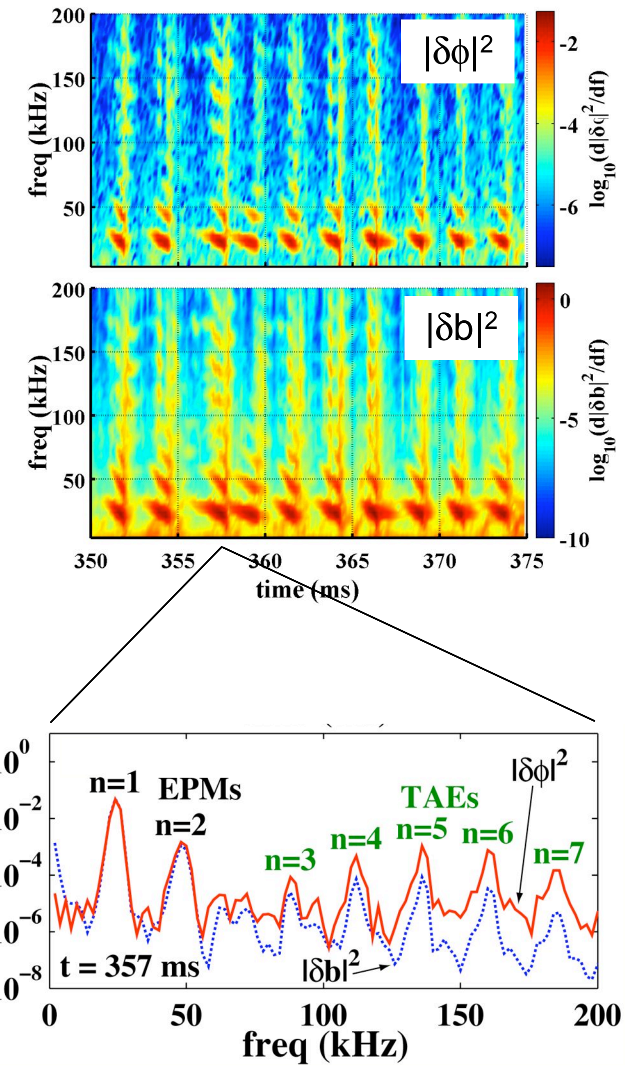
$$b_\Psi(\omega_1,\omega_2) = \frac{\left\langle \hat{\Psi}(\omega_1)\hat{\Psi}(\omega_2)\hat{\Psi}^*(\omega_1+\omega_2)\right\rangle}{\left\langle \left|\hat{\Psi}(\omega_1)\hat{\Psi}(\omega_2)\right|^2\right\rangle^{1/2}\left\langle \left|\hat{\Psi}(\omega_1+\omega_2)\right|^2\right\rangle^{1/2}}$$

- Bicoherence may be viewed as coherence of nonlinear product with sum or beat wave

Three-wave interactions observed between TAEs and EPMs

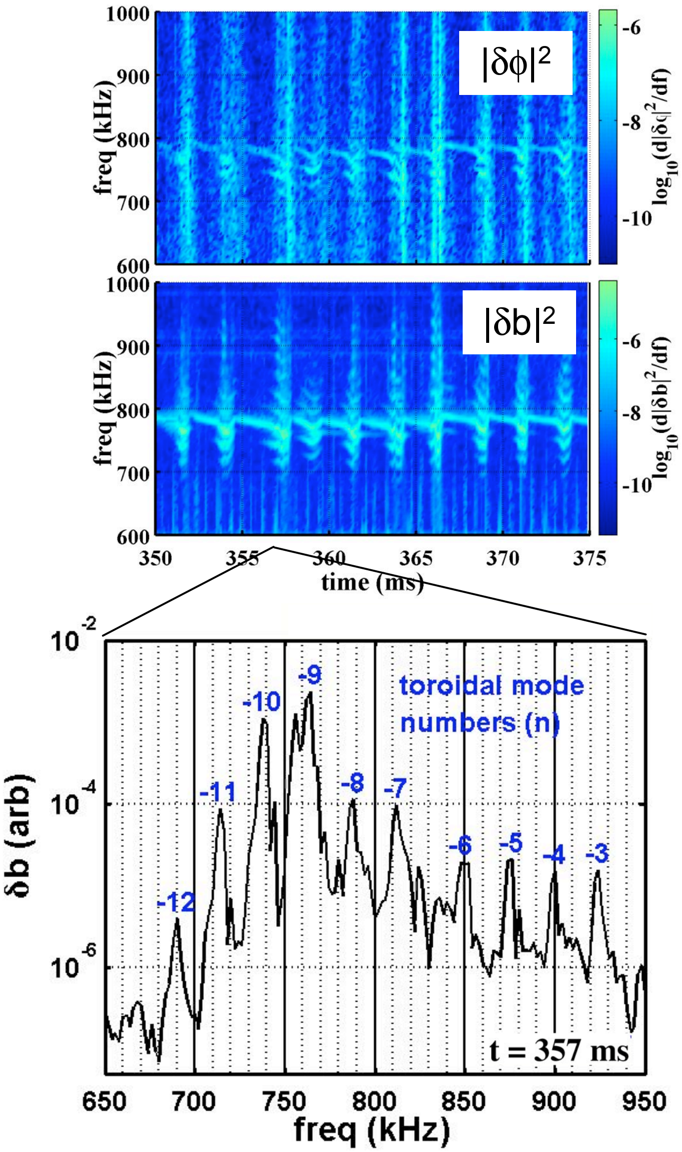
- EPM: Harmonics, $f \sim 25$ kHz, 50 kHz, $n = 1,2$
- TAEs: $f \sim 80$ - 200 kHz, $n = 3$ - 7
  - uniformly spaced in f and n: $\Delta f \sim 25$ kHz, $\Delta n = 1$
- EPMs interact with pairs of TAEs:
  - neighboring TAEs satisfy matching requirements: $\Delta f_{TAE} = f_{EPM}$ and $\Delta n_{TAE} = n_{EPM}$, so for TAE pairs (f,n) and (f',n'): $f' = f + \Delta f_{TAE} = f + f_{EPM}$ and $n' = n + \Delta n_{TAE}$ $= n + n_{EPM}$
  - interacting modes show high bicoherence (bottom left)

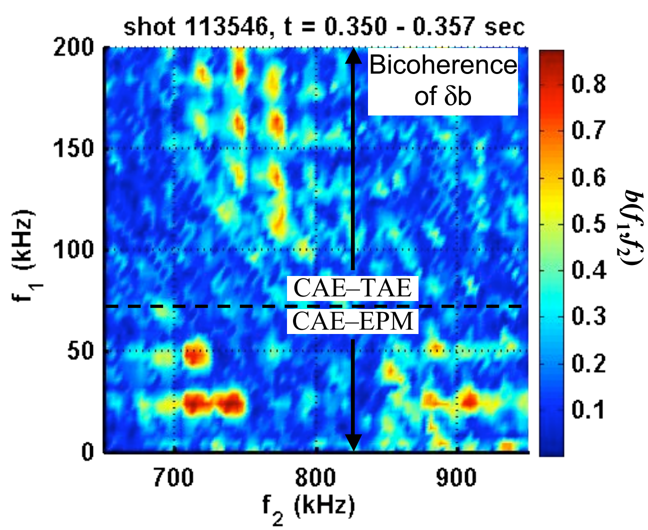




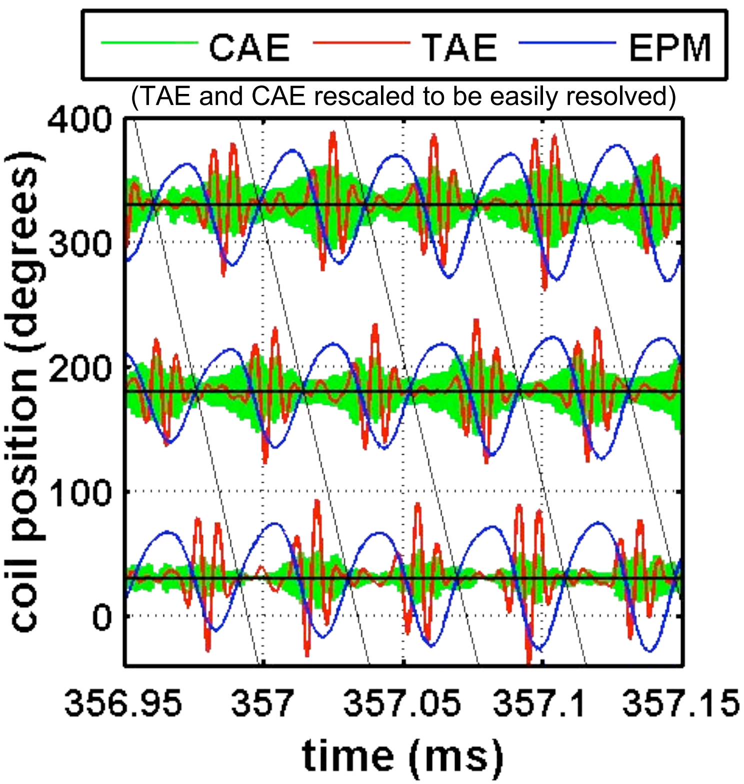
Three-wave interactions observed between CAEs and both TAEs and EPMs

- CAEs: $f \sim 690 - 925$ kHz, $n = -12 – -3$
- Two groups: $n = -12 – -7$ and $n = -6 – -3$
  - uniformly spaced in each group: $\Delta f \sim 25$ kHz, $\Delta n = 1$
- Neighboring CAEs form triplets with EPM
  - Within each group, $\Delta f = f_{EPM}$ and $\Delta n = n_{EPM}$
- Dominant TAE ($n = 5$, $f \sim 135$ kHz) forms triplet with one CAE from each group:
  - For n = -3 and n = -8, $\Delta f \sim 135$ kHz, $\Delta n = 5$ …
- Interacting triplets show high bicoherence
  - Other EPMs and TAEs also form triplets





Interaction with EPM forms TAEs and CAEs into toroidally localized wave-packets

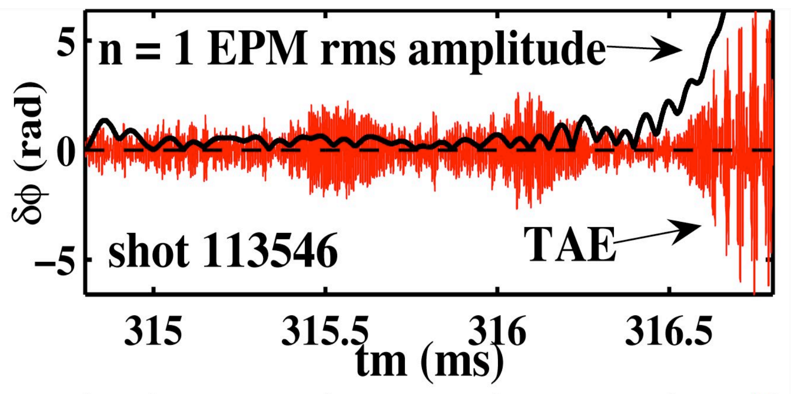


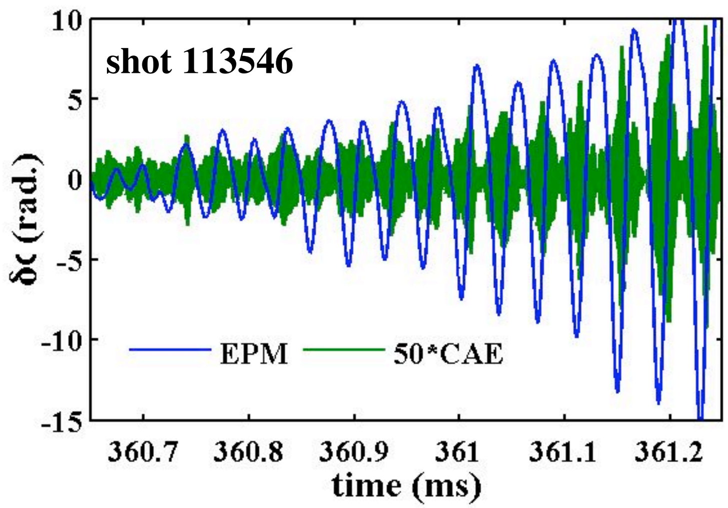
Amplitude modulation is three-wave interaction:

$$\{A_0+\delta A\cos(\omega_2 t)\}\sin(\omega_1 t) =$$
$$A_0\sin(\omega_1 t) + (\delta A/2)\{\sin([\omega_1+\omega_2]t) + \sin([\omega_1-\omega_2]t)\}$$

- Bandpass filtering δb isolates total EPM, total TAE and total CAE
- TAE and CAE amplitudes are modulated - correlates with EPM
- Comparing toroidal locations shows modulation “propagates” with EPM

Three-wave interactions necessary for wave-packets to form





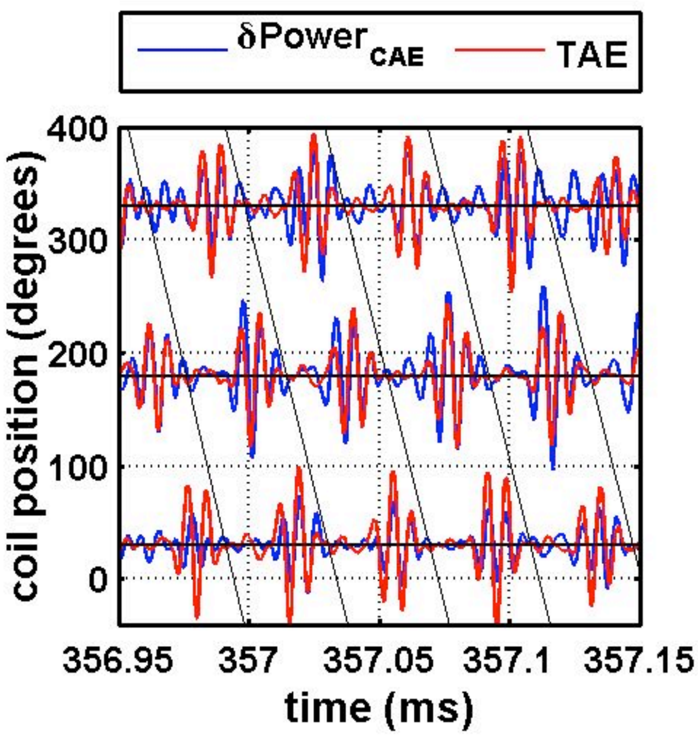
- TAEs and CAEs frequently active without EPMs
- TAE and CAE modulated ONLY when EPM active

Interaction with TAEs subdivides CAE wave-packet

- Total CAE fluctuation power is time-dependent
  - power calculated by averaging square of CAE fluctuation over CAE period

$$\mathrm{Power}_{\mathrm{CAE}}(t) = \int_{t-T_{\mathrm{CAE}}}^{t} dt' \left|\delta b_{\mathrm{CAE}}(t')\right|$$

- Bandpass filtering CAE power in TAE frequency range shows ~ 10 % modulation of total power
- Modulation highly correlated with TAE wave-packet at multiple toroidal locations



Conclusions

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Future work

- Use code such as ORBIT to calculate impact of wave-packet on fast-ion orbits
- Use NOVA-K linear code to determine energetics of three-wave interaction (e.g. non-linear energy transfer between modes)
- Experimentally assess effect of three-wave interaction on fast-ion transport in NSTX
- Look for evidence of three-wave interaction in other devices, such as DIII-D

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